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Development of the Lower and Middle Old Red Sandstone sedimentary basin in eastern Sutherland, North-West Scotland

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Pracę tą dedykuję swoim rodzicom

Dedicated to my parents

ABSTRACT

The Golspie basin is a NE-SW trending, marginal component of the post- or late-orogenic Old Red Sandstone Orcadian basin. Structural evidence indicate the Late Caledonian strike-slip as a logical framework for initiation of the Old Red Sandstone sedimentation in the area. Deposits of the Golspie basin are represented by two sequences of the Lower and the Middle Old Red Sandstone age separated by an angular unconformity.

Up to 400 m thick basal conglomerates of the Beinn Lunndaidh Formation (BLF), most extensively developed along the southern and the western margin of the basin, represent deposits of alluvial fans whose sedimentation was dominated by deposition from debris flows (Facies B and B1), often accompanied by sheetflood sedimentation (Facies C). The NE edge of the basin is fringed by sheetflood fanglomerates of Facies C1, whose maximum thickness is 180 m.

Although the fault-controlled basin margins provided a physiographic framework for the alluvial fan development, sediment supply appears to have been a significant factor controlling the distribution and the diversity in style of the sedimentation. While the texturally homogeneous, sheetflood arkoses of Facies C1 represent a classical example of first-cycle sedimentation, the textural heterogeneity of the debris flow deposits of Facies B and B1 (i.e. presence in the same beds of chaotically distributed bimodal and polymodal textures, common bimodal-only beds, abundance of sandstone matrix (locally of distinctly different provenance than the gravel fraction - Facies B1), presence of outsize semi-lithified sandy intraclasts) strongly suggests that the debris flow-dominated alluvial fans were supplied by pre-existing, sand-enriched gravels, which had undergone a significant size segregation prior to resedimentation, remoulding with sand, and the deposition on the alluvial fans as debris flows. Although, clast composition of the BLF conglomerates mimics lithology of the adjacent Caledonian basement, diverse degree of clast roundness additionally indicates presence of the resedimented (second-cycle) deposits as well as a possible first-cycle component.

The textural signatures of Facies B and B1 also suggest a cohesive nature of the debris flows. The cohesion factor might have been imparted not merely by

electrostatic/electromagnetic interactions between clay particles but also by chemical bonds of early cements, present in the source sediments prior to the mobilisation. Deposits transitional between the debris flow and the sheetflood conglomerates have been recognized as subordinate.

In the southern part of the Golspie basin, the development of gravelly alluvial fans was dramatically succeeded by sandy stream flow/sheetflood sedimentation (Facies G2) which resulted in the deposition of the over 600 m thick Beinn a' Bhragaidh Member(Glen Loth Formation). As a result of poor exposures it is impossible to infer detailed palaeodispersal and to correlate these deposits with distinctly different sediments of the Beinn Dhorain Member and the Ben Uarie Member (BDM and BUM), appearing above the BLF fanglomerates in the northern sector of the basin.

In response to subsidence in the area of Glen Loth the sheetflood-dominated alluvial fans were brought into fan-delta-related interplay with a lacustrine environment, which was abundantly, externally supplied with exotic mud. This transgressive scenario is reflected in a dramatic, fining-upward transition from the BLF into the BDM. The subaqueous setting of the resulting fan-delta was dominated by cohesive mudflow sedimentation, and *en mass* mixing of the fan-borne, first-cycle gravels with the second-cycle lacustrine sediments. The resulted Facies E1 and E2 are characterised by shear-layering reflecting predominant laminar flow conditions (layer-parallel extension and shearing) during the mass flow emplacement. The main part of the BDM consists in the majority of the subaqueous mudflow deposits of Facies E2 derived from the north. An analogous fan-delta environment is represented by the lowest part of Ousdale Mudstones in Badbea basin, although here it was succeeded by stream flow and by lacustrine sedimentation (Facies G1).

In the continuously subsiding northern sector of the Golspie basin the mudflow sedimentation of the BDM was followed by a northward emplacement of cohesive sandy debris flows of Facies F1 and sheetfloods of Facies F2. These well sorted very fine- to fine-grained sandstones make the up 150 m thick Ben Uarie Member (BUM). Various palaeocurrent data consistently indicate that intrabasinal uplift in the central part of the basin might have been responsible for the mobilisation of the pre-existing, considerably reworked sands and formation of extensive sandy aprons.

Sedimentation of the Middle Old Red Sandstone Beinn Smeorail Formation (BSF) was preceded by a phase of local folding and erosion of the lower group of the infill of the basin, possibly related to the strike-slip activity of the Great Glen Fault system. The development of the BSF resembles the general palaeogeographic scenario of the BLF. While in response to the rejuvenation of the source areas the second-cycle debris flow-domianted alluvial fans formed along the western margin of the basin (Facies Band B1), the first-cycle, locally derived sheetflood and stream flow fans developed at the eastern margin (Facies C1 and C2). However, unlike during the period of the BLF sedimentation, when the thickest fanglomerates formed in the south, the depocenter of the BSF sedimentation was located in the northern part of the basin. A new element in the development of the Golspie basin, associated with the BSF sedimentation was an additional westward and south-westward component of palaeodispersal indicating at least temporary isolation of the Golspie basin from the east.

The dramatic passage of the BSF into sandstones of the Col-bheinn Formation (CbF) reflects a phase of widespread recession of the alluvial fan sedimentation. At Leadoch Rock and at Duchary Rock the transition is represented by sandstone sheetflood and debris flow deposits which formed at the toe of the retreating Oldtown-Killin Rock fan.

Upper part of the CbF represents probably fluvial system analogous to Facies G2 and dispersing to the NE.

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LIST OF PLATES

Chapter 7.2.

Chapter 7.4.

LIST OF SOME COMMONLY USED ABBREVIATIONS

RCGC - Rogart Central Granodiorite Complex

RMC - Rogart Migmatite Complex

BLF - Beinn Lunndaidh Formation

GLF - Glen Loth Formation

BDM - Beinn Dhorain Member

BUM - Ben Uarie Member

BBM - Beinn a' Bhragaidh Member

BSF - Beinn Smeorail Formation

CbF - Col-bheinn Formation

MPS - maximum particle size

BTh - bed thickness

LPS - largest particle size

PLF - low-grade metamorphic, pelitic lithic fragments

PPL - plain-polarized light

XPL - cross-polarized light

AV - average

C - claystone

S - siltstone

SS - sandstone

VFG - very fine-grained

FG - fine-grained

MG - medium-grained

CG - coarse-grained

VCG - very coarse-grained

CGL - conglomerate

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1. Introduction and objectives of the present study

Most of the research works concerning the deposits of the Orcadian basin have been focussed on the distal, fluvio-lacustrine sediments, which in fact dominate the exposed infills of the basin (Rayner, 1963; Donovan, 1971, 73, 75, 80; Donovan & Foster, 1972; Donovan *et al.*, 1974; Donovan *et al.*, 1976; Donovan & Collins, 1978; Fannin, 1969, 70; Friend & Williams, 1978; Astin, 1985; Parnell, 1985; Melvin, 1985; Richards, 1985a,b; Trewin, 1976a,b, 1986). The proximal, mainly very coarse, conglomeratic sediments, occurring along the western marginal zone of the Orcadian basin have attracted so far little attention and have not been studied in detail. Read *et al.*(1925) remark on the deposits of the Golspie basin (their *Brora Outlier*): "The strip of Old Red Sandstone on the east side of the gneisses is sufficiently typical but presents no characteristics of distinctive importance". The works of Armstrong (1964), Stephenson (1972), Mykura (1983b) and Mykura & Owens (1983) are rather general in nature with emphasis on elucidating the structural arrangement of the Old Red Sandstone deposits.

Allen (1981) interprets the Rova Head Conglomerate, from the base of the Middle Devonian, fluvio-lacustrine sequence in SE Shetland, as fanglomerates represented mainly by longitudinal bar deposits. Sweet (1985) documents proximal and distal alluvial fan, playa lake and stream channel facies from the Lower Old Red Sandstone of Turriff basin.

The present study is the first extensive, detail approach toward understanding of sedimentology of the proximal conglomerates and the associated deposits from the Orcadian basin. In spite of the small size, the Golspie basin whose outcrop is 32 km long and 4 - 7.2 km wide, has been selected as the area of study because of the relatively good degree of exposure and absence of considerable deformations. Consequently it has been possible to map and correlate many of the sedimentary units in the basin. The structure of the outcrop and position of Golspie basin with regard to the surrounding Caledonian basement, suggest that it might represent an individual, marginal Old Red Sandstone sub-basin, possibly with its own distinctive dispersal systems (Mykura, 1983a).

The palaeogeographic reconstructions for the Old Red Sandstone proximal sedimentation further south in the Foyers, Mealfuarvonie and Struie areas (Mykura, 1983b; Mykura & Owens, 1983) are very general and highly speculative because of the problems with correlation of the tectonically juxtaposed sedimentary units and lack of palaeoflow indicators (?).

The prime objective of the present facies analysis-based approach is to clarify the aspects of environment of sedimentation and sediment sources for the infills of the Golspie basin, and to establish a sequence of events which lead to the creation of the present structure of the basin. The textural and the petrographic signatures of the proximal conglomerates, fringing the basin margins carry also a particularly "good quality" record of the provenance of the sediments entering the basin.

It is believed that the proximal facies of the Orcadian basin, although clearly subordinate to the fluvio-lacustrine deposits, should represent a subtle, direct and well pronounced form of the sedimentary response to the external factors controlling the development of the basin (tectonism, sediment supply, climate) (Steel, 1976, 80; Steel *et al.*, 1977; Steel & Gloppen, 1980; Steel *et al.*, 1985). This is particularly the case in the circumstances of lack of reliable data regarding history of subsidence in the Old Red Sandstone basins in the area (Enfield & Coward, 1986, 87; Kirton & Hitchen, 1987). In the process of the studies the lithostratigraphic division of the deposits of the Golspie basin has been modified.

An attempt has been made to evaluate a feasibility of reliable inferences of a particular style of the tectonic control over the development of the Golspie basin (extensional versus strike-slip), basing purely on the recognized model of sedimentation and the provenance. These considerations are particularly engrossing in the light of of the recently polarized views concerning the nature of the tectonism of the Orcadian basin and other Old Red Sandstone basins in Scotland (Astin, 1985; Enfield & Coward, 1986, 87; McClay *et al.*, 1986; Frostick & Reid, 1987; Trewin , 1985; Watson, 1984, 85; Smith & Watson, 1983; Bluck, 1984,85).

2. Methodology and approach

2.1. Field methods

Approximately 8 months of field study over a period of 4 summers (1983, 1984, 1985, 1986) were conducted in the course of this project, the bulk of which was occupied with detailed sedimentological work in the Golspie basin. Reconnaissance studies in the Badbea and Braemore basins to the north were carried out to investigate possible equivalents to the deposits of the Golspie basin.

A facies analysis approach was used to interpret in detail sedimentary processes responsible for formation of the studied deposits. Such an approach may involve various levels of interpretation of a sedimentary environment (e.g. ripple migration -> turbidity current -> deep sea fan progradation) (Anderton, 1985). In the thesis the level of the undertaken facies analysis changes, and while e.g. Facies E1 and E2 represent a very specific type of mass flow deposition and essentially differ with each other only with regard to textural characteristics; Facies G1, G2 and C2 comprise deposits representing a much wider range of sedimentary processes within the interpreted fluvial and alluvial fan environment. This apparent methodological "inconsistency" is a result of poor quality of data available in the latter case, owing to limited exposures not allowing to maintain a constant level of analysis. The adopted herein approach enables also to elucidate textural evolution of the involved sediments.

The sedimentary sequences were described through detailed one-dimensional logging and recording of structural and textural characteristics, bed shape, bed thickness, bed contacts (when possible), grain size and fabric. The maximum particle size (MPS = mean of 10 largest clasts locally in bed after omitting the largest and the smallest) was determined for the conglomerates.

Clast composition of the gravel fraction was determined by counting clasts in selected sites and their proportions were calculated according to size. Roundness of the clasts was estimated visually using chart after Powers (1953). The accuracy of the visual comparison is low and for the same grains different operators may estimate roundness values that differ by whole roundness class (Blatt, *et al.* 1980). Nevertheless it was attempted to gather at least most significant differences and trends in the degree of clast roundness between the studied conglomeratic units. Analogous roundness estimations were applied to sand fraction in the study of thin sections.

Selected outcrops, horizons, beds and sets of beds were mapped in detail (occasionally with a help of earlier taken photographs) in order to depict two-dimensional variability with regard to the above mentioned characteristics and to appreciate nature of lateral relationships between the facies.

Mapping was carried out in selected "suspect" zones of the basement adjacent to the outcrop of the Golspie basin in order to locate possible faults.

2.2. Laboratory methods

Many sedimentary features of the deposits of Facies E1, E2, E3 and F1 were described from the cut and polished large slabs up to 30 cm in size and 40 thin sections. 5 selected thin sections were examined under cathodoluminescence microscope with a view to recognize possible generations and other features of the carbonate component.

A total of 95 thin sections of sandstones and sandstone matrix from the conglomerates was examined in order to:

(1) establish composition and its trends;

(2) describe textural features (particularly with regard to the matrix material);

(3) determine types of cement;

The examination of the textural features of the matrix in thin sections was supplemented by scanning electron microscopy (SEM). A total of 15 samples of clay fraction separated from the matrix of Facies B, E1, E2 and the mudstones of Facies G1 was examined through X-ray diffraction (XRD) in order to determine clay mineralogy. Organic matter, iron oxides and carbonates had been chemically removed prior to the analyses.

3. Orcadian basin and position of the Golspie basin

The Orcadian basin is a vast structure, located astride the NE termination of the Great Glen Fault in Northern Scotland, Orkney and Shetland (Fig. 3.1. & 3.2.). The size of the basin is unknown for the majority of its outcrop continues under the North Sea. The Orcadian basin is mainly inffiled by rocks of Middle Old Red Sandstone age. Over 5 km of strata are present in Caithness, with possibly up to 10 km in Shetland. The major part of the Middle Old Red Sandstone in Caithness and Orkney consists of the Caithness Flagstone Group (> 3.8 km thick) and its correlatives, which contain an abundant fauna of fishes at several horizons (e.g. Achanarras Limestone). It is underlain by Lower and Middle Old Red Sandstone conglomerates resting unconformably on the highly deformed and metamorphosed rocks of the Caledonian province. The NW part of the basin is underlain by the Moine metasediments. To the SE of the Great Glen Fault the Moine as well as the Dalradian rocks represent the substrate of the basin. Small, isolated Old Red Sandstone outliers scattered west (Tongue, Kirtomy, Strathy, Ben Griams) and south (Rhynie, Gamrie, Turriff basin) of the main outcrop may be regarded as remnants of the most marginal deposits of the Orcadian basin. Because the Middle Old Red Sandstone commonly rests directly on the basement, it is likely that it was more extensive than the Lower Old Red Sandstone (Watson, 1985); Ziegler (1982), however, represents both Lower and Middle Old Red Sandstone as co-extensive.

The western edge of the main outcrop of the Orcadian basin is commonly defined by vertical to high-angle faults trending parallel to the Great Glen Fault and roughly follows the structural grain in the basement (Fig. 3.2.). In Caithness the basin margin has an irregular outline. The southern margin of the outcrop of the basin appears to transect both the structural grain and the faults of the basement (Watson, 1985), although the isolated outliers like Rhynie, Gamrie and the small outcrop SE of Inverness are bounded by the NE-SW trending faults.

The deposits of the Orcadian basin are generally weakly deformed and non-metamorphosed.

In the southern part of the basin, in the vicinity of the Great Glen Fault the Old Red

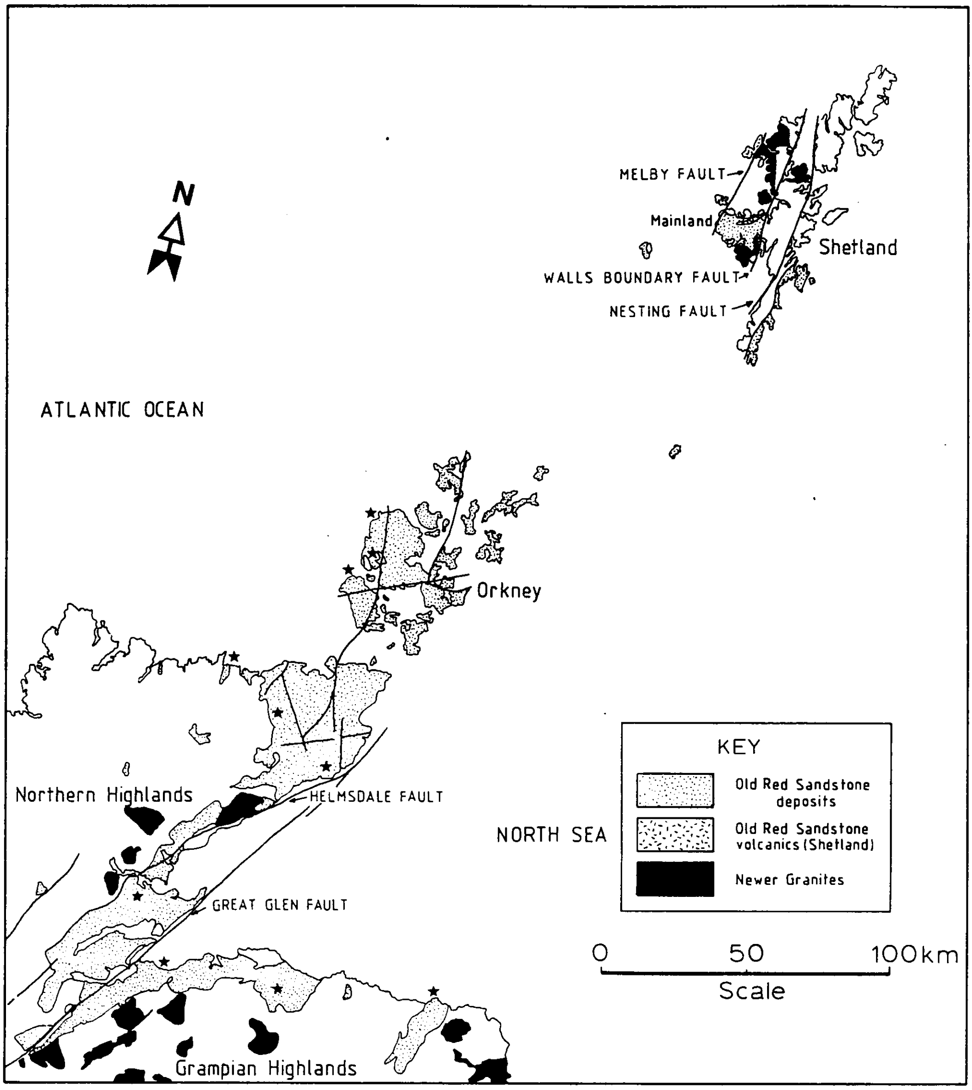


Figure 3.1. Generalized map of the outcrop of the Old Red Sandstone Orcadian Basin including Shetland. ★ Achanarras limestone horizon and equivalents. (After Donovan *et al.*, 1976 and Friend & Williams, 1978)

Sandstone is involved in folds, trending generally parallel to the vertical or high-angle faults (Crampton *et al.*, 1914; Read *et al.*, 1925; Mykura, 1983b; Mykura & Owens, 1983; Watson, 1985). Conjugate folds with geometrical effects of reversed faults are not uncommon and small thrusts occur both within the succession and at certain basement contacts (Mykura, 1983b; Mykura & Owens, 1983; Armstrong, 1964, 1977; Watson, 1985). For example in the Lower Old Red Sandstone Mealfuarvonie outlier the major NE-SW trending folds pre-date the gently inclined thrusts, which cut steeply inclined strata. The thrusting might have, however, been the final manifestation of the compressive stresses which gave rise to the folds (Mykura & Owens, 1983). The relationship of thrusting to folding appears to be the same as in the Middle Old Red Sandstone of the Foyers area, where the Devonian NNW movement of thrust sheets is postulated (Mykura, 1983b). In Orkney and Caithness the tracts between fault zones are characterised by very open, upright folds (usually with N or NW axial trend) that are traversed by steep, narrow monoclines or zones of minor folding (Watson, 1985). From the same area Enfield and Coward (1987) present evidence for folding and faulting associated with the low-angle thrust systems and sinistral strike-slip faults which pre-date intrusion of late Permian dykes. The major N-S trending transcurrent faults, which pass through Shetland Mainland separate three distinct Lower Old Sandstone sequences (Mykura, 1976; Mykura & Phemister, 1976). The Walls and Sandness formations, separated by major N-S trending Melby and Walls Boundary faults, were affected by two episodes of tight N-NNE trending folds. A penetrative cleavage and a lineation were locally developed in the finer sediments during both periods of folding (Donovan *et al.*, 1976; Mykura & Phemister, 1976; Mykura 1983a). Prior to the first folding episode the Walls Formation was intruded by the late Caledonian Sandwick Plutonic Complex (360 ± 11 Ma and 369 ± 10 Ma, K-Ar), which produced a thermal aureole up to 2 km wide (Mykura, 1983a).

Volcanic rocks. In the Orcadian basin the Old Red Sandstone volcanics occur in four horizons.

In Shetland they are represented by the Lower Old Red Claust Volcanics, made up of basaltic and andesitic lavas, rhyolitic ignimbrites, tuffs, several cones of predominantly acid agglomerate and some concordant intrusions of felsite and by the Middle Old Red

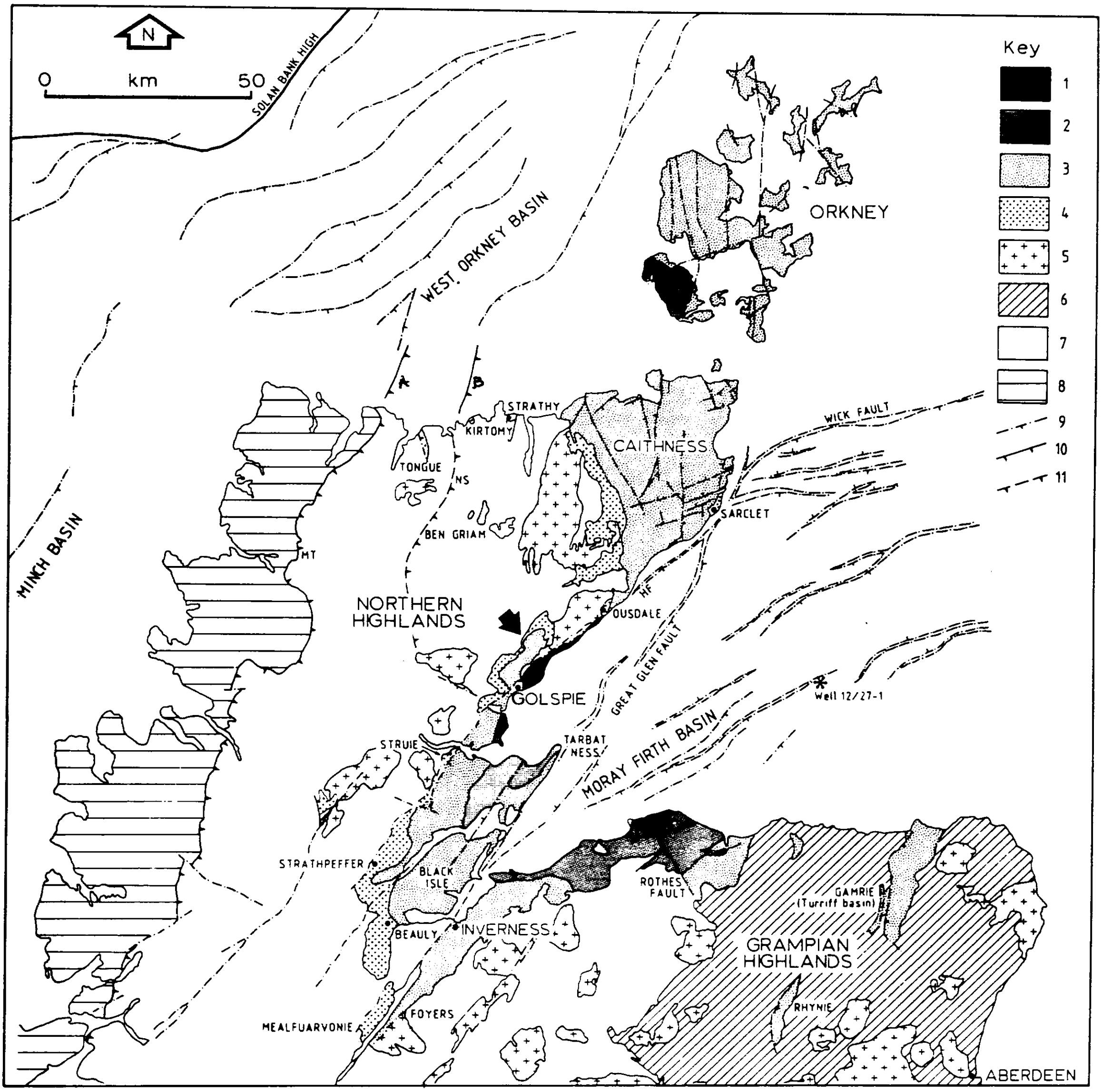


Figure 3.2. Geological map of the outcrop of the Orcadian basin and the surrounding terranes. The outcrop of the Golspie basin is arrowed. Compiled from: Geological Survey "Ten-Mile" map (Sheet One); IGS Sheet 58NO4W (Caithness); Kirton & Hitchen (1987, fig.3); Mykura & Owens (1983); Blackbourn (1981b). **KEY**: **1**- Mesozoic rocks; **2** - Upper Old Red Sandstone; **3** - Middle Old Red Sandstone; **4** - Lower Old Red Sandstone; **5** - granites; **6** - Dalradian Supergroup; **7**- Moine Series; **8** - Lewisian & Torridonian; **9** - faults; **10** - thrusts (MT - Moine Thrust; **A, B** - possible positions of the Moine Thrust after Brewer & Smythe (1984)); **11** - Naver Slide (NS); **Well 12/27-1** (Lower Old Red Sandstone deposits described by Richards (1985b)).

Sandstone rhyolites, underlying the Melby Formation and which are probably contiguous with the volcanic succession of the neighbouring island of Papa Stour (Mykura & Phemister, 1976; Mykura, 1983a). The latter comprises a lower sequence of basalts overlain by flows of rhyolite, each overlain by the rhyolitic tuff. The probable northward continuation of this volcanic suite crops out at on NW Mainland where it contains, in addition to basalts and rhyolites, higher flows of mugearite and andesite, thick deposits of andesitic agglomerate, as well as a rhyolitic ignimbrite (Mykura, 1983a). Thirwall (1979) has shown that on geochemical grounds, the Shetland lavas have some characteristics transitional between calc-alkaline and tholeitic types.

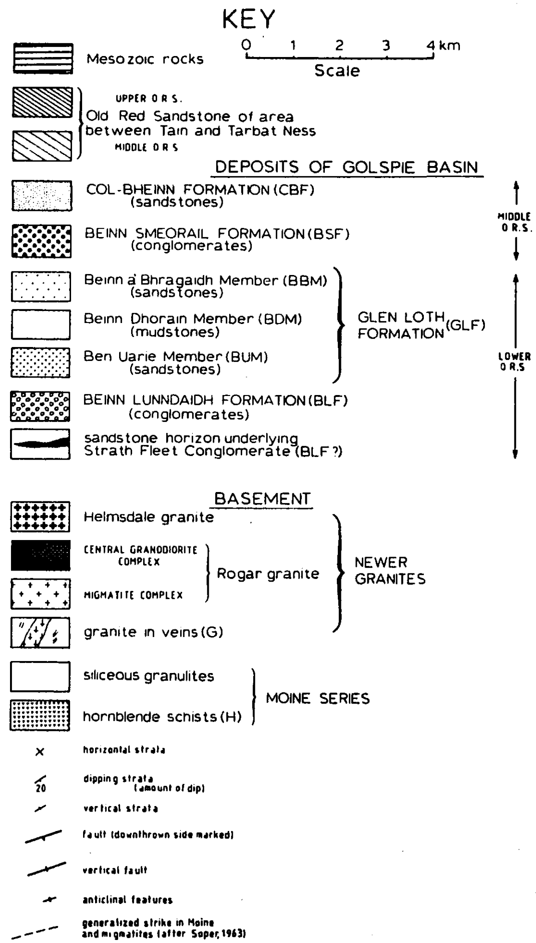
In Orkney the Lower Old Red Sandstone calc-alkaline basalts, tuffs and minor intrusions occur within the Eday Flags (Thirwall, 1979; Mykura, 1983a). The Upper Old Red Sandstone Hoy Sandstone is underlain by tuffs and tuffaceous sandstones. These are overlain by akaline basalts (Mykura, 1983a; Thirwall, 1979).

It is worth to mention that as far south as Scarlet the Lower Old Red Sandstone Scarlet Conglomerate Formation, derived from the SE, contains abundant basalt clasts, which suggest a contemporaneous volcanism (Mykura, 1983; Storhaug & Storetvedt, 1985).

Position of the Golspie basin

The Golspie basin belongs to the western, marginal zone of the Orcadian basin. Its 4 - 7.2 km wide outcrop extends for 32 km NW of Brora. High relief of the outcrop of the Golspie basin is in a marked contrast to the eroded crystalline Moine basement on the west and to the low coastal plain of Mesozoic sediments lying on the east. The western edge of the basin is defined by the prominent escarpment which runs from Ben Tarvie in the south through Mound Rock, Cnoc na Gamhna, Meal Horn, Kilbraur Hill, Beinn Smeorail to beyond The Craggan. The eastern margin of the basin is defined by escarpments of of Ben Uarie, Beinn Dhorain (the highest elevation in main area of study), Creag a' Chrionaich, Killin Rock. Further to the south the eastern limit of the outcrop of the basin is defined by the prominent Helmsdale fault.

Loch Fleet and Loch Brora transect the outcrop of the Golspie basin in its southern and in the middle part respectively.


KEY
0 1 2 3 4 km
Scale
Mesozoic rocks
UPPER O.R.S.
Old Red Sandstone of area between Tain and Tarbat Ness
MIDDLE O.R.S.
DEPOSITS OF GOLSPIE BASIN
COL-BHEINN FORMATION (CBF) (sandstones)
BEINN SMEORAIL FORMATION (BSF) (conglomerates)
MIDDLE O.R.S.
Beinn a Bhragaidh Member (BBM) (sandstones)
Beinn Dhorain Member (BDM) (mudstones)
Ben Uarie Member (BUM) (sandstones)
GLEN LOTH FORMATION (GLF)
BEINN LUNNDAIDH FORMATION (BLF) (conglomerates)
sandstone horizon underlying Strath Fleet Conglomerate (BLF ?)
LOWER O.R.S.
BASEMENT
Helmsdale granite
CENTRAL GRANODIORITE COMPLEX
MIGMATITE COMPLEX
Rogar granite
granite in veins (G)
NEWER GRANITES
siliceous granulites
hornblende schists (H)
MOINE SERIES
horizontal strata
dipping strata (amount of dip)
20
vertical strata
fault (downthrown side marked)
vertical fault
anticlinal features
generalized strike in Moine and migmatites (after Soper, 1963)

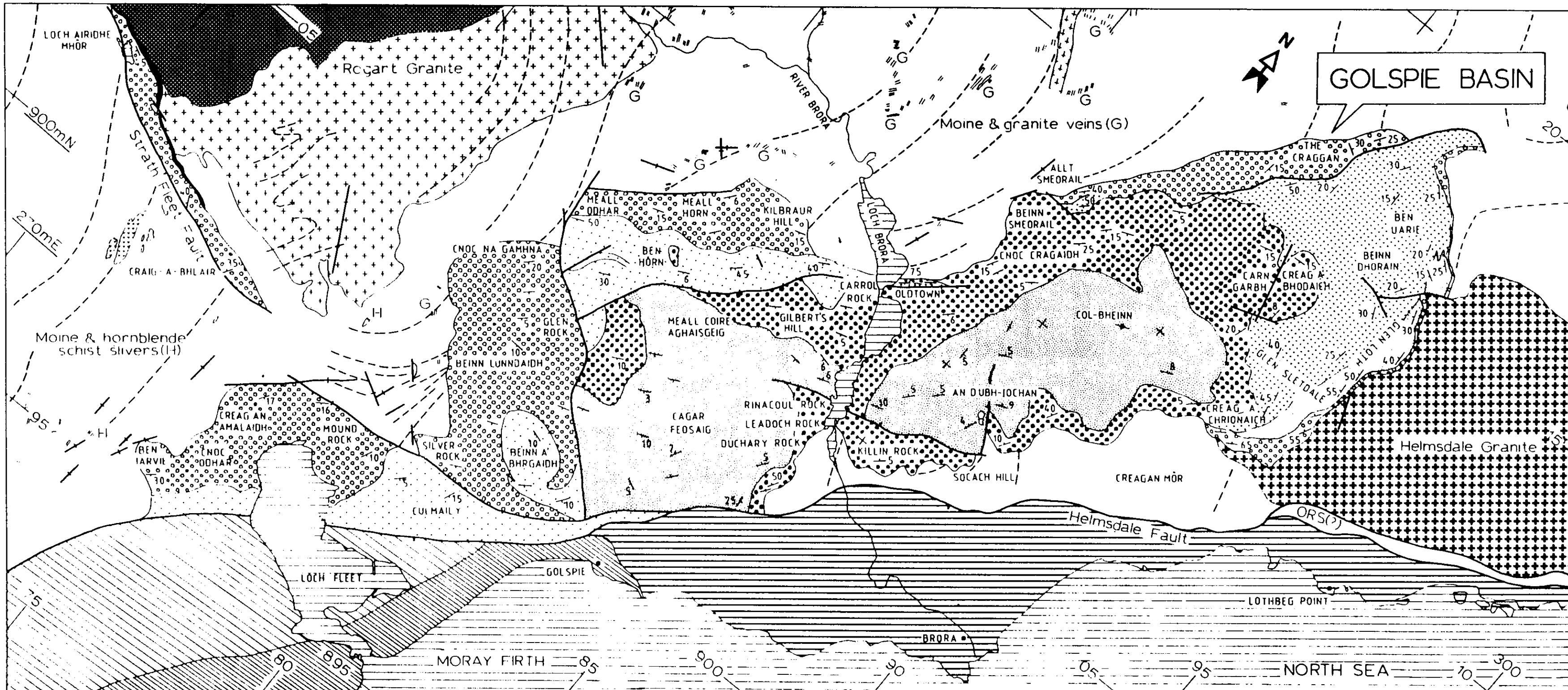


Figure 3.3. Geological map of the outcrop of the Golspie basin based on: Scotland sheet 103 (Read *et al.*, 1925), author's data, IGS Sheet 58NO4W (1: 250 000) and data from Soper (1963).

4. Geology of the substrate of the Golspie basin

4.1. Moine Series

The substrate of the Golspie basin is dominated by the metasediments of the Moine Series, which are represented by the Morar Division and the Migmatitic Complex of eastern Sutherland (Johnstone *et al.*, 1969; Johnstone, 1975). The unmigmatized metasediments are distinctive of the Morar Division but are also a significant component of the migmatitic complex NW of the Rogart intrusion.

The dominant type of metasediments is a pink or gray siliceous granulite, occasionally massive, but usually flaggy with foliation planes defined by thin micaceous layers. Mineral assemblages range from quartz-andesine to quartz-microcline-oligoclase-biotite-(muscovite). With an increase in mica the granulites grade into homogeneous, darker grey semipelites or strongly banded types consisting of psammitic and pelitic bands. Two fairly distinct types of semipelite may be distinguished, one microcline-free, the other microcline-rich, with oligoclase/andesine-biotite-quartz-(almandine) and microcline-oligoclase-biotite-quartz-(muscovite) assemblages respectively. Garnet is rarely abundant in the semipelites but is widely distributed in the microcline-free types, usually as very small anhedral grains. Petrographic details of the rocks of the Moine Series are given in the British Geological Survey Memoirs (Read *et al.*,1925; Read *et al.*, 1926).

According to the metamorphic zonal map prepared by Winchester (1974) the Golspie basin is located astride the boundary between the zones of sillimanite and kyanite - the minerals which became stable during the Caledonian metamorphism (see further in text).

Linear structures from the unmigmatized Moine rocks reveal system of folds with axes plunging to the ESE (Soper, 1963). Poor exposure and the rarity of distinctive lithological units render it impossible to trace the closures of major folds in this group, and north of the Strath Fleet fault minor folding is uncommon. Folds with gentle SE plunges occur throughout central Sutherland. Soper (1963) suggests that the attitude of the folds in the Rogart area may be related to deformation during the emplacement of the central granodiorite (see further in text).

South of Strath Fleet fault, quartz veins are involved in the folding and become rodded and disrupted. The veins appear to have been emplaced during the folding. The presence of occasional undeformed aplite veins cutting linear structures associated with these folds indicates that the phase of folding and quartz veining pre-dates the Newer Granite activity.

The linear structures associated with this fold system include mullions, grooving and corrugation of foliation surfaces in granulites, mineral orientation in pelites and amphibolites and, as already mentioned, the incipient rodding of vein quartz. Lineations plunging to the SE or ESE are of widespread occurrence in the Moine rocks throughout Sutherland; the fold phase with which they are associated was accompanied by the last major Caledonian metamorphic episode which, in the Rogart area, produced the equilibrium assemblages of almandine-amphibolite facies mentioned above. Structural evidence of earlier phases of folding and metamorphism is limited in the Rogart area to rare isoclinal fold closures which are refolded by minor, SE plunging folds. The schistosity and compositional banding, although largely coincident with the original bedding, are probably related to an earlier phase of deformation, and by analogy with other Moine areas where overprinting has been less intense, more than one such phase may have occurred. In the absence of direct evidence of the nature of the earlier phases the SE plunging fold system is designated F_1 (Soper, 1963).

The bulk of the strain during the Caledonian deformation in the Northern Highlands took place in 456 - 440 Ma period (Fettes *et al.*, 1986), with the last contractional slip in the Moine thrust belt dated at 425 Ma ago (Johnson *et al.*, 1985).

Butler and Coward (1984) and Butler (1985) propose a model of "thin - skinned", foreland-propagating thrust tectonics involving development of three duplexes and associated estimated minimum 140 km shortening. In order of their development they are: 1) the interthrust of Moine and Lewisian rocks of the Moine thrust sheet, 2) the imbricates of Cambrian, Torridonian and Lewisian rocks within the Moine thrust belt, 3) a crustal duplex of Lewisian basement.

According to the "deep crustal" model proposed by Soper and Barber, (1982), Blundell (1984), Blundell *et al.*(1985) the crustal thickening in the Northern Highlands was achieved by imbrication of thrust flakes from the SE, in which the thrust front propagated northwards into the foreland and at the same time cut down so that the basal decollment deepened relative to the Moho, and eventually into the mantle. Sinistral strike-slip is suggested to have been superimposed on the shortening events (Hutton, 1987). Soper and Barber (1982) estimate that 21.5 km were eroded during the period of shortening between c. 480 Ma and 420 Ma and further 11 km subsequently in response to the continuing uplift up to the Lower Devonian. Thus the present day crust in the Northern Highlands for the most part should represent the lower crust of the Caledonian orogen, though perhaps modified during its subsequent history.

The late Ordovician age(456 - 440 Ma) of the crustal thickening is in the variance with the timing of the orogenic events in the Grampian Highlands (c. 500 Ma). The uplift ages are similar on both sides of the Great Glen Fault and are as late as 407 ± 18 Ma in the north (Miller & Brown, 1965) and 387 ± 6 Ma in the south (Pidgeon & Aftalion, 1978).

4.2. Newer Granites

In late Silurian times the metamorphosed and deformed Moine Series in the area was intruded by Newer Granites - Rogart granite(420 ± 30 Ma, K-Ar, Brown *et al.*, 1968) and Helmsdale granite(c. 420 Ma,U-Pb; 400 ± 15 Ma,K-Ar, Pidgeon & Aftalion, 1978).

4.2.1. Rogart granite (Read *et al.*, 1925; Soper, 1963; Brown *et al.*, 1968)

The Rogart igneous complex extends over 72 km^2 between Strath Fleet Fault and Strath Brora. The complex consists of two principal components termed by Soper (1963) *central granodiorite complex* and *migmatite complex.*

The Rogart central granodiorite complex (40 km^2) is a composite body composed of tonalite, porphyritic hornblende-biotite-granodiorite and biotite granite. The tonalite occurs at the margin of the body (except along the southern boundary, which is formed by the Strath Fleet Fault) and grades inwards into porphyritic granodiorite; the biotite-granite has a sharper, cross-cutting relationship to both.

<u>The tonalite</u> Along the eastern and most of the northern margin of the central granodiorite complex the outer tonalite is in contact with the fringing migmatite complex and the two groups are generally concordant. In the NW the tonalite is in discordant contact with the unmigmatized Moine metsediments. The tonalite consists of plagioclase (An_{20} to

An_{25}), microcline microperthite, quartz, hornblende and biotite with minor sphene and accessory apatite, magnetite, zircon, orthite and epidote. An average modal composition is given by Soper (1963). The tonalite is variable in both in mineralogy and texture, the most widespread type being an even-grained grey rock with foliation defined by the planar orientation of minerals, the plane flattening of inclusions, and less commonly, by a poor compositional banding.

At extreme margin of the central granodiorite complex a narrow zone of tonalite shows evidence of reaction with the enclosing migmatites. It contains a higher proportion of potassium feldspar and less hornblende than the normal tonalite, is finer-grained and has a characteristic streaky appearance owing to the presence of inclusions.

The porphyritic granodiorite With an increase in grain size and abunndance of feldspar phenocrysts the tonalite grades inwards into porphyritic hornblende-biotite-granodiorite. An average modal composition indicates that in comparison with the tonalite the porphyritic granodiorite is richer in potassium and quartz and poorer in ferromagnesian minerals, particularly hornblende (Soper, 1963).

The biotite-granite constitutes a minor proportion of the central granodiorite complex (2 km^2). It is a coarse, pink, homophanous rock with subhedral potassium feldspar crystals surrounded by aggregates of anhedral quartz and plagioclase. Biotite is subsidiary, and hornblende appears as a accessory constituent. The rock is adamelite and shows an increase in potassium feldspar and quartz and a decrease in mafic minerals as compared with the granodiorite.

Veins in the central granodiorite complex are of the following types in order of abundance: aplite, pegmatite and compound pegmatite-aplite, biotite-microgranodiorite, microdiorite and porphyritic granodiorite.

The migmatite complex

To the east and north of the central granodiorite complex the Moine metasediments are involved in a peripheral zone of migmatization. South of Strath Fleet Fault the country rock are unmigmatized. There is a general increase in the degree of migmatization towards the tonalite contact. Soper (1963) recognized three zones of progressive migmatization, the boundaries of which are completely gradational. The *outer zone* corresponds broadly to the "zone of appohyses" in Read *et al.*(1925) the *intermediate* and *inner* zones to the "zone of inclusions".

The outer migmatite zone. The outer margin of this zone has been drawn where the siliceous granulites lose their characteristic flaggines owing to the welding of foliation planes. Within the zone, lineation on the foliation surfaces becomes progressively obliterated. Textrally the granulites and semipelites are recrystalized to a coarser texture. The igneous portion of the migmatites is a variable biotite-granodiorite that first appears along the movement planes in the metasediments as diffuse veins. These stringers of migmatitic granodiorite become more frequent towards the inner part of the zone and may widen into cross-cutting masses. The concordant granitic material and the metasediments are cut by parallel-sided pegmatite and aplite veins and by discordant or irregular masses. These veins occur throughout the Moine rocks outside the zone of migmatization but become much more common at the edge of the complex.

The intermediate migmatite zone In this zone concordant "igneous" material constitutes between 1/3 and 2/3 of the entire rock. Foliation in the metasedimentary portion loses its consistent orientation over small areas and developes swirls and contortions, particularly in the pelitic horizons, and shows evidence of extreme plasticity. Relationships between migmatitic granodiorite and rock of recognizable metasedimentary origin are complex, but distinctive types of migmatite are developed from the various metasedimentary hosts.

Banded granulites give rise to *lit-par-lit* migmatites in which coarsely recrystalised psammitic material is interbedded with biotite-poor migmatitic granodiorite.

Abundance of cross-cutting granitic material is present in the intermediate migmatite zone. Stuctureless or poorly foliated pink, biotite-poor aplitic granodiorite occurs as dykes or large masses throughout the migmatites.

The inner migmatite zone In this zone which borders the central granodiorite complex to the east, migmatitic granodiorite is predominant over metasedimentary material. The zone is absent the northern margin where banded migmatites of the intermediate zone are in xenolithic contact with the tonalite. The irregular swirling of the foliation characteristic of the intermediate zone gives place to a more ordered system of syn-migmatization folds. *Lit-par-lit* migmatites persist into this zone, discrete bands of psammitic material maintaining sharp contacts with the migmatitic granodiorite.

Although the migmatites are genetically related to the central igneous complex they are not in a static contact-effect. Sóper (1963) suggested that the ascending body of granodiorite magma was preceded by "front" of migmatization which it eventually overtook and continued forceful intrusion, deforming the migmatites into a plastic envelope around the expanding body of magma.

4.2.2. Helmsdale Granite (Read et al., 1925; Tweedie, 1979; Pidgeon & Aftalion, 1978; Torsvik & Storetvedt, 1987)

The Helmsdale granite extends between Golspie and Badbea basin and covers an area of around 100 km^2 (Fig. 7.2.22.). Along the NW margin the granite is in a sharp contact with the Moine metasediments. In the west the granite is unconformably covered by the Ousdale Arkose Conglomerate(Beinn Lunndaidh Fm.). Along the SE margin the granite is separated from the Old Red Sandstone deposits(?) and Jurassic sediments by Helmsdale fault. In the Badbea basin the Ousdale Arkose Conglomerate rest unconformably on the granite, although at Ceann Ousdale the cliff exposure shows a fault contact between the granite and arkoses (Fig. 7.2.22.).

The Helmsdale granite is represented by two main types: 1) a pink, coarse-grained porphyritic adamelite which occupies an outer zone and is roughly parallel to the western margin of the granite and has an average width of 1.6 km; 2) a fine-grained, pink adamelite which occupies the central and NE portion of the intrusion (Fig. 7.2.22.). A variety with scarce phenocrysts (intermediate type) appear next to the porphyritic type. It is probably safe to assume that the Helmsdale fault does not represent the eastern limit of the intrusion and that the ring of coarse, porphyritic granite extended further to the NE (Read *et al.*, 1925).

The porphyritic type of Helmsdale granite is composed of orthoclase, plagioclase and quartz with a small proportion (c.5%) of mafic minerals of which the chief is biotite. Orthoclase occurs as anhedral crystals up to 5 cm long and as interstitial grains which with quartz form the base of the rock and enclose crystals of plagioclase. The plagioclase which is always considerably decomposed has an approximate composition $Ab_{90}AN_{10}$. A characteristic feature is enclosure of small perfect plagioclase crystals in the phenocrysts of microperthite(poikilitic texture). Quartz forms small interstitial grains in the plagioclase clusters, but mainly builds spherical aggregates, often 1.6 cm across. Biotite forms thick prisms, about 1 mm long, usually altering to chlorite and iron-oxide.

The fine-grained less porphyritic, intermediate type still presents all the above features, the only difference lying in the smaller size of the phenocrysts and quartz aggregates.

The fine-grained type of the Helmsdale granite consists of anhedral plates of orthoclase usually from 1 to 2 mm in size, euhedral and subhedral prisms of oligoclase, and anhedral grains of quartz larger than those of orthoclase. The plagioclase appears to be fairly consistently an acid oligoclase, slightly more basic than the plagioclase of in the porphyritic type.

All types of the Helmsdale granite contain accessory zircon, apatite, magnetite and altered sphene.

The granite is pervasively jointed and fractured. The zones of fractures and shear permited enrichment in uranium (locally up to 70 ppm) (Tweedie, 1979). The U mineralisation is associated with potassic alterations (affecting only the fine-grained type) and with formation of limonite and hematite sealing fractures and cracks in all varieties of the granite.

The mode of emplacement of the Helmsdale granite intrusion remains unknown.

5. Structure of the Golspie basin

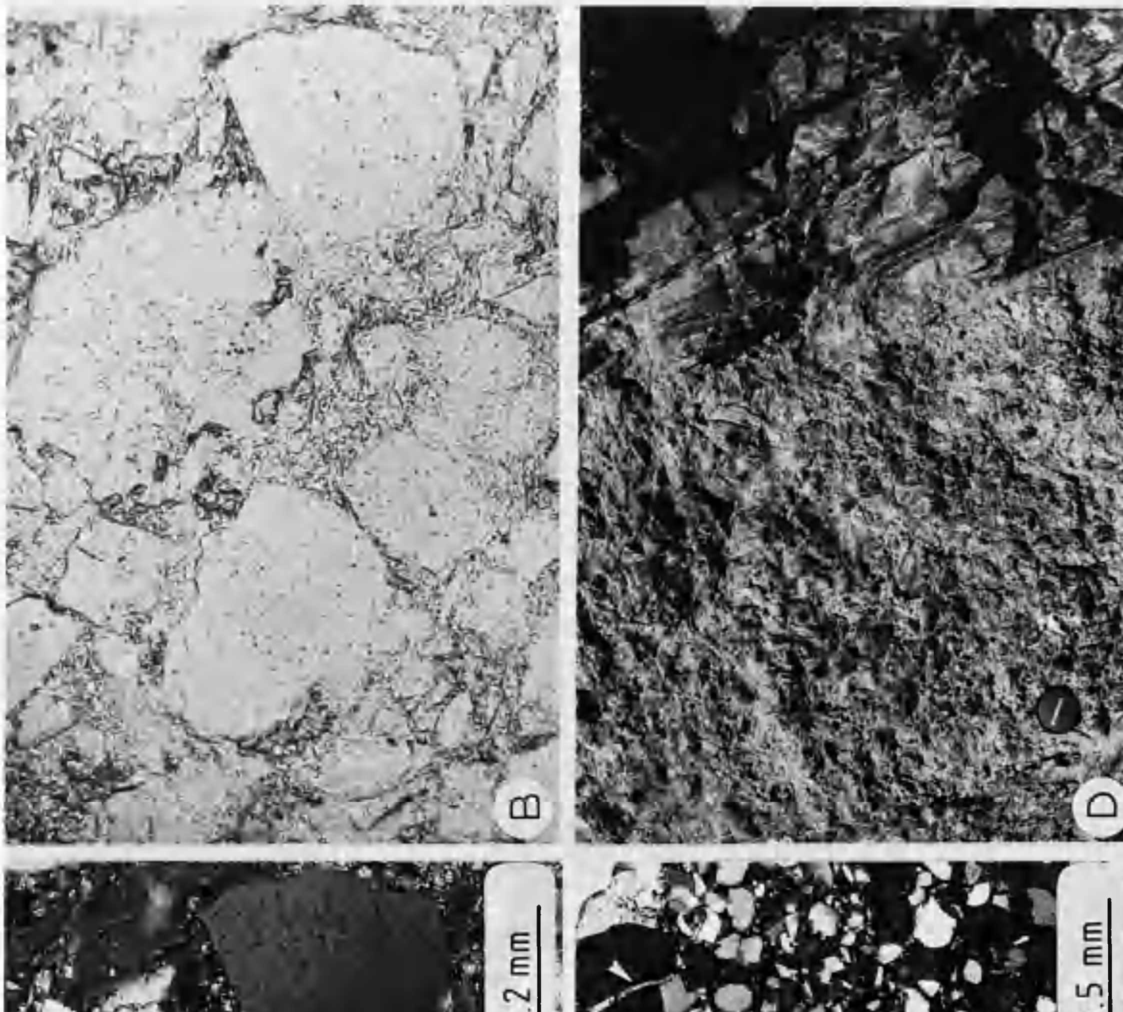
In the southern part of the outcrop of the Golspie basin the basal conglomerates of the Beinn Lunndaidh Formation and the sandstones of the Glen Loth Formation(Beinn a' Bhragaidh Member) lie undisturbed with a uniform gentle SW dip. In the remaining portion of the corresponding sediments are folded in a marked syncline (Fig. 3.3.). The axis of the syncline is almost parallel to the western margin, passing to the NE from Glen Rock to a point about 2 km NNW of Ben Uarie. Here the outcrop of the basin terminates and two limbs of the syncline come together in a narrow wedge.

Plate 5.1. A-D: Cataclasites associated with vertical to high-angle faults mapped in the vicinity of the outcrop of the Golspie basin.

Photomicrographs **A-C** show a characteristic mortar texture - quartz clasts surrounded by recrystallized fine quartz and mica matrix. In **C** the arrows point to tensional cracks filled with calcite affecting quartz clasts. **A** & **C** - XPL, **B** - PPL (Locality: N of Mound Rock [NH 768 995]);

D: Vertical sheet of cataclasite cutting Moine metasediments. Lens cap is 5 cm wide (Locality: W of Silver Rock [NH 784 998]).

Plate 5.1.



The syncline is cut by numerous vertical to high-angle faults. The NE-SW trending system is most prominent and some of these faults bound the basin from the NW (the faults NW of Creag an Amalaidh and Meal Horn) and from the SE - Helmsdale fault. The latter is a major dislocation with the SE downthrow.

The effect of combined folding and faulting which succeeded the deposition of the Beinn Lunndaidh and Glen Loth Formations is seen in the steep, SE dip of the sandstones of the latter formation to the west of the fault line between Ben Horn and Oldtown, and again along the eastern edge of The Craggan and NE of it. Along this fault line the westerly dipping sandstones of the Glen Loth Formation (Ben Uarie Member) on the eastern limb of the syncline are downthrown against the easterly dipping basal conglomerates of the western limb (Beinn Lunndaidh Fm.).

The eastern edge of the Golspie basin is defined by the roughly N-S trending margin of the Helmsdale granite. Here the arkoses and the mudstones of the Ousdale Arkose Conglomerate (BLF) and mudstones of the Beinn Dhorain Member (GLF) are steeply inclined basinward. Furhter to the S the SE basin margin is defined by the elevated ridge of the Moine metasediments.

The conglomerates of the Beinn Smeorail Formation(BSF) rest unconformably upon the eroded surface of the steeply inclined sandstones and mudstones of the Glen Loth Formation (see chapter 7.4.2.). and on the eastern margin of the outlier overlap on to the Ousdale Arkose Conglomerate (Beinn Lunndaidh Fm.), and finally rest direcly upon the Moine basement exposed between Creagan Mor and Killin Rock. In the west the conglomerates appear to overstep the fault line and form the hight of Beinn Smeorail and the high ground to the NE of it. South of Loch Brora the outcrop of the BSF conglomerates is truncated by the Helmsdale fault, while on the western side of the basin it is limited by the fault running from Glen Rock to Oldtown, and on the southern edge by the fault running SW of Meal Odhar towards Golspie.

The sandstones of the Col-bheinn Formation which form the highest outcrop occupy the centre of the basin. They are almost horizontally bedded and build up the mass of Col-bheinn to the north and Meal Coire Aghaisgeig and Cagar Feosaig to the south of Loch Brora.

The N-S and NW-SE trending faults are less abundant and the one most prominent of them runs SW of Meal Odhar.

Planes of the majority of faults located within the outcrop of the Golspie basin are not exposed. Only at Oldtown the fault plane is seen and is represented by a vertical, 1m thick sheet of cataclasite. At the latter dislocation the near horizontal conglomertes of the Beinn Smeorail Formation are faulted against the steeply dipping sandstones and conglomerates of the Glen Loth and Beinn Lunndaidh formations. The fault-splays mapped in the Moine basement in the vicinity of the outcrop of the basin are also defined by vertical to high-angle sheets of cataclasite which are in sharp contact with the undeformed siliceous granulites (Plate 5.1.D)

Cataclasis of the Moine granulites associated with the faulting lead to generation of mortar texture in which angular porphyroclasts of granulite are set in a fine-grained aggregate of quartz and mica (Plate 5.1.A-C). Locally the granulite or individual quartz phenocrysts are affected by extensional cracks sealed with sparry calcite, which probably post-dated the cataclasis. The Moine basement which is exposed between Mound Rock and Beinn Lunndaidh is considerably affected by joints and transected by NW-SE trending vertical sheets of cataclasite.

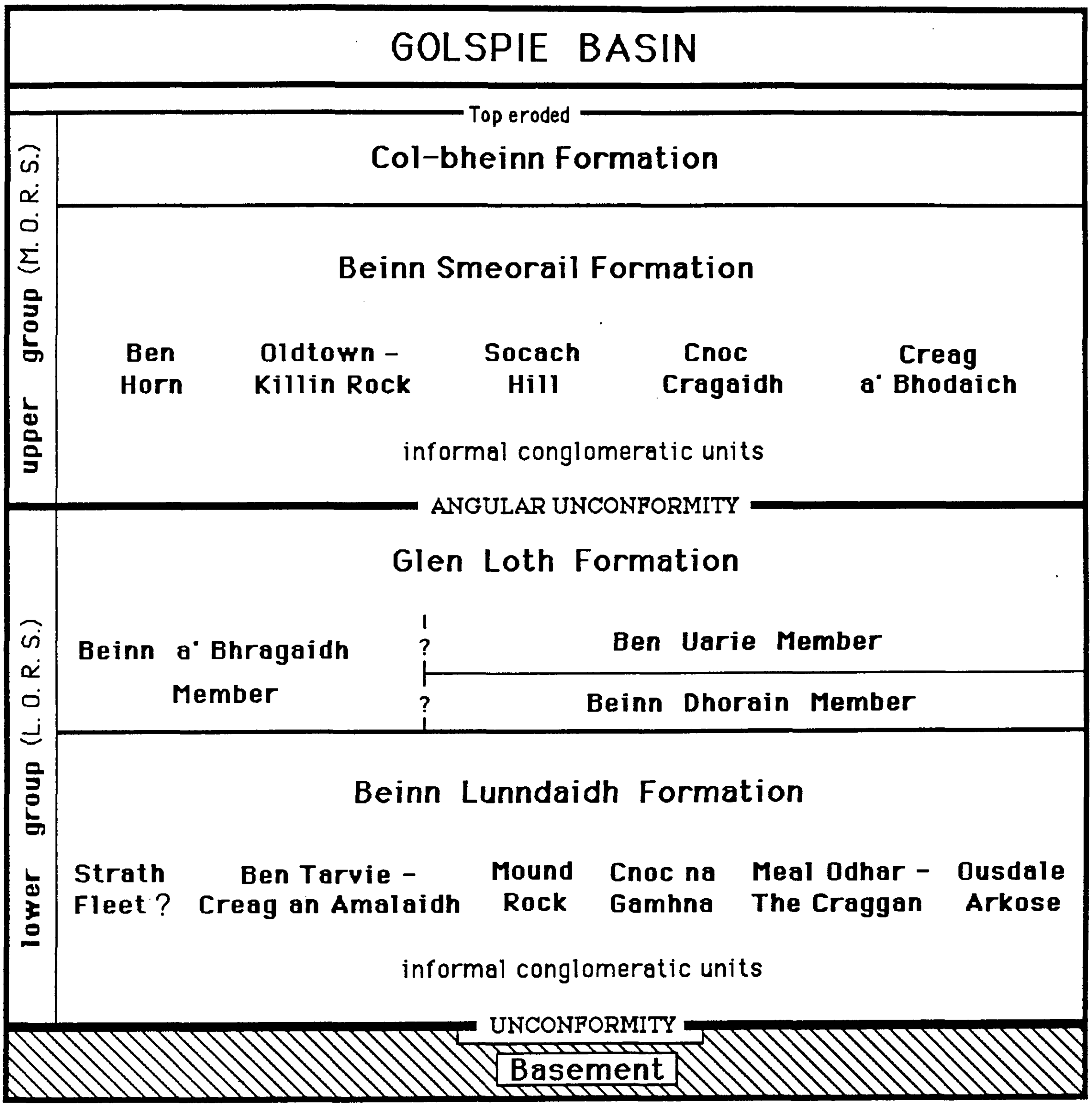
The southern boundary of the Rogart complex is formed by the Strath Fleet Fault, which consists of series of crush-splays trending NWW-SEE. Along the principal Strath Fleet Fault the unmigmatized Moine metasediments are brought against the central granodiorite complex or migmatites overlain by the Strath Fleet Conglomerate (BLF ?). Widespread hematization and cataclasis occurred in all the rock-types present in the crush-zone and are particularly strongly developed on either side of the main fault (for details see Soper, 1963,p. 466). Recognition of the complex history of movement (Soper, 1963) indicates that the dislocation is a high-angle fault, downthrown to the S before the deposition of the Old Red Sandstone and subsequently reactivated to a limited extent in the opposite sense.

6. Age of the infill of the Golspie basin

No fossils have been found in the lower group of the Golspie basin BLF and GLF)

Figure 6.1. Lithostratigraphic correlation chart showing position of the infills of the Golspie basin in relation to the Old Red Sandstone deposits of the areas south and north of the basin (see Fig. 3.2.). Modified after Mykura (1983a, Table 8.1.).

	Strathpeffer, Beauly and Black Isle	Tain to Tarbat Ness Peninsula	Golspie Basin	Badbea Basin	Braemore Basin
M.O.R.S.	Gentle folding, producing slight angular unconformity	Period of folding, faulting and thrusting of Struie Group sediments over Moine basement at Struie	Col-bheinn Formation	Berriedale Flagstone Formation Berriedale Sandstone Formation	
M.O.R.S.			Beinn Smeorail Formation	Badbea Breccia	Conglomerates of Morven, Smean & Maiden Pap
			ANGULAR UNCONFORMITY		
L.O.R.S.	Strathpeffer Group	Struie Group (Absent in Tarbat Ness)	Glen Loth Formation	Ousdale Mudstones	Braemore Mudstones & Sandstones
L.O.R.S.	BASAL CONGLOMERATE AND BRECCIA	BASAL CONGLOMERATE AND BRECCIA	Beinn Lunndaidh Formation	Ousdale Arkoses	Braemore Conglomerate & Breccia
			UNCONFORMITY		
	Basement				



? Position of the Strath Fleet Conglomerate is tentative

? Relationship between the Beinn a' Bhragaidh Member and the other members of the Glen Loth Foramation is unceratain

Figure 6.2. Lithostratigraphic chart of the deposits of the Golspie basin. Modified from Mykura (1983a, Table 8.1.).

and its Lower Old Red Sandstone age is inferred on account of lithological similarities with the documented Lower Old Red Sandstone deposits to both south and north (Mykura, 1983a).

Greenish shales of Ousdale Mudstones (Facies G1, Badbea basin, Fig. 7.2.22.) yield moderately well preserved, slightly carbonized spores which indicate Lower Emsian age (Richardson, 1967; Collins & Donovan, 1977). This age is supported by the presence of *Pachytheca* (first recorded plant from the Moray Firth area) and *Porolepis* scales (Collins & Donovan, 1977). The Ousdale spore assemblage is comparable with the flora recovered from the Strathpeffer Group (probable equivalent of the lower group in the Golspie basin) (Fig. 6.1.) and to the flora from the Strathmore Beds (Midland Valley (Richardson, 1967).

At Sarclet (Fig. 3.2.) the grey-green mudstone intercalated with the Ubster/Ires Geo Sandstone Formation yield an assemblage which most likely to be Upper Emsian age (Collins & Donovan, 1977).

Spore population recovered from siltstones (Mealfuarvonie Outlier, Inverness-shire, Fig. 3.2.) is most comparable to the assemblages from the Strathmore Beds (=Strathmore Group ?) and Strathpeffer Group and have been designated a late Emsian or earliest Eifelian age (Mykura & Owens, 1983).

The Middle Devonian age of the upper group of the sequence of the Golspie basin is tentatively inferred from the position of these deposits above the unconformity (Fig. 3.3. & 6.2.) (Mykura, 1983a)

7. Characteristics of the infill of the Golspie basin

7.1. Beinn Lunndaidh Formation (BLF)

7.1.1. Introduction

The Beinn Lunndaidh Formation (BLF) represents the lowest, basal sequence of the infill of the Golspie basin (Fig. 6.1., 6.2. & 3.3.). It is a lithostratigraphic equivalent of the *"Basal Conglomerate and Arkose"* in Read *et al.* (1925). The BLF is also a lateral equivalent of the *"Basal Conglomerate and Ousdale Arkose"* in Crampton *et al.* (1914). The formation is composed chiefly of coarse conglomerates and breccias that rest directly on the Caledonian basement which has made a direct contribution to the sediments.

Name of the formation has been introduced by Mykura (1983a), after the name of the prominent summit in the southern part of the basin, Beinn Lunndaidh. In fact, this area is dominated by the BLF conglomerates.

The present author has subdivided the BLF into six units which differ with regard to both clast composition and sedimentary characteristics (see chapters 7.1.5.2. & 7.1.5.3.). They represent six independent alluvial fans (or fan-systems). They are as follows:

(1) Ben Tarvie - Creag an Amalaidh Conglomerate;

(2) Mound Rock Conglomerate;

(3) Cnoc na Gamhna Conglomerate;

(4) Meall Odhar - The Craggan Conglomerate;

(5) Ousdale Arkose Conglomerate;

(6) Strath Fleet Conglomerate.

(1) Ben Tarvie - Creag an Amalaidh Conglomerate occupies the southernmost part of the Golspie basin and is represented by two interfingering conglomeratic bodies, differing with regard to textural features (Fig. 7.1.23.). The unit is also present at Mound

Rock where it forms the lower, around 200 m thick, half of the sequence (Fig. 7.1.24.). As the conglomerate is absent at Silver Rock it is understood that it wedges out north of Mound Rock. Limited exposure has precluded a reliable estimation of the original extent of this conglomeratic unit.

(2) Mound Rock Conglomerate partly covers the Ben Tarvie - Creag an Amalaidh conglomeratic unit. At the top of Creag an Amalaidh the contact is identified with a sudden (over 2 m of section) appearance of clasts of the Rogart Central Granodiorite Complex (RCGC) (Fig. 7.1.23.). A similar contact can be observed in the middle part of the Mound Rock sequence where the sudden introduction of the RCGC debris coincides with a rapid, though gradational increase in the maximum particle size (Fig. 7.1.24.) (see also chapter 7.1.5.2.).

(3) Cnoc na Gamhna Conglomerate is a minor, lensoid unit, stretching from Cnoc na Gamhna 1 to 2 (Fig. 7.1.25.). It underlies the Mound Rock conglomerate and probably rests directly on the basement. An estimated thickness of the conglomerate is around 20 m.

(4) Meall Odhar - The Craggan Conglomerate is represented by two horizons, which outcrop along the western margin of the Golspie basin (Fig. 3.3.). The conglomerate rests directly on the basement, though in places it is bounded from the west by vertical to high-angle faults.

(5) Ousdale Arkose Conglomerate outcrops along the NE margin of the Golspie basin (Fig. 3.3). It is, however, best exposed in the Badbea basin (Ousdale Arkose) in a cliff section at Ceann Ousdale, where it is faulted against the Helmsdale granite and against the Ousdale Mudstones (Fig. 7.2.22.).

(6) Strath Fleet Conglomerate forms a lenticular outcrop that stretches from Loch Airidhe Mhor to east of Creig-a-bhlair (Fig. 3.3. & 7.1.23.C). The eastern part of the conglomerate rests on the Moine metasediments. In the west, the rocks of Rogart intrusion form a substrate. A several meters thick sandstone horizon separates in places the conglomerate from the basement (see chapter 7.1.2.). The entire conglomeratic belt is bounded from the south by the vertical to high-angle, Strath Fleet Fault.

The above units have not been nominated as formal *members* because of their overall, significant compositional and sedimentological similarities. The author takes a view that the designating formal *members* on the grounds of subtle compositional and sedimentological aspects would not be fully justified and attempting doing so would not serve a useful purpose (see Hedberg, 1976, p. 33). Analogous reasoning applies to nominating informal conglomeratic units in the Beinn Smeorail Formation (see chapter 7.4.).

Some of the conglomeratic units of the BLF are also referred to in the text as "fans" (e.g. Mound Rock fan). The units differ mainly with regard to clast composition although the Ousdale Arkose Conglomerate and the Strath Fleet Conglomerate display also distinctly different facies characteristics (chapters 7.1.5.2. & 3.).

7.1.2. Relationship of the BLF with the Caledonian basement - lower boundary

The contact of the BLF with the underlying basement is either a high-angle to vertical fault or an unconformity. The former relationship is apparent NW and N of Creag an Amalaidch and Mound Rock respectively. NW of Meall Odhar and Meall Horn the conglomerates of the BLF are separated from the basement by a vertical fault. The Strath Fleet Conglomerate is bounded by the Strath Fleet Fault from the SW.

The unconformity between the BLF and the basement can be observed in three localities:

(1) 50 meters north of Loch Airidhe Mhor, a sandstone which is a few tens of meters thick directly covers an undulating surface of the central granodiorite of the Rogart intrusion (Rogart Central Granodiorite Complex in Soper (1963)) (Plate 7.1.1.A). The granodiorite below the unconformity is considerably weathered. Both sandstone strata as well as the surface of the unconformity dip to the SW at 45^{o}. This sandstone horizon appears to be discontinuous and underlies the main sequence of the Strath Fleet Conglomerate (Fig. 7.1.23.). In spite of the vicinity of the contact with the granodiorite the sandstone contains no coarse arkosic detritus and it is a fine- to medium-grained, very well sorted lithic arenite with cross-bedding, possibly of aeolian origin. The cross strata could

Plate 7.1.1. A: Well sorted, fine-grained sandstone resting directly on the granodiorite (Rogart Central Granodiorite Complex). The sandstone is probably of aeolian origin (see Plate 7.1.11. D). Lense cap is 5 cm wide (Locality: Loch Airidhe Mhor, BLF ?);

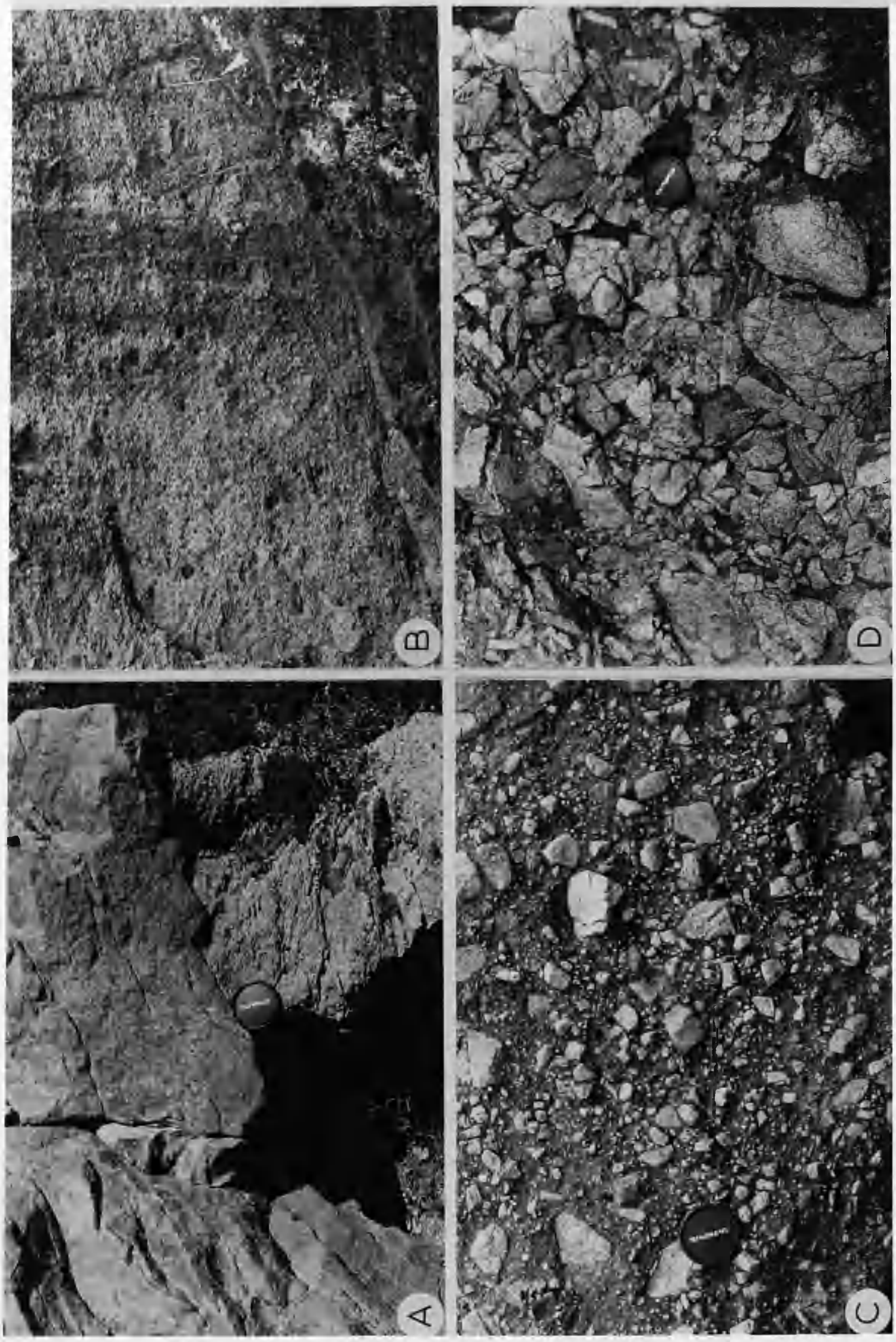
B: Amalgamated debris flow units of Facies B1. Scale (arrowed) is 2 m long. (Locality: Creag an Amalaidh [NH 763 985], BSF);

C & D: Photographs taken 2 m apart demonstrate the textural heterogeneity of the debris flow deposits of Facies B;

C: Poorly sorted, polymodal conglomerate;

D: bimodal and polymodal texture (upper left corner). Lense cap is 5 cm wide. (Locality: Allt Smeorail, BLF)

Plate 7.1.1.



not be examined in detail and measured because of the very limited exposure.

(2) At the summit Kilbraur Hill (323 m), massive conglomerates have been found resting on the Moine siliceous granulites. This local rise of the basement probably represents an original Old Red Sandstone topographic feature buried under the BLF deposits. The conglomerates dip to the SE at 15°. Their clast composition reflects the lithology of the basement. Many clasts are fractured without offset and this brittle deformation appears to be identical to the one, recognized in the basement below.

(3) At Killin Rock the basement has a topographic elevation of 130 m and is buried under nearly horizontal conglomeratic deposits.The basement surface dipping dramatically to the SW have conglomerates resting on the ancient basement slope and overstepping to the east. The exact lithostratigraphic position of these rocks is problematic and they may well belong to the Beinn Smeorail Formation (BSF) (see chapter 7.4.1.).

Analogous, eastward and south-eastward overstepping can be seen on the opposite side of Loch Brora, 500 m north of Duchary Rock. Clasts composition of the conglomerates on both sides of Loch Brora resembles the lithology of the basement outcropping to the SE. The strata at the latter locality are vertical or dip to the NW at 50°.

7.1.3. Distribution and thickness

The Beinn Lunndaidh Formation (BLF) dominates the southernmost part of the Golspie basin but forms also a somewhat almost continuous outcrop along its W and the NE margin. At Mound Rock it reaches its maximum thickness of around 400 m and thins to the SW and NE (Fig. 7.1.24.). At Creag an Amalaidh it is at least 170 m. At Beinn Lunndaidh and Meall Horn the estimated thickness is approximately 180 m. The BLF is probably absent between Kilbraur Hill and Beinn Smeorail except for Oldtown where its thickness is in a range of several meters (?). At Cnoc Cragaidh a few meters thick conglomerate, which underlies the Cnoc Cragaidh unit (BSF) my belong to the BLF (?) (Fig. 7.4.1.). It is impossible to determine, whether the BLF has been removed by denudation or has never been deposited in the area.

In the Allt Smeorail stream section the conglomerates of the BLF are only around 40 m thick and seem to thicken slightly to the NE, though poor exposure and variable dips do not permit to assesstheir thickness. NE of The Craggan the BLF terminates on the high angle fault.

Along the N and the NE margin of the basin, arkosic variety of the BLF conglomerates (Ousdale Arkose Conglomerate), adjacent to the Helmsdale granite, is normally 150 m thick. E of Creag a' Chrionaich it reaches up to 180 m in thickness.

The deposits of the BLF are either absent along the eastern margin of the Golspie basin or only maximum 11 m thick, assuming that the Socach Hill Conglomerate does belong to the BLF (?) (see chapter 7.4.2.).

7.1.4. Upper boundary of the Beinn Lunndaidh Formation

Over the most area of the Golspie basin the conglomerates of the BLF pass gradationally upwards into sandstones and mudstones of the Glen Loth Formation (GLF). The transition can be well seen at four localities.

(1) One kilometer east of Mound Rock and along the southern slope of Beinn Bhragaidh the conglomerates pass into pebbly sandstones and sandstones of the Glen Loth Formation (Beinn a' Bhragaidh Member), over the distance of a few meters. The boundary is inclined to the SE at around 10^{0} but the strata on the top of Beinn Bhragaidh are almost horizontal (Plate 7.2.21.A). Thus, there appear to be here a minor angular disconformity. The dipping contact may represent an original depositional surface of an alluvial fan system, which accumulated in the Mound Rock area (see chapter 7.1.5.3.).

(2) In the stream sections of Allt Smeorail (north of Beinn Smeorail) and in Glen Sletdale, before it joins Glen Loth [NH 935 127], the conglomerates of the BLF (Ousdale Arkose Conglomerate) pass rapidly into pebbly mudstones, and mudstones of the Glen Loth Formation (GLF) (Fig. 7.2.1).

7.1.5. Sedimentary characteristics of the Beinn Lunndaidh Formation

7.1.5.1. Main sedimentary facies

Four major facies are documented from the Beinn Lunndaidh Formation (BLF): **Facies A**: Disorganised conglomerates, **Facies B & B1**: Heterogeneous, structureless conglomerates (Mound Rock and Cnoc Cragaidh variety), **Facies C**: Homogeneous, stratified conglomerates (Mound Rock variety) and **Facies C1**: Homogeneous, stratified conglomerates (Ousdale Arkose variety).

They differ with regard to structure, texture, fabric and also to some extend in terms of clast composition. The best developed deposits of Facies B1 occur in the Beinn Smeorail Formation and are discussed in chapter 7.4.5.1.

7.1.5.1.1. Facies A: Disorganised conglomerates

Description

This is the least common conglomeratic facies recognized in the Beinn Lunndaidh Formation. Its occurrence is restricted to two localities. Along the northern bank of Loch Airidhe Mhor, Facies A makes up an over 90 m thick, coarsening-upward sequence (Fig. 7.1.23.B). West of Silver Rock the similar deposits form a several meters thick body which is in a vertical fault contact with the Moine basement (Plate 7.1.2.).

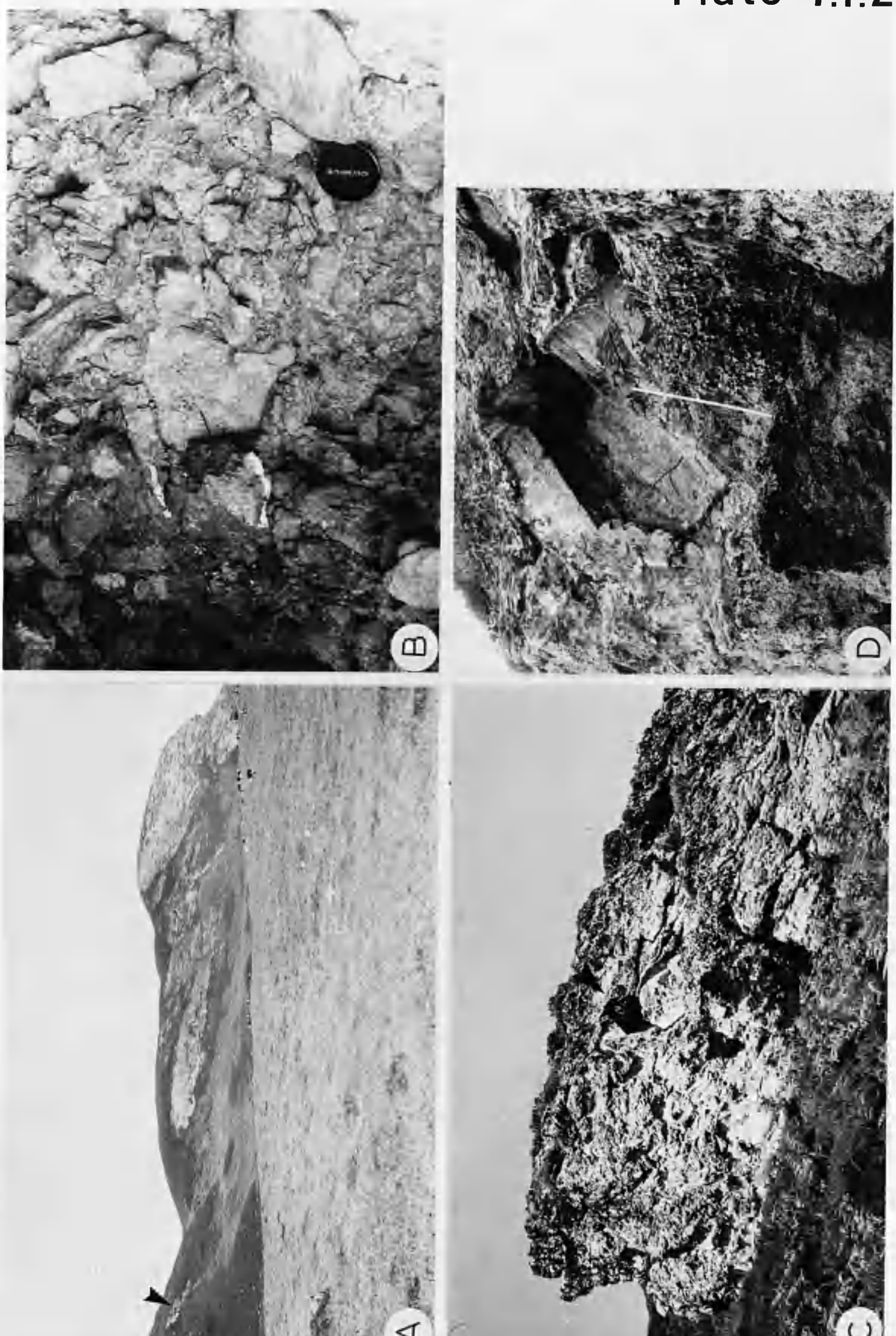
The deposits of Facies A can be classified as massive breccias or breccio-conglomerates with a chaotic fabric, composed predominantly of angular clasts varying from clay to boulders of up to 3 m in size (Plate 7.1.2.B-D) (Collinson & Thompson, 1982). However, the present author has decided to substitute the term "breccia" with a term "conglomerate", clearly specifying its structural and textural features.

The conglomerates of Facies A are mainly clast-supported, though finer-grained matrix normally fills spaces between particles. The matrix is poorly sorted, very coarse-grained sand with variable (0 - 20%) amount of clay fraction. The conglomerates are essentially

Plate 7.1.2. A: Photograph shows Silver Rock, which is composed of the conglomerates of Facies B and C (Mound Rock Conglomerate, BSF). Bedding is near parallel to the base of the photograph. The conglomerates are locally underlain by the deposits of Facies A (arrowed), resting directly on the basement;

Photographs **B** - **D** show characteristics of Facies A: lack of structure, clast-supported texture and outsize boulders (**C** & **D**). Lens cap is 5 cm wide. Scale is 2 m long. (Locality: W of Silver Rock [NH 790 997])

Plate 7.1.2.



texturally homogeneous and do not appear to be organised in recognizable beds or bed-like forms. Only at Loch Airidhe Mhor one sandstone bed identifies the general bedding.

Interpretation

In view of the extreme diversity in the clast size and the total lack of internal structure, the conglomerates of Facies A are seen as a product of *en mass* deposition of very poorly sorted gravels, possibly derived through redeposition of colluvial sediments.

The exceptionally large maximum particle size (over 100 cm) and lack of pronounced bedding suggest a very proximal environment of deposition.

Marginal **scree and landslide deposits** are regarded as a likely recent analog.

Unfortunately, the poor exposure and the overall scarcity of Facies A have probably precluded recognition of many features that might have revealed more about the origin and mechanism(-s) of the emplacement of the gravels. The conglomerates of Facies A closely correspond to the Middle Old Red Sandstone "breccia deposits" of the Farigaig Forest Formation and Dun Deardnil Granodiorite-Breccia Member (Inverness shire) interpreted by Mykura (1983b) as debris flow, scree and landslide deposits.

7.1.5.1.2. Facies B: Texturally heterogeneous, structureless conglomerates (Mound Rock variety)

Data regarding deposits of Facies B and C come primarily from exposures in the southern part of the basin: Ben Tarvie, Mound Rock, Silver Rock, Beinn Lunndaidh, Cnoc na Gamhna and Glen Rock (Fig. 3.3.). Additional information are derived from the conglomerates that form part the Beinn Smeorail Formation and are well exposed at Carrol Rock, Oldtown, Creag a' Bhodaich and Killin Rock.

Description

Conglomerates of Facies B are structureless, generally poorly sorted and matrix-clast supported. In contrast to the deposits of Facies A the conglomerates of Facies B are texturally heterogeneous (Plate 7.1.1.C & D) and the general bedding is better defined, owing mainly to the interbeddings of Facies C (Fig. 7.1.1a. - 1e., see also next chapter).

Maximum particle size (MPS = mean of ten largest clasts locally in bed after omitting the smallest and the largest clast) varies between 5-50 cm, averaging around 19-17 cm (Fig. 7.1.4.). It is characterised by a normal frequency distribution (Fig. 7.1.6.). Plots of the MPS against the largest particle size (LPS) in the beds reveal common presence of outsize boulders (Fig. 7.1.5.).

Although there generally seems to be a continuum in grain size from clay to boulders, the grain size distribution commonly varies from bed to bed as well as within individual beds. Most of them, although predominantly polymodal, contain irregular, diffuse patches displaying bimodal texture and these may be regarded as "gravelly intraclasts" derived from previous gravelly unit (Plate 7.1.1.D, 7.1.3.B&C; see also chapters 7.1.5.4., 7.4.1.1. & 7.4.5.1.6.). There is a smaller proportion of beds which are chiefly bimodal, and these again may contain areas with polymodal texture (polymodal intraclasts) (Plate 7.1.3.D & 7.1.4.B).

Matrix in the conglomerates of Facies B is normally poorly sorted medium- to very

Plate 7.1.3. Textural features of the debris flow deposits of Facies B.

A: Unremoulded early lamination is locally preserved in the matrix (arrowed). Lens cap is 5 cm wide. (Locality: Oldtown, BSF);

B: Debris flow conglomerates of Facies B are interpreted to have formed through redeposition of previously reworked gravels and sand. This is reflected in the textural heterogeneity of the structureless deposits of Facies B - patchy distribution of irregular clast- to matrix supported areas with variably of well sorted gravel fractions. (Locality: the same as above);

C: The arrow points to compressional ridges in the matrix developed around the rounded clast. (Locality: the same as above);

D: Matrix-supported, bimodal/polymodal bed of Facies B is erosionally covered by the finer-grained and polymodal conglomerate of Facies C. Note an outsize granodiorite clast in Facies B, projecting to the overlying bed, and near vertical orientation of the particles. (Locality: Silver Rock, BLF)

Plate 7.1.3.

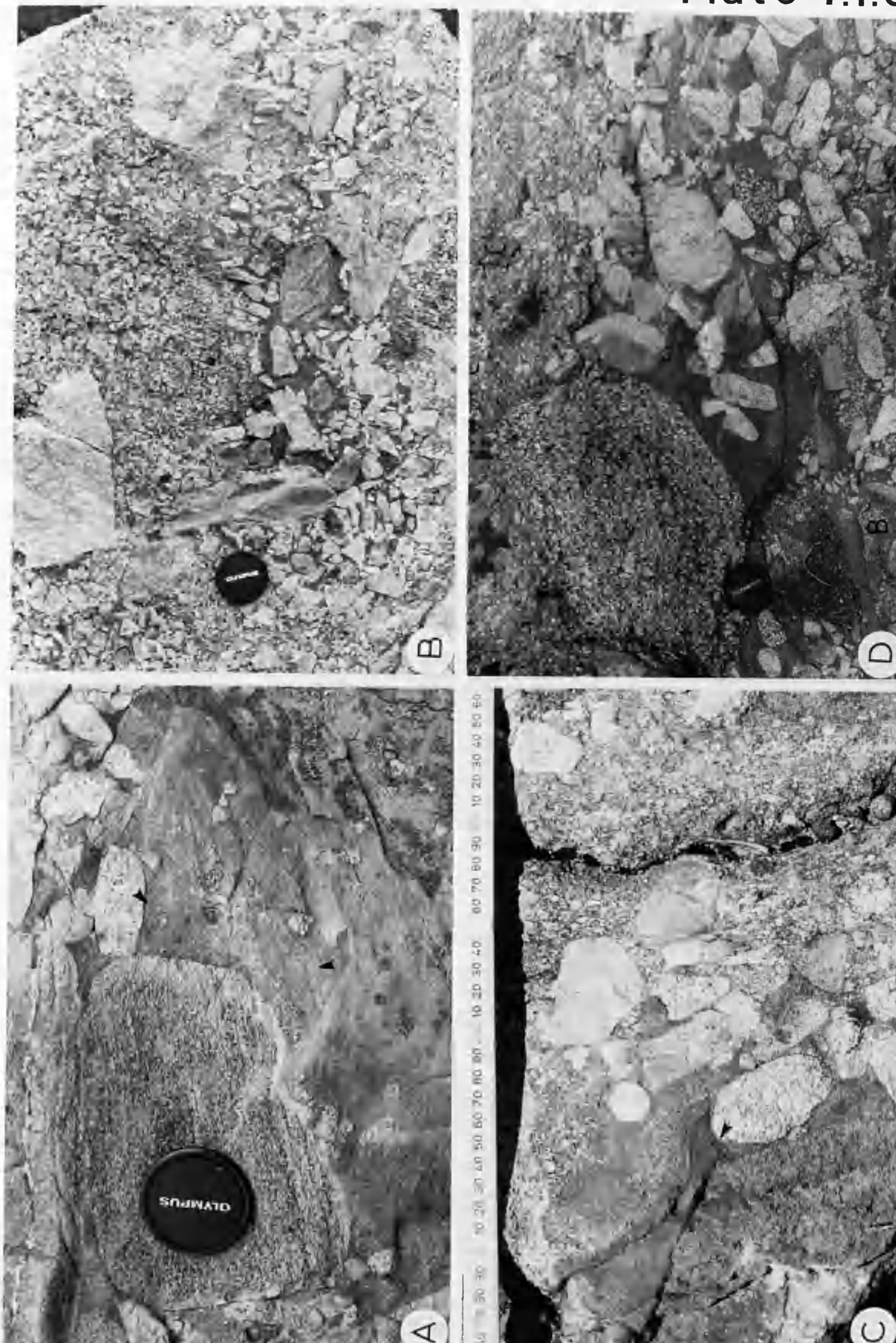


Plate 7.1.4. Textural and fabric features of the debris flow conglomerates of Facies B and B1.

A: Polymodal matrix-supported conglomerate. Scale is in millimeters. (Locality: Ben Tarvie, BLF);

B: Polymodal, openwork "clusters" (arrowed) enclosed in bimodal conglomerate. Ruler is 22 cm long. (Locality: Oldtown, BSF);

C: Ungraded, bimodal bed of Facies B1 overlain and underlain by the finer-grained, polymodal deposits of Facies C. No particular preferential clast orientation is apparent in Facies B1. Lens cap is 5 cm wide. (Locality: Creag an Amalaidh, BLF);

D: Locally the conglomerates of Facies B show strong imbrication. Note that some of the clasts are vertical or near vertical. (Locality: Silver Rock, BLF)

Plate 7.1.4.

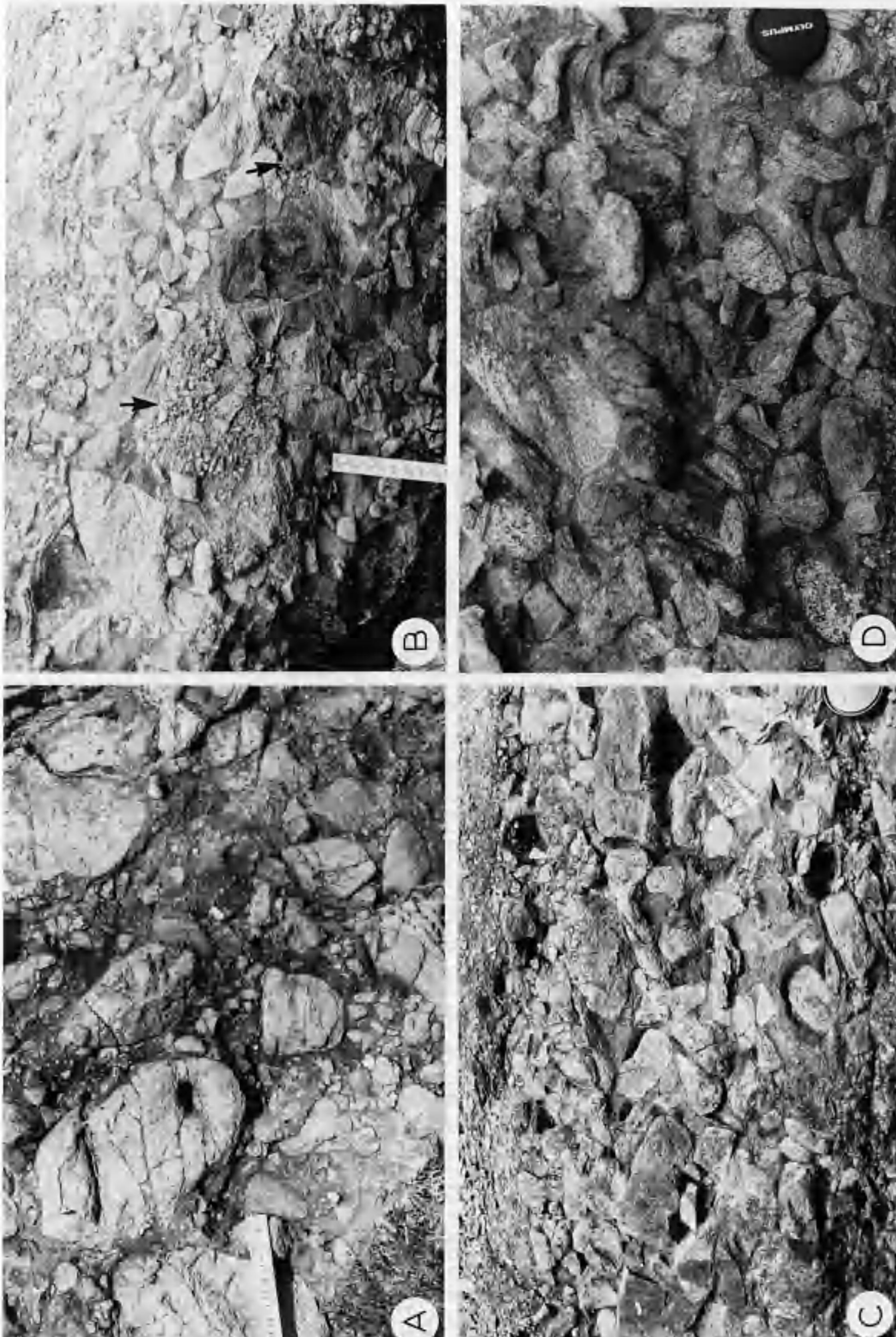
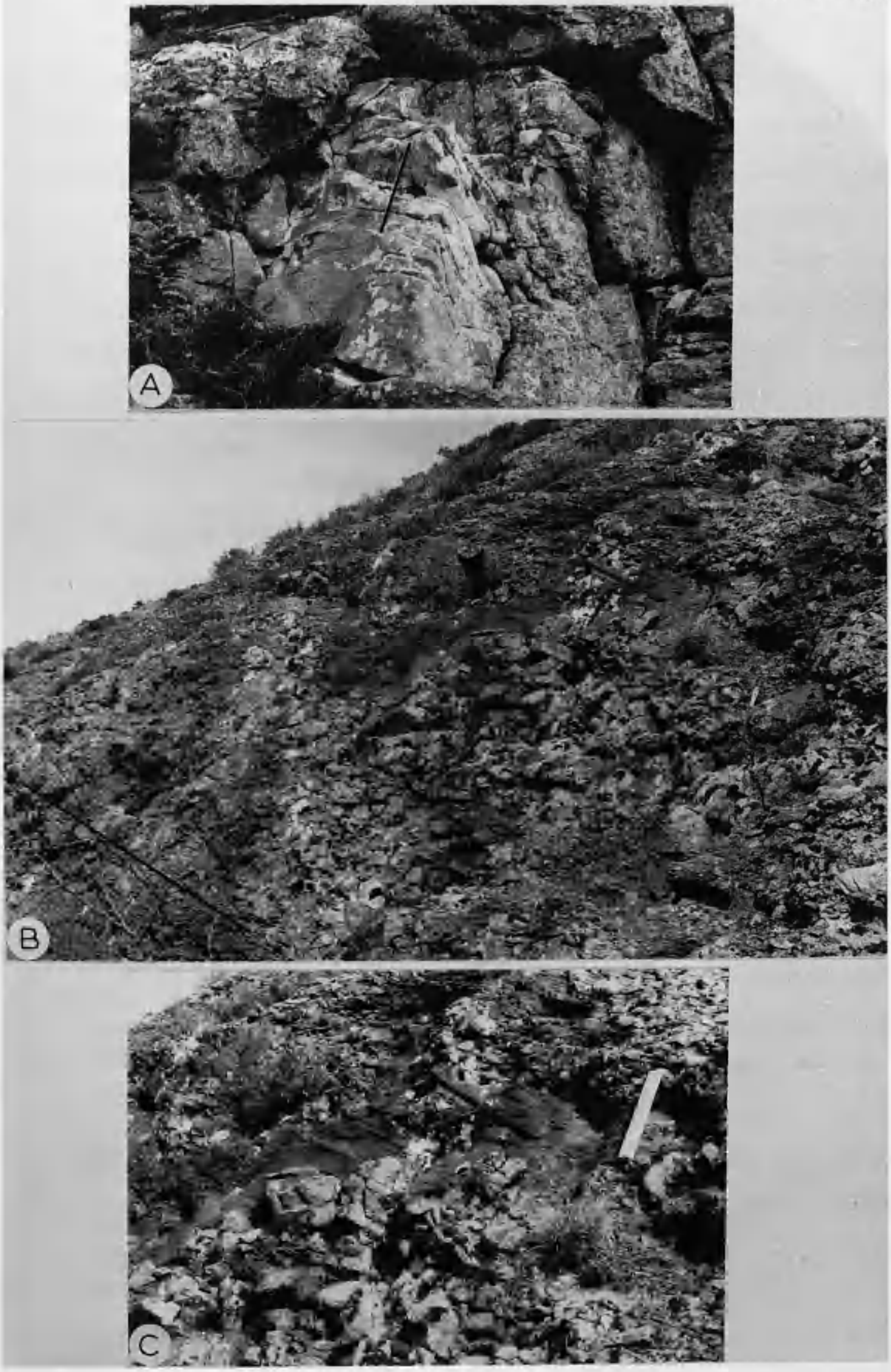


Plate 7.1.5. A: Large sandstone chunk enclosed in the deposits of Facies B. Note that the stratification in the sandstone clast is at high angle to the general bedding, which is parallel to the base of the photograph. Scale bar is 1 m long.(Locality: Killin Rock, BSF);
B: Another example of a sandstone intraclast enclosed in the structureless deposits of Facies B (arrowed). The black line shows general bedding trend. In this instance the planar-stratification in the intraclast is concordant with the bedding (see **C** for close up, scale is 0.25 m long). (Locality: Mound Rock, BLF);
In both cases (**A**, **B** & **C**) the sandstone chunks are marginally remoulded with the surrounding conglomerate, what indicates that they were semi-lithified during the resedimentation. Their thickness measured normal to the preserved stratification indicates that the sandstone beds, which yielded the clasts must have been minimum 2-1 m thick. No such beds have been recorded from the studied deposits.

Plate 7.1.5. A: Large sandstone chunk enclosed in the deposits of Facies B. Note that the stratification in the sandstone clast is at high angle to the general bedding, which is parallel to the base of the photograph. Scale bar is 1 m long.(Locality: Killin Rock, BSF);
B: Another example of a sandstone intraclast enclosed in the structureless deposits of Facies B (arrowed). The black line shows general bedding trend. In this instance the planar-stratification in the intraclast is concordant with the bedding (see **C** for close up, scale is 0.25 m long). (Locality: Mound Rock, BLF);
In both cases (**A, B** & **C**) the sandstone chunks are marginally remoulded with the surrounding conglomerate, what indicates that they were semi-lithified during the resedimentation. Their thickness measured normal to the preserved stratification indicates that the sandstone beds, which yielded the clasts must have been minimum 2-1 m thick. No such beds have been recorded from the studied deposits.

Plate 7.1.5.



coarse-grained sand (Plate 7.1.10.A & 7.1.11.A). The percentage of haematite-stained clay material in the matrix, which has been estimated by pointcounting, varies from 28-16% and averages 21.7% (see also chapter 7.1.5.2.). It occurs normally as thick uneven coatings on the clastic grains. The coatings are not interrupted along the contacts between the clasts and are commonly thicker in the concave areas of the grains (Plate 7.1.10.A). On the SEM images they appear as "crusts", covering the detrital grains with clay particles oriented parallel to the grain surface (Plate 7.1.10.A). The haematite/clay material appears also as irregular, more extensive patchy concentrations, chaotically distributed in the rock. The latter do not have a well defined outline, which could suggest their origin as intraclasts. The above said, non-uniform form of occurrence of the clay suggests that a substantial portion of it was derived through a mechanical infiltration (Walker *et al.*, 1978; Turner, 1980). For the clay material is not interrupted at clast contacts, then a fair amount of it must be primary (but see also chapter 7.1.5.4.).

The amount of the matrix varies markedly between beds, from 20-50%, averaging 45%. The matrix content changes also significantly within the individual beds and has a distinctive "patchy" distribution (Plate 7.1.3.A-C, 7.1.4.B, 7.1.7.A). Thus, the beds of Facies B typically consist of chaotically arranged clast- and matrix-supported parts, with variable amounts of matrix (Fig. 7.1.2.A&B & 7.1.3.). The clast-supported intraclasts show in places an open framework (openwork) (Plate 7.1.4.B). The latter features have irregular, roughly spherical outlines.

The sandy, matrix-forming material appears often as rip-up intraclasts up to 2 m in size, normally smaller than 0.5 m. They are either "squeezed" within the conglomeratic mass (Plate 7.1.5. & Fig. 7.1.7.) or "smeard out" along the bedding (Plate 7.1.6.). The unremoulded intraclasts frequently display a preserved grain lamination (Plate 7.1.3.A & 7.1.5.). The lamination can be partly obliterated, especially along the edges the intraclasts. The diffuse appearance of the sandy intraclasts implies their relatively unlithified state during incorporation into the sediment, yet sufficiently cohesive so that the lamination is preserved.

In one locality (Oldtown) the matrix shows compressive ridges "wrapping" rounded

Plate 7.1.6.A: Photograph shows matrix-supported area in a bed of Facies B. The enhanced by weathering parting features may represent shear features associated with mass flow transport (laminar flow). See also **B** (arrowed) and **C**. These discontinuous parting planes are not related to any textural or structural facets of the matrix. The photograph **B** shows a clear distinction between true sedimentary lamination (left of the lens cap) and the parting features. The lamination passes into massive sandstone, partly remoulded with the surrounding conglomerate. Lens cap is 5 cm wide. Scale in **C** is in millimeters. (Locality: Mound Rock, BLF)

Plate 7.1.6.

clasts (Plate 7.1.3.C).

A very distinctive feature of Facies B are discontinuous parting planes which are enhanced by weathering. They diverge around clasts and are subparallel with the bedding (Plate 7.1.7.A & B). A smaller-scale variety of the latter features are a few centimeters long, discontinuous parting planes, developed locally in the sandy intraclasts and in the matrix (Plate 7.1.6.). They may give a superficial impression of being a type of lamination, formed by depositional processes. However, careful examination of these structures reveals that they are not related to any grain-size or textural variability in the sediment. They are believed to represent shearing planes which are normally concordant with the bedding, though in number of instances they are parallel to margins of adjacent, variously oriented boulders. The shearing planes have not been found to be restricted to any particular parts of the beds.

The both types of parting planes, described above, seem to be analogous to the "splintery fractures" reported by Lindsay (1966) from mass flow deposits (see also Facies F1, B1, chapter 7.2.4.1.9. & 7.4.5.1.1. for description and discussion of analogous structures).

The Facies B conglomerates occur typically as amalgamated, more or less pronounced lenticular bodies in a wide range of thickness from 0.2-15 m but averaging around 0.6 m (Plate 7.1.1.B, 7.1.5.B, 7.1.7. & 7.1.9.A; Fig.7.1.1a-e. & 7.1.4.).

The bed thickness data display a substantial and statistically significant departure from a theoretical, normal frequency distribution (see Fig. 7.1.4. & 7.1.6.).

Because of the merged nature of the contacts between the beds (see for example Plate 7.1.7.C & 7.1.9.D) satisfactory identification of bed boundaries and determination their either erosional or non-erosional attitude is either extremely difficult or impossible. Discontinuous, finer-grained conglomeratic or rare, sandstone interbeddings (see Facies C further in text) as well as the textural and grain-size variations within Facies B may help in the identification of the bed boundaries. However, in light of the mentioned above, common textural heterogeneity the two latter criteria have to be handled with caution. For

Plate 7.1.7. A & B: Large scale parting features in the deposits of Facies B. In **A** the arrow points to one of the outsize boulders with a attached sandy chunk (intraclast ?). Scale is 0.5 m long in **A** and 1 m long in **B**;

C: Amalgamated deposits of Facies B. The lensoid sandstone interbedding indicates the amalgamation, even though no obvious bed boundaries are visible within the conglomerates. Scale is 0.5 m (Locality: **A** & **C** - Beinn Lunndaidh, BLF; **B** - Ben Tarvie, BLF)

Plate 7.1.7.

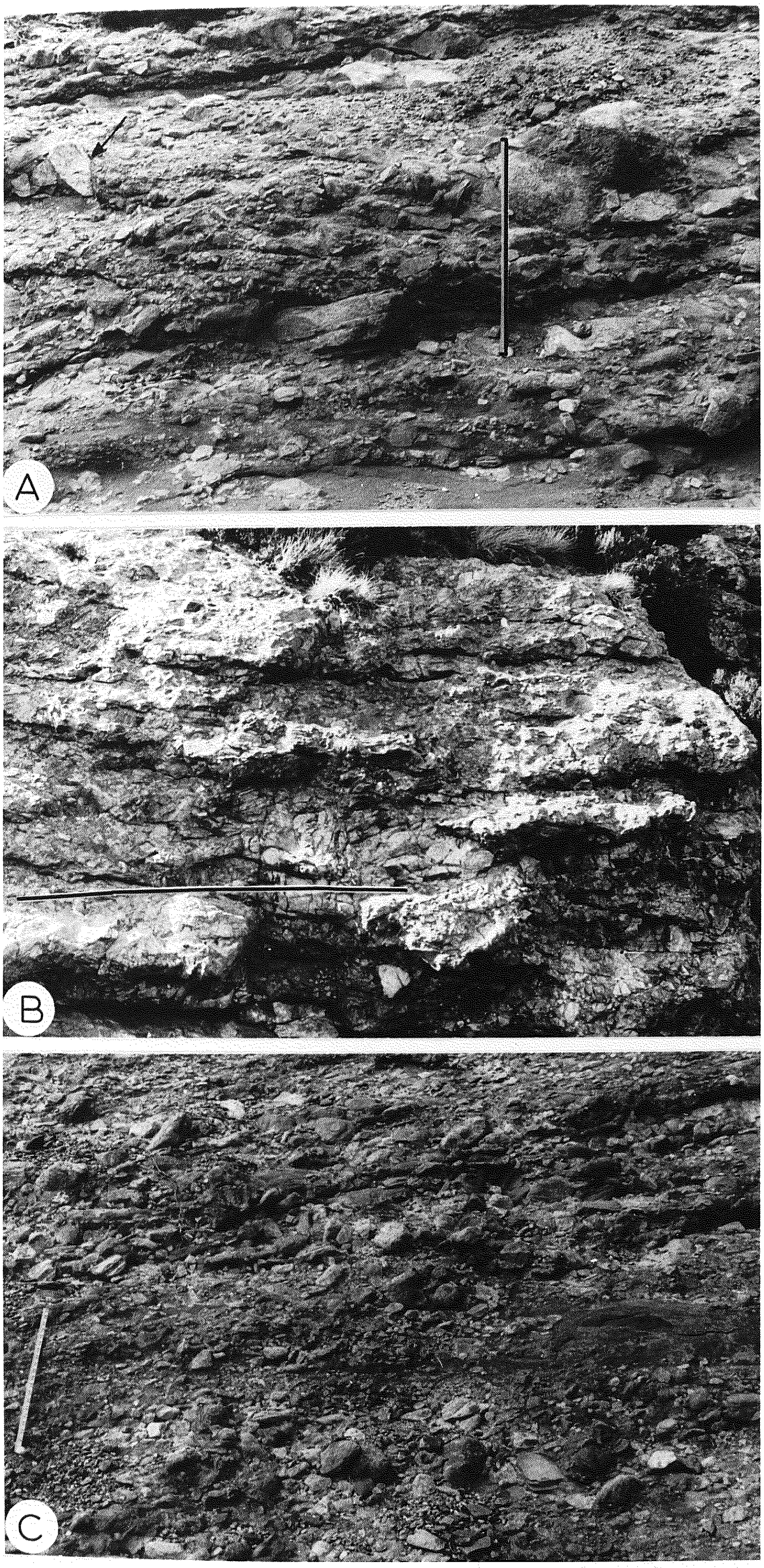


Figure 7.1.1a. Typical vertical distribution of the debris flow and the sheetflood deposits (Facies B & C), which make up the Beinn Lunndaidh Formation (BLF). Fining-upward cycles (thin arrows) probably represent surges of gradually less competent debris flows, followed by sheetflood deposition, all possibly associated with single depositional events (Johnson & Rodine, 1984). Type of grading is indicated by triangles. **OW** - open framework (openwork); **CW** - "closed" (filled framework); ≋ unremoulded early lamination; **50 - 40** - estimated percentage of sandstone matrix (only in Fig. 7.1.1c. & 1d.). (Locality: Mound Rock, BLF)

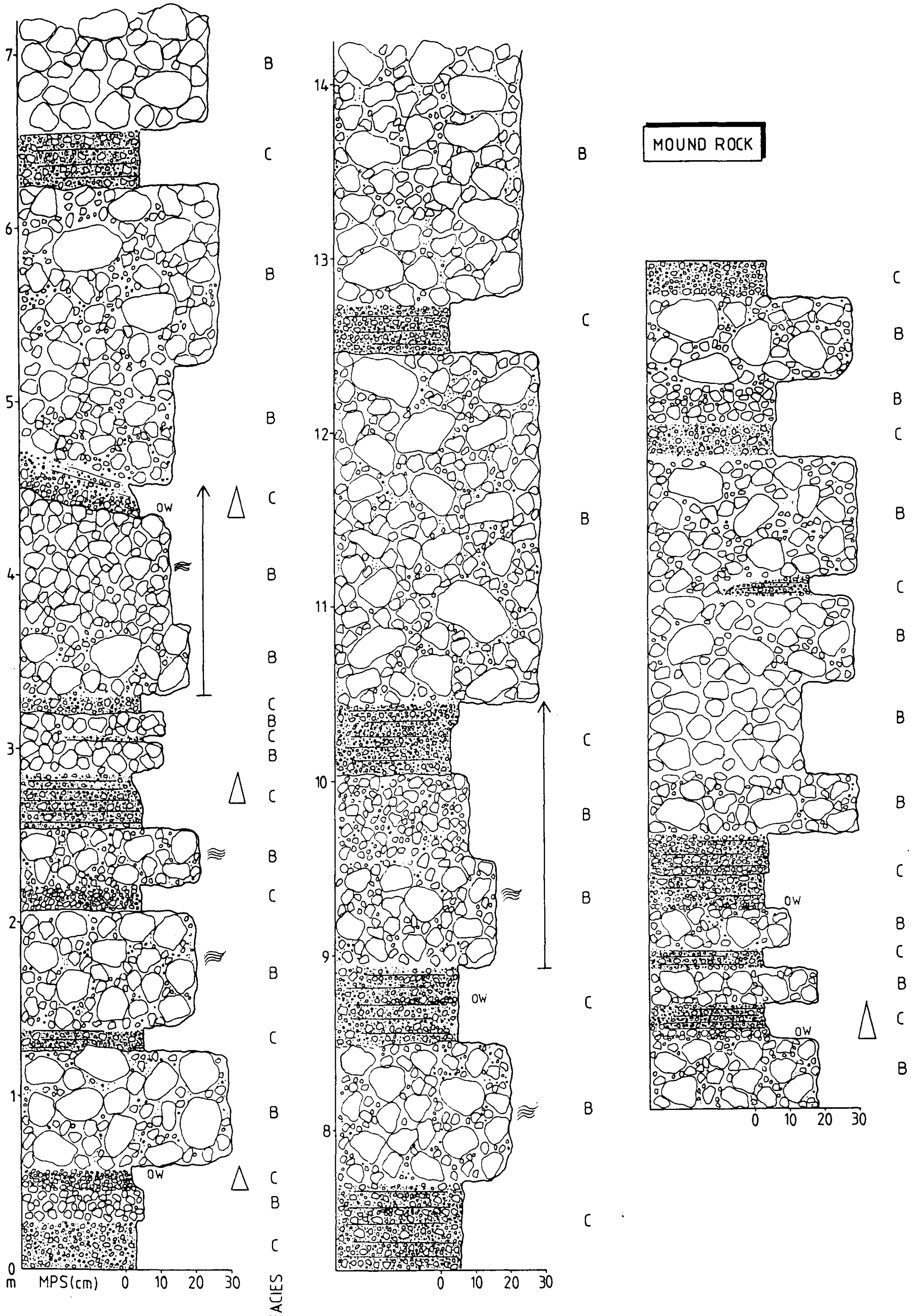
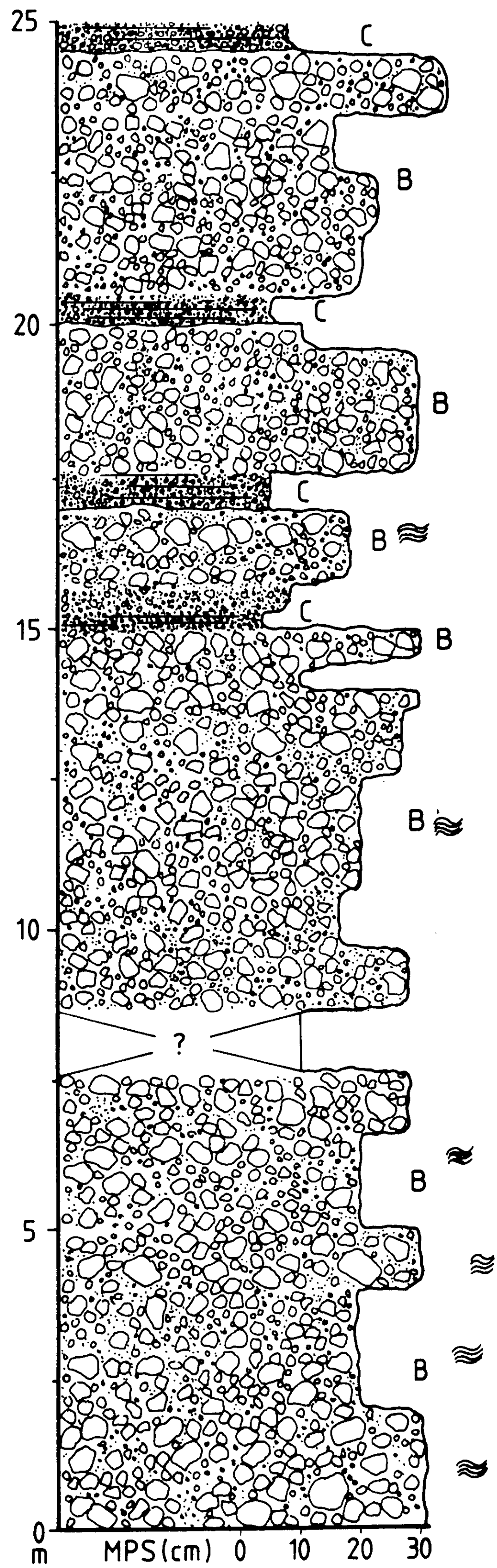

MOUND ROCK
m
MPS(cm)
0
10
20
30
FACIES
OW
B
C

Figure 7.1.1b. Continuation of the log from the Fig. 7.1.1a. The log represents the part of the sequence, which is almost entirely composed of amalgamated debris flow beds. (Locality: Mound Rock, BLF)


25
20
15
10
5
0
m
MPS (cm) 0 10 20 30
C
B
C
B
C
B
C
B
B
?
B
B

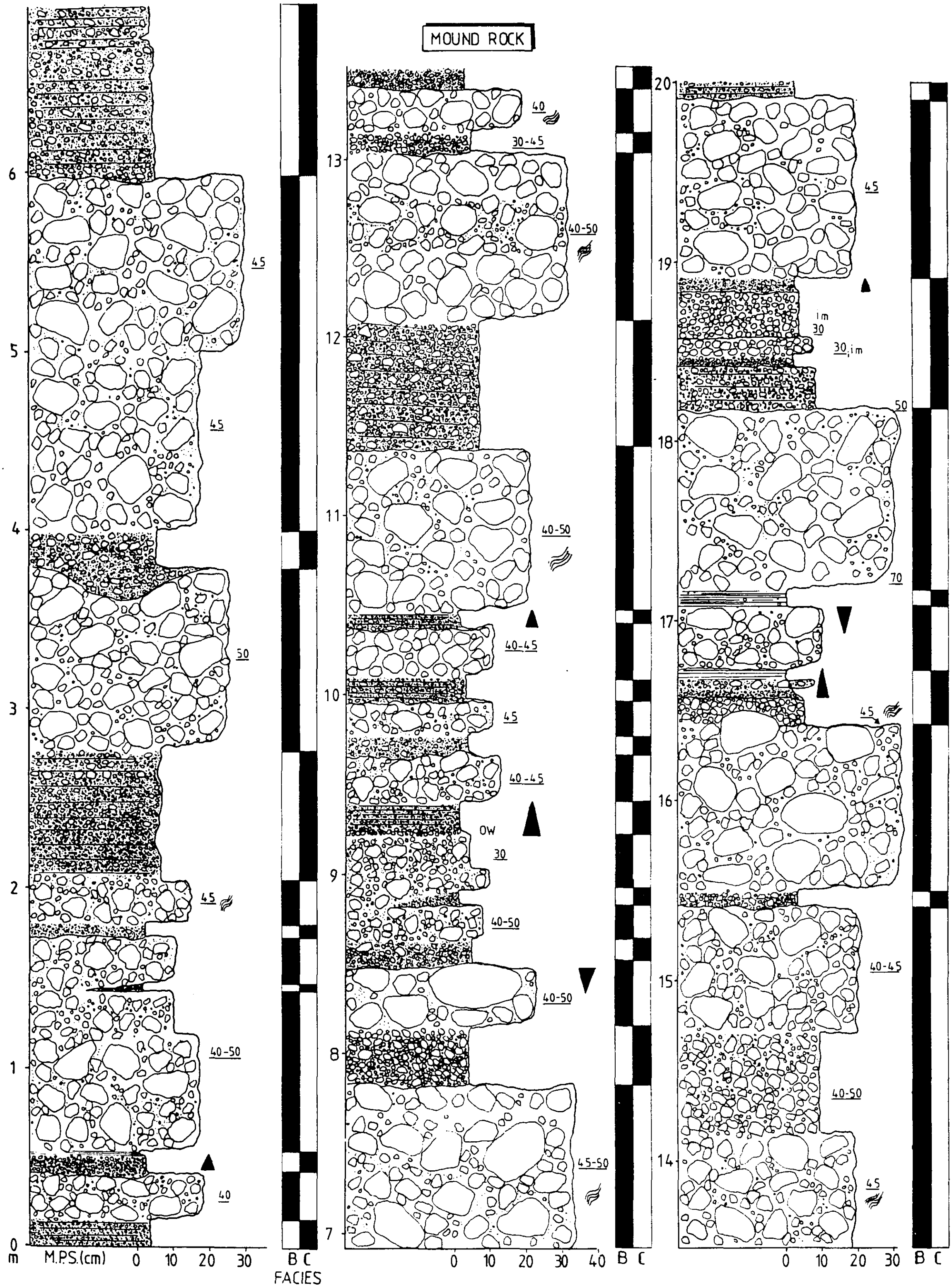


Figure 7.1.1c. Another example of vertical stacking of the debris flow and the sheetflood conglomerates (Facies B and C) - continuation from Fig. 7.1.1b. (Locality: Mound Rock, BLF)

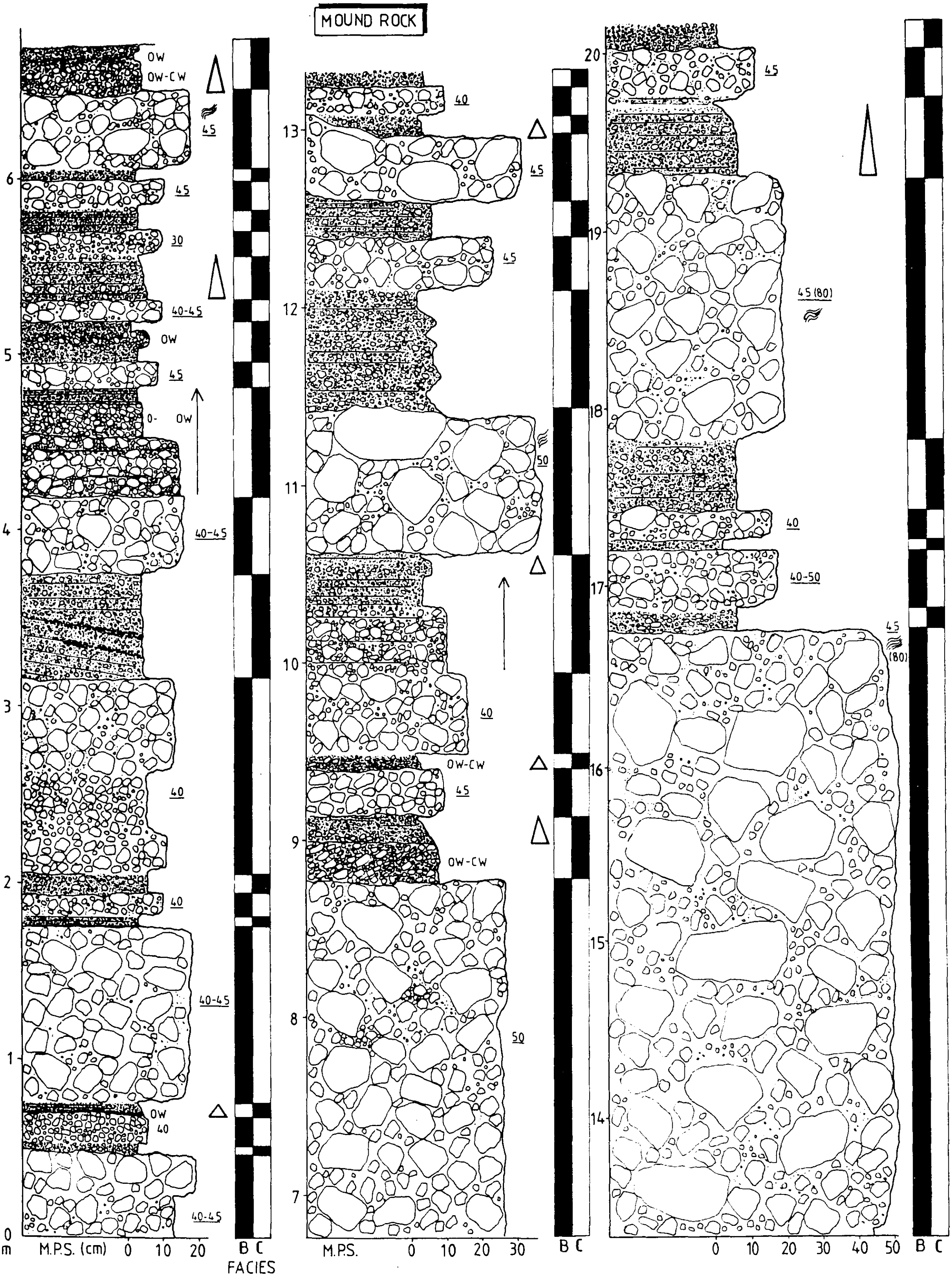
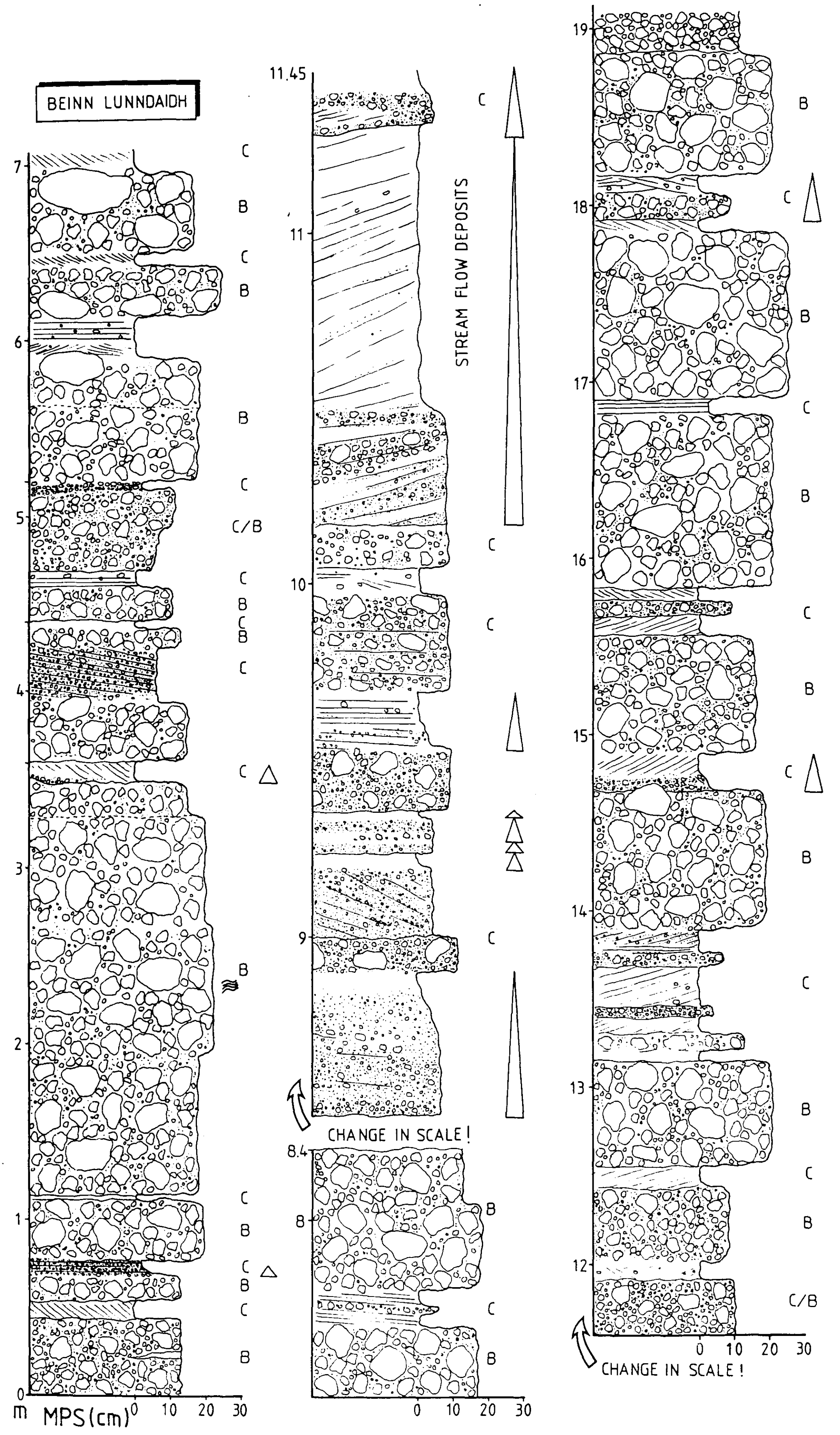


Figure 7.1.1d. Continuation of the log from the Fig. 7.1.1c. (Locality: Mound Rock, BLF).

Figure 7.1.1e. Vertical distribution of Facies B and C. (Locality: Beinn Lunndaidh 1, Fig. 7.1.25.). Here Facies C is mainly represented by sandstone lenticular interbeddings that cap directly the debris flow beds of Facies B. **C/B** - conglomerates transitional between the debris flow and the sheetflood deposits. Large scale, trough cross-stratified, stream flow conglomerates are extremely scarce in the BLF.


BEINN LUNNDAIDH
STREAM FLOW DEPOSITS
CHANGE IN SCALE!
CHANGE IN SCALE!
m MPS (cm) 0 10 20 30
0 10 20 30
0 10 20 30
0
1
2
3
4
5
6
7
8
8.4
9
10
11
11.45
12
13
14
15
16
17
18
19
B
C
C/B

instance, lenticular gravelly or sandy intraclasts can be sometimes easily missidentified as representing individual beds (Plate 7.1.6.C) (see also Facies B1, E1, E2 & F1).

It is emphasized that scoured bases of some of the beds of Facies B do not automatically imply an erosional event associated with the deposition of these beds. The erosional surfaces may well indicate earlier phases of erosion, unrelated to the depositional processes, represented by the overlying Facies B beds.

Contacts with rare laminated sandstone interbeddings are highly distinctive. Close examination reveals that the laminated sandstone is continuous with the sandy matrix in the succeeding, conglomeratic bed. The lamination is convolute and/or completely obliterated along these contacts (Plate 7.1.8. & Fig. 7.1.18.) and occasionally pebbles and cobbles load into the sandy interbeddings. In a number of exposures it is clearly seen as the sandy material has been "incorporated" by the "overriding" conglomeratic bed (Plate 7.1.8. & Fig. 7.1.18.). It is noteworthy that although the matrix is continuous with the sandy interbeddings, the lamination within the matrix is completely destroyed and small shearing planes (?) are developed.

A significant, positive, linear correlation between the maximum particle size (MPS) and the bed thickness (BTh) has been recognized for three sets of data from different localities (Fig. 7.1.4.). Only selected beds have been considered - the once well defined between the interbeddings of Facies C - which might have formed from single depositional events. There is also a significant but weaker positive correlation between the largest particle size in the bed (LPS) and the BTh (Fig. 7.1.8.).

Conglomeratic fabric is generally disorganised, and vertically oriented clasts are common, yet a large number of beds display a very well pronounced, up-stream dipping, most likely *a* (long)-axis imbrication (Plate 7.1.3.D & 7.1.4.D). The imbrication appears to be developed only locally within mainly disorderd beds (Fig. 7.1.3.A). Unfortunately, systematic measurements of of the fabric were precluded by the nature of the exposures. In two localities at Creag an Amalaidh relatively good outcrop enabled measuring the imbrication, though a reliable determination of an orientation of the a-axes was not possible. Rose-diagram plots of these data show a strong preferential clast orientation (Fig.

Plate 7.1.8. The photographs **A-C** have been taken along the same horizon and demonstrate the interpreted progressive stages of a gravity driven remobilisation of the fanglomerates and *en mass* remoulding of gravel and sand. Note a fold (slump) feature (**B**); the arrows point to the parting (shearing ?) planes.

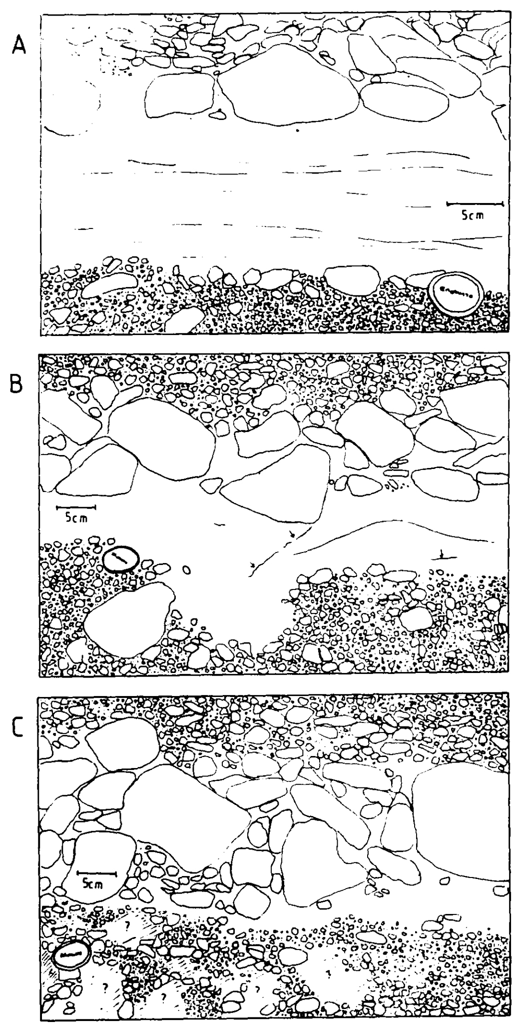
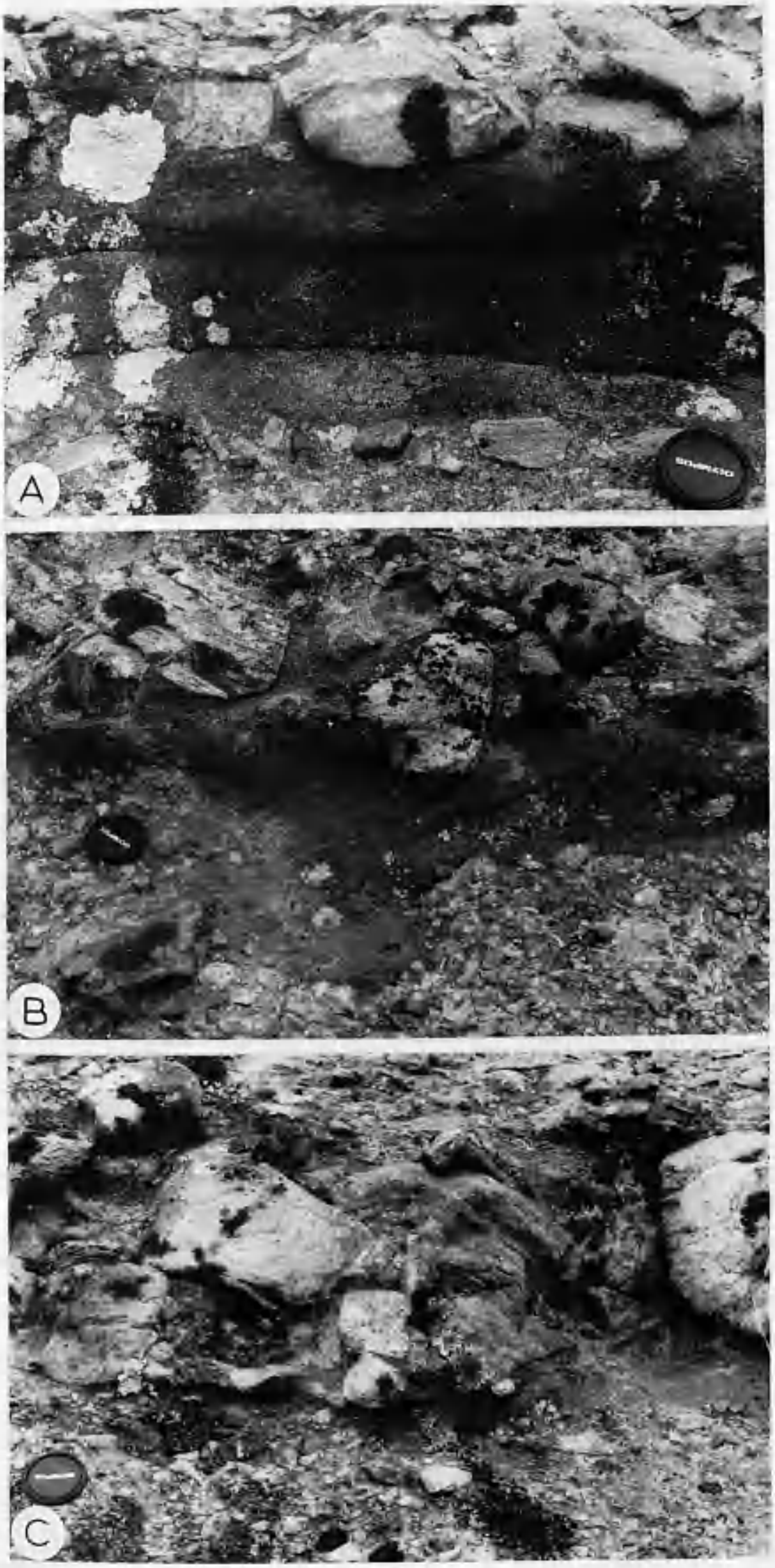


Plate 7.1.8.



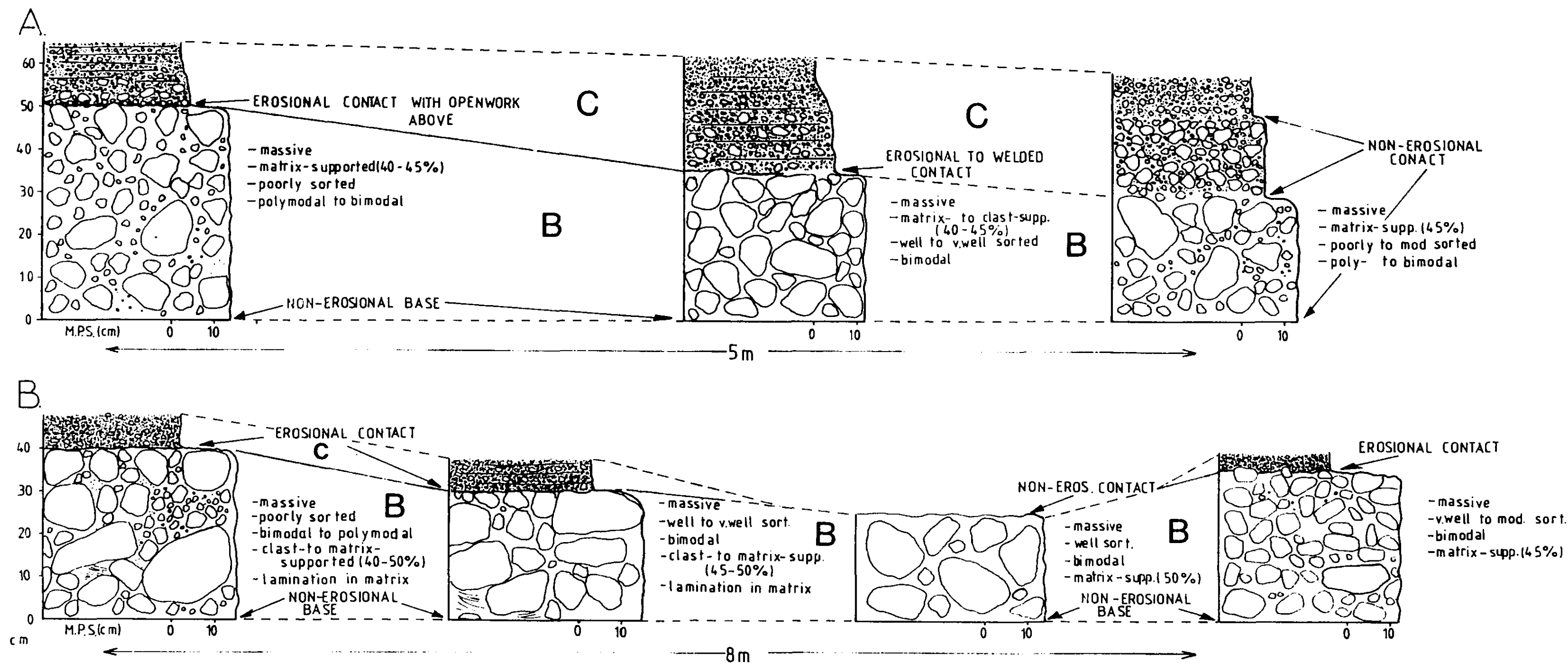


Figure 7.1.2. A & B: Typical vertical/lateral relationships between the debris flow deposits of Facies B and the sheetflood deposits of Facies C. Note the textural heterogeneity of Facies B. (Locality: Mound Rock, BLF)

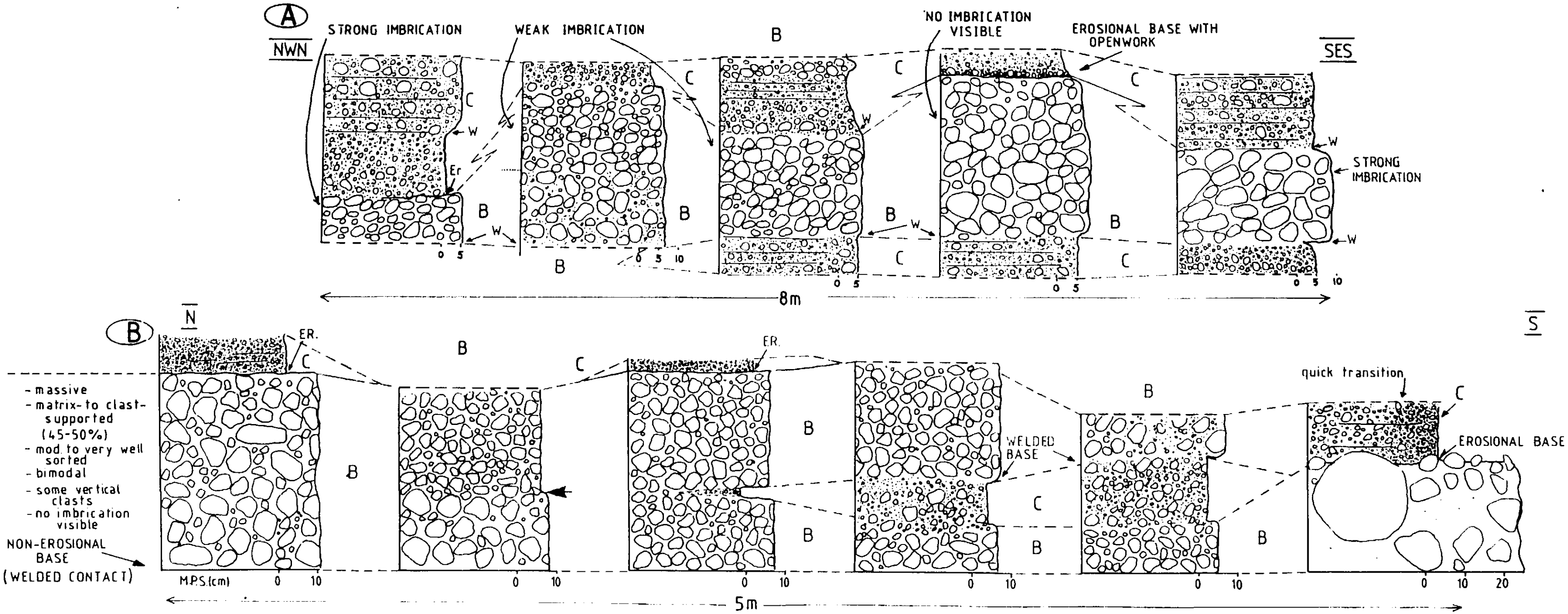
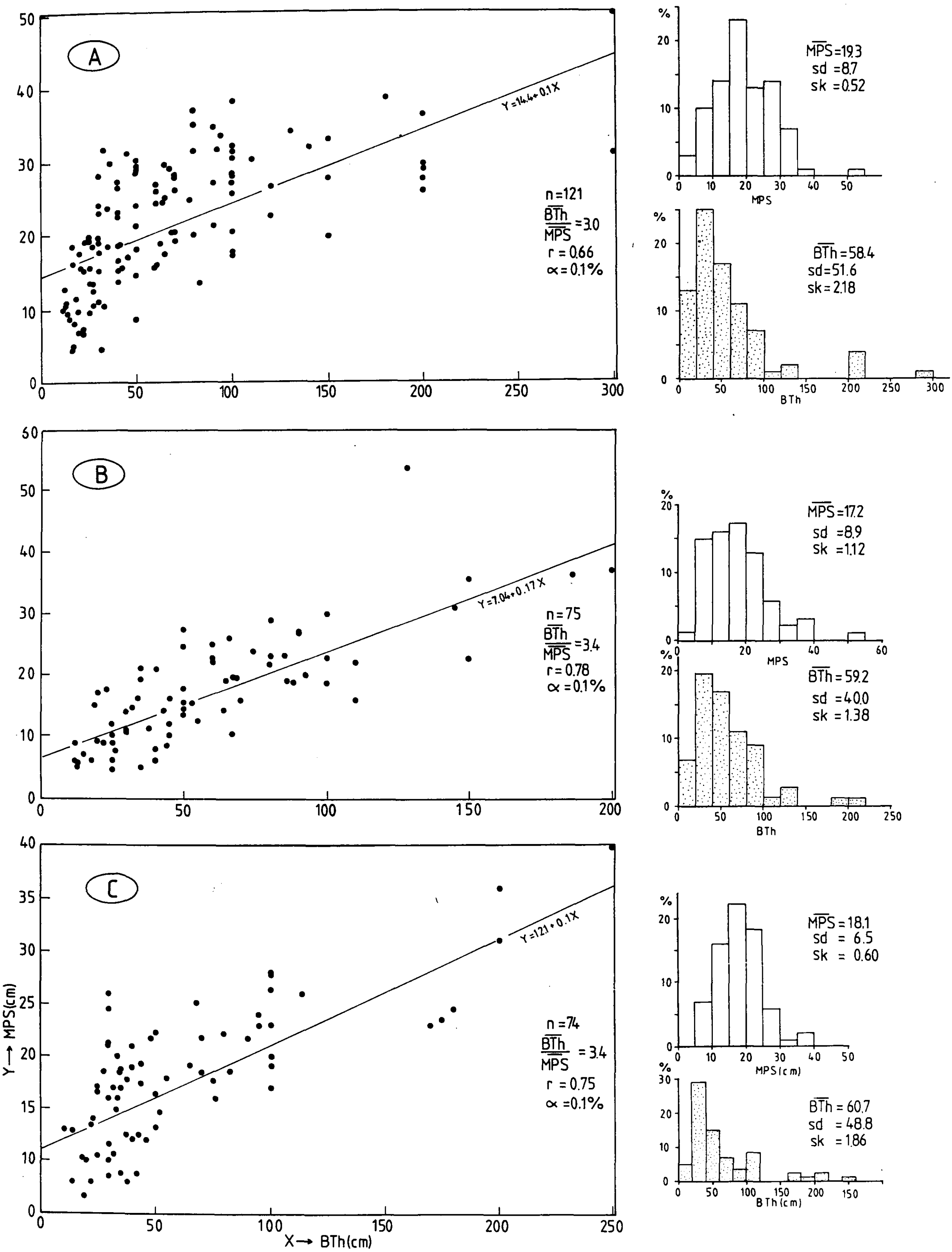


Figure 7.1.3. A: Predominantly bimodal Facies B bed buried under Facies C deposits. **W** - "welded", possibly non-erosional contact. Note that thickness of the Facies C deposits is largest in the depressions on the surface of the Facies B bed. (Locality: Mound Rock, BLF);

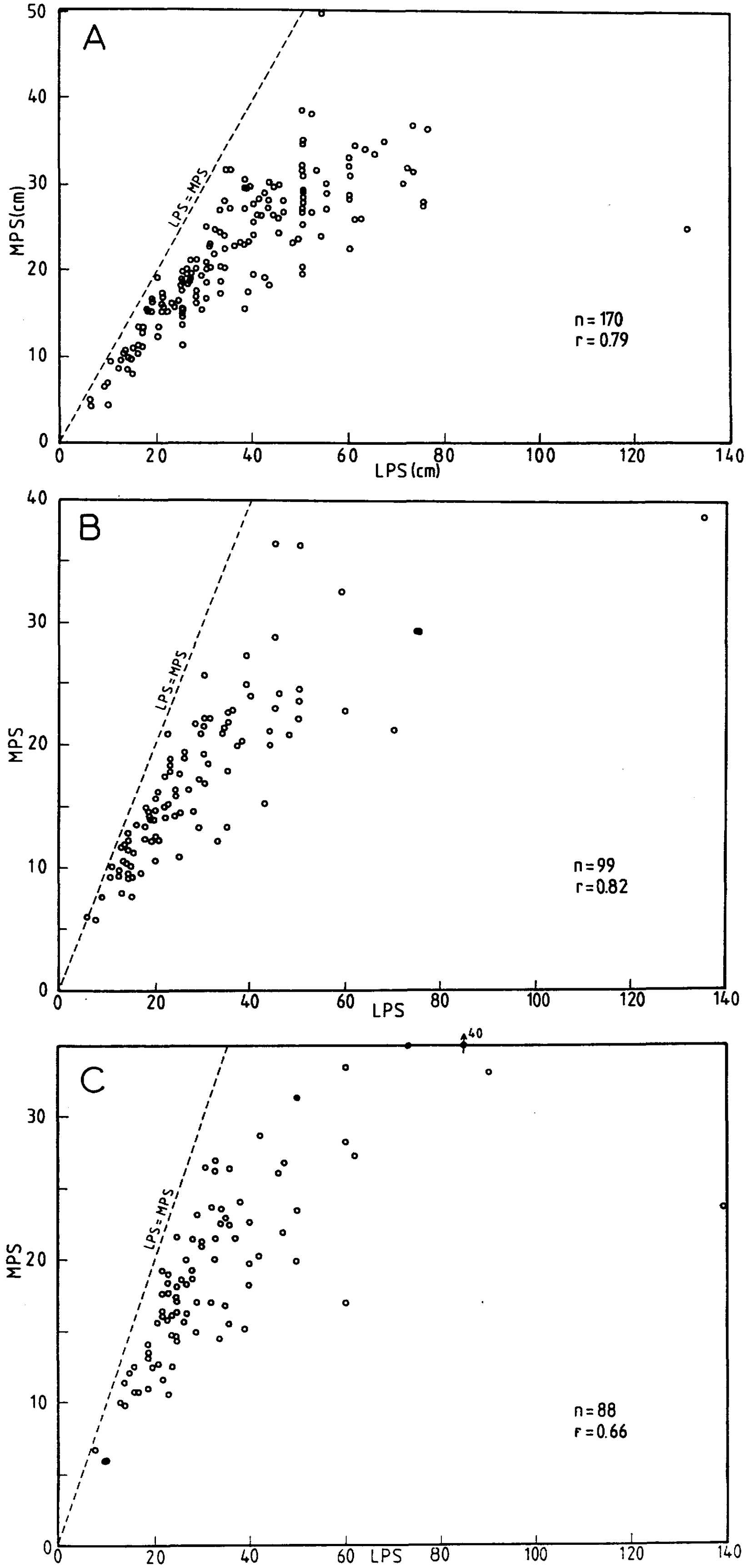
B: Another example of the bimodal debris flow deposits of Facies B erosionally/non-erosionally covered by the sheetflood beds of Facies C. The diagram illustrates uncertainty associated with identification of boundaries between the beds of Facies B. Note that in the area, where the bed of Facies C thins out the boundary between the beds of Facies B becomes unrecognizable (arrowed).

Figure 7.1.4. Scatter plot of the calculated maximum particle size(MPS) versus bed thickness(BTh) for the beds of Facies B from three localities: **A** - Mound Rock, **B** - Silver Rock, **C** - Beinn Lunndaidh. The histograms represent number frequency distribution of the MPS and BTh data (**n** - number of data, **sd** - standard deviation, **sk** - skewness). The oblique lines are regression lines fitted to the data (**r** - correlation coefficient, α - significance level). Results of the goodness-of-fit test for these three sets of data are given in Fig. 7.1.6.



A
Y=14.4+0.1X
n=121
BTh/MPS = 3.0
r = 0.66
∝ = 0.1%
MPS=19.3
sd =8.7
sk =0.52
MPS
BTh=58.4
sd=51.6
sk=2.18
BTh
B
Y=7.04+0.17X
n=75
BTh/MPS = 3.4
r= 0.78
∝ = 0.1%
MPS=17.2
sd =8.9
sk =1.12
MPS
BTh=59.2
sd =40.0
sk =1.38
BTh
C
Y=12.1+0.1X
n=74
BTh/MPS = 3.4
r = 0.75
∝ = 0.1%
MPS=18.1
sd = 6.5
sk = 0.60
MPS (cm)
BTh=60.7
sd = 48.8
sk = 1.86
BTh (cm)
Y→ MPS(cm)
X→ BTh(cm)

Figure 7.1.5. Scatter plot of largest particle size(LPS) vs. maximum particle size(MPS) fo[r]
the debris flow deposits of Facies B. Localities: **A** - Mound Rock, **B** - Silver Rock, C -
Beinn Lunndaidh.



A
MPS (cm)
LPS (cm)
LPS = MPS
n = 170
r = 0.79
B
MPS
LPS
LPS = MPS
n = 99
r = 0.82
C
MPS
LPS
LPS = MPS
40
n = 88
r = 0.66

Figure 7.1.6. Results of the goodness-of-fit test for the maximum particle size (MPS) and bed thickness (BTh) frequency distribution for the beds of Facies B and C. Data sets (localities) are the same as in Fig. 7.1.4. & 7.1.11.. In the test the observed distributions are "confronted" with a theoretical normal distribution.

GOODNESS-OF-FIT TEST

Data Set (locality)	Number of Intervals		Expected Frequency		Goodness-of-Fit Value X2		Critical Chi-square Value at 95%	
	FACIES B							
	MPS	BTh	MPS	BTh	MPS	BTh	MPS	BTh
A	11	5	13.82	22.4	10.395	29.161	15.507	5.991
B	9	7	8.3	10.7	4.32	17.867	12.592	9.488
C	9	5	8.2	14.8	5.292	52.486	12.597	5.991
FACIES C								
A	8	5	11.25	17.8	13.202	33.528	11.071	5.991
B	6	5	13.33	16.0	18.7	54.625	7.815	5.991

Null Hypothesis: distributions are normal

Null hypothesis is accepted at 95% probability level when Godness-of-Fit Value X2 is smaller than the Critical Chi-square Value.

A - Mound Rock

B - Silver Rock

C - Beinn Lundaidh

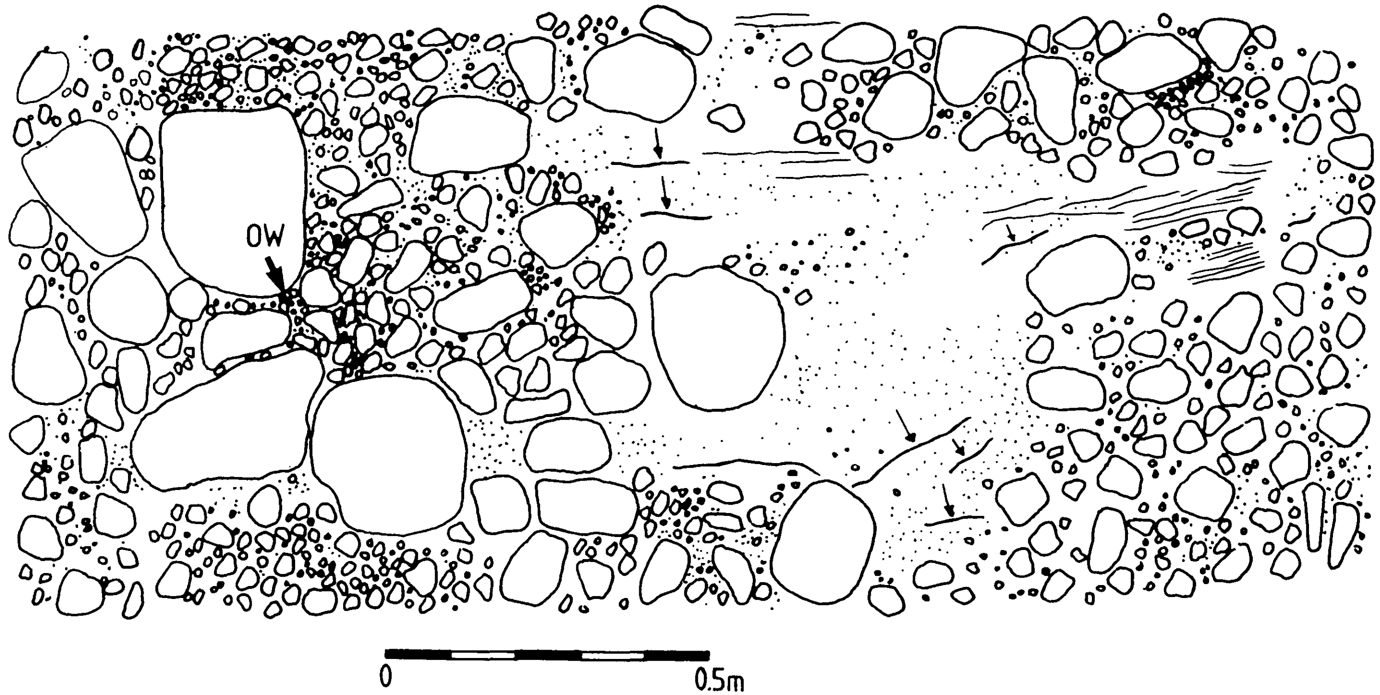


Figure 7.1.7. Probable sandy rip-up intraclast "squeezed" within the debris flow deposits of Facies B. Primary lamination is only locally preserved. The sandy material of the intraclast is partly "remoulded" with the conglomerate. Arrows point to, what are believed to be, shearing features. **OW** - small openwork area (Locality: Beinn Lunndaidh 1, BLF, see Fig. 7.1.25.)

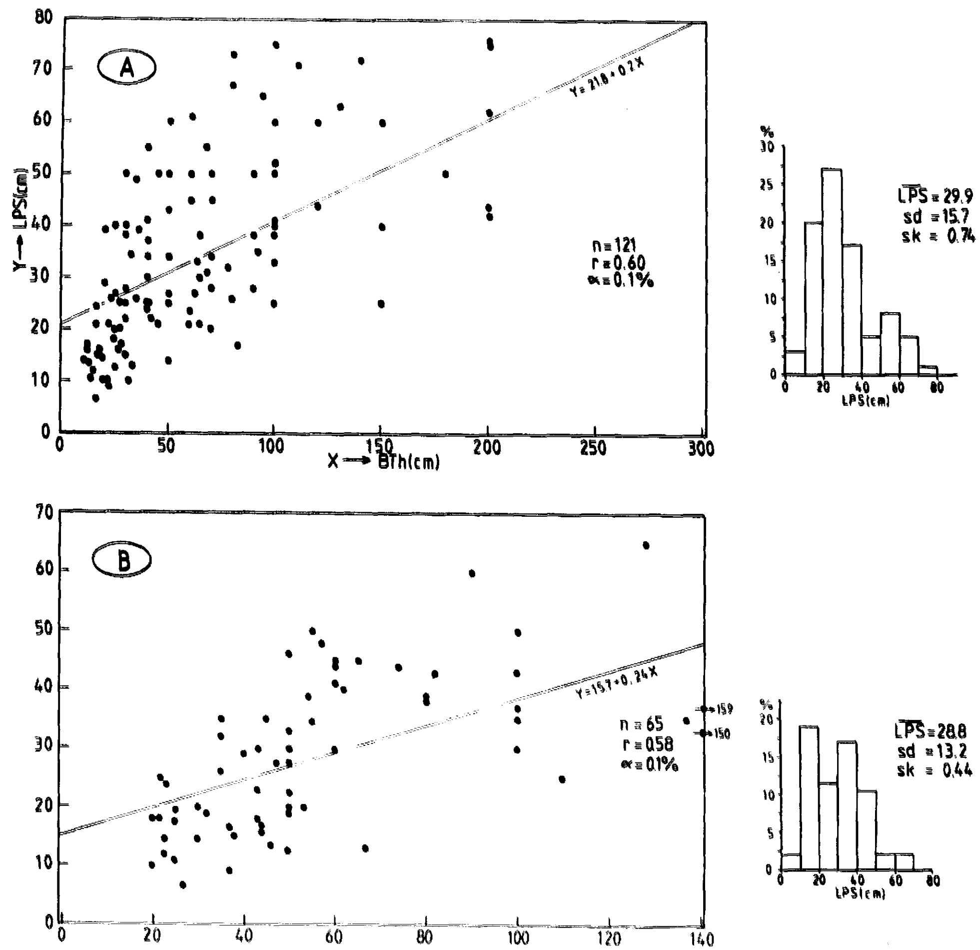


Figure 7.1.8. Scatter plot of the largest particle size(LPS) versus bed thickness(BTh) for Facies B from two localities: A - Mound Rock, B - Silver Rock.

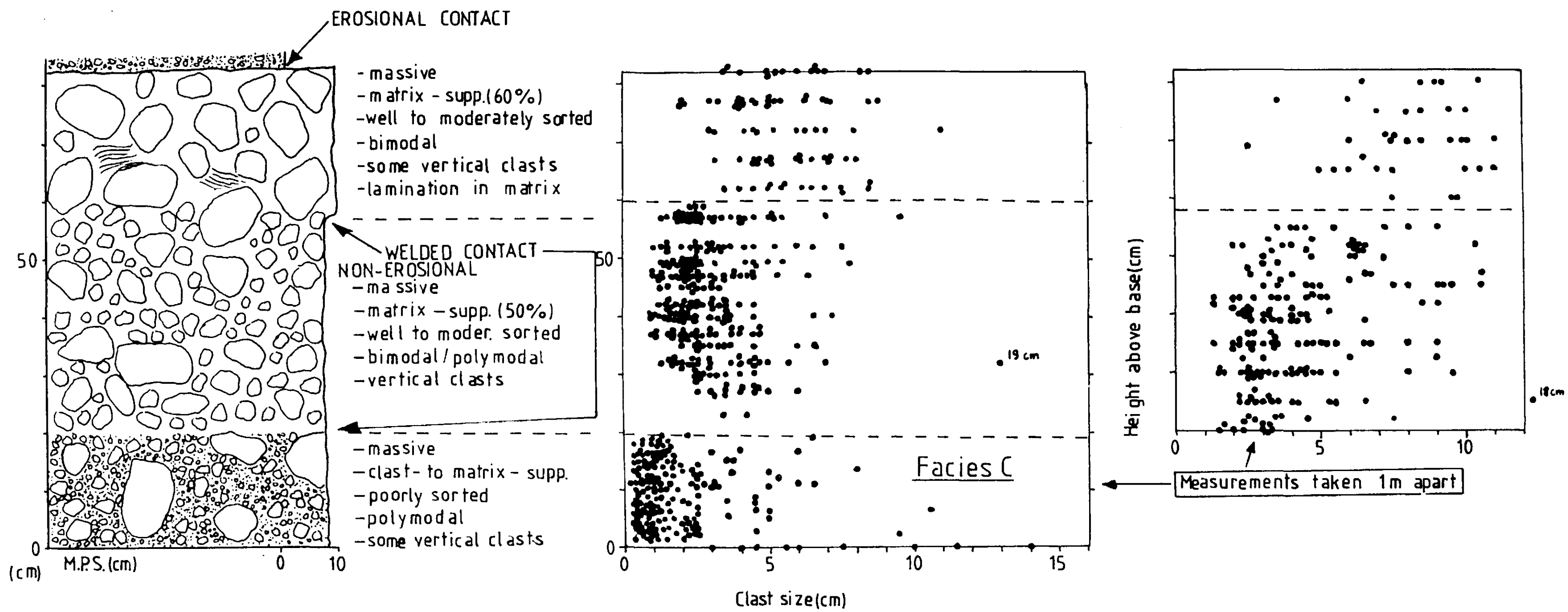


Figure 7.1.9. An example of two superimposed Facies B beds which may give the impression of a single, inversely graded bed. Plot of the clast size vs. the height above the base reveals a composite nature of the unit. Note sharp "jumps" in grain size distribution. (Locality: Oldtown, BSF)

7.1.22.).

Stereonet plots of the orientation of disk-shape clasts from four beds, exceptionally well exposed on the coast (SE of Mound Rock), show that clasts in two of them have a highly variable orientation of the *ab* planes. The two remaining beds display statistically strong preferential dip of the *ab* planes to the NE at the angle of around 45^{o} (Fig. 7.1.16).

Beds of Facies B are typically ungraded, although single outsize clasts commonly project above the tops of the beds (Plate 7.1.4.C & D & 7.1.9.B & D). Close examination of many apparently normally graded and sporadically inversely graded beds reveals a multiple depositional history of their formation (Fig. 7.1.9.). Hence, the individual beds of Facies B, seen here as having formed from separate acts of deposition, can be arranged in fining- or coarsening-upward units (the latter are very rare). The fining-upwards is associated with a decrease in the amount of sandy matrix and with a successive transition into deposits of Facies C. A "true" normal grading (seen as a result of a single depositional event) is very rare (Plate 7.1.9.C) and usually restricted to the uppermost portions of the beds. In these instances the fining upwards also involves a drop in the matrix content and eventual gradation into Facies C. In several beds analogous fining can also be traced laterally, in the down-current direction (Fig. 7.1.10a. & 7.1.10b.). An inverse grading *sensu stricto* is extremely rare.

7.1.5.1.3. Facies C: Texturally homogeneous, stratified conglomerates (Mound Rock variety)

Description

These are poorly sorted deposits, though clearly, the degree of sorting is much better than in case Facies B. The conglomerates of Facies C are mainly polymodal and clast-supported. They may appear unstratified or display well to poorly defined horizontal stratification and low angle, planar cross-stratification. The structures are pronounced by

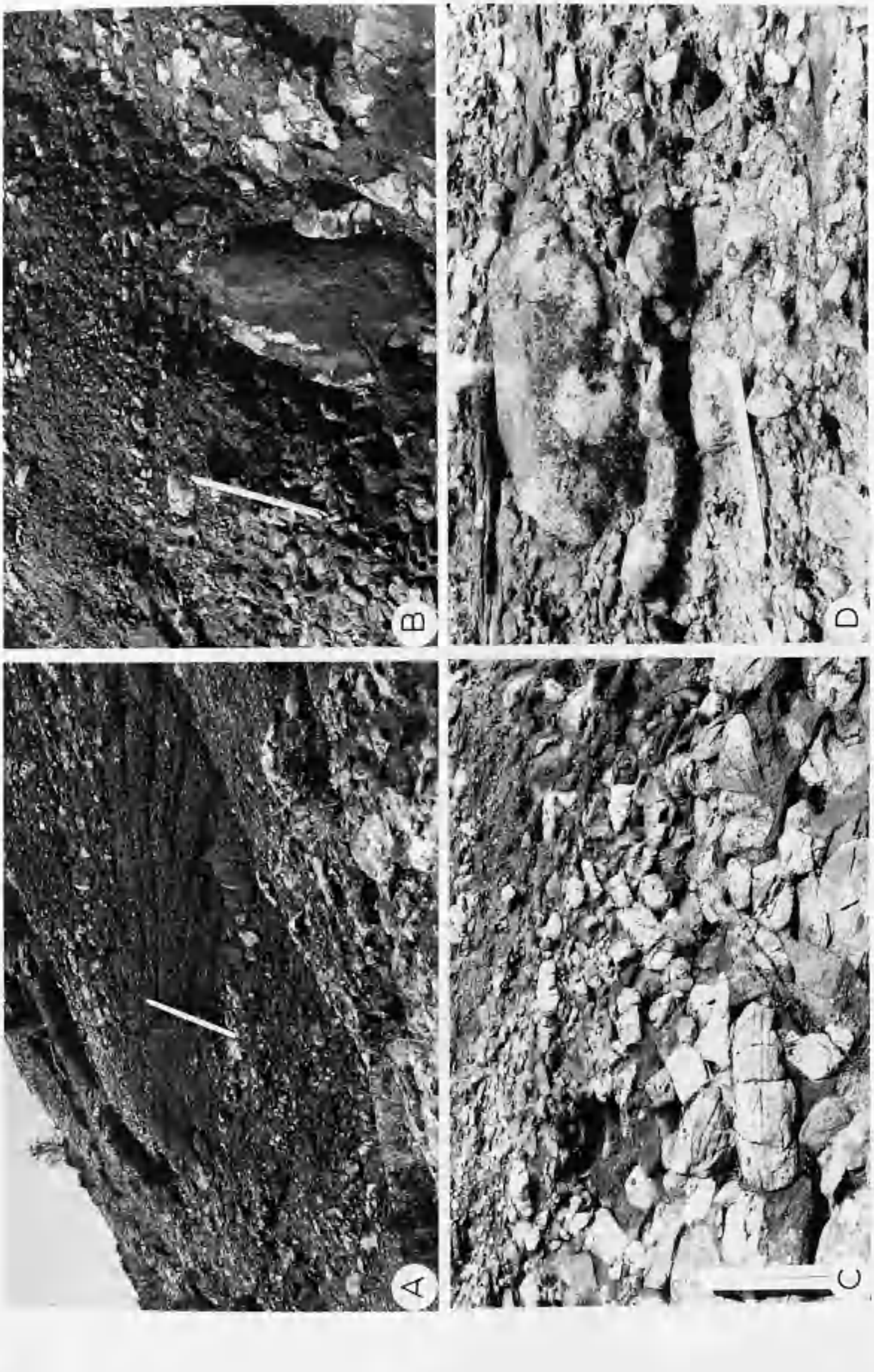
Plate 7.1.9. A: Planar-stratified and low angle cross-stratified sheetflood deposits of Facies C stand out in a sharp contrast with the massive and coarser-grained debris flow conglomerates of Facies B. Scale is 0.5 m long. (Locality: Mound Rock, BLF);

B: Normally graded bed of Facies C erosionally covers the ungraded deposits of Facies B. Note perfect sorting of the conglomerates of Facies C. Scale is 0.25 m long. (Locality: Mound Rock, BLF);

C: Rare normally graded bed of Facies B passing upward into the planar-stratified deposits of Facies C. Scale is 0.25 m long. (Locality: Mound Rock, BLF);

D: Debris flow bed of Facies B is covered and underlain by the winnow-stage, stratified sandstone beds - a rare variety of Facies C. Scale is 0.25 m long. (Locality: Beinn Lunndaidh 1, BLF; see also Fig. 7.1.1e. and Fig. 7.1.25.)

Plate 7.1.9.



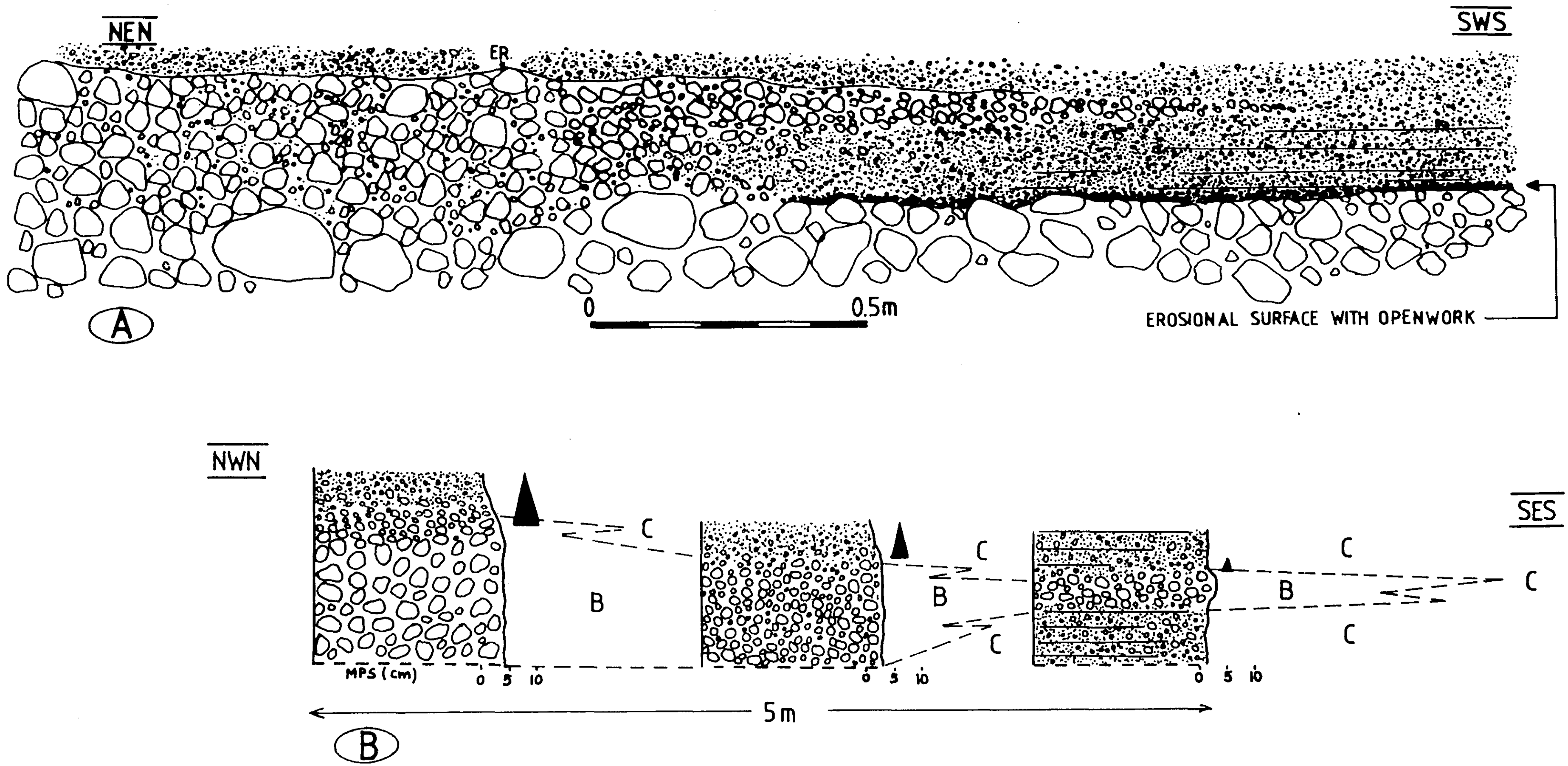


Figure 7.1.10a. A & B: Very rapid lateral as well as vertical transition of Facies B into Facies C is seen as representing a dilution of the upper part of debris flow due to water in-take and a dramatic transformation into turbulent flow. Such processes are thought to have involved a considerable loss of competence of the debris flow and hence, a rapid deposition (see also Fig. 7.1.10b.). (Locality - Mound Rock, BLF)

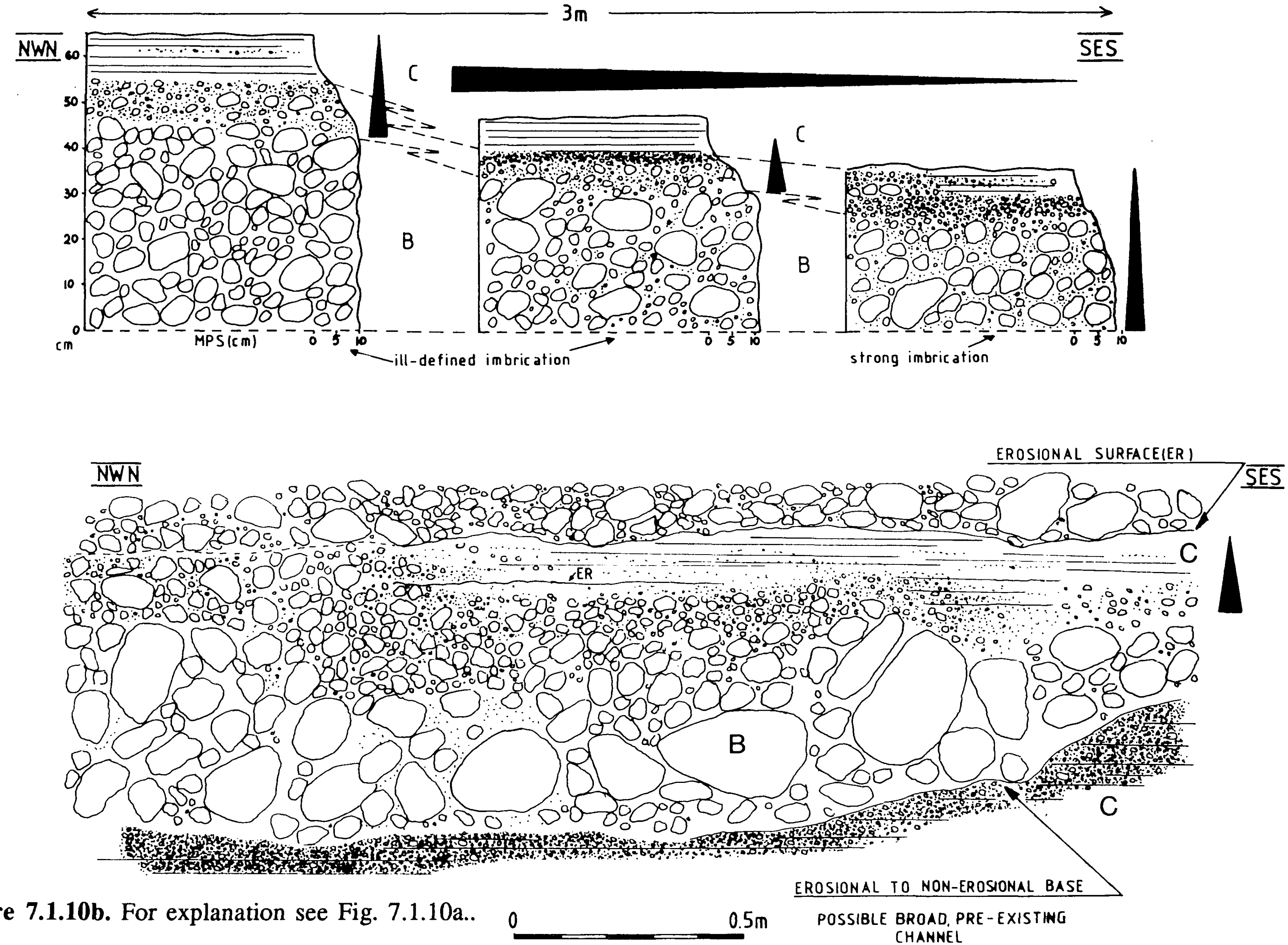
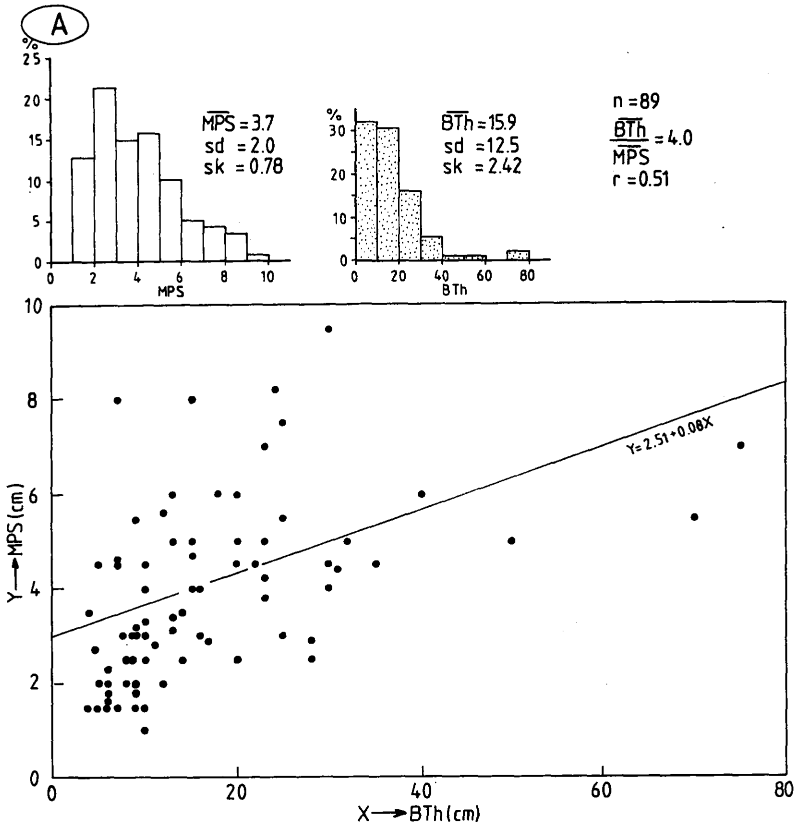
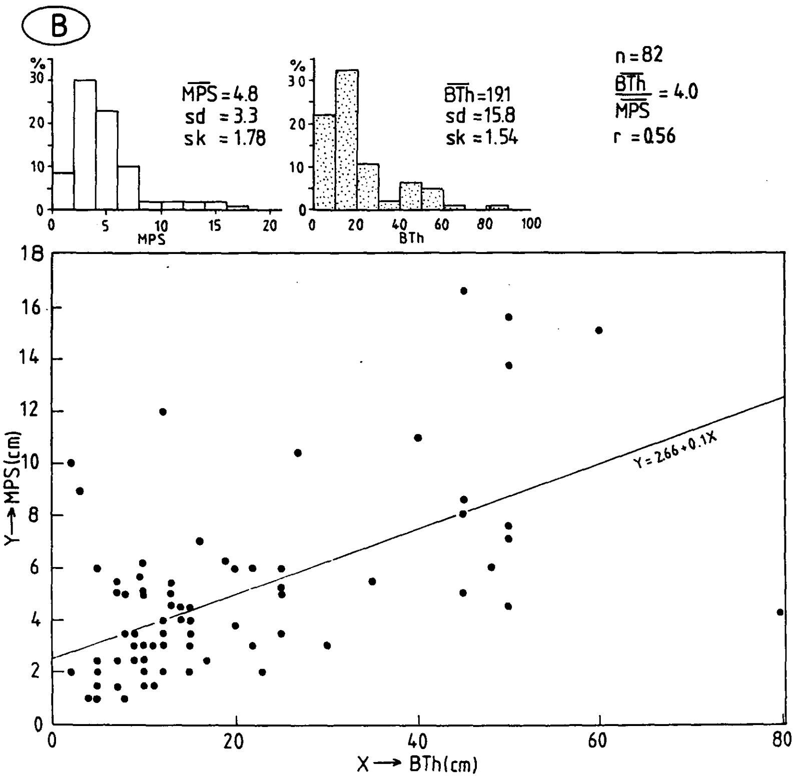


Figure 7.1.10b. For explanation see Fig. 7.1.10a..

Figure 7.1.11. Scatter plot of the maximum particle size (MPS) versus bed thickness (BTh) for the beds of Facies C from two localities: **A** - Mound Rock, **B** - Silver Rock. The histograms represent number frequency distribution of the MPS and the BTh data. Results of goodness-of-fit test for the two sets of data are given in Fig. 7.1.6. For explanation of symbols see Fig. 7.1.4.


A
%
MPS
$\overline{MPS}$ = 3.7
sd = 2.0
sk = 0.78
BTh
$\overline{BTh}$ = 15.9
sd = 12.5
sk = 2.42
n = 89
$\overline{BTh}$ / $\overline{MPS}$ = 4.0
r = 0.51
Y = 2.51 + 0.08X
Y → MPS (cm)
X → BTh (cm)


B
%
MPS
$\overline{MPS}$ = 4.8
sd = 3.3
sk = 1.78
BTh
$\overline{BTh}$ = 19.1
sd = 15.8
sk = 1.54
n = 82
$\overline{BTh}$ / $\overline{MPS}$ = 4.0
r = 0.56
Y = 2.66 + 0.1X
Y → MPS (cm)
X → BTh (cm)

variation in grain-size, sorting and amount of sandy matrix (Plate 7.1.9.A). Planar cross-stratification is extremely rare.

The conglomerates are typically finer-grained than the deposits of Facies B. The maximum particle size (MPS) is from 0.2-16.2 cm, averaging around 4 cm. An observed number frequency distribution of the MPS differes significantly from a theoretical normal distribution (Fig. 7.1.6. & 7.1.11.).

Proportion of very coarse-grained, granule to pebble rich, sandy matrix varies between 5-30%. The matrix is thoroughly dispersed in the conglomerate; it does not appear as homogeneous intraclasts. Neither there are any gravelly intraclasts. Thus, laterally, the individual beds appear texturally homogeneous throughout, in contrast to the strongly heterogeneous Facies B deposits. The textural changes within Facies C, when occur, have an organised form of stratification and/or grading.

There are common, a few centimeters thick (max. 30 cm), bimodal, clast- to matrix-supported interbeddings. They often have at the top a few centimeters thick openwork horizons. The latter are normally covered by a finer-grained, polymodal conglomerate with filled framework (Fig. 7.1.14.).

The beds of Facies C are present as well defined sheets and lenses (Fig. 7.1.2. & 7.1.3.), ranging in thickness from 1-100 cm, averaging 16-19 cm. The highest computed goodness-of-fit values confirm a significant discrepancy between the BTh frequency data and an ideal normal distribution (Fig. 7.1.11.). The discrepancy is generally larger than the one recognized for Facies B. Lateral extent of the beds reaches maximum 20 meters but it is usually between 0.5-5 m (in section oblique to the inferred local palaeotransport direction).

The deposits of Facies C normally rest erosionally on the beds of Facies B, filling depressions and irregularities (Fig. 7.1.3., 7.1.14.A, 7.1.14a.), but major scours or channels have been rarely observed (Fig. 7.1.14.B). Openwork horizons appear commonly right above the erosional bases.

There is a significant, positive correlation between the MPS and the BTh though clearly weaker than for the deposits of Facies B (Fig. 7.1.11.). BTh/MPS ratio is consistently of a larger value than for the beds of Facies B.

Plate 7.1.10. A: Photomicrograph and SEM photograph of sandstone matrix of Facies B. The iron oxide-stained clay occurs as uneven coatings on the grains as well as "free" concentrations filling the pore spaces. The attached SEM photograph shows that the clay particles in the coatings are oriented parallel to the grain surface(left). Quartz overgrowth on the right and also arrowed in the photomicrograph. PPL (Locality: Mound Rock, BLF);

B: Apart from the most abundant quartz cement the calcite is also locally present (arrowed) replacing the quartz overgrowths. XPL (Locality: the same as A);

C: Photomicrograph of the sandstone from the Ousdale Arkose Conglomerate. Note abundant quartz cement and scarcity of the clay material. The arrow points to a compatible boundary between two overgrowths. (Locality: Glen Loth, BLF);

D: Detail of the quartz overgrowth. The arrows points to the well developed habit of the quartz the overgrowth. XPL (Locality: the same as above)

Plate 7.1.10.

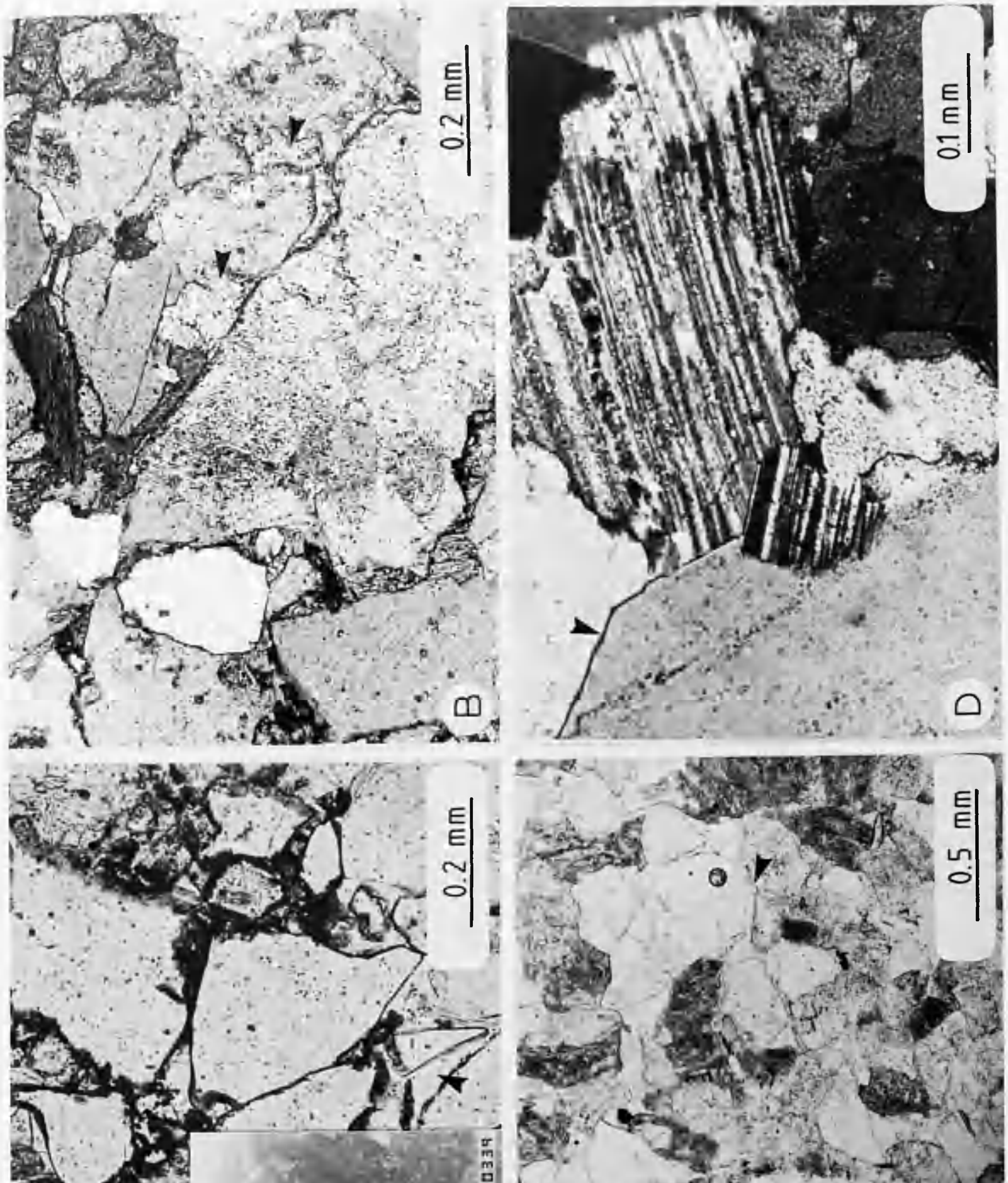


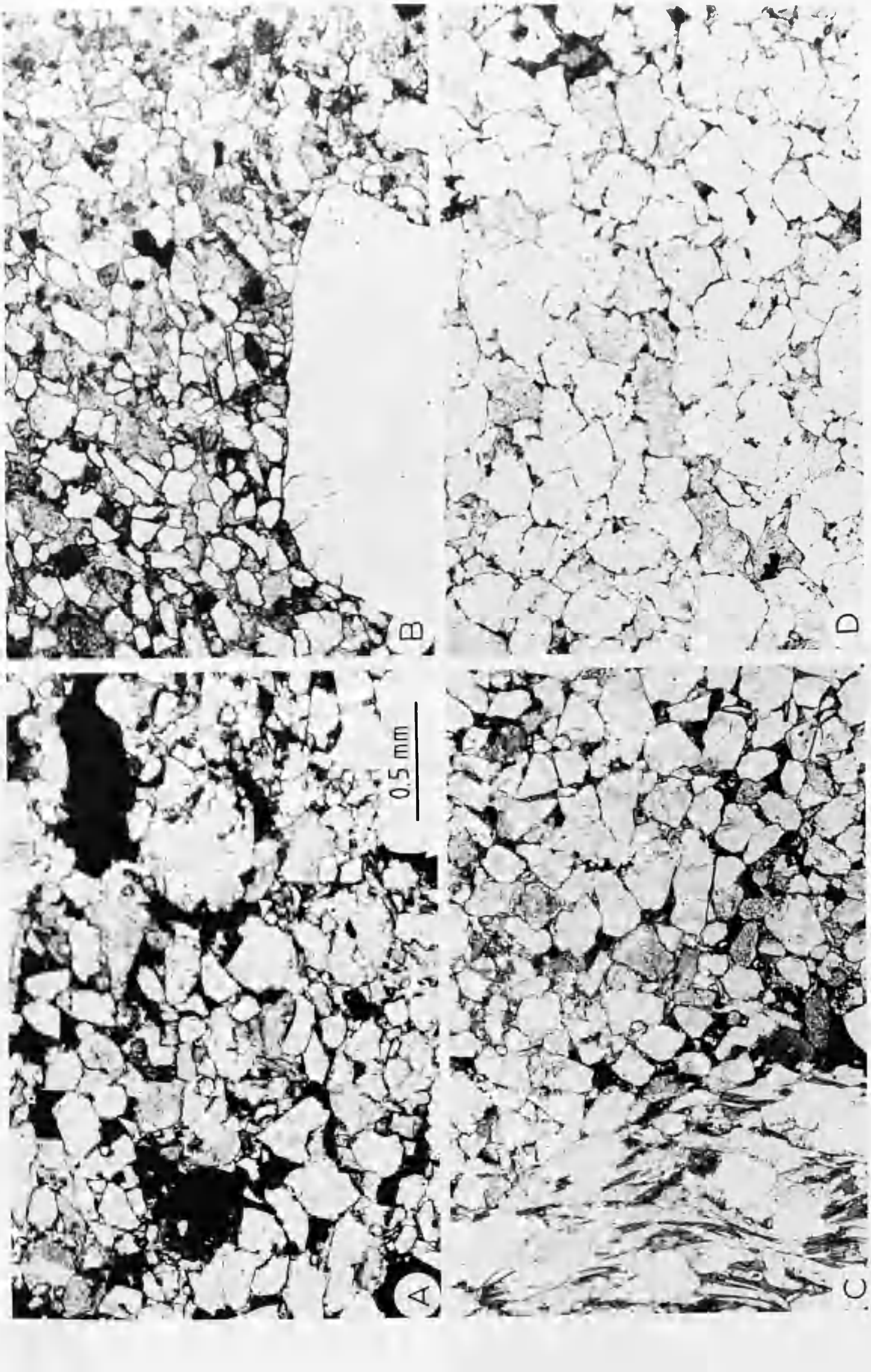
Plate 7.1.11. A: Photomicrograph of sandstone matrix of Facies B. Note abundance of the clay material and poor sorting. Decomposed biotite (upper right corner) was one of the main sources of clay and iron oxide (PPL). (Locality: Meall Odhar, BLF);

B: Photomicrograph of very well sorted matrix of Facies B1. Cloudiness of the abundant quartz cement may be due to dispersed particles of primary clay (PPL). (Locality: Creag an Amalaidh, BLF);

C: Another example of well sorted sandstone matrix of Facies B1 from the Socach Hill Conglomerate (PPL). (Locality: Killin Rock, BSF ?);

D: Photomicrograph of well sorted sandstone, which rests directly on the granodiorite of the Rogart Central Granodiorite Complex. The sandstone is probably of aeolian origin (see Plate 7.1.1.A) (PPL). (Locality: Loch Airidhe Mhor)

Plate 7.1.11.



The majority (61%) of the analysed Facies C beds show no grading (Fig. 7.1.12.). 25% of them display normal grading throughout and 4% at the top only. The lower, coarser members of the normally graded beds are usually more sandy, matrix-supported in places, and may be crudely-stratified. Bases of such beds seem to be non-erosional. Two to twenty centimeters thick, sandstone lenses sporadically appear at the top of the normally graded beds. They are parallel-stratified or trough cross-stratified and have a similar grain-size distribution as the matrix in the surrounding conglomerates. In most instances the sandstone beds rest directly on beds of Facies B (Plate 7.1.9.D & Fig. 7.1.1e.).

The normal grading is commonly associated with similar lateral fining and occasionally thinning of the beds (Fig. 7.1.10a. & 7.1.10b.).

Rarely, two or three beds of Facies C are arranged in fining-upward units (Fig. 7.1.1c., 7.1.1d., 7.1.22.).

An imbrication is particularly well developed in the moderately to very well sorted, stratified beds. The less sorted, sandy varieties display non to poorly-defined preferential clast orientation.

7.1.5.1.4. Facies B and C - Interpretation

The Facies B conglomerates are interpreted as **debris flow deposits** on account of the assemblage of their following features:

(1) lack of stratification;

(2) generally poor sorting, presence of outsize boulders;

(3) lack of grading in the beds;

(4) single outsize clasts projecting above the tops of the beds;

(5) abundance of primary matrix, commonly "supporting" clasts;

(6) texturally heterogeneous, disorganised character, non-uniform dispersion of particles;

(7) chaotic fabric, some vertical clasts, locally developed long-axis imbrication;

(8) presence of semi-lithified, sandy intraclasts with preserved lamination - unremoulded "matrix" (primary sediment);

(9) distinctive "soft-deformational" style of the basal contacts of the beds;

(10) positive, significant, linear correlation between the maximum particle size (MPS) and the bed thickness (BTh), and between the largest particle size (LPS) and the bed thickness.

The above individual features of Facies B should not be considered in isolation, while evaluating their significance to recognition of debris flow deposits. Some of them, like for instance: lack of stratification, disorganised fabric and poor sorting may well occur in proximal fluvial environments (Bluck, 1976,1986; Rust, 1978). It is the assemblage of the characteristics of the deposits of Facies B which suggests their mass flow origin. The features 5, 6, 8 and 10 are incompatible with a "grain-by-grain", fluvial deposition.

A striking facet of Facies B is a scarcity of sandstone interbeddings, contrasting with the abundance of the primary sandy matrix in the conglomerates. If these deposits were to form in streams one would expect a periodic deposition of sand, reflecting varying discharge, discontinuous accretion and local flow separations. Such stream flow behavior should be highlighted by an intimate association of deposited gravels and laminated sands (Eynon & Walker, 1974; Steel & Thompson, 1983; Nemec & Steel, 1984). It is suggested herein that the conglomerates of Facies B represent a simultaneous, *en mass* , emplacement of sand and gravel.

The non-uniform (matrix- to clast-supported), patchy distribution of the matrix in the filled framework conglomerates and presence of the sandy intraclasts gradational to the matrix suggest the primary origin of the matrix. There is also lack of source sandstone beds from which the sand might have infiltrated into the underlying gravels. It seems unlikely that all these source sandy beds were successively entirely eroded.

The majority of the depositing debris flows are believed to be relatively cohesive, with an active role being played by cohesive properties of the matrix (Lowe,1982; Nemec & Steel, 1984; Blair, 1987a,b) (see further in the text).

In such medium the still-plastic, semi-lithified sandy and gravelly intraclasts did not completely disperse during transport (see also Kochel & Johnson, 1984, p. 116). The generally disorganised fabric, the lack of grading and the common matrix-supported texture additionally indicate the cohesive regime with a high shear strength, that prevented turbulence, settling of particles and effective clast interaction (Bull, 1964; Lowe, 1979; Nemec & Steel, 1984).

The dominant clast-supported texture does not rule out the cohesiveness of the debris flows; even if the beds do not show obvious presence of preserved "soft" intraclasts. In many cohesive debris flows clasts have been reported to be in contact during transport (Lowe,1982; see also Bagnold, 1954; Curry, 1966; Lowe 1979; Sharp & Nobles, 1953).

The amount of clay-water matrix can make up as little as 5 % of the total volume of such flows (Rodine & Johnson, 1976). Proportion of clay fraction in modern debris flows have been reported to be as low as 1% (Curry, 1966) or even less (Vessell & Davis, 1981). Debris flows active at the front of Matanuska Glacier contain 3% of clay-size particles though most of it is quartz, well-crystallized mica, well-crystallized chlorite, feldspar and carbonates (Lawson, 1982). In debris flows accumulating on an alluvial fan at Mt. Thomas (New Zealand) a clay fraction of 11% has been recorded (Pierson, 1981). It consists mainly of illite, non-swelling chlorite and kaolinite.

It seems impossible to determine exactly how much, what kind of clay material and of what origin, was present in the debris flows during their emplacement. In view of the proposed resedimented origin of the Facies B, B1 and C deposits (see chapter 7.1.5.4.) it seems logical to propose that the source gravels and sands had been enriched in clay prior to the mobilisation.

In the Pliocene first-cycle fanglomerates of the Sonoran Desert (USA), derived mostly from metamorphic and granitoid sources, amount of secondary clay is as high as 25% with mechanically infilltrated clay constituting 10 - 20% (Walker, 1967; Walker *et al.*, 1967; Walker *et al.*,1978). It is important to mention in the Sonoran Desert the most abundant clay is interstratified illite-smectite with 80 - 95% expandable layers

Regardless whether in the case studied here the clay material had been introduced to the primary sediments prior to mobilisation by the infiltration or through the replacement (possibly illite and expandable illite-smectite mixed layers, chapter 7.1.5.2.), the both mineral phases together with other cements (e.g. iron-oxides, carbonates) would have affected to some extent the debris flow mechanics, by contributing their properties of cohesion. The only type of clay, which appears to be effective with regard to cohesion, understood as electrostatic/electromagnetic interactions between the particles, is expandable smectite. Montmorillonite has specific surface area 800 m^2/g and cation exchange capacity 100 meq/100g compared to illite 80m^2/g and 25 meq/100g and kaolinite 15 m^2/g and 5 meq/100g respectively (Kenny, 1984, table 2.2.; but see also chapter 7.1.5.3).

Certainly, additional amounts of clay might have been added after the final deposition of the gravels, through infiltration and/or further authigenic alterations of detrital grains.

It seems that buoyancy was another crucial particle supporting factor. This is indicated by the abundance of the poorly sorted, argillaceous sandy matrix and high proportion of the poorly sorted coarse-grained material. The both sediment properties provided optimal conditions for a reduced dissipation rate in excess pore pressure (Hampton, 1979; Pierson, 1981). The excess pore pressure must have also improved mobility of the debris flows by reducing their shear strength (Hampton, 1979; Pierson, 1981). It is believed that the substantial clast concentration (clast-supported texture) could maintain a mechanism of of static grain-to-grain contact which held a certain portion of the weight of the clasts (Rodine

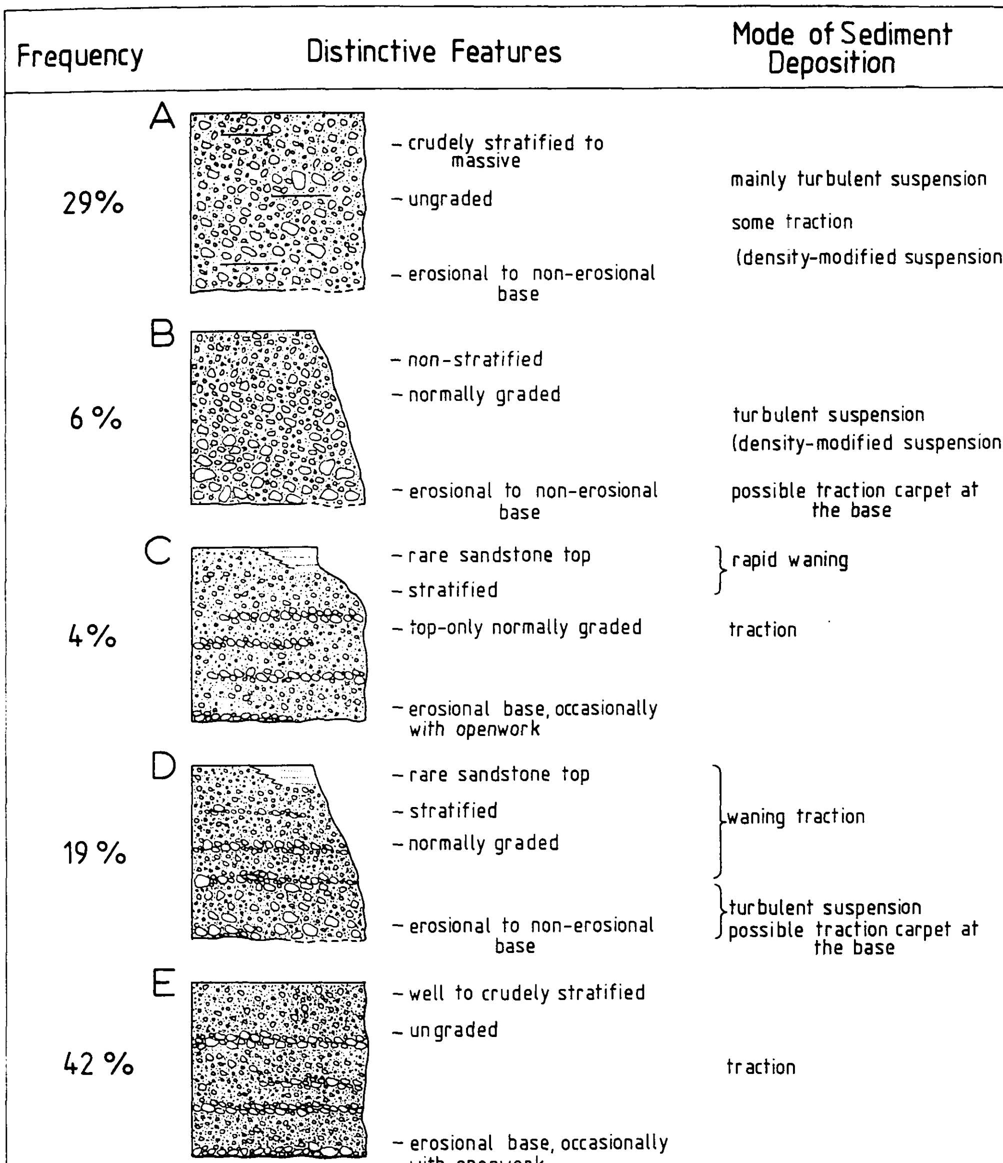


Figure 7.1.12. A summary of characteristics of the beds of Facies C and their interpretation.

& Johnson, 1976; Pierson, 1981; Costa & Williams, 1984). The latter particle supporting agent would have applied especially to a "rigid plug" type of transport. This is also indicated by the presence of large, intact sandy chunks with preserved lamination and the lack of grading in the beds.

The smeared out, diffuse intraclasts point to shear zones within the flows (Hampton, 1975; Kleinsphen *et al.*, 1984). The characteristic parting planes may also reflect the pervasive shearing and hence, laminar flow conditions in the depositing debris flow (Lindsay, 1966) (see also chapter 7.2.4.1.9. & 7.4.5.1.1. for discussion of analogous structures).

In more rapidly moving, sheared flows the static grain-to-grain contact might have been at least partly replaced by disperssive pressure, resulting from collisions and near approaches of the particles (Bagnold, 1954). This could produce the up-current long-axis imbrication (Lindsay, 1966; Davis & Walker, 1974; Lowe, 1979).

The preferred current-transverse orientation of a-axes and b-axes imbrication, observed in two beds (Fig. 7.1.16.C & D) can be explained in three ways. Firstly, the clast orientation within the debris flow gravels could have been modified be the succeeding sheet flood (see interpretation of Facies C further in text). This is suggested by the small amounts of sandy matrix, left between clasts, possibly winnowed by the turbulent flow. Secondly, in many recent, debris flows some of the clasts were reported to have been carried in traction (Lowe, 1979; Sharp & Nobles 1953; Pierson, 1981; Costa & Williams, 1984). In such conditions, the "fluvial" type of clast imbrication would be expected. Thirdly, the recorded clast orientation may represent an up-flow dipping "push-fabric", developing in clast-rich pressure ridges of subaerial debris flows (Rust, 1981; Lawson, 1982; Wells & Harvey, 1987 see also Plate 7.4.4.).

The positive, linear correlation between the maximum particle size (MPS) and the bed thickness (BTh) has been seen by many workers as a significant interdependence between either the flow competence (Hampton, 1975, 1979) or the suspension competence (Pierson, 1981) and the flow thickness - capacity (Bluck,1967; Gloppen & Steel, 1981; Porebski, 1981, 1984; Nemec & Muszynski, 1982; Nemec & Steel,1984). The MPS/BTh correlation coefficients determined by the present author for the ungraded beds (Fig.

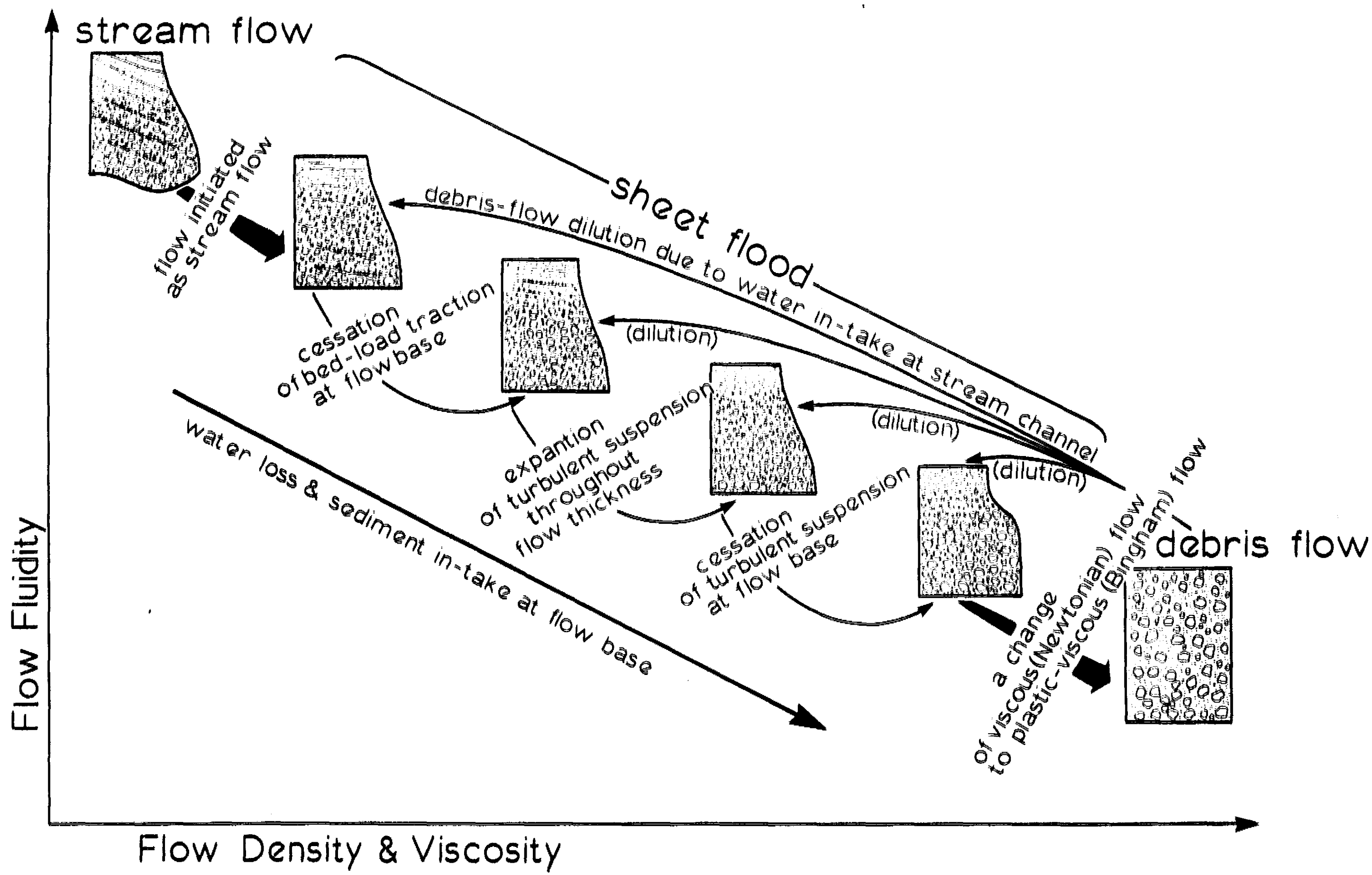


Figure 7.1.13. Hypothetical model of genetic relationships between the stream flow, sheetflood and debris flow beds (after Nemec & Muszynski, 1982).

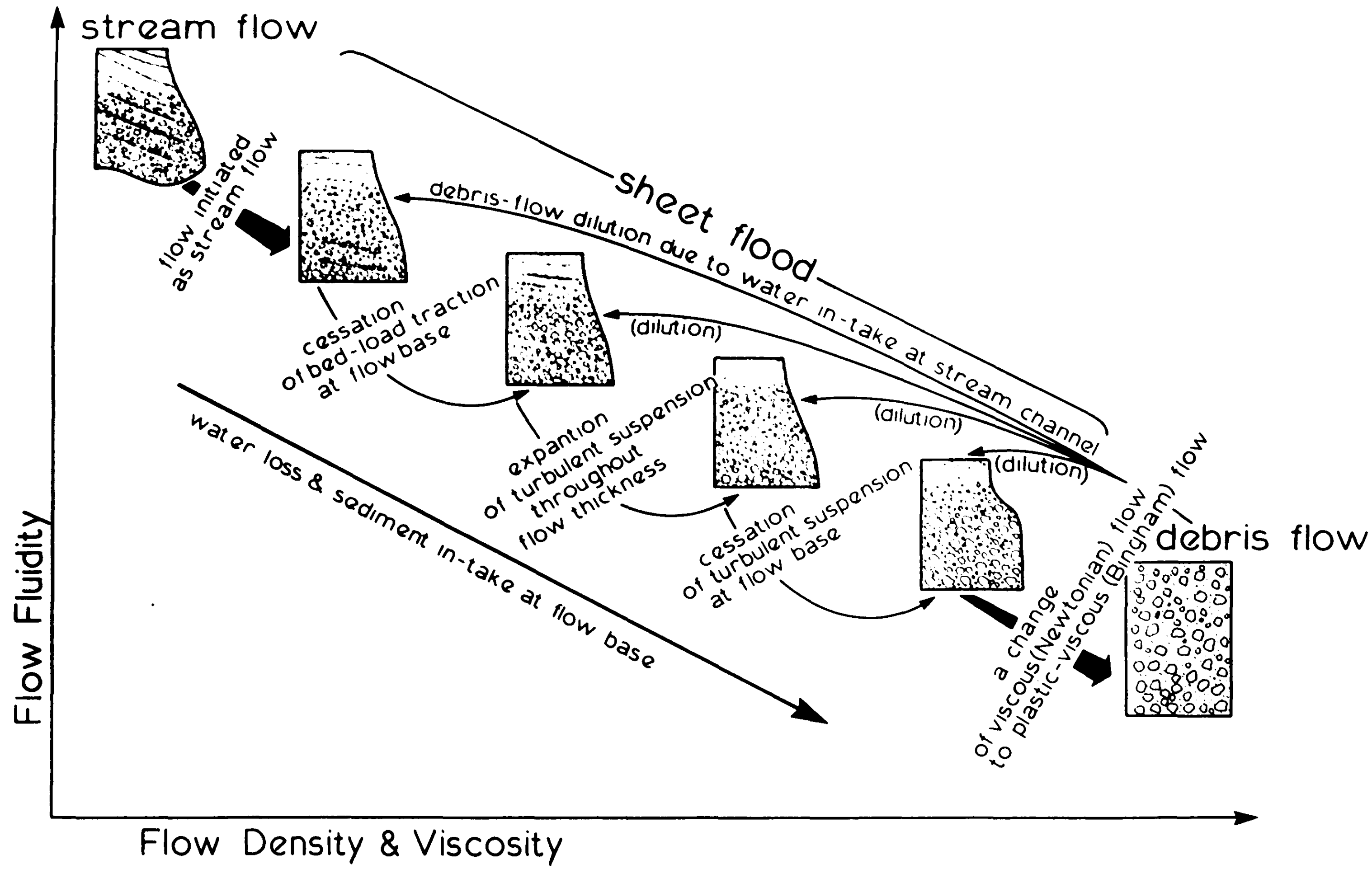
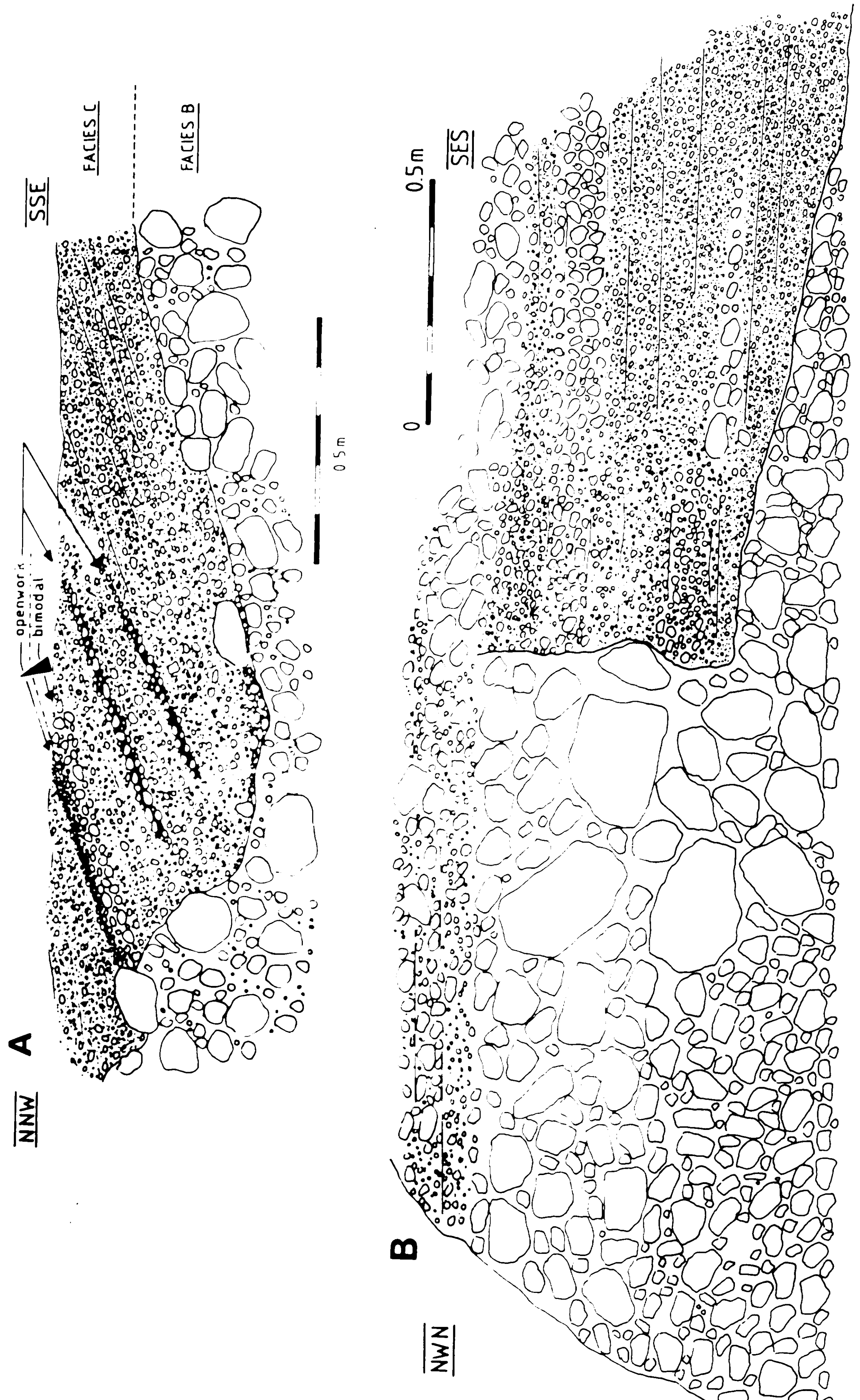


Figure 7.1.13. Hypothetical model of genetic relationships between the stream flow, sheetflood and debris flow beds (after Nemec & Muszynski, 1982).

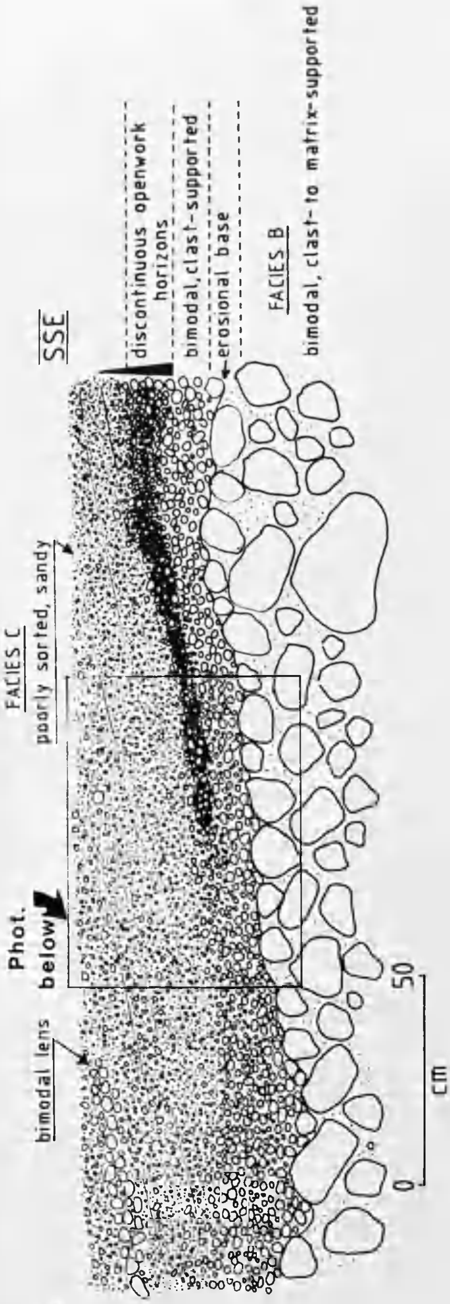
Figure 7.1.14a. A: Rarely, Facies C is represented by planar cross-stratified conglomerates, resting erosionally on the debris flow deposits of Facies B. The perfect sorting of these deposits is thought to be a result of reworking of the earlier deposited debris flow and sheetflood gravels. The normal grading reflects a waning flow stage. (Locality: Silver Rock, BLF);

B: A rare example of dissection of the debris flow deposits (Facies B) by the sheetflood event(-s) (Facies C). The filled triangles mark vertical and lateral decrease in clast size. (Locality: Mound Rock, BLF)



A
NNW
SSE
FACIES C
FACIES B
openwork
bimodal
0.5m
B
NWN
SES
0
0.5m

Figure 7.1.14b. For explanation see Fig. 7.1.14b.


NNW
SSE
FACIES C
poorly sorted, sandy
bimodal lens
Phot. below
discontinuous openwork horizons
bimodal, clast-supported
erosional base
FACIES B
bimodal, clast-to matrix-supported
0
50
cm


Scale
25 cm

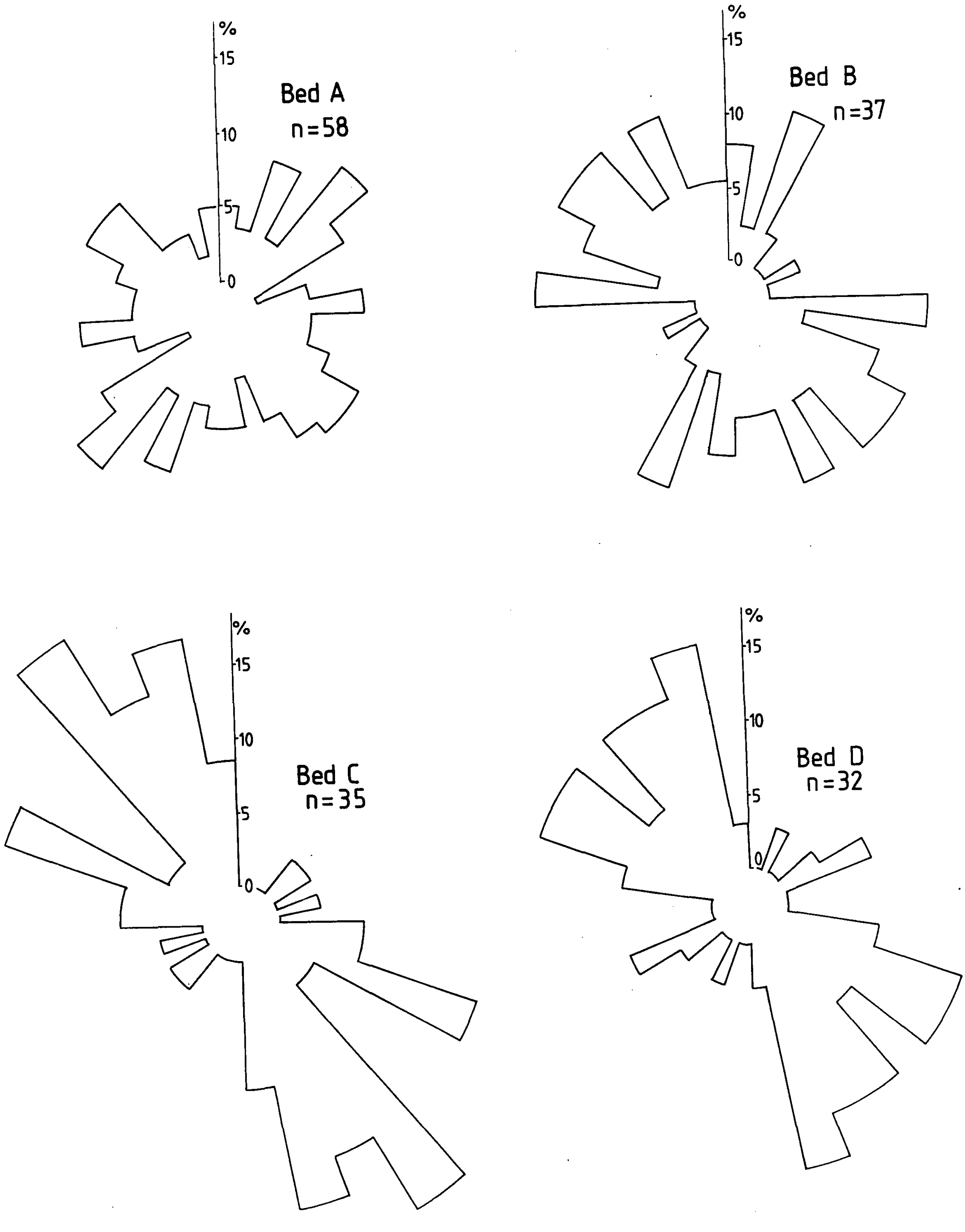
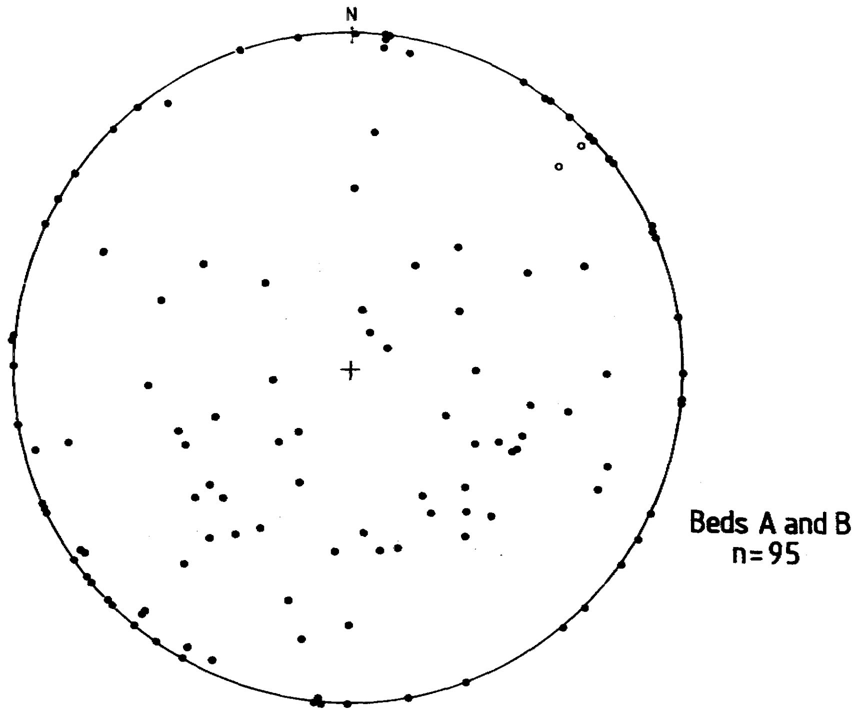


Figure 7.1.15. Rose diagrams of the strike of the long axes of disc-shape clasts from four beds of Facies B (**A-D**) (see also Fig. 7.1.15.). (Locality: SE of Mound Rock[NH 776 983], BLF)



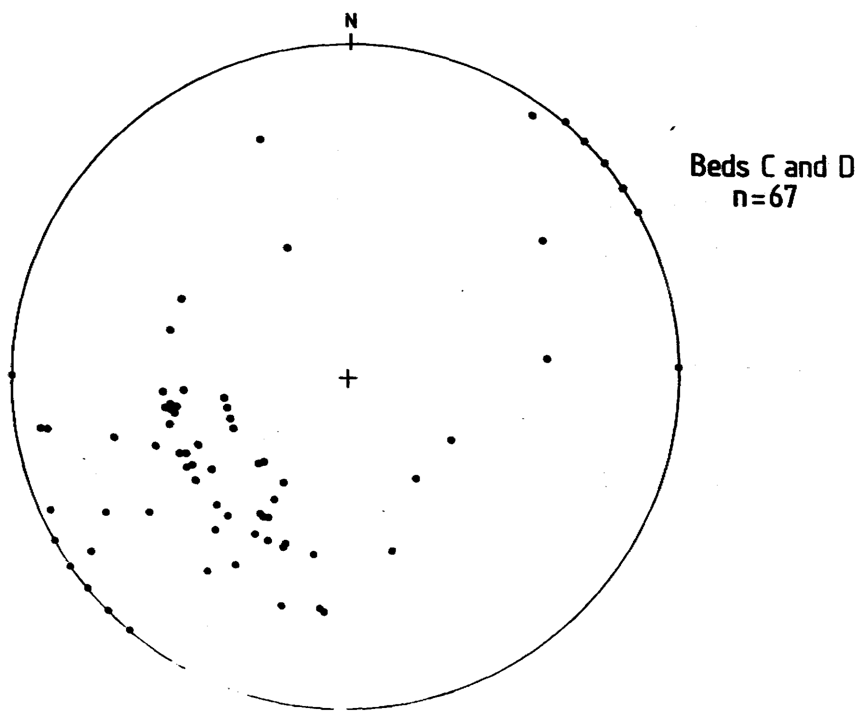


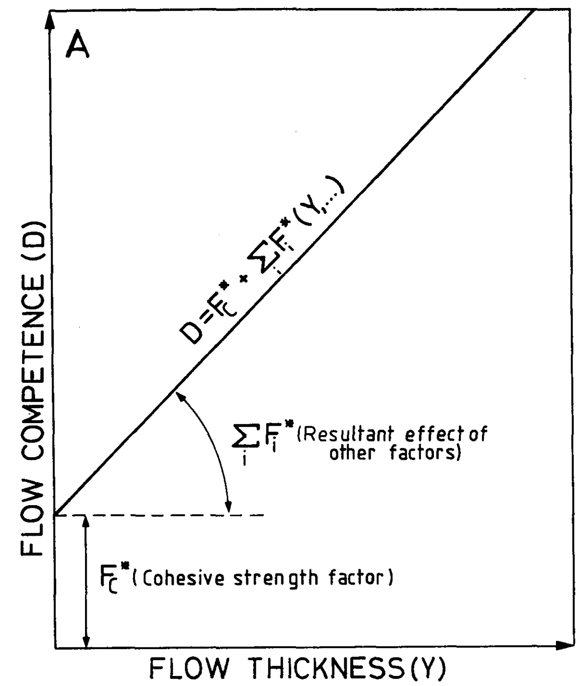
Figure 7.1.16. Poles of the *ab* planes of the disc-shape clasts from four beds of Facies B(**A-D** in Fig. 7.1.15), ploted on Lambert equal-area projection of the lower hemisphere. The beds **A** and **B** display no preferential clast orientation. Note a considerable number of vertical clasts. Orientation of the clasts from the beds **C** and **D** indicates palaeotransport to the SW. (Locality: SE of Mound Rock[NH 776 983], BLF)

7.1.4.) are lower than the values obtained by Nemec & Steel (1984) and Porebski, (1981,1984) for inversely graded, inversely-to-normally and normally graded beds. However, the author's data are close to their values for the ungraded beds (their data from submarine, debris flow dominated fan-delta). Besides, Nemec & Steel (1984), basing on their observations from various, mass flow-dominated sedimentary settings conclude that the high MPS/BTh correlation is characteristic for cohesionless debris flows, with a strong disperssive pressure component. Thus, the relatively weaker MPS/BTh correlation recognized for Facies B deposits would suggest rather moderate equilibrium between the competence and the flow thickness. This might have resulted from the high shear strength of the depositing debris flows which restrained disperssive pressure and rejection of the outweight boulders. The scatter of the MPS/BTh plots may also imply that the debris flows discussed here thinned and froze fairly rapidly, before the clasts "adjusted" to the competence of the flow (Johnson, 1984; Nemec & Steel, 1984).

According to Hampton, (1975, 1979) and Nemec & Steel (1984), size of the largest clasts within flow (LPS) provides, a better than MPS, estimate of flow competence. The correlation between the LPS and the BTh recognized for the beds of Facies B is statistically significant but clearly weaker than the correlation between the MPS and the BTh. Hence, it is argued here that while LPS seems to be a good criterion of competence for well "balanced" cohesionless debris flows (Nemec & Steel, 1984), MPS, which omits the largest clast, appears to be more adequate estimate in case of cohesive flows. Accordingly the above mentioned, lower LPS/BTh correlation coefficients indicate that the cohesive debris flows, interpreted here, had a tendency to be "over-competent". Note that LPS/BTh data scatter especially above the regression line and this trend may reflect the tendency of the depositing flows to be "over-loaded" and to carry outsize boulders (see also Fig. 7.1.5.).

It is emphasized that the scatter of the plots may be to some degree biased due to missidentification of the bed boundaries i.e. overestimation of the bed thickness in case of amalgamated beds with merged boundaries and/or underestimation resulting from a contemporaneous intrastratal erosion.

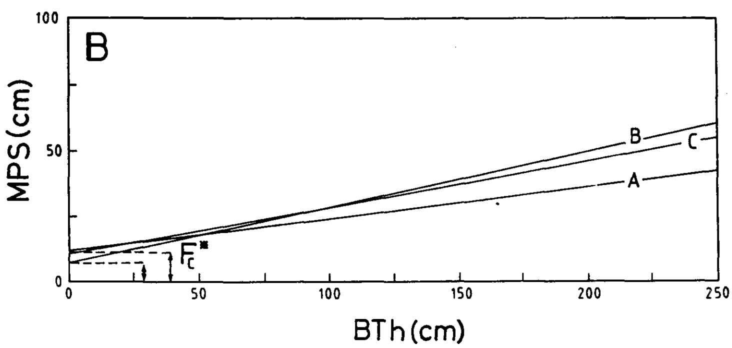
Figure 7.1.17. Regression lines fitted to the Facies B MPS vs. BTh data (see Fig. 7.1.4. earlier in text) (**B**) have been confronted with the model of cohesive and cohesionless debris flow by Nemec & Steel. (1984) (**A**). According to the model the fact that the Facies B regression lines intercept the vertical axis of flow competence (Q) represented by maximum particle size (MPS), suggests an active role of cohesion factor (**Fc***) in the interpreted debris flows.



$D = F_C^* + \sum_i F_i^*(Y,..)$ COHESIVE DEBRIS FLOW

$D = \sum_i F_i^*(Y,...)$ COHESIONLESS DEBRIS FLOW

$\sum_i F_i^*(Y,...)$ = other possible factors dependent on the flow's thickness (Y)



It has been suggested by Nemec & Steel (1984) that MPS/BTh diagrams may serve a simple tool in discriminating between cohesive and cohesionless debris flows, providing that the data display a significant, high positive linear correlation. It is also advised that data should be collected according to facies. The concept is based on the argument that debris flow competence (D) is a resultant of interaction of two groups of factors: thickness-independent component which is represented by cohesive strength (Fc*) and thickness-dependent component represented by: frictional strength (Ff*), viscous resistance (Fv*) and other supportive factor(-s) (Fm*) i.e. disperssive pressure, turbulence and pore-fluid expulsion.

The cohesive debris flows are characterised by an active role of the cohesive strength (Fc*) in supporting particles whereas in the cohesionless regime the competence is controlled mainly by the thickness-dependent factors (Fi*) (Eq. 7.1.1 & Fig. 7.1.1). Consequently Nemec & Steel (1984) propose that absence or presence of the cohesive strength factor can be inferred directly from the regression line fitted to the data, and this makes possible to identify cohesive or cohesionless attitude of the interpreted debris flows.

If the above reasoning is correct the fact that the regression lines fitted to the Facies MPS/BTh data intercept the axis of flow competence (D) (Fig. 7.1.17.), should provide an additional argument, supportive to the earlier formulated thesis, based on the other sedimentary features, that the deposits discussed here represent cohesive debris flows.

$$D = \frac{b1\ C}{\Delta p'\ g} + \frac{b2\ \partial'n\ \tan\phi}{\Delta p'\ g} + \frac{b3\ \mu c\ es}{\Delta p'\ g} + \frac{b4\ fi}{\Delta p'\ g}$$

cohesive strength factor, Fc*	frictional strength factor, Ff*	viscous resistance factor, Fv*	other supportive factor(-s), Fm*

D = clast longest dimension

$\Delta p'$ = density contrast between dispersed clasts and the total debris mixture (pc - pd);

b1-4 = constants (which appear here as propotionality coefficient, but also take account of clast and the total debris mixture);

g = acceleration due to gravity;

ø = angle of effective internal friction;

$\partial n'$ = effective normal stress;

C = cohesion;

μc = coefficient of flow viscosity;

es = rate of shear strain;

fi= upward component of any other clast-supporting factor which offers lift to the clast.

Eq. 7.1.1. (after Nemec & Steel, 1984)

The rare, normally graded beds are interpreted as liquefied, probably turbulent, especially in their upper parts, debris flows in which vertical clast segregation took place but the high clast concentration and the sediment cohesiveness did not permit traction structures to develop (Davis & Walker, 1974; Lowe, 1974). It is understood that cohesiveness of such flows was considerably reduced.

The normally graded Facies B beds usually pass upwards into much fine-grained and better structurally and texturally organised Facies C conglomerates. However, in most cases the sheet-like, little channelised Facies C beds erosionally overlie the debris flow deposits.

They are interpreted as a product of deposition from **sheetfloods** (Blissenbach, 1954; Bull, 1964,1972; Wasson, 1977; Blair, 1987a,b), which are mainly characterised by conditions of the upper flow regime (Collinson, 1978; Blair, 1987a). The interpreted below sheetfloods carried gravel and sand in traction and/or turbulent suspension.

It is thought that lateral expansion of the sheetfloods involved surficial winnowing and reworking of the finer gravel and sand from the surface of the earlier emplaced debris flow and sheetfloods deposits (Rich, 1935; Davis, 1938; Jahns,1949; Johnson, 1970; Gloppen *et al.*, 1981). Only in a very few instances a significant rill-wash dissecting of the underlying deposits can be demonstrated (Fig. 7.1.14.B).

The consistently very low average MPS values (5 - 4 cm) suggest that competence of the sheetfloods was considerably lower than the competence of the debris flows. The log-normal frequency distribution of the MPS data indicates also that the transporting capacity did not vary significantly between the flows and they could generally carry only a very narrow range of particles. It was despite the abundance of the very wide spectrum of clast sizes, available upstream in the form of the previously laid down debris flow deposits. Such limited transporting potential of the discussed sheet floods stands in a vivid contrast with the tendency of the debris flows to carry an extreme variety of sizes of clasts. This is mirrored in the normal frequency distribution of the Facies B MPS data.

The short duration and low competence are typical features of sheetfloods (Blissenbach, 1954; Blair, 1987a). They are active on sections of the fans below so called "intersection point", where they are no longer confined to channels (Hooke, 1967; Wasson, 1974). After leaving the distributary channel the sheetfloods quickly die out. This is mainly due to their rapid radial expansion on the alluvial fan surface, resulting in reduction in flow depth and velocity (Bull, 1977). Incorporation of new material by the propagating sheetflood and downward escape of water into permeable surficial fan deposits are likely to increase sediment concentration of the flow and eventually advance the deposition (Beaty, 1963; Bull, 1964; Nemec & Muszynski, 1982).

The predominant upper flow regime conditions of the sheetfloods of Facies C, together with the low thickness of the generated deposits, suggest a very ephemeral nature of the flows. The lack of grading in 71 % cent of the deposited beds additionally indicates a very dramatic loss of the competence. The 23 % of the stratified, normally graded beds represent action of tractive currents of more or less rapidly decreasing competence, related to a waning flow stage.

The sudden deceleration of some of the flows, that carried their load in suspension, could have triggered a direct settling of the particles. This would have resulted in deposition of structureless, normally graded beds (only 6 % of the examined population). A traction carpet might have developed at the base of such flows (Lowe, 1982).

The massive, ungraded beds may represent flows in which combined mechanisms of disperssive pressure, buoyancy and matrix strength assisted the turbulence in holding the particles in suspension (Davis and Walker, 1974; Hampton, 1975). Such flows can be regarded as density-modified turbulent suspensions (Nemec & Muszynski, 1982).

The sudden loss of competence of the sheetfloods is also reflected in dramatically fining and thining out of some of the Facies C beds (Fig. 7.1.4., 7.1.6., 7.1.12. & 7.1.13.) as well as in the significant, positive MPS/BTh correlation (Fig. 7.1.11.).

Rarely, two to four beds of Facies C are arranged into fining-upward units. They are up to 1.5 m thick and the Facies B deposits always occur as their substrate (Fig. 7.1.1a.). These fining-upward cycles are interpreted as a result of deposition from pulses of successively less competent flows, all possibly associated with one, major depositional event (Bull, 1964; Johnson, 1984).

The good to perfect sorting of of some of the conglomerates Facies C could have also been achieved through a multiple reworking of the winnowed material (see also Larsen &

Steel, 1978). Most of the winnowed sand did by-pass the areas of gravel deposition. At Beinn Lunndaidh1, Cnoc Cragaidh and Killin Rock (BSF) Facies C is represented by cross- to parallel-stratified sandstone beds, directly capping the debris flow deposits (Fig. 7.1.1d., 7.4.2., 7.4.3a., 7.4.9.; Plate 7.1.9.D). Here the flows were only capable of transporting in traction maximum very coarse-grained sand. The maximum thickness of the cross-sets indicate a minimum 35 cm depth of such flows.

The unimodal, openwork horizons, associated with erosion surfaces and horizontally or low angle cross-stratification, represent a process of bypassing or winnowing of the finer gravel and sand at higher discharge. The polymodal, finer-grained layers formed during a discharge decrease (Smith, 1974). These multiple fluctuations in the discharge and in the competence of the individual depositional episodes, reflect a surging character of the sheetfloods.

Detail observations of a catastrophic flooding event in Colorado, USA, which formed an alluvial fan suggest that variations in grain size and sorting in the gravelly, planar-stratified sheetflood deposits may reflect velocity fluctuations following breaking of antidunes (Blair, 1987a). Deposition of coarse sand and granules from the sheetfloods studied by Blair (1987a) was caused by local decrease in flow velocity, due to the destruction of antidunes, increase in bed roughness due to bed load deposition and by flow separation around the created bedforms.

The locally developed in Facies C bimodal, clast- to matrix-supported interbeddings are seen as a product of simultaneous deposition of sand and gravel. The distinct bimodality suggests that the gravel and the sand must had been already segregated further "upstream", prior to the redeposition during the sheetflood event. The openwork, occasionally normally graded armours, appearing at the tops of the bimodal beds (Fig. 7.1.14.A & 7.1.14a.), reflect probably processes of winnowing and reworking of the finer fraction during the wanning flow stage (Steel & Thompson, 1983; Bluck, 1976, fig. 5). Continuing decrease in the flow competence resulted in deposition of polymodal, finer-grained gravels with filled framework (Steel & Thompson, 1983, fig. 6).

7.1.5.1.4.1. "Between-end-member" processes

Facies B and C generally represent "end-member" sedimentary processes which are characterised by distinctly different modes of sediment transport and deposition. It is important to realize that some of the deposits, included into these two categories may represent "between-end-member" processes, that is transitional between cohesive debris flows and fully turbulent sheetfloods. The liquefied, partly turbulent debris flows depositing the normally graded beds (Plate 7.1.9.C) and density-modified flows, represented by the massive, ungraded or normally graded Facies C beds (Fig. 7.1.12.) are regarded as such.

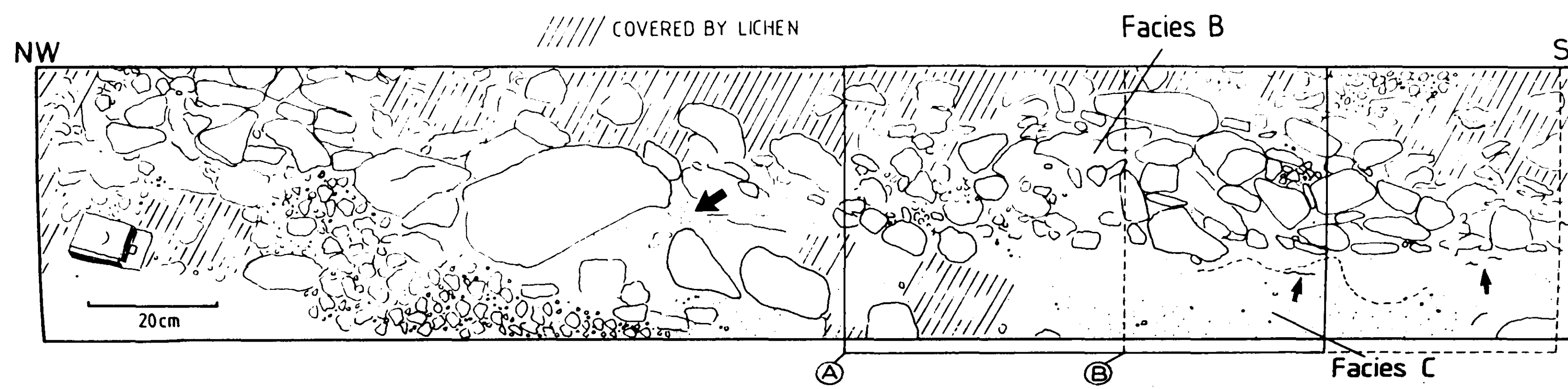
In a number of exposures the beds of Facies B clearly pass laterally into finer-grained and better organised deposits of Facies C. Such trend may demonstrate a possible genetic connection between the debris flows and the sheetfloods. However, it is striking that such transitions are apparent over a very short distance (Fig. 7.1.10a.A & B).

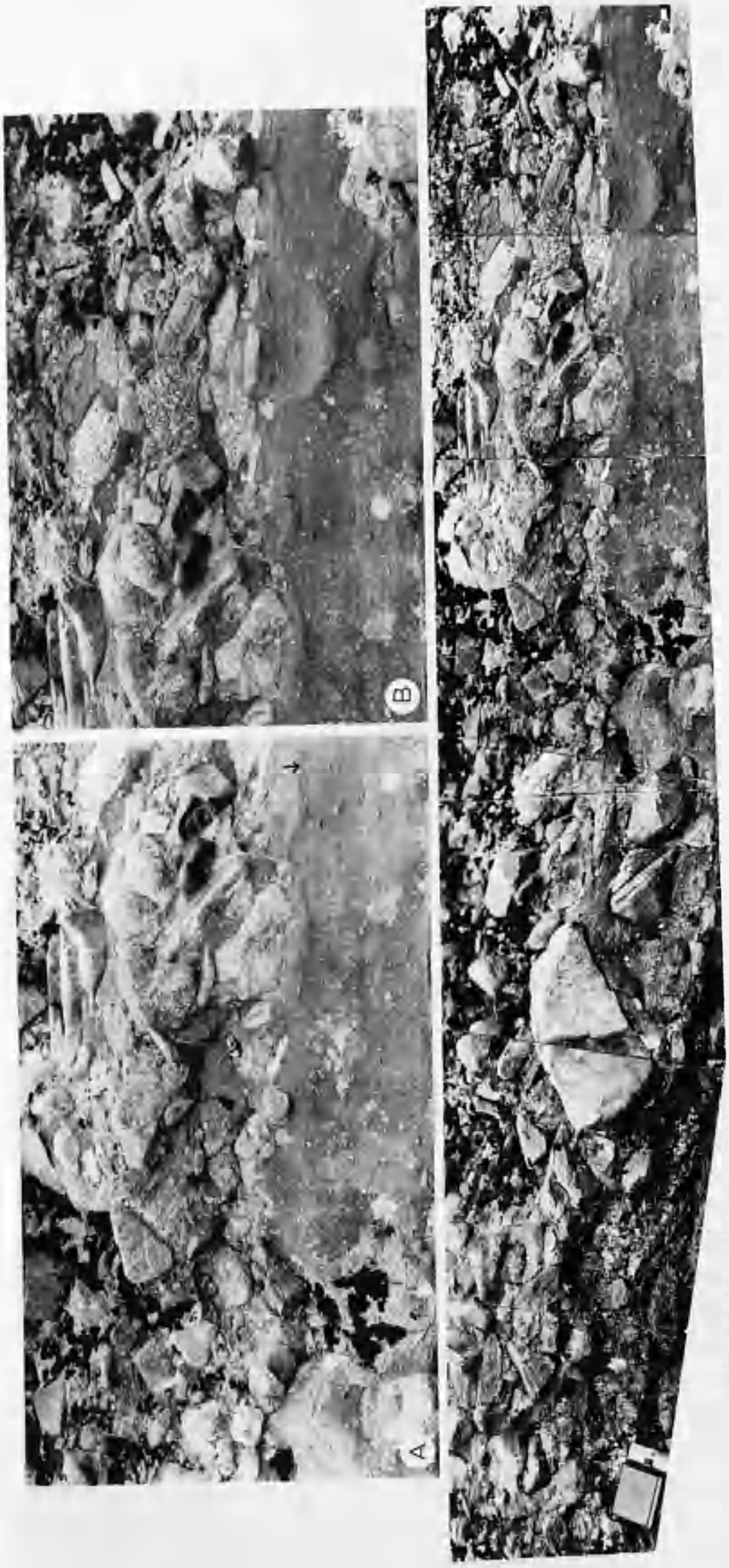
Nemec and Muszynski (1982) proposed a hypothetical model of genetic relationships between debris flows and sheetfloods (Fig. 7.1.13.). From a standpoint of this concept viscosity and density of a debris flow can be considerably reduced due to water in-take (see also Hampton, 1975). As slight as 5% introduction of water to a slurry of low water content significantly reduces competence of the flow, though further minor additions of water have much lesser effect (Hampton, 1975). Consequently, such diluted debris flow may evolve into a sheetflood, transporting its load in traction and/or in turbulent suspension.

The observed gradational, though very rapid, transitions from Facies B into C may reflect the dilution, and the loss of competence of the debris flow when it entered, simultaneously operating and depositing in the vicinity sheetflood. It is likely that very small proportion of the deposits Facies C deposits did form in this way. However, there is no evidence here for suggesting, that the majority of the sheetfloods did evolve from the debris flows, as the Nemec and Muszynski's (1982) model implies.

It is postulated herein, that the debris flows and sheetfloods operated independently on the alluvial fan surface. It is thought that the debris flows mobilised *en mass* whereas sheetfloods originated after leaving the distributary channel and operated concurrently

Figure 7.1.18. Diagram and the photographs below show how the sandy material (Facies C) has been partly remoulded with the overriding debris flow (Facies B). Lamination in the sandy bed has been almost completely destroyed. Larger arrow points to the faint lamination preserved locally within the remoulded sandy material. Note convolute folds in the sandstone bed, indicating a relative debris flow movement from the left to the right. Smaller arrows point to possible shearing features. (Locality: Beinn Lunndaidh 1(see Fig. 7.1.25., BLF))




B
A

or/and preceded or followed the emplacement of the debris flows.

It is understood that the spreading sheetfloods could branch locally between the elevations of the previously deposited debris flows, depositing thicker beds in shallow depressions on their surface (Fig. 7.1.3.A).

As it has already been mentioned above the debris flows provided the source of diverse clastic material for the sheetfloods and this seems to be the only significant, genetic link between Facies B, B1 and C.

7.1.5.1.5. Facies C1: Texturally homogeneous, stratified conglomerates (Ousdale Arkose variety)

Conglomerates of Facies C1 make up the Ousdale Arkose Conglomerate and its stratigraphic equivalent in the Badbea basin (Ousdale Arkose) (Fig. 7.2.22.). The description is based on a short cliff section at Ceann Ousdale (Badbea basin) as well as on small outcrops in Glen Loth, Glen Sletdale and at Creag a' Chrionaich (Golspie basin). Data from similar deposits which constitute parts of the Creag a' Bhodaich and Socach Hill conglmerates (Beinn Smeorail Formation) and exposed at Creag a' Bhodaich and Killin Rock respectively have also been taken into consideration.

Description

The Ousdale Arkose variety of Facies C (C1), is characterised by a clast- supported texture and a considerably less sandy matrix than found in Facies C. Sandstone interbeddings are scarce.

The most distinctive feature of Facies C1 is its composition which in fact is largely responsible for the textural nature of the conglomerates. They are almost entirely made up of arkosic debris derived from the fractured, coarse-grained, porphyritic variety of Helmsdale granite (adamelite) (Plate 7.4.8.C&D). The fact that the Helmsdale granite yielded predominantly pebble fraction(mostly individual orthoclase phenocrysts) did have a direct effect upon the grain-size distribution of the deposits of Facies C1, which makes up the Ousdale Arkose Conglomerate. The deposits of Facies C1 from the Socach Hill Conglomerate are entirely composed of angular clasts of Moine granulite of similar size (see chapter 7.4.5.1.3.). In the latter case the relatively small "Moine" maximum particle size reflects probably the distal alluvial fan environment (chapter 7.4.5.1.4.).

The conglomerates of Facies C1 are polymodal. Bimodal texture has not been found. Maximum particle size (MPS) ranges between 0.5 - 3 cm, averaging around 2 cm and it is thought to have been controlled by the size of the orthoclase feldspar phenocrysts in the

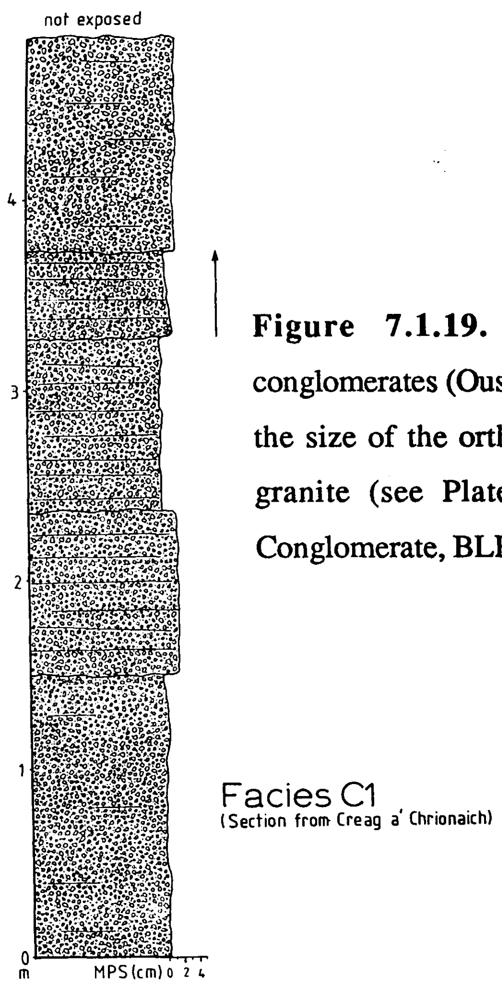


Figure 7.1.19. Facies C1 - Texturally homogeneous, planar-stratified sheetflood conglomerates (Ousdale Arkose variety). The maximum particle size (MPS) is "dictated" by the size of the orthoclase feldspars derived from the porphyritic portion of Helmsdale granite (see Plate 7.4.8.C&D). (Locality: Creag a' Chrionaich, Ousdale Arkose Conglomerate, BLF)

source granite (Fig. 7.1.19. & Plate 7.4.8.C&D). Typically the orthoclase feldspars, up to 4 cm long, occur as individual clasts in the conglomerates, giving them a spectacular appearance and sometimes it is very difficult to distinguish these arkoses from the source granite.

South-east of Craeg a' Chrionaich a local change in composition - an introduction of minor portion of Moine granulite clasts, involves an increase in the maximum particle size without change in structural characteristics.

The Facies C1 conglomerates predominantly display well to crudely defined planar stratification, highlighted by grain-size variations and flat erosional surfaces (Fig. 7.1.19. & Plate 7.4.8.C&D). Boundaries between individual beds are are poorly defined. Thickness of the recognized individual beds(?) is between 150 - 50 cm.

Interpretation

The Facies C1 conglomerates are interpreted as deposits of gravelly **sheetfloods** on account of the prominent planar stratification and lack of obvious scouring or larger scale channels. The aspects of initiation of sheetfloods are discussed in chapter 7.1.5.1.4.

The very narrow spectrum of clast sizes, characterising all the examined deposits of Facies C1 may again indicate a very limited competence of the discussed here flows. Considerations of the clast composition in the deposits of Facies C2 (Creag a' Bhodaich Conglomerate; see chapter 7.4.5.1.3. and Fig. 7.4.4.) suggest that the Helmsdale granite did in fact yield minor volumes of boulder-size detritus (see also chapters 7.1.5.3. & 7.1.5.4.). Such coarse particles are absent in the deposits of Facies C1 both in the Ousdale Arkose as well as in the Creag a' Bhodaich conglomerates. The interpreted sheetfloods, analogous to the ones observed on the recent alluvial fans, being normally very shallow, with dramatically declining depth, would have had a considerably reduced competence (see also chapter 7.1.5.1.3.) and incapable of transporting the cobble-boulder debris. One can also speculate that the sheetfloods of Facies C1 were, however, somewhat "underloaded" with respect to the maximum particle size. This is indicated by the significant increase of the MPS in the conglomerates of Facies C1 which contain, typically larger, Moine clasts (see also Facies C2, chapter 7.4.5.1.2.).

7.1.5.1.6. Stream flow deposits

The large scale cross-stratified conglomerates, which could be interpreted as channel/bar deposits are negligible in the Beinn Lunndaidh Formation. One large scale, trough cross-stratified sandy conglomeratic horizon, 2 - 5 m in thickness, representing migration of gravelly mega-ripples have been found only in the Mound Rock Conglomerate at Beinn Lunndaidh 1 (Fig. 7.1.1e.). The palaeocurrents from this large scale cross stratified horizon concur with the general palaeodispersal, inferred from the cross-strata in the sandy interbeddings of Facies C below and above.

7.1.5.2. Petrographic composition and clast roundness in the Beinn Lunndaidh Formation

One of the most distinctive features of the Beinn Lunndaidh Formation is a close affinity between the petrographic composition of the gravel fraction in the conglomerates and the lithology of the Caledonian, predominantly Moine, basement that forms a substrate of the Golspie basin.

Although the conglomerates appear to be essentially locally derived, data regarding roundness of the clasts, combined with information on composition and roundness of the grains in the matrix, put some new light onto the origin of the Beinn Lunndaidh Formation.

Ben Tarvie - Creag an Amalaidh Conglomerate

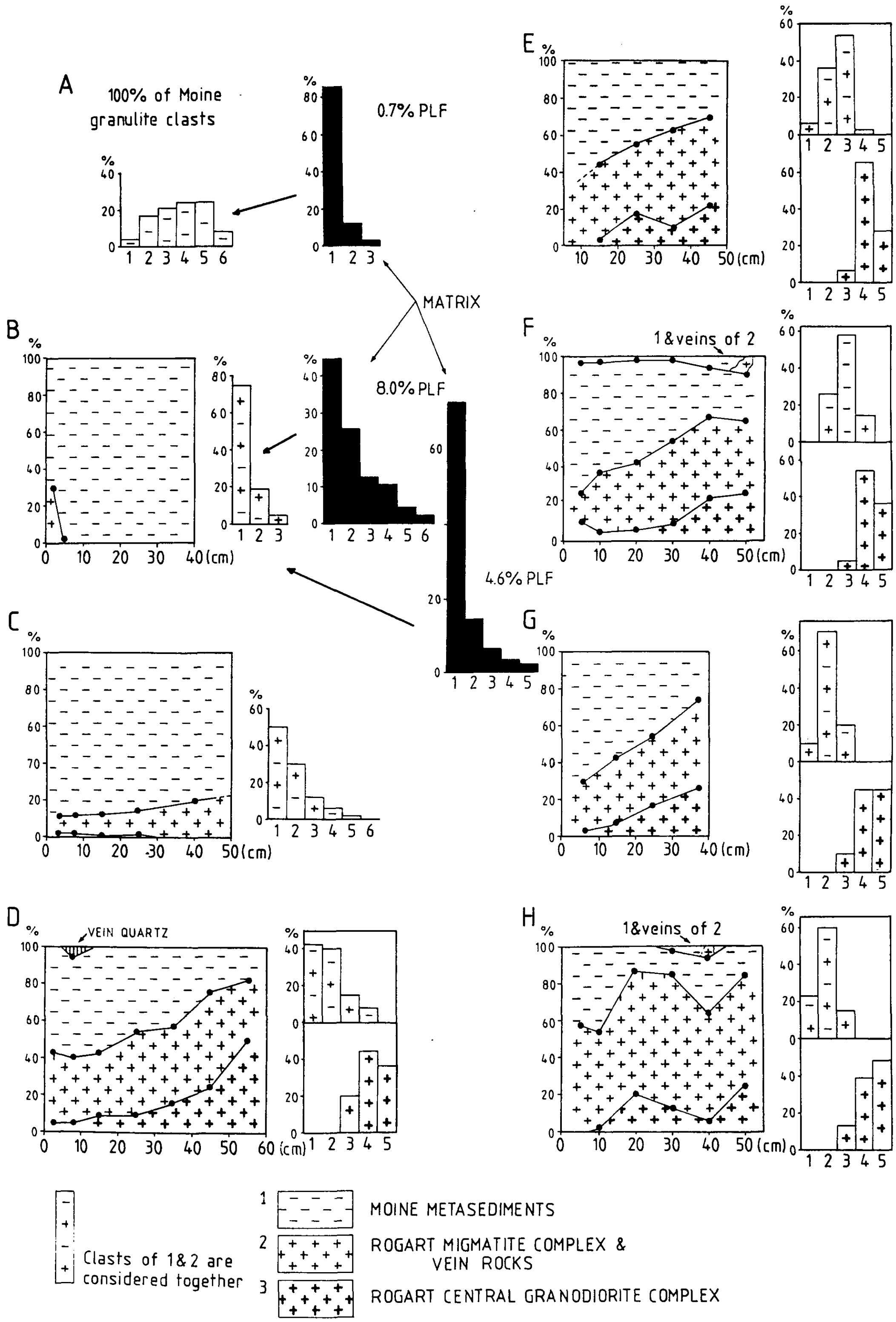
The conglomerate is composed chiefly of Moine siliceous granulites and semipelitic schists. In spite of this uniform, monomictic nature there are some significant differences between the conglomerates exposed at Ben Tarvie(Ben Tarvie Conglomerate) and the deposits of Creag an Amalaidh(Creag an Amalaidh Conglomerate) (Fig. 7.1.20a. A&B). The latter is represented by the lower half of the Mound Rock sequence (Fig. 7.1.24.).

The conglomerate, exposed at Ben Tarvie and Cnoc Odhar, has Moine clasts ranging from angular to very well rounded (Fig. 7.1.19.A). The matrix comprises a lithic wacke with mainly angular grains. The rock fragments in the matrix are predominantly derived from the Moine Series and from undifferentiated granitoid rocks. Haematite/clay material constitutes around 23% of the matrix and occurs predominantly as thick, uneven, iron-oxide/clay coatings on the grains (for details see chapter 7.1.5.1.2.).

Common, altered biotite seems to be one of the most important sources of the haematite and clay (Walker *et al.*, 1967; Walker *et al.*, 1978; Turner, 1980). Many of the biotite flakes have been almost entirely decomposed (Plate 7.1.11.A).

The XRD analyses of the clay fraction have revealed presence of illite with "chlorite behavior" (Thorez, 1976), though it is possible that a true chlorite intervenes in the

Figure 7.1.20a. Diagrams show clast composition and clast roundness for the BLI conglomerates. The unfilled histograms represent roundness of the gravel fraction. The filled histograms apply to the grains in the matrix in the corresponding conglomerates. The categories of roundness for sediment grains are after Powers (1953): 1 - angular, 2 - subangular, 3 - subrounded, 4 - rounded, 5 - well rounded. Localities: **A** - Ben Tarvie, **B** - Creag an Amalaidh(Creag an Amalaidh Conglomerate), **C** - Creag an Amalaidh(Mound Rock Conglomerate), **D** - Mound Rock(Mound Rock Conglomerate), **E** - Silver Rock, lower part (Mound Rock Conglomerate), **G** - Silver Rock, upper part (Mound Rock Conglomerate), **H** - Beinn Lunndaidh 1(see Fig. 7.1. 25.) (Mound Rock Conglomerate).


A
100% of Moine granulite clasts
0.7% PLF
MATRIX
8.0% PLF
4.6% PLF
B
C
D
VEIN QUARTZ
E
F
1&veins of 2
G
H
1&veins of 2
Clasts of 1&2 are considered together
1 MOINE METASEDIMENTS
2 ROGART MIGMATITE COMPLEX & VEIN ROCKS
3 ROGART CENTRAL GRANODIORITE COMPLEX

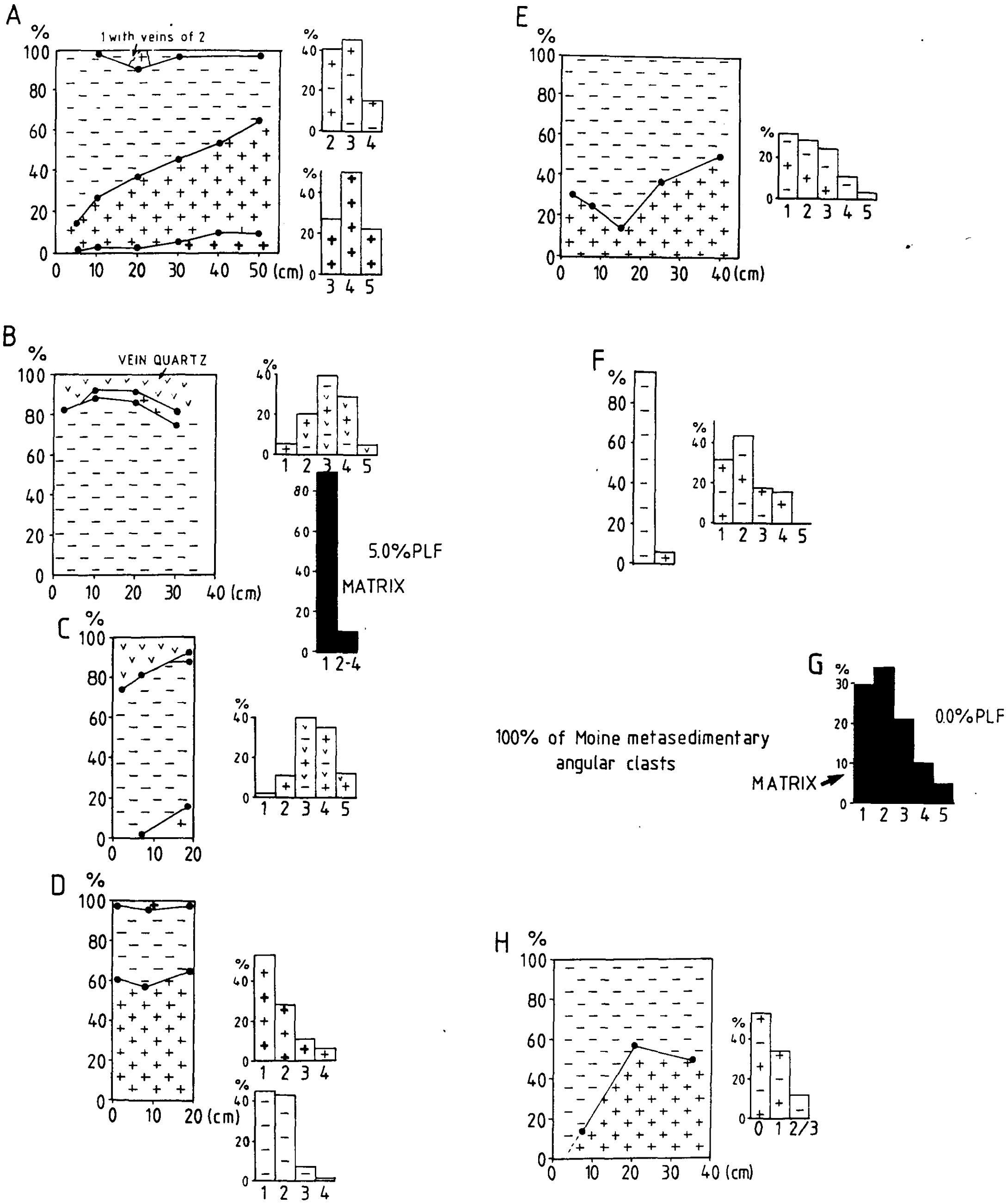


Figure 7.1.20b. Composition and clast roundness for the BLF conglomerates (continuation from Fig. 7.1.20a.). Localities: **A** - Beinn Lunndaidh 2(Fig. 7.1.25.), **B** - Cnoc na Gamhna(Cnoc na Gamhna Conglomerate, upper part), **C** - Cnoc na Gamhna(Cnoc na Gamhna Conglomerate, basal part), **D** - Cnoc na Gamhna(Mound Rock Conglomerate), **E** - Kilbraur Hill, **F** - Loch Airidhe Mhor(Strath Fleet Conglomerate), **G** - Killin Rock (lithostratigraphic position of this conglomeratic unit is uncertain; see Socach Hill Conglomerate in chapter 7.4.2.), **H** - The Craggan(Meall Odhar - The Craggan Conglomerate).

structure (Fig. App.2.E) (iron oxides, organic matter and carbonate have been chemically removed before the analyses).

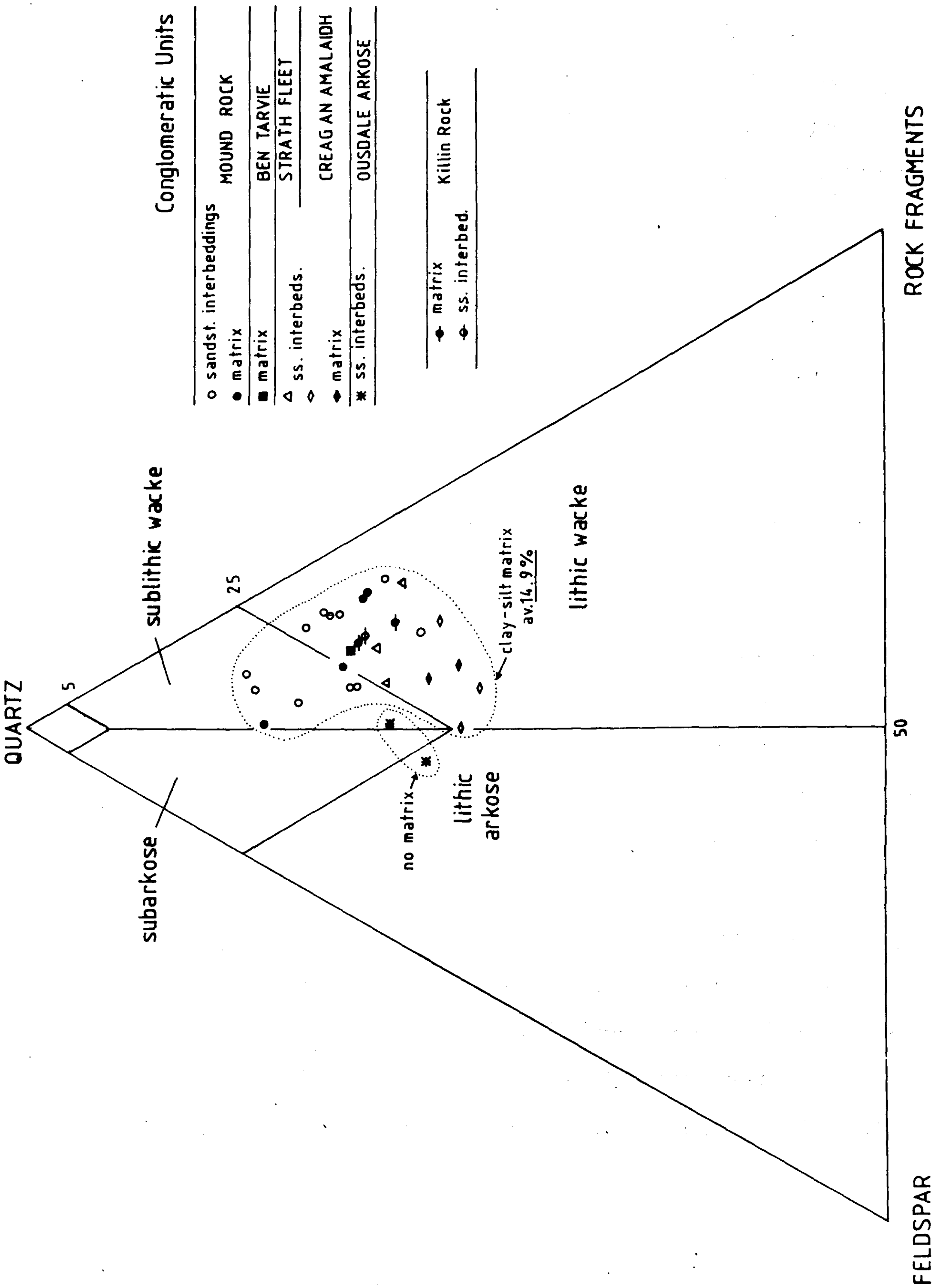
Apart from the iron oxide/clay material authigenic quartz is the most common cement, forming extensive overgrowths (Plate 7.1.10.A&B, 7.1.11.B). It constitutes on average 16.4% of the whole rock. Sparry calcite, postdating the authigenic quartz formation, is much less abundant and has been found only locally in proportions between 3.8 - 27.3% (Plate 7.1.10.B). Authigenic potassium- and plagioclase feldspar, chlorite and muscovite appear as other, generally subordinate, forms of cement. Similar phases of cement occur in all the remaining units of the Beinn Lunndaidh Formation.

The Ben Tarvie and Creag an Amalaidh conglomerates interfinger laterally. The latter is characterised by dominant angular and subangular Moine clasts with some minor constituent of the finer-grained, vein granite detritus (Fig. 7.1.20a. B). Moine clasts with a few centimeters thick granitic veins are commonly found. There is also a minor amount of vein quartz which normally concentrates among the cobble-size particles. Contrary to the generally poor sorting of the gravel fraction, the lithic wacke matrix shows a strikingly good sorting of the sand mode (Plate 7.1.11.B). In addition there is in the matrix a significant proportion of subrounded to very well rounded clasts (Facies B1, see also chapter 7.4.5.11.) (Fig. 7.1.20a. & 7.1.20b.). Furthermore, apart from the Moine and granitic grains there is a noticeable amount (8 - 7%) of low-grade pelitic, chlorite-muscovite bearing, lithic fragments(PLF) of an enigmatic provenance (for description see chapter 7.4.5.1.3.). The PLF clasts gradually disappear while passing into the Ben Tarvie Conglomerate.

Mound Rock Conglomerate

This unit contains distinctive clasts derived from the Rogart Central Granodiorite Complex (RCGC). At the top of Creag an Amalaidh the base of the Mound Rock Conglomerate is identified with a sudden (over 2m of section) appearance of RCGC clasts (Fig. 7.1.23.). A similar contact can be observed in the middle part of the Mound Rock sequence, where the sudden introduction of the RCGC debris coincides with a rapid,

Figure 7.1.21. Three-modes diagram with plotted data for sandstone interbeddings and matrix from the conglomerates of the Beinn Lunndaidh Fm.. Classification of the sandstones after Pettijohn *et al.* (1973). Average proportion of the haematite-stained clay and silt matrix is 14.9%, except of the sandstones from the Ousdale Arkose Conglomerate, which contain no argillaceous matrix.



Conglomeratic Units
o sandst. interbeddings
● matrix
MOUND ROCK
■ matrix
BEN TARVIE
Δ ss. interbeds.
◊
STRATH FLEET
◆ matrix
CREAG AN AMALAIDH
✱ ss. interbeds.
OUSDALE ARKOSE
matrix
ss. interbed.
Killin Rock
QUARTZ
ROCK FRAGMENTS
FELDSPAR
5
25
50
sublithic wacke
subarkose
lithic wacke
lithic arkose
clay-silt matrix av.14.9%
no matrix

though gradational increase in the maximum particle size (Fig. 7.1.24.). However, there is clearly a much more gradual, upward increase in proportion of clasts of the Rogart Migmatite Complex, including debris derived from granitoid veins, aplites and pegmatites that cut the entire Rogart intrusion as well as the surrounding Moine metasediments.

The RCGC clasts define the extent of the Mound Rock Conglomerate. It appears at the top of Creag an Amalaidh and probably extended slightly further to the west and south-west. Unfortunately, a reliable estimation of the original extent of the conglomerate is precluded as its upper part is eroded at Creag an Amalaidh (Fig. 7.1.25.).

Cnoc na Gamhna 2 (Fig. 7.1.25.) is the northernmost locality where the RCGC detritus has been identified. It appears suddenly, together with vein granite clasts, above the Moine granulite clasts-dominated Cnoc na Gamhna Conglomerate (see further in text).

The Mound Rock Conglomerate consists of three principal components: two main types of granitic debris, derived largely from the Rogart intrusion and clasts of Moine Series. The clast distribution is characterised by concentration of RCGC detritus among the largest particles (Fig. 7.1.20a. & 20b.). The RCGC material is most abundant as boulders over 40 cm in size (max.100 cm). They appear as considerably weathered in contrast to the other granitic and Moine clasts. Commonly, in the outcrops, only cavities with oblate walls are the only remnants of the RCGC boulders. The granitic clasts of the Rogart Migmatite Complex(RMC), including vein rock debris, have a similar distribution as the RCGC component, though the trend of the increasing proportion with the increasing clast size is less conspicuous. Similar tendencies of the granitic clasts, to concentrate in the coarsest gravel fraction, have been documented from the Lower Old Red Sandstone conglomeratic Crawton Group (Haughton, 1986) and from the Ordovician and Silurian conglomerates (Bluck, 1983) in the Midland Valley and all three cases demonstrate the importance of size in determining composition (see also chapter 7.4.5.1.3.). Data from the lowest part of the Mound Rock conglomerate (Mound Rock sequence, Fig. 7.1.24.), show an opposite tendency in the distribution of the RMC constituent. An analogous clast composition characterises the upper part of the Creag an Amalaidh Conglomerate.

The clasts derived from Moine Series are most common in fraction of up to around 30 cm and their content gradually decreases with the increasing particle size. Such trend has been found to be typical of the studied conglomerates (Fig. 7.1.20a. & 20b.), including deposits of the Beinn Smeorail Formation.

The majority of the clasts in the Mound Rock conglomerate, that is the clasts of the Rogart Migmatite Complex, vein rocks together with the Moine detritus have a similar, diverse degree of roundness. Angular to subrounded particles dominate, though there is also a noticeable proportion of rounded clasts (Fig. 7.1.20a. & 20b.). The RCGC boulders are predominantly rounded and very well rounded.

Sandstone matrix in the Mound Rock conglomerate shows no significant variability with regard to petrographic composition and roundness (Fig 7.1.20a., 20b. & 7.1.21.). It is a poorly sorted, sublithic to litharenite wacke. The lithic fragments closely resemble the rocks forming the gravel fraction. The amount of haematite-stained clay and silt material varies from 25.5 - 3.0%, averaging 14.9%. The XRD analyses of four representative samples of the clay fraction have revealed in two of them presence of illite and chlorite (Fig. App.2.C&B). The other two samples contain illite-smectite mixed layers (Fig. App.2.D). Texturally, the matrix is very similar to the matrix from the Ben Tarvie Conglomerate.

It is noteworthy that although hornblende is a significant constituent of the RCGC as well as of some of the rocks of the Moine Series (Fig. 3.3.), the mineral has not been found in these deposits. It has probably been completely altered to iron oxide and clay minerals (Walker *et al.*, 1967). No hornblende has also been found in the Creag an Amalaidh-Ben Tarvie unit.

Cnoc na Gamhna Conglomerate

The conglomerate is made up in the majority of granulite clasts of the Moine Series (Fig. 7.1.20b.B&C). There is also a minor proportion of vein granite and vein quartz detritus. The most distinctive feature of the Cnoc na Gamhna Conglomerate is a great proportion of subrounded to very well rounded clasts.

Matrix, texturally and petrographically, is very similar to the matrix in the Ben Tarvie and Mound Rock conglomerates (Fig. 7.1.21.).

Meall Odhar - The Craggan Conglomerate

Composition of this conglomerates mimic the lithology of the basement, which outcrops to the west (Fig. 7.1.20b.E, F, H). It is a mixture of Moine granulite clasts and debris which represents the granitic portion of the Rogart Migmatite Complex. The conglomerate contains also debris derived from vein granites, aplites and pegmatites. The clasts are predominantly angular and subangular, though at Kilbraur Hill there is a noticeable proportion of subrounded and rounded material.

Matrix displays very similar characteristics as previously described in case of the Ben Tarvie and the Mound Rock conglomerates (Fig. 7.1.21). It is a sublithic wacke with rock fragments closely reflecting the composition of the gravel fraction. Percentage of the argillaceous matter is around 30%. The XRD analyses of three representative samples of the clay fraction have revealed in one of them illite and illite-smectite mixed layers (Fig. App.2.A). In the remaining samples illite and chlorite have been found.

Ousdale Arkose Conglomerate

Monomict composition of the conglomerate reflects the lithology of the basement upon which it rests - which is either the coarse-grained, porphyritic adamelite of Helmsdale granite or Moine substrate consisting of siliceous granulite and vein rocks. Mixed composition reflects a proximity of the contact between the Helmsdale granite and the Moine country rocks.

Th fractured Helmsdale granite(see chapter 4) yielded predominantly relatively finer-grained gravels, with the average maximum particle size(MPS) around 2cm. The MPS is "dictated" by the size of the individual orthoclase feldspar phenocrysts, derived from the granite (Plate 7.4.8.C&D). Sometimes, it is very difficult to distinguish these arkosic deposits from the source granite. SE of Creag a' Chrionaich and east of Ben Uarie, the local change in composition - an introduction of minor amount of Moine granulite clasts, involves an increase in the MPS.

The particles in the conglomerate, regardless their source, are angular to subangular (Fig. 7.1.19.).

The Ousdale Arkose Conglomerate contains very little sandstone matrix, which in fact compositionally and texturally corresponds to the character of the gravel fraction (Plate 7.1.10.C&D). In thin section sporadic sandstone interbeddings display abundant authigenic quartz cement (up to 23%). Calcite cement becomes more abundant in the uppermost part of the Ousdale Arkose unit, and reaches up to 23%. It is absent at its basal portion.

Amount of clay fraction is generally negligible throughout the unit, though increases near the transitional contact with the deposits of the Glen Loth Formation.

Starth Fleet Conglomerate

The gravel fraction in the lowest, 15 meters of the Strath Fleet Conglomerate at Loch Airidhe Mhor, is composed in 95% of Moine granulite clasts (Fig. 7.1.20b.F). The remaining 5% is represented by debris yielded by the Rogart Migmatite Complex. Here, there is also a very small, negligible proportion of detritus derived from the Rogart Central Granodiorite Complex. The clasts are predominantly angular. Matrix is poorly sorted, very coarse- to coarse-grained, granule rich sand with negligible amounts of clay. It displays an open framework. Its composition has not been studied in detail, but it generally mirrors the lithology of the coarser constituents.

The upper part of the Loch Airidhe Mohr sequence is made up in the majority of very large angular, granitic blocks that belong to the Rogart Migmatite Complex. There is also a minor proportion of subrounded boulders. Matrix is a very poorly sorted argillaceous, coarse-grained sand but its composition has not been analysed.

The conglomerate exposed at Craig-a-bhlair is composed of angular boulders of Moine granulites; some of them are over 2 m in size. The latter conglomerate contains a very small proportion of sandy matrix.

In all the mentioned conglomeratic units, clasts of tectonic breccia have been found, and they are identified with phases of cataclasis affecting the basement, prior to the yielding of the debris into the basin. At Kilbraur Hill they are particularly abundant especially above the contact with the basement. The features of cataclasis and brittle shattering, recognized in the Moine granulites and and associated granitic veins, are identical to the once observed above in the clasts in the overlying conglomerates (Plate 7.1.1.C&D & 7.1.2.B).

Fragments of the metasediments and the granodiorite that had undergone cataclasis, before their incorporation into the sediment, have been reported by Soper(1963) from Loch Airidhe Mhor (Strath Fleet Conglomerate). Hematization and the cataclasis are common in crush-zones associated with the faults appearing in the proximity of the Golspie basin (see chapter 5.).

Clasts of cataclasite have also been found in the conglomerates of the Middle Old Red Sandstone Beinn Smeorail Formation (Plate 7.4.5.D).

7.1.5.3. Sedimentary environment of the Beinn Lunndaidh Formation

The abundance of the conglomeratic debris flow and sheetflood deposits, recognized in the Beinn Lunndaidh Formation (BLF), the fan-like paleocurrent patterns, indicating a palaeotransport from the proximally located, fault -controlled basin margins and a considerable rate of down-current decrease in the average maximum particle size suggest an **alluvial fan environment** of sedimentation for the lowermost formation of the infill of the Golspie basin (Beaty, 1963; Bull, 1964,1972,1977; Hooke, 1967, 1968,1987).

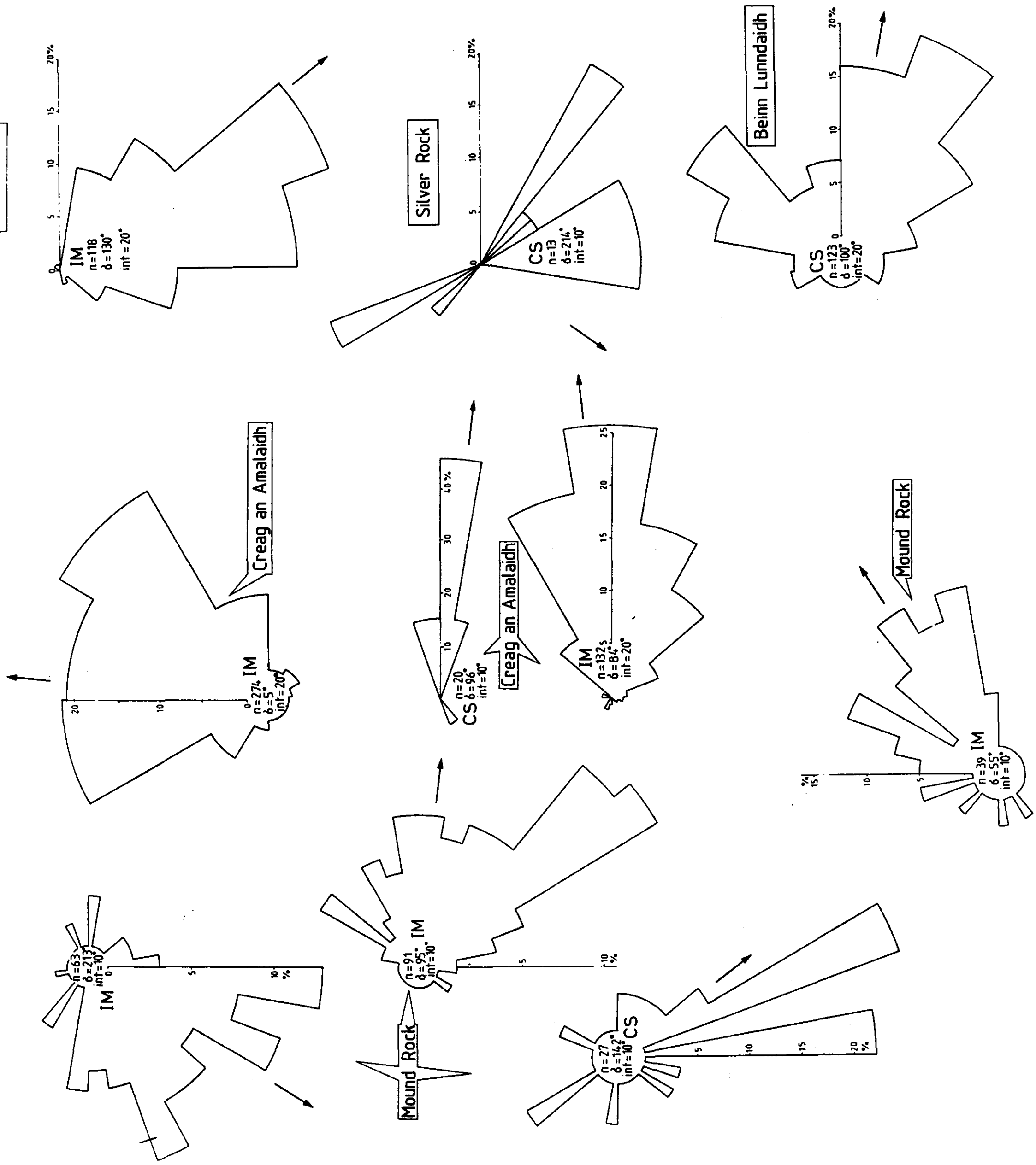
Widespread predominance of Facies B in most of the units of the BLF points to mass flows, as prominent fan building processes. Debris flow-dominated alluvial fan deposits have also been reported from the Lower and Middle Old Red Sandstone south of the Golspie basin, east and west of Loch Ness where they occur along the SE and SW margins of the Orcadian basin (Stephenson, 1972; Mykura, 1983b; Mykura & Owens,1983). Subordinate debris flow conglomerates have also been recorded from the Turriff basin(Gamrie outlier) by Sweet (1985). Similar in origin conglomerates constitute probably some of the marginal facies in the Caithness sector of the Orcadian basin (Crampton *et al.*, 1914).

The Ousdale Arkose Conglomerate, made up entirely of Facies C1, represents a system of sheetflood-dominated alluvial fans, which were mainly derived from a proximally located granitic source.

Very good vertical as well as some lateral control over the structural, textural and compositional variability of the two, most extensively developed conglomeratic units, dominating the southern part of the Golspie basin (Ben Tarvie - Creag an Amalaidh and Mound Rock), provide an insight into facies distribution within the debris flow-dominated alluvial fan bodies. They also allow some crude estimations regarding size of the alluvial fans (or systems of coalesced fans).

Lateral variability

Figure 7.1.22. Rose diagrams of imbrication (inferred palaeoflow direction) and low-angle cross-strata orientation from the BLF.



Silver Rock
IM
n=118
δ=130°
int=20°
Silver Rock
CS
n=13
δ=214°
int=10°
Beinn Lunndaidh
CS
n=123
δ=100°
int=20°
Creag an Amalaidh
IM
n=274
δ=5°
int=20°
Creag an Amalaidh
CS
n=20
δ=96°
int=10°
IM
n=132
δ=84°
int=20°
Mound Rock
IM
n=39
δ=55°
int=10°
IM
n=63
δ=213°
int=10°
Mound Rock
IM
n=91
δ=95°
int=10°
CS
n=27
δ=142°
int=10°

Debris flow conglomerates of Facies B form a majority of the deposits of the BLF and are especially abundant in the coarsest, most proximal, fanhead sectors of the fans. At Ben Tarvie Facies B constitutes the total of the over 30 m thick conglomeratic sequence (Fig. 7.1.23.B). At Creag an Amalaidh the variety of Facies B(Facies B1) represents around 75% of the examined alluvial fan deposits (Fig. 7.1.23.A). More distal, finer-grained parts of these fans, observed at Cnoc Odhar and Mound Rock, contain an increased proportion of up to 75% of sheetflood conglomerates(Facies C). Such down-fan decrease in the proportion of mass flow facies has been documented by many workers from recent (Bull, 1968, 1972, 1977; Hooke, 1967, 1987; Blair, 1987a) as well as ancient alluvial fan environments (Heward, 1978; Nemec & Muszynski, 1981; Steel *et al.*, 1977; Gloppen & Steel, 1981; Kochel, 1984; Wells, 1984). The sheetflood deposits are particularly abundant below the intersection point (Hooke, 1967; Blair, 1987a) (see also chapter 7.1.5.1.4.).

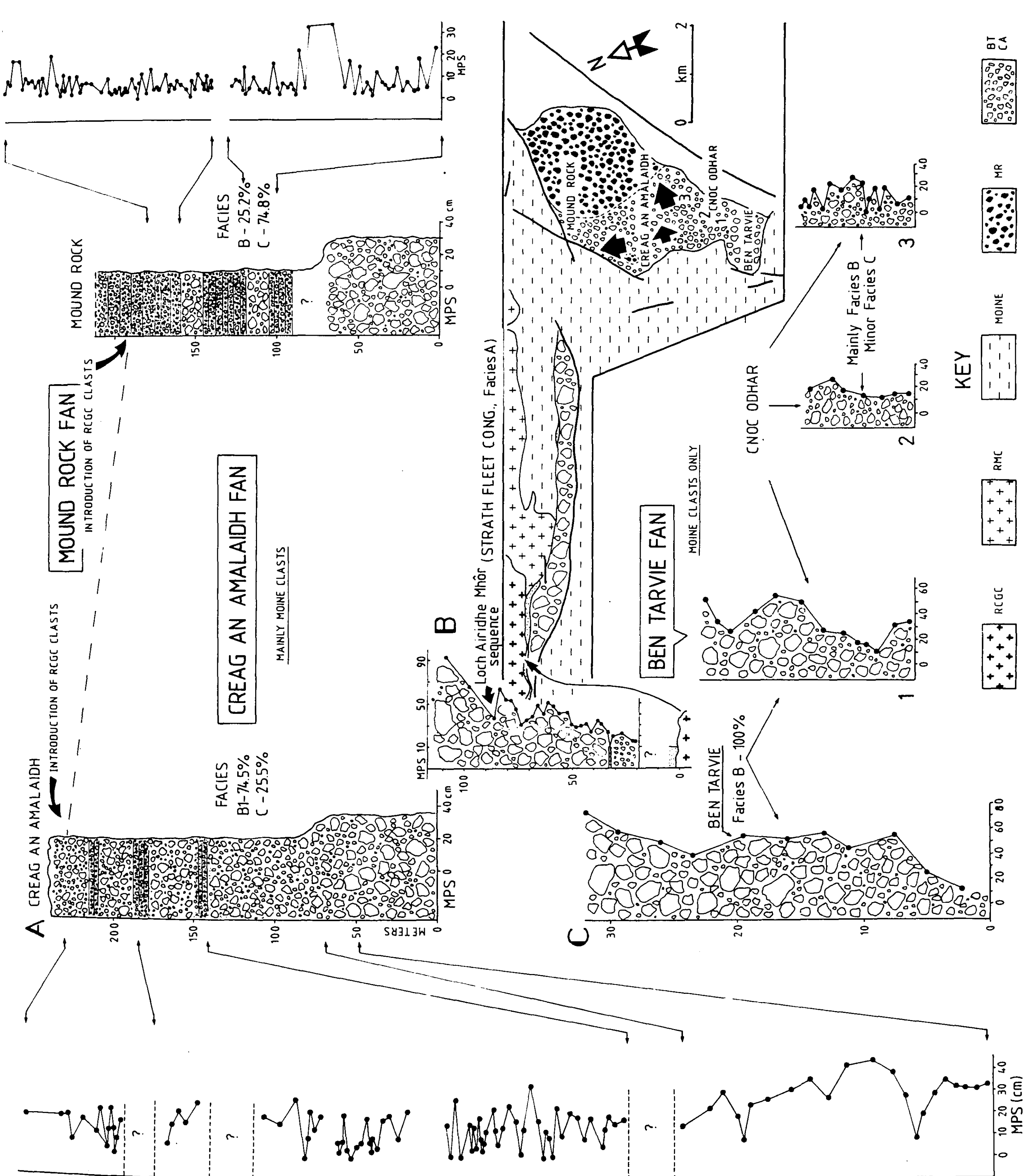
No significant tendencies in facies variability have been recorded from the Mound Rock alluvial fan system, and this is believed to be due to a limited exposure along the palaeotransport direction (Fig. 7.1.25.). The Mound Rock Conglomerate represents the upper fan(fanhead) environment, being clearly dominated by the debris flow deposits of Facies B, although proportions of Facies B and C vary insignificantly in vertical sequences (Fig. 7.1.1a.-1e.).

Cnoc na Gamhna Conglomerate comprises mainly the sheetflood deposits of Facies B (Fig. 7.1.25.) but this information is based only on one, around 30 m thick section. It may represent a distal sector of an alluvial fan body, resting directly on the basement.

Predominant (90 - 100%) proportion of the debris flow deposits of (Facies B) characterises the Meall Odhar - The Craggan Conglomerate, indicating an environment of very proximal, upper parts of alluvial fans that formed locally along the western margin of the basin. Poor exposure precludes examination of the lateral variability within this conglomeratic unit.

There is also no information regarding lateral facies changes within the Ousdale Arkose Conglomerate, sheetflood-dominated alluvial fan system, though the fanglomerates derived from the Moine granulite source are coarser-grained than their, Helmsdale granite

Figure 7.1.23. A: Creag an Amalaidh fan sequence displays fining upwards tendency, though the fining is limited only to the lower part of the sequence; **B**: Conglomerates of the most proximal part of Ben Tarvie fan are arranged in coarsening-upwards sequence. The both fan bodies (**A** & **B**) fine to the NE. Proportion of debris flow deposits (Facies B and B1) decreases in the same, down-fan direction. Palaeotransport determined for Creag an Amalaidh fan additionally indicates the NE dispersal (mean vectors are given). **C** - At Loch Airidhe Mhor the Strath Fleet Conglomerate is represented by a coarsening-upward sequence, underlain by the aeolian sandstone horizon which rests directly on the granodiorite basement (RCGC, see also Plate 7.1.1.). **RCGC** - Rogart Central Granodiorite Complex; **RMC** - Rogart Migmatite Complex; **MR** - Mound Rock Conglomerate; **BT-CA** - Ben Tarvie - Creag an Amalaidh Conglomerate.


A
CREAG AN AMALAIDH
INTRODUCTION OF RCGC CLASTS
FACIES
B1-74.5%
C -25.5%
CREAG AN AMALAIDH FAN
MAINLY MOINE CLASTS
MOUND ROCK FAN
INTRODUCTION OF RCGC CLASTS
MOUND ROCK
FACIES
B - 25.2%
C - 74.8%
MPS
METERS
MPS (cm)
B
Loch Airidhe Mhôr sequence
(STRATH FLEET CONG., Facies A)
C
BEN TARVIE
Facies B - 100%
BEN TARVIE FAN
MOINE CLASTS ONLY
CNOC ODHAR
Mainly Facies B
Minor Facies C
MOUND ROCK
CREAG AN AMALAIDH
CNOC ODHAR
BEN TARVIE
N
km
KEY
RCGC
RMC
MOINE
MR
BT
CA

derived, lateral equivalents.

No data are available on lateral variability from the Strath Fleet conglomeratic unit.

Vertical variability

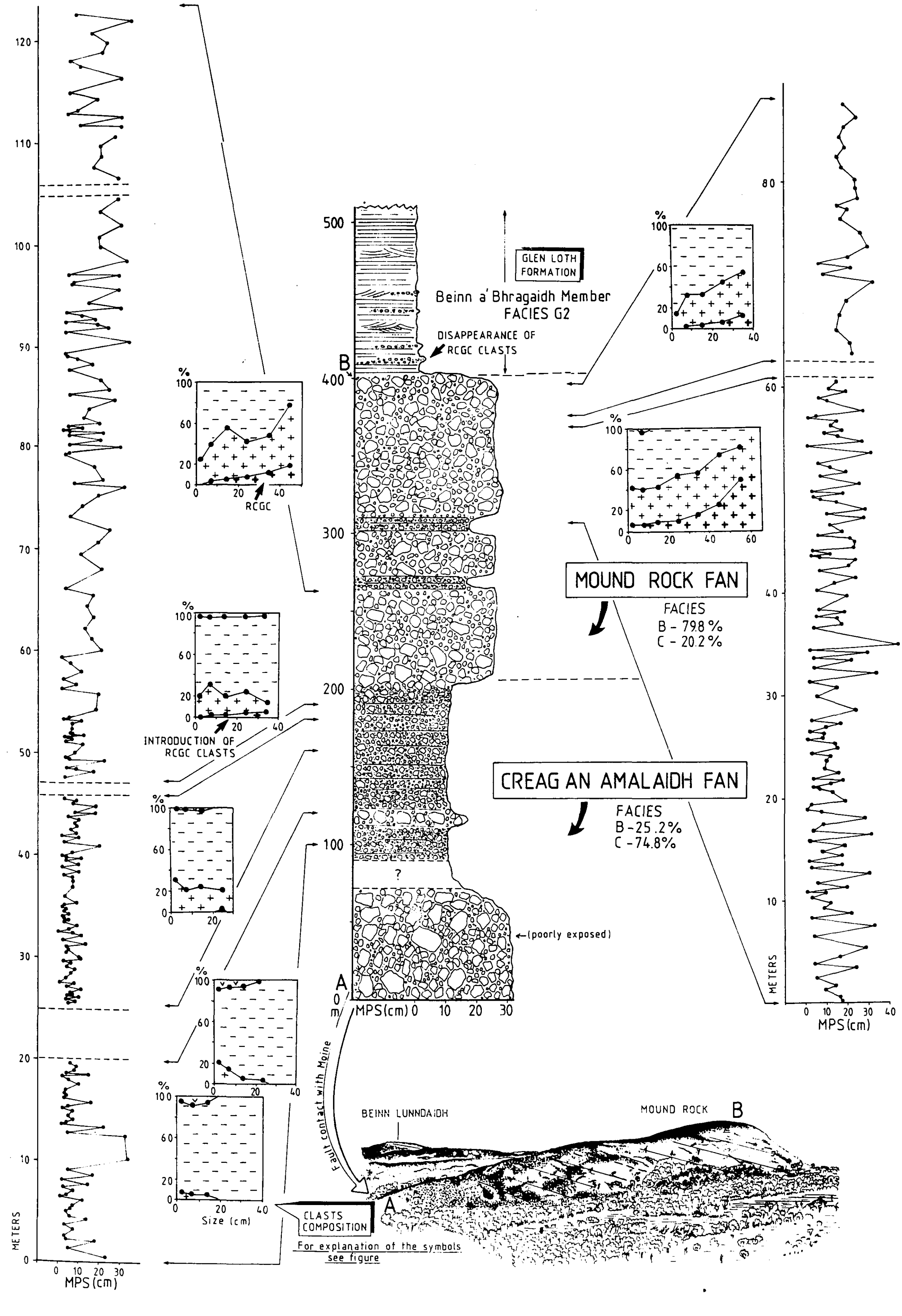
Data regarding vertical variations in the maximum particle size (MPS) and distribution of the facies come only from two alluvial fan bodies, which occupy the southernmost part of the basin: Creag an Amalaidh - Ben Tarvie and Mound Rock. Some information are also available from the Strath Fleet Conglomerate.

The Creag an Amalaidh fan displays an observable fining-upward trend, though clearly the trend is not uniformly "spread out" throughout the entire sequence and the actual "fining" is confined to its approximately middle portion (Fig. 7.1.23.A). The remaining parts of the sequence do not manifest any significant fining- or coarsening-upward tendencies. The fining always reflects an increase in proportion of the sheetflood deposits (Facies C).

An analogous fining-upwards has been identified at Mound Rock, below the Mound Rock fan sequence, from the distal equivalent of the Creag an Amalaidh fan (Fig. 7.1.24.). Here, the upward decrease in the MPS is also confined only to the 50 m thick portion of the sequence. Such dramatic fining-upward trend is more likely to represent a relatively sudden shift of depositional activity from one sector of the fan to the another, rather than a gradual retreat of the fan lobe (Bluck, 1967; Steel, 1974; Steel & Wilson, 1975; Steel *et al.*, 1975).

While the latter alluvial fan body shows a fining-upwards tendency the Ben Tarvie fan displays a coarsening-upward trend, though the examined deposits are only 30 m thick, and probably represent only a portion of the original fan body. In view of insufficient data regarding lateral/vertical variability of the Ben Tarvie fan, it is impossible to evaluate a significance of tectonic and autocyclic factor in generating the coarsening-upward unit (Steel *et al.*, 1977), and even to determine whether the Ben Tarvie and the Creag an Amalaidh fans have significantly different vertical MPS trends.

Figure 7.1.24. Summary log, measured at Mound Rock, shows vertical distribution of the maximum particle size(MPS), clast composition and facies through the two stacked alluvial fan bodies: Creag an Amalaidh fan and Mound Rock fan. The coarsening upward trend, at the base of the Mound Rock fan, coincides with introduction of the debris derived from the Rogart Central Granodiorie Complex(RCGC). Similar, rapid appearance of the RCGC clasts can be also observed at Creag an Amalaidh (Fig. 7.1.22.). Note that the initial coarsening does not continue further up the sequence. The sudden change in MPS and clast composition is interpreted as boundary between two independent alluvial fans(or fan systems), characterized also be diverse dispersal patterns (Fig. 7.1.25) and different facies proportions. Beinn a' Bhragaidh Member (Glen Loth Formation) represents another independent depositional system (see chapter 7.2.6.1.15.).


GLEN LOTH FORMATION
Beinn a' Bhragaidh Member
FACIES G2
DISAPPEARANCE OF RCGC CLASTS
MOUND ROCK FAN
FACIES
B - 79.8 %
C - 20.2 %
CREAG AN AMALAIDH FAN
FACIES
B - 25.2%
C - 74.8%
(poorly exposed)
INTRODUCTION OF RCGC CLASTS
RCGC
CLASTS COMPOSITION
For explanation of the symbols see figure
Fault contact with Moine
BEINN LUNNDAIDH
MOUND ROCK
A
B
MPS (cm)
METERS
Size (cm)

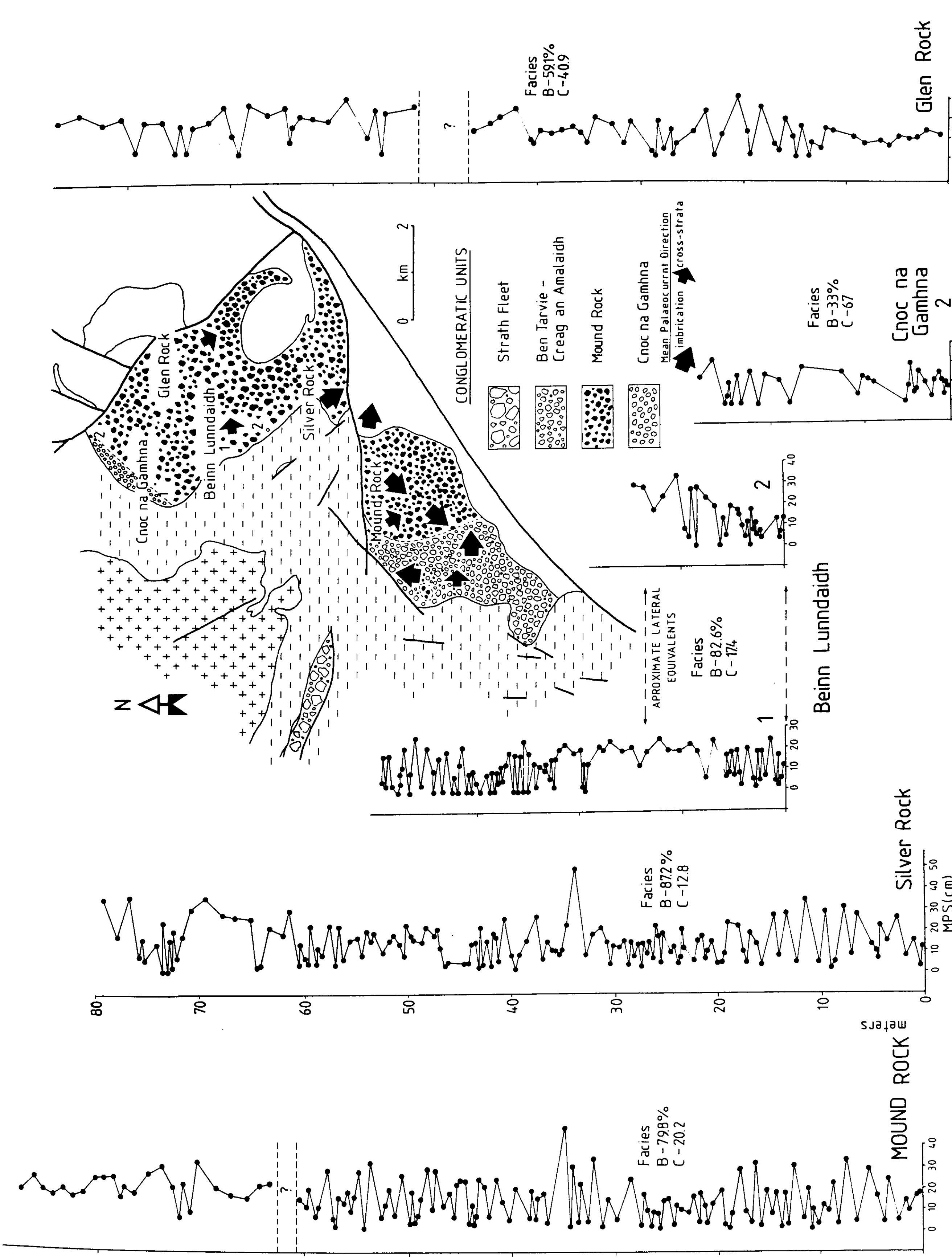
The sequence of Strath Fleet Conglomerate exposed at Loch Airidhe Mhor clearly coarsens upwards, right through its entire 90 meters (Fig. 7.1.23.C), and it is likely, considering its thickness, to represent a progradation of an alluvial fan in response to fault movement(-s) in the fanhead region (Steel, 1976; Steel *et al.*, 1977). It has to be noted, however, that the data come only from one section.

The Mound Rock unit appears rapidly, though gradationally, as a markedly coarser conglomerate, containing also a new granitic(RCGC) component (Fig. 7.1.24.). The increase in the MPS does not, however, continue upwards throughout the entire sequence of the Mound Rock alluvial fan body, and has a relatively constant distribution. Lack of any significant, large scale, tendencies in the vertical MPS variation has also been identified at Silver Rock, Beinn Lunndaidh, Cnoc na Gamhna and Glen Rock, though the conglomerates at the two latter localities have generally smaller MPS (Fig. 7.1.25.). In fact, they represent the most distal, observed, portions of the Mound Rock fan system.

The sudden grain-size (MPS) increase, combined with significant changes in clast composition (Fig. 7.1.23.A & 7.1.24.), marking the base of the Mound Rock unit, is seen as result of rapid invasion of the basin floor by a new alluvial fan system, in response to a rapid uplift in the hinterland to the north. However, it is interesting that the initial, rapid progradation, signaled in the coarsening-upwards, did not continue further up, and hence, in terms of the facies distribution and the MPS trends, the entire Mound Rock unit represents essentially the same, upper fan or fanhead environment.

The examined sequences of the Mound Rock unit display smaller scale, a few to tens of meters thick, fining- and coarsening-upward trends (Fig. 7.1.24. & 7.1.25.). They do not correlate across the entire Mound Rock Conglomerate, and may represent autocyclic phenomena, that is shifting of the depositional activity, within the particular, individual fan of the system. Gradual abandonment of one sector of the fan would have resulted in generating a fining-upward sequence; a progradation would be marked by a coarsening-upward trend. A rapid switch of the locus of sedimentation, following an avulsion of a distributary channel can be identified with rapid changes in the MPS and in relative proportions of the debris flow and sheetflood deposits of Facies B and C (Gloppen &

Figure 7.1.25. Vertical distribution of MPS for Mound Rock fan system, measured in five localities, shows no obvious general trends of fining- or coarsening-upwards. Local, smaller-scale fining- and coarsening-upward units are seen as result of gradual or rapid shifting of depositional activity within individual fans of the system. Note a significant difference in palaeodispersal between the Creag an Amalaidh and Mound Rock fans.


Glen Rock
Facies
B - 59.1%
C - 40.9
Cnoc na Gamhna 2
Facies
B - 33%
C - 67
CONGLOMERATIC UNITS
Strath Fleet
Ben Tarvie - Creag an Amalaidh
Mound Rock
Cnoc na Gamhna
Mean Palaeocurrnt Direction
imbrication
cross-strata
0 km 2
N
Cnoc na Gamhna
Glen Rock
Beinn Lunndaidh
Silver Rock
Mound Rock
Beinn Lunndaidh
1
2
APROXIMATE LATERAL EQUIVALENTS
Facies
B - 82.6%
C - 17.4
Silver Rock
Facies
B - 87.2%
C - 12.8
MPS(cm)
meters
MOUND ROCK
Facies
B - 79.8%
C - 20.2

Steel, 1981; Steel, 1977; Heward, 1978).

Palaeodispersal

Regarding the series of fault splays, maped SW of the Ben Tarvie - Creag an Amalaidh Conglomerate, as a dislocation, which controlled a physiographic escarpment from which alluvial fans were building up to the N and NE, radius of this alluvial fan (or fan system) was around 5 km, as the fanglomerates wedge out between Mound Rock and Silver Rock. The N-NE direction of the fan growth is clearly indicated by the palaeotransport data derived from the Creag an Amalaidh Conglomerate (Fig. 7.1.22.) and also by the fact that both, Creag an Amalaidh and Ben Tarvie units fine in the same direction (Fig. 7.1.23.A&B). One can speculate, however, that the northward and north-eastward progradation of this alluvial fan system could have been to some extent obstructed by the intrabasinal escarpment, associated with a local elevation of the basin floor N of Mound Rock as evidenced by the area of basement affected by brittle deformation and traversed by a number of variously oriented vertical faults (Fig. 7.1.25.). The local basement elevation could have deflected the dispersal to the E and SE. In such circumstances, the true extent of the alluvial fans, making up the Ben Tarvie - Creag an Amalaidh Conglomerate, would remain unknown. It is also possible that the marginal sectors of these fans, that encroached onto the basement north of Mound Rock, were later denudated and recycled during the development of the Mound Rock fan (see further in text).

The Strath Fleet fan was probably derived from the S, fringing the Strath Fleet Fault-controlled escarpment. Such an inference is based on very close similarities between the composition of the conglomerates and the lithology of the basement, outcropping south of the Strath Fleet Fault. No other palaeotransport indicators are available from this unit. Small proportion of the granodioritic detritus in the lowest part of the sequence indicate a temporary and rather insignificant sediment input from the N.

The Mound Rock alluvial fan system is identified by its unique composition - considerable proportion of the RCGC clasts and also by a different palaeodispersal than the

Creag an Amalaidh - Ben Tarvie fans palaeodispersal (Fig. 7.1.25.). It also manifests itself in vertical succession at Mound Rock through a rapid increase in the MPS (Fig. 7.1.24.). The Mound Rock fan was building up to the S, SE and N. It seems to have been accreting off the local elevation, fault-controlled bulge of the basement, N of Mound Rock (Fig. 7.1. 25. & 7.1.27.).

No data are available from the Meall Odhar - The Craggan Conglomerate regarding its palaeotransport, though in view of its composition, closely resembling the lithology of the basement to the NW, it is reasonable to suggest that it may represent alluvial fans that have only locally developed along the western margin of the basin, fringing escarpments controlled by the NE-SW trending faults. It is noteworthy that these alluvial fans, building up to the SE did not reach the opposite margin of the basin, as no deposits of the BLF are probably present there.

The clast composition, directly corresponding to the lithology of the underlying basement, suggests that the Ousdale Arkose Conglomerate alluvial fans were fringing the NE margin of the Golspie basin, defined probably by a fault-controlled escarpment along the front of the uplifted highland. Unfortunately, poor exposure have not permitted detail mapping of faults, that might have been responsible for creating the NE trending margin of the basin. Analogous basinward alluvial fan outbuilding is proposed for Ousdale Arkose unit fringing margins of the Badbea basin (Fig. 7.1.27. & 7.2.27.A)

Alluvial fan geometry

Bull (1964, 1968) and Hooke (1968, 1967, 1987) documented with field and experimental data that debris flow-dominated alluvial fans have steeper slopes than the fans composed of water-laid deposits. It is for the mass flows tend to accumulate near the fanhead and rarely reach the toes of the fans. Stream flows or sheetfloods spread their load over much wider area of the fan, and even at extreme flooding events invade the flood plain (Blair, 1987a).

In view of such observations, the debris flow fans developing along the SW and W margin of the Golspie basin would have had much steeper slopes than the sheetflood-dominated fans fringing the NE margin. The debris flow fan deposits have also generally larger thickness (200 - 180 m) than the sheetflood-dominated fanglomerates (100 - 150 m). Considering the present extent of the Mound Rock Conglomerate and its palaeotransport pattern, an estimated radius of the debris flow alluvial fans, that coalesced into this entire system, was around 7 km. If the upper boundary of the Mound Rock conglomerate, exposed at Beinn a' Bhragaidh does indeed represent the original depositional surface (Plate 7.2.21.), then slope of the discussed here alluvial fans was around 10^{o}.

The Ousdale Arkose, sheetflood-dominated alluvial fan system had probably a lower slope and a larger lateral extent (Bull, 1964; Hooke, 1968).

Such relationships between the fan geometry and the depositional processes responsible for its formation have been convincingly demonstrated by Steel (1976), Steel *et al.* (1977) and Gloppen & Steel (1981) from the middle Devonian Hornelen Basin, Norway. According to them, the differences between the fans of the N and the S margin of the Hornelen basin, reflect the NW tilting of the basin floor. In such circumstances the large fluvial fans developed on long, low, northward slopes, while the small, debris flow fans fringed the much steeper slopes in the north.

It will be argued in the next chapter that the formation of such two different types of alluvial fans, characterising the development of the BLF, was not merely a function of a diverse tectonic control, but a resultant of significant differences in character and amount of debris by which the fans were supplied. In fact there are no clear evidence whether the tectonic factor had a significant influence on the diversity in style of alluvial fan sedimentation of the BLF.

7.1.5.4. Textural evolution and provenance of the Beinn Lunndaidh Formation

7.1.5.4.1. Debris flow dominated fans - second-cycle, resedimented

conglomerates

One of the principal prerequisites for development of debris flows is abundance in the source area of relatively unconsolidated sediments, that can be mobilised and transported en mass. In the majority of cases of the modern, subaerial debris flow activity, known to the present author, the source material is represented by extremely texturally immature, colluvial sediments (Sharp & Nobles, 1953; Bull, 1964; Lustig, 1965; Curry, 1966; Johnson & Rodine, 1981; Pierson, 1981; Kochel & Johnson, 1984). Amount of clay fraction, varies considerably between 17 and less than 1%, though normally it is less than 3% (Bull, 1964; Lustig, 1965; Curry, 1966; Vessell & Davis, 1981; Lawson; 1982).

Moraine deposits are the source of clastic material for subaerial debris flows, active at the terminus of the Matanuska Glacier, Alaska (Lawson,1982). Debris flows, depositing on alluvial fans in northwest England, are derived from suliflucted till (Wells & Harvey, 1987). Mobilised, volcaniclastic deposits of glowing avalanche flows form debris flows (lahars) that accumulate on alluvial fans around the volcano in an active fore arc basin (Guatemala) (Vessell & Davis, 1981). Nemec *et al.* (1984) documented from the Middle Devonian Hornelen Basin a debris flow-dominated fan-delta (Domba conglomerate), derived through a resedimentation of pre-existing, segregated to some degree, alluvial gravels.

Apart from the Domba fan-delta, no significant reworking and segregation of the source material has been reported to had taken place prior to the formation of the alluvial fans.

Predominance of the debris flow deposits (Facies B) in the BLF alluvial fan units implies that copious volumes of gravel and sand material must have been available in the drainage area prior to the formation of the fans. Distinctive textural signatures of the Facies B conglomerates, discussed earlier in chapter 7.1.5.1.2., apart from being an indicator of the nature of the debris flow transport (see chapter 7.1.5.1.4.), provide also an insight into aspects of provenance of the deposits in question, in particular they put a light onto sedimentary characteristics of the source sediments. Basing on the textural/structural features of the Facies B and C, attempts have been made to reconstruct an overall sedimentary evolution of considered alluvial fans.

The most striking feature of the Facies B conglomerates is their textural heterogeneity, that is presence in the same beds of clast- to matrix-supported and polymodal to bimodal textures. Many of the Facies B beds have been found to be bimodal throughout (see chapter 7.1.5.1.2.). The clast-supported parts often contain clusters of clasts with open framework. Another distinctive feature of Facies B are common sandy intraclasts, and many of them in spite of having been partly remoulded with the gravel, still display early sedimentary lamination (Plate 7.1.3.A. & 7.1.5.). It is noteworthy that the minimum estimated thickness of sandy beds from which the intraclasts have been derived exceeds 2 m. No such thick sandstone beds have been found in the examined sequences and in fact the recorded sandstone interbeddings are negligible. It is significant, that in contrast, in the Facies B conglomerates, the conglomerates of Facies B contain a considerable proportion of sandstone matrix, filling the spaces between clasts, and often forming the dominant mode(matrix-supported texture). The matrix is generally coarse-grained and poorly sorted sublithic to lithic wacke with angular to subangular grains (Plate 7.1.10.A & 7.1.11.A) (see chapter 7.1.5.1.2. for details). Only the Craeg an Amalaidh Conglomerate has a very well sorted sandstone matrix with significant proportion of subrounded to well rounded grains (Fig. 7.1.20.A & Plate 7.1.11.B). The matrix at Craeg an Amalaidh contains also, an exotic, absent in the other BLF units, component of the low-grade pelitic lithic fragments(PLF) (Fig. 7.1.20. B).

It is postulated herein, that the Facies B deposits originated through a <u>resedimentation</u> of pre-existing piles of gravels, considerably enriched in sandy fraction; the latter occurring as separate sandy beds and possibly also as a matrix in the gravels. It is believed that these sediments had achieved some degree of lithification prior to the resedimentation, associated with enrichment in clay minerals, iron-oxides and possibly caliche related carbonates (see chapters 7.1.5.1.2. & 7.1.5.2. for details). The source sediments might have represented early alluvial bodies, related to pre-existing sedimentary basins (see also Haughton, 1986).

Remoulding of the variously segregated gravels with the sand is thought to have

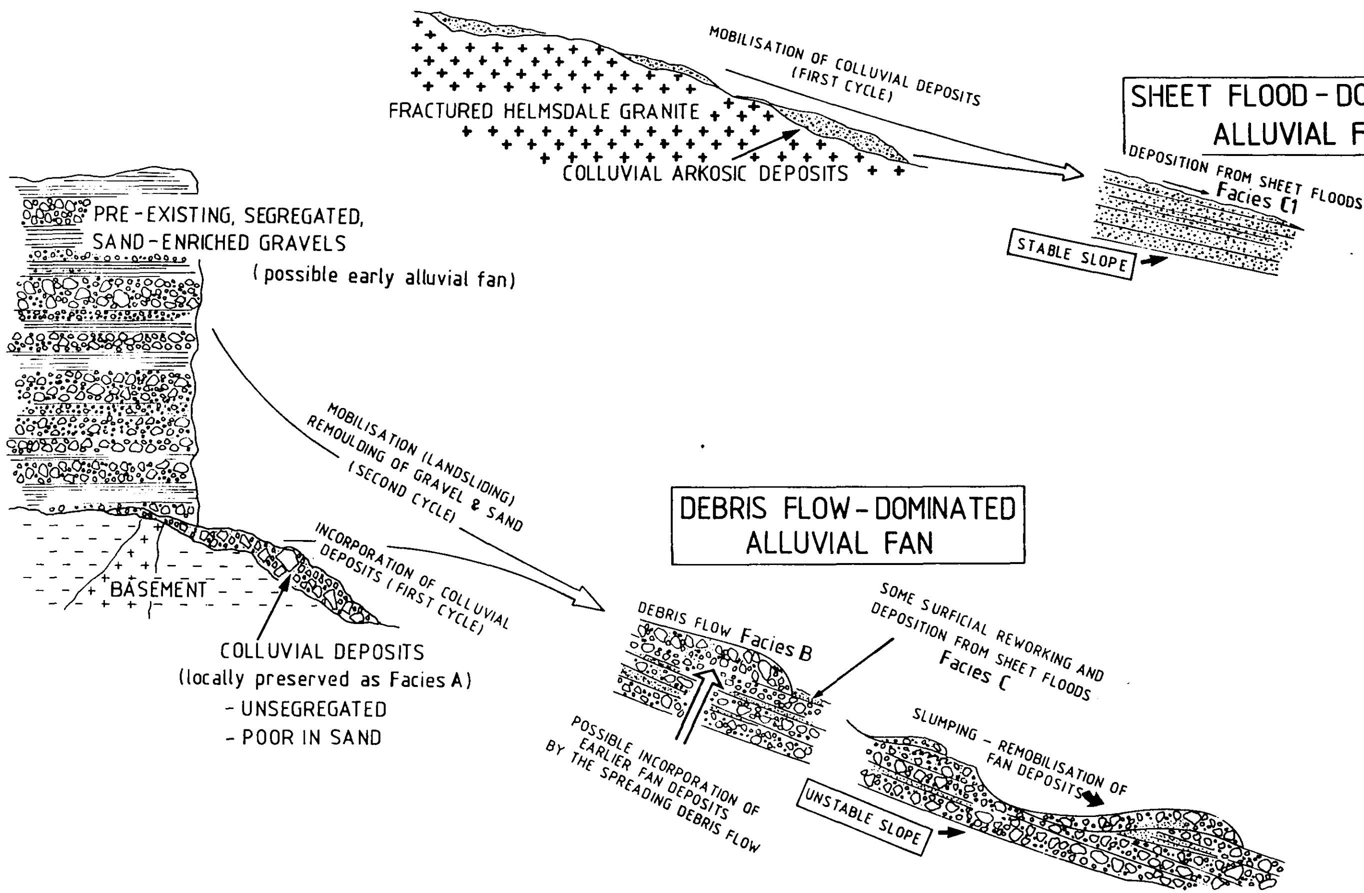


Figure 7.1.26. A schematic, summary diagram shows the inferred sedimentary and textural evolution of the debris flow- and the sheetflood-dominated alluvial fans - two principal sedimentary environments represented by the Beinn Lunndaidh Formation.

generated the characteristic textural heterogeneity of the debris flow deposits. Substantial proportion of the source gravels must have had a unimodal distribution prior to the remoulding in order to generate the bimodal textures. As vigorous sorting of gravels and formation of unimodal distributions may take place in the upper sectors of alluvial fans (Beaty, 1963; Larsen & Steel, 1978; Pierson, 1981), it can be argued that the bimodal textures, observed in the Facies B deposits, could have originated on the surface of the devêloping BLF fans. Such an concept, however, fails to explain the abundance of the primary sandstone matrix in the Facies B conglomerates, for it has to involve a vigorous winnowing and bypassing of sand associated with the reworking and segregation of the gravels, as coarse as boulders.

The presence of the large, rip-up sandstone intraclasts with lamination supports the thesis of resedimentation, as it indicates existence in the drainage area, semi-lithified sandy beds of the minimum thickness exceeding 2 m. Such beds are absent in the examined fan deposits, and it is argued, that the sand and the gravel were derived from the earlier accumulated, pre-existing sediments.

Although in most of the BLF conglomerates (Ben Tarvie, Mound Rock, Meall Horn - The Craggan) the matrix compositionally closely corresponds to the gravel fraction, its abundance is difficult to explain by involving only a first cycle model of sedimentation, that is mobilisation of unsegregated colluvial sediments and their deposition on the fan surface (Sharp & Nobles, 1953; Bull, 1964; Curry, 1966; Pierson, 1981).

Moine siliceous granulites, providing between 100 - 40% of the clasts in the discussed conglomerates, are very resistant rocks, characterized by the uniaxial compressive strength value in range of 200 - 300 MPa (Harris, 1977). Thus, in the scenario of the first-cycle sedimentation, the Moine rocks are an unlikely source of such substantial amounts of sandy matrix, present in the conglomerates. Similarly, granitic rocks, especially considering their tendency to concentrate in the coarsest gravel fractions, would not yield sufficient volume of sand if the discussed gravels were to be deposited on the fans directly after denudation, without having been earlier reworked and enriched in sand.

The idea of polycyclism and resedimentation of the previously accumulated, partly reworked, sand-enriched gravels does explain all the mentioned above textural signatures of the Facies B deposits.

A study of 31 first-cycle quaternary alluvial fans in southeast Spain (Harvey, 1984) has revealed that on high-grade metamorphic rocks fluvial fans are common. Debris flow fans are only produced by much less resistant, sedimentary and low-grade metamorphic sources. Similar relationships between the lithology, the drainage area and the alluvial fan sedimentology have also been recognized by Hooke (1968), Wells (1976) and Wells & Harvey (1987).

In view of the presented data, the suggested concept of resedimentation (second-cycle sedimentation) does elucidate the derivation of the BLF debris flow fans from the high-grade, resistant Moine metamorphic and granitoid rocks.

The data regarding roundness of the clasts in the BLF conglomerates provide an independent evidence for existence of early gravelly sediments that had undergone some segregation and textural modification prior to the resedimentation. Significant proportion of subrounded to well rounded Moine siliceous granulite clasts in the Ben Tarvie debris flow conglomerates clearly indicates that the large portion of the gravels, deposited as debris flows in the fanhead environment, had undergone earlier, prolonged processes of abrasion and reworking. Similarly, the Mound Rock, Cnoc na Gamhna and Meall Odhar - The Craggan conglomerates contain a considerable amount of subrounded to well rounded clasts derived from the Moine rocks, and the associated vein granites.

Very good roundness of the granodioritic clasts derived from the Rogart Central Granodiorite Complex(RCGC), should not be overestimated with regard to the proposed thesis of the recycled origin of the BLF conglomerates. The granodiorite seems to have been considerably affected by weathering during the denudation, and thus its clasts could have achieved the good roundness *in situ*, prior to entering the dispersal system (Davis, 1938). Hence, they may well represent a first-cycle component, derived directly from the unroofed granodiorite.

Large portion of angular and subangular clasts derived from the Moine metasediments, the Rogart Migmatitic Complex and the related vein rocks, additionally indicate a considerable input of the first-cycle debris, that become at some stage admixed with the polycyclic sediments.

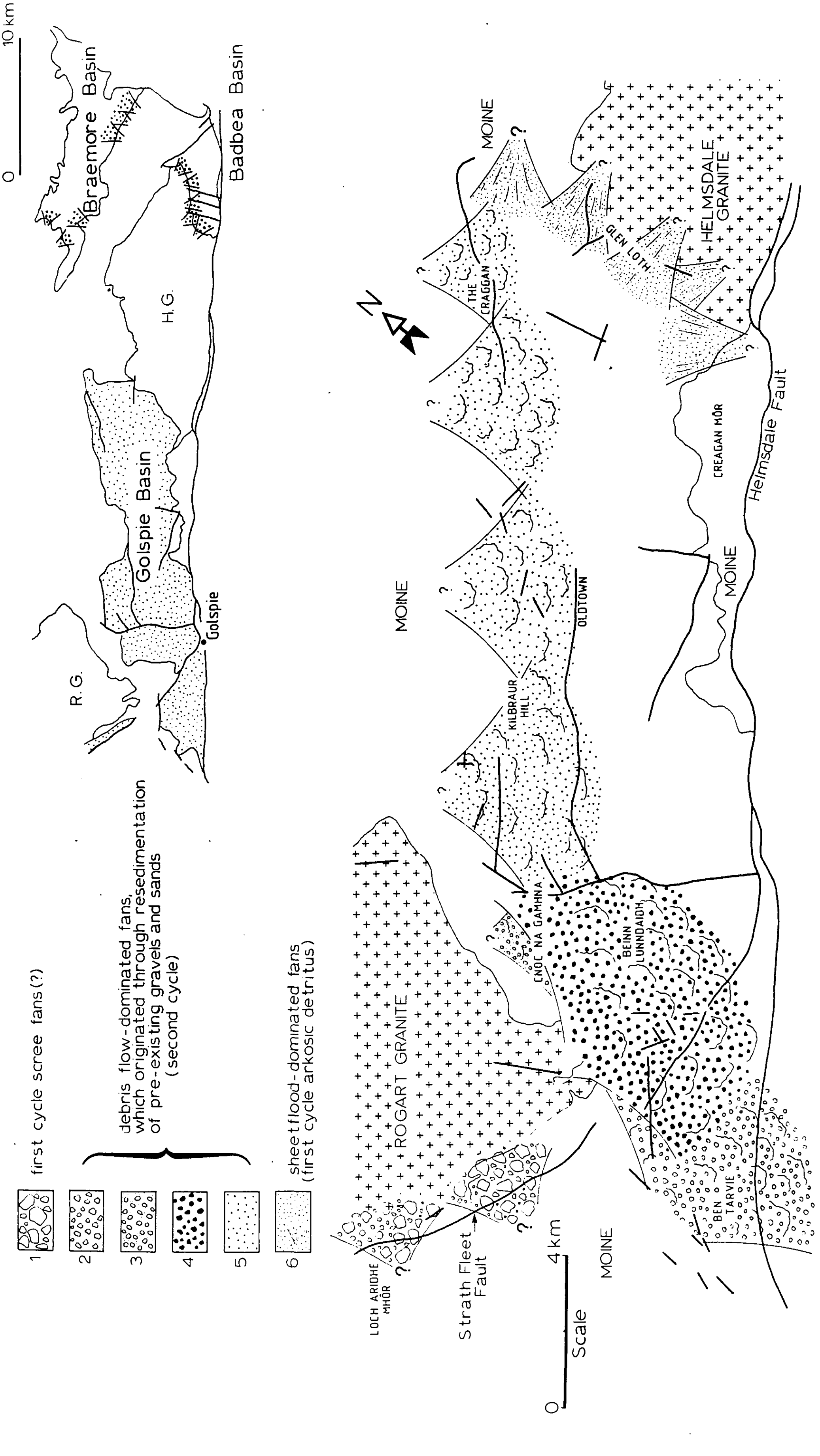
The Creag an Amalaidh Conglomerate, dominated by the deposits of Facies B1, consists in the majority of generally poorly sorted, angular and subangular Moine granulite clasts and thus it could be regarded as product of first cycle mobilisation of the colluvial deposits and their deposition on the fan surface. However, the matrix in this conglomeratic body differs texturally and compositionally from the gravel fraction. Its strikingly good sorting, significant proportion of subrounded and well rounded clasts and presence of exotic pelitic lithic fragments(PLF) (Fig. 7.1.20a. & Plate 7.1.11.) suggest that the matrix forming material is genetically unrelated to the gravel fraction and had been independently derived from some distal source, being possibly at some stage reworked by wind (Lustig, 1965) (see also chapter 7.4.5.5.). According to McArthur (1987), airborne silt and fine sand supplied to the fan catchments and fan surfaces during glacier decay and in early postglacial period resulted in bimodal gravels and mixtones being added to the Pleistocene fan sequence, the former being transported by debris flows.

It is proposed that the independently deposited in the source area gravelly and sandy material mixed together, possibly during the final mobilisation and emplacement onto the fan surface. The features of the textural heterogeneity, typical of Facies B are common in the Creag an Amalaidh Conglomerate and suggest that in this case at least a portion the gravelly material must had undergone some segregation prior to the final resedimentation and remoulding with the exotic sandy fraction.

In view of the evidence presented above, supporting the concept of the polycyclic origin of the BLF conglomerates, the following model of a sedimentary development of the BLF debris flow-dominated alluvial fan, and a textural evolution of its deposits can be formulated (Fig. 7.1.26.).

The debris flows generated through a *en mass* mobilisation (possibly by landsliding (Sharp & Nobles, 1953; Pierson, 1979, 1981; Johnson & Rodine, 1984)) of the earlier

Figure 7.1.27. Envisaged palaeogeography during the sedimentation of the Beinn Lunndaidh Formation. ? - no palaeocurrent data indicators. The palaeotransport is inferred from the clast composition of the conglomerates. Margins of the Braemore and Badbea basins were probably locally fringed by alluvial fans; their dispersal is hypothetical.


1 first cycle scree fans (?)
2
3
4
5
debris flow-dominated fans, which originated through resedimentation of pre-existing gravels and sands (second cycle)
6 sheetflood-dominated fans (first cycle arkosic detritus)
0
10 km
Braemore Basin
Badbea Basin
H.G.
Golspie Basin
Golspie
R.G.
MOINE
THE CRAGGAN
GLEN LOTH
HELMSDALE GRANITE
CREAGAN MÔR
Helmsdale Fault
OLDTOWN
KILBRAUR HILL
ROGART GRANITE
CNOC NA GAMHNA
BEINN LUNNDAIDH
BEN TARVIE
LOCH ARIDHE MHÒR
Strath Fleet Fault
Scale
0
4 km

accumulated in the drainage area, vast amounts, variously reworked, semi-lithified gravels and sands. Mobilisation of debris flows is usually triggered by heavy, storm rainfalls (Bull, 1964, 1977; Pierson, 1979; Wells & Harvey, 1987). An increase in pore-water pressure in source sediments results in reduction of their shear strength to the point of failure (Johnson, 1970).

The substantial amounts of haematite/clay material, present in the matrix, and its textural features are consistent with the assumed processes of the primary lithification and the clay infiltration, that modified the petrographic and textural characteristics of the pre-existing, source sediments. The introduced clay, iron-oxides and possibly carbonate(caliche) cements are believed to had increased cohesiveness of the source sediments (Ingles, 1962; Mitchel, 1976; Dapples, 1979), and by decreasing the textural maturity, improved potential, effective buoyancy (Pierson, 1981). These two sediment properties are thought to have contributed, in the interpreted Facies B debris flows, the main clast-support mechanisms (see chapter 7.1.5.1.4.).

Remoulding, associated with the mobilisation of the semi-lithified gravels and sands and the en mass transport, are interpreted to have given rise to the textural inversion and the characteristic textural heterogeneity of Facies B. In the cohesive debris flows, clumps of variously segregated gravels mixed with sand as well as large sandy intraclasts did not disperse and homogenize completely and thus preserved their original structure and texture.

At some stage, during the transport or during the mobilisation, an incorporation of the first-cycle colluvial sediments, derived from the weathered and penecontemporaneously denudated basement bedrock, could take place (Fig. 7.1.26.).

The debris flows, spreading onto the fan surface might have incorporated the earlier deposited debris flow and texturally more mature sheet flood deposits (Johnson & Rodine, 1984). This can be demonstrated along some of the contacts of the debris flow beds with the sandstone interbeddings (Fig. 7.1.18.). The sandstone bed, gradually passing, laterally as well as upwards, into the matrix in the conglomerate can be interpreted as an incorporation(remobilisation) of the sandy material by the overriding debris flow.

The remobilisation of the alluvial fan deposits could have also been achieved by a gravitational sliding in response to instability of the depositional surface (Shumm, 1973; Weaver & Shumm, 1974). The latter phenomena can be demonstrated with confidence only on the sandstone beds, as any slump features, normally identified with contorted lamination, would be completely unrecognizable in the predominantly massive conglomerates. Sequence of photographs taken along the same sandstone bed (Plate 7.1.8.) clearly demonstrates a slump-like deformation of the sandy bed, loading of cobbles and local mixing with the the gravel (see also Fig. 7.1.18.) .

Both types of remobilisation and further mixing of the fan deposits would lead to a second-stage of textural inversion of the earlier reworked gravels and to a new generation of the heterogeneous, Facies B deposits.

Analogous processes of the gravity remobilisation and related textural inversion have been documented by Larsen & Steel (1978) from a debris flow-dominated alluvial fan in the middle Devonian Hornelen basin(Norway), though in the latter case the debris-flow deposited and later reworked gravels mixed with fine-grained floodplain sediments, that have been invaded by the prograding alluvial fan.

The occurrence of gravitational slumping, affecting the fan deposits, is fully consistent with the inferred here intense, erratic sediment supply and relatively steep slopes, characterizing the BLF debris flow-dominated alluvial fans. Rapid uplift in the adjacent highlands during the BLF sedimenation might have been a supplementary condition contributing to the exceeding by the fans the threshold of stability. Intense rainfalls, responsible for the pore-pressure increase, and seismic tremors are seen as a factors triggering the slumping and remobilisation.

7.1.5.4.2. Sheetflood dominated fans - first-cycle conglomerates

While the processes of resedimentation and formation of debris flow fans characterised the SW and the W margin of the Golspie basin, the alluvial fans fringing the NE flank of the basin (Ousdale Arkose Conglomerate) developed through deposition from the sheetfloods (see Facies C1, chapter 7.1.5.1.5.).

Contrary to the debris flow deposits (Facies B), these conglomerates have poorly developed sandy matrix and are texturally homogeneous. They also appear typically monomict, made up of angular clasts, derived mainly from the Helmsdale porphyritic adamelite. There are no textural evidence that the arkosic detritus had undergone any significant reworking prior to the mobilisation and the final deposition.

The striking feature of the Facies C1 conglomerates is their constantly small clast size. The maximum particle size (MPS) of 5 - 2 cm is a function a size of the large orthoclase crystals in the coarse-grained, porphyritic Helmsdale granite from which the Facies C1 gravels have been derived. It is thought that such clast size distribution, in spite of the direct proximity of the source granite, is a resultant of mechanical properties of the granite. It is characterised by exceptionally low uniaxial compressive strength values (60 - 70, ave. 67.1 MN/m^2) (Dr. Gribble, pers. comm.,1987). This is due to the intense fracturing, which affected the granite prior to the BLF sedimentation (see chapter 4.). These data are perfectly consistent with the analyses of clast composition from the Creag a' Bhodaich conglomerate (Fig. 7.4.4.), that show that the Helmsdale derived debris, in contrary to the distribution of the RCGC clasts, concentrates in the finest gravel fraction. Hence, it is suggested that the fractured Helmsdale granite, unlike most granitic plutons (Haughton, 1986; Bluck, 1983), produced predominantly relatively finer-grained, gravelly detritus instead of boulders.

It is interpreted that the sheetflood dominated alluvial fans in the NE were derived through a mobilisation of colluvial arkosic sediments, resting on the unroofed porphyritic part of the Helmsdale granite, and through a direct denudation of the granitic bedrock. Therefore, they are regarded as a product of a first-cycle sedimentation (Fig. 7.1.26.B).

Probably the insufficient volumes of the debris available in the drainage area during the mobilisation as well as lack of finer-grained matrix (high frictional resistance and low pore water pressure) could not facilitate a mass flow transport of the arkosic gravels onto the fan surface. These two factors are seen as the principal in controlling the sedimentary processes, and consequently, the geometry of the discussed alluvial fans (Hooke, 1968;

Wells & Harvey, 1987). There are no evidence, whether a tectonic factor played here any particular role.

7.1.5.4.3. Loch Airidhe Mhor - first-cycle conglomerate(?)

This belt of the mass flow emplaced conglomerates (see Facies A, chapter 7.1.5.1.1.) may represents first-cycle, scree and landslide deposits(?), laid down in the most proximal sectors of the fans developed along the NWW-SEE trending, Strath Fleet Fault-controlled scarp.

7.2. **Glen Loth Formation (GLF)**

7.2.1. Introduction

The Glen Loth Formation(GLF) constitutes the upper part of the lower, Lower Old Red Sandstone group of the infill of the Golspie basin (Fig. 3.1 & 6.1.). This lithostratigraphic unit is termed *"Mudstones and Sandstones"* in Read *et al.* (1925) and is regarded as a lateral equivalent of *"Ousdale Mudstones"* (Badbea basin) and *"Braemore Mudstones and Sandstones"* (Braemore basin) by Crampton *et al.*(1914) and Mykura (1983a).

Name of the formation has been introduced by Mykura (1983a) after Glen Loth, where the sediments are best exposed and reach total thickness of up to 600 m (Plate. 7.2.10.).

The GLF has been subdivided by the present author into three lithostratigraphic members (Fig. 3.3 & 6.2.) all of which differ significantly from each other with regard to: (1) setting within the Golspie basin; (2) facies characteristics; (3) palaeodispersal and (4) composition and provenance. The Beinn a' Bhragaidh Member (BBM) occurs in the SW part of the basin, the Beinn Dhorain Member(BDM) and the Ben Uarie Member (BUM) dominate its N sector. For discussion of the aspects (2), (3) and (4) see the further chapters. The BBM is regarded as a possible equivalent of the BDM and the BUMn (Fig. 6.2.). The exact relationship between these two groups of deposits of the GLF is uncertain, owing to the poor exposure in the central part of the basin.

7.2.2. Distribution, thickness and lower boundary

The deposits of the Beinn a' Bhragaidh Member (predominantly sandstones of Facies G2) appear in the SW half of the Golspie basin(SW of Loch Brora, Fig. 3.3.), where they rest on the conglomerates of the Beinn Lunndaidh Formation. The distribution and shape of the outcrop of the BBM are grossly controlled by the SSW-NNE and NW-SE trending faults. The strata dip generally to the E and SE at angles of 10 - 40^{o}. At the top of Beinn a' Bhragaidh their orientation is near horizontal (Plate 7.2.21.A). Thickness of the BBM is around 530 m and south of Kilbraur Hill the sandstones seem to wedge out to the

NW.

The **Beinn Dhorain Member** outcrops along the NE margin of the Golspie basin (Plate 7.2.10.A). It is in a rapid but gradational contact with the Ousdale Arkose Conglomerate of the Beinn Lunndaidh Formation. This 5.6 km long lenticular subunit (composed mainly of Facies E2 & E3) is up to 450 m thick and dips to the W and SW at angles 40 - 70°. The name of the member is after summit Beinn Dhorain at whose base the rocks are best exposed (Plate 7.2.10.A&B).

The Beinn Dhorain Member is overlain by the sandstones of the **Ben Uarie Member** (Plate 7.2.10.A&B). The name of this subunit is after Ben Uarie - the summit north of Beinn Dhorain, which is entirely composed of the sandstones of Facies F1 and F2. Although the outcrop of the latter unit dominates the NE area of the basin its thickness is only 150 m. It is for the strata have much more gentle dips(20 - 30°). They strike N-S to NW-SE, following the orientation of the eastern margin of the basin. South of Creag a' Chrinoich the BUM strata appear to adjust to the changing orientation of the basin margin nearby and dip to the NW at angle of 50°.

The 230 m thick succession of sandstones of Facies F1, outcropping in Allt Smeorail above the conglomerates of the Beinn Lunndaidh Formation (BLF), has been included into the BUM on the grounds of close affinities with regard to sedimentary features and textural/compositional characteristics. Lateral contacts of the outlier are not mappable, though there appear to be a fault contact to the S (Fig. 3.3.). The strata at the latter locality dip at angles 50 - 60° to the SE. In the stream section near Oldtown muddy sandstones and mudstones, grading from the underlying BLF conglomerates, display roughly similar characteristics as the deposits in Allt Smeorail. They dip to the SE at angle of 70°. The strata are in a vertical fault contact along the strike with the conglomerates of the Beinn Smeorail Formation. The sediments have thickness of 120 m and wedge out dramatically in the SW and NE direction.

7.2.3. Ousdale Mudstones (Badbea basin)

This lithostratigraphic unit (Crampton *et al.*, 1914) appears in the Badbea basin (Fig. 7.2.22.) (*Berriedale Outlier* in Crampton *et al.* (1914)). The sediments are arranged in a shallow syncline, whose axis runs in the NE-SW direction. While in the vicinity of the contact with Ousdale Arkose the rocks dip to the NE, the strata exposed in the cliff section at Ceann Ousdale dip inland to the N and NW. Angle of dip ranges from 20-50^{o}. Thickness of the Ousdale Mudstones is around 210-240 m (Crampton *et al.*, 1914).

7.2.4. Braemore Mudstones and Sandstones (Braemore basin)

The Braemore Mudstones and Sandstones belong to the Braemore basin (*Morven and Braemore District* in Crampton *et al.* (1914)) (Fig. 7.2.22.) and together with the underlying and overlying conglomerates and breccias are arranged in a syncline, whose axis runs rather south of the centre and parallel with the length of this tongue-shaped basin (Crampton *et al.*, 1914). Locally the mudstone strata rest directly on the basement without intervention of any basal conglomerates. The mudstones and sandstones are generally dipping toward the axis of the trough, but directions and angles of dip are locally very variable (see Crampton *et al.*, 1914). The angles of dip range between 5 - 50^{o}. Assuming an average dip of 10^{o} thickness of the Brameore Mudstones and Sandstones would be 450 m.

7.2.5. Upper boundary

The deposits of the Glen Loth Formation are uncomformably covered by conglomerates of the Beinn Smeorail Formation. Description of this unconformity is given in chapter 7.4.3.

Figure 7.2.1. A: Graphic summary log depicts vertical facies distribution within the Beinn Lunndaidh Formation (BLF) and the Glen Loth Formation (GLF) in NE part of the Golspie basin - Glen Sletdale section [NH 935 127];

B & C - Graphic logs from the lowermost portion of the GLF; see log **A** for their location.

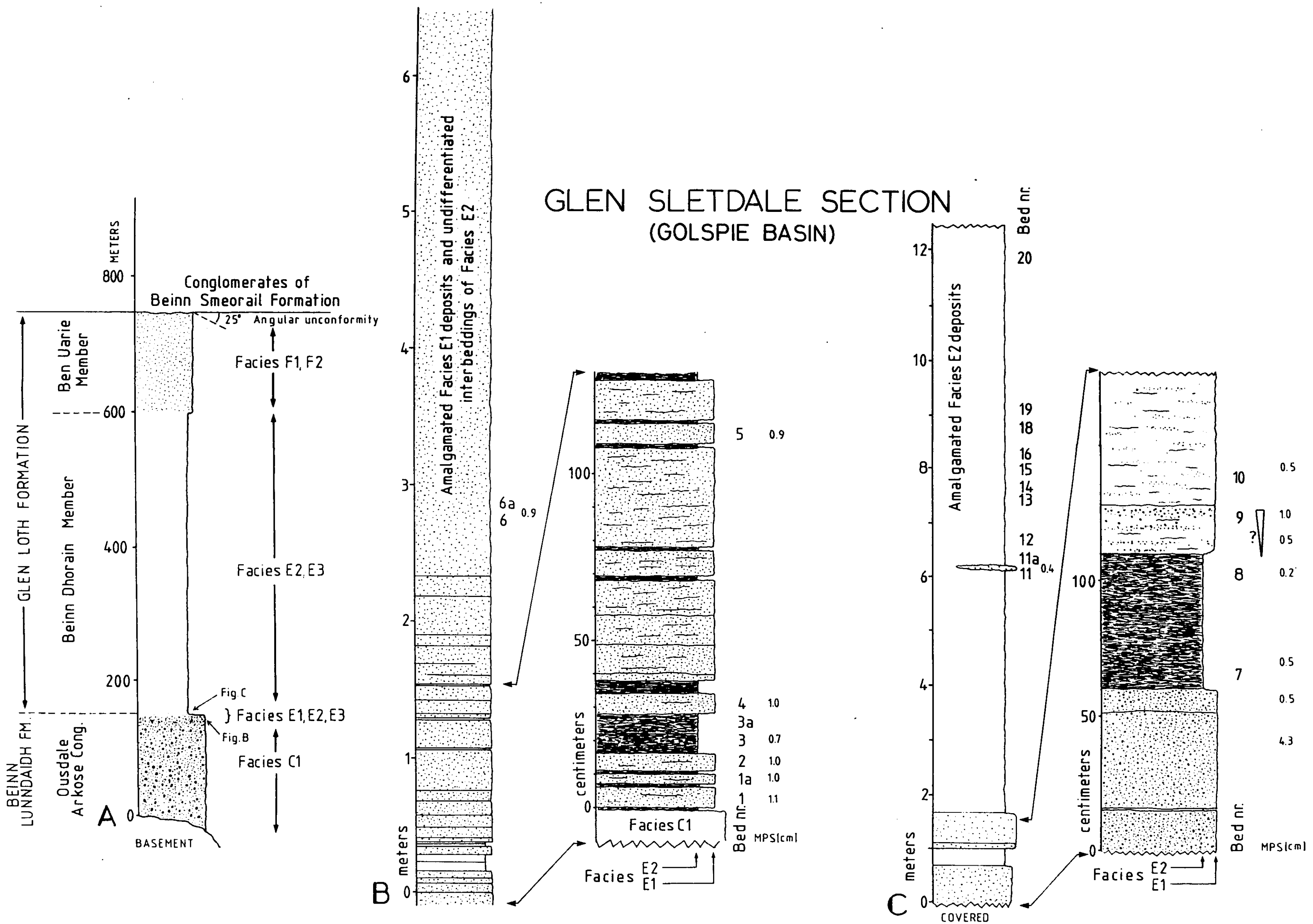
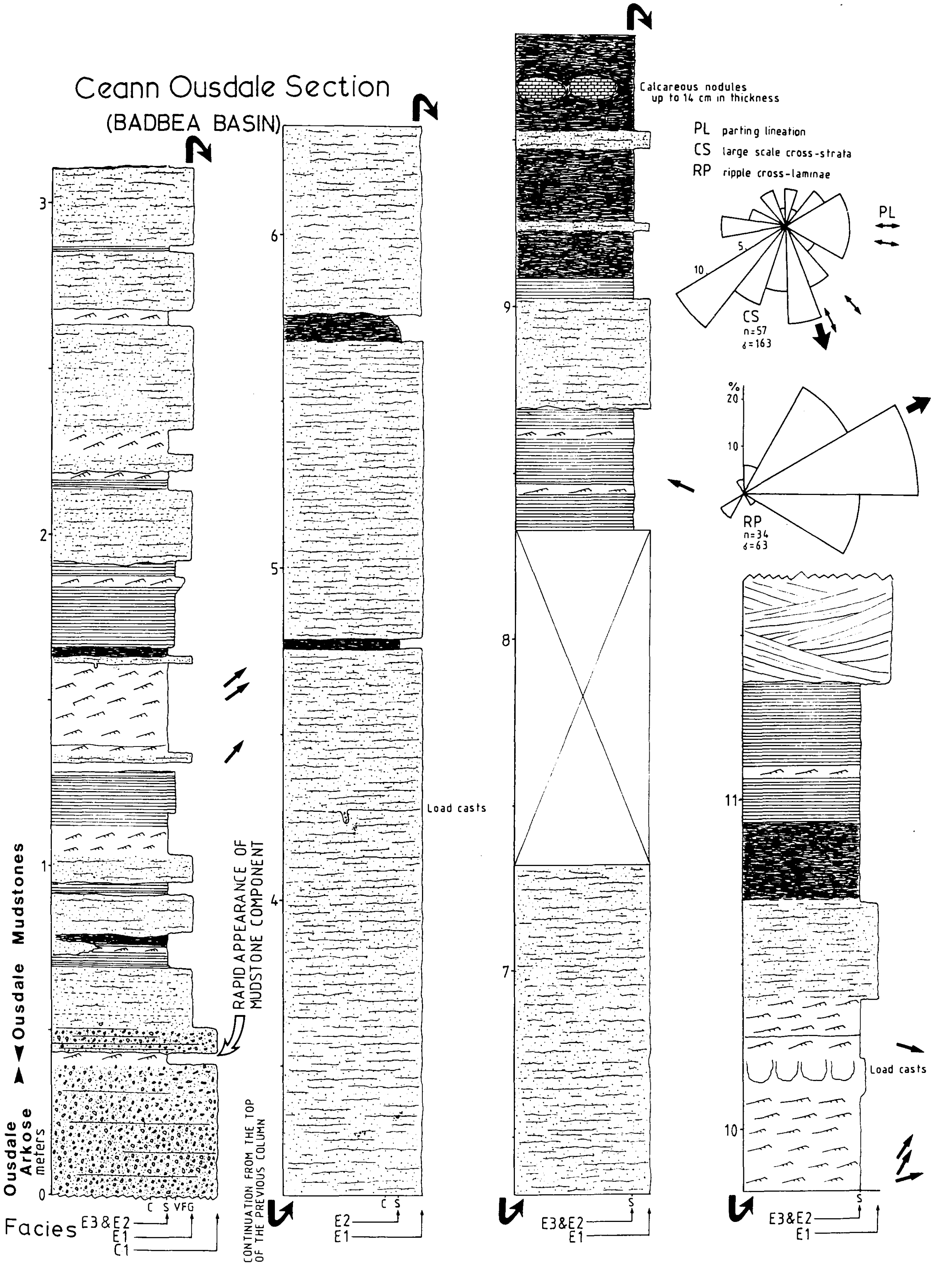

GLEN SLETDALE SECTION
(GOLSPIE BASIN)
A
METERS
800
600
400
200
0
BASEMENT
Conglomerates of
Beinn Smeorail Formation
25° Angular unconformity
Ben Uarie
Member
Beinn Dhorain Member
Ousdale
Arkose Cong.
GLEN LOTH FORMATION
BEINN
LUNNDAIDH FM.
Facies F1, F2
Facies E2, E3
Fig.C
Facies E1, E2, E3
Fig.B
Facies C1
B
meters
Amalgamated Facies E1 deposits and undifferentiated
interbeddings of Facies E2
6a 0.9
6
centimeters
Facies C1
Facies E2
E1
Bed nr.
MPS(cm)
5 0.9
4 1.0
3a
3 0.7
2 1.0
1a 1.0
1 1.1
C
meters
COVERED
Amalgamated Facies E2 deposits
Bed nr.
20
19
18
16
15
14
13
12
11a 0.4
11
centimeters
Facies E2
E1
Bed nr.
MPS(cm)
10 0.5
9 1.0
? 0.5
8 0.2
7 0.5
0.5
4.3

Figure 7.2.2. Graphic log from the basal part of Ousdale Mudstones at Ceann Ousdale made up of Facies E1, E2 and E3 (Badbea basin). These deposits appear rapidly above the fanglomerates of Ousdale Arkose and are regarded as a lithostratigraphic equivalent of the Beinn Dhorain Member. They pass into the sandstones, conglomerates and mudstones of Facies G1. Palaeotransport rose-diagrams of azimuth of dip of: **RP** - current ripple cross-laminae (Facies E3); **CS** - cross-strata and **PL** - orientation of parting lineation (Facies G1).



Ceann Ousdale Section
(BADBEA BASIN)
Ousdale Arkose
Ousdale Mudstones
meters
0
1
2
3
4
5
6
7
8
9
10
11
RAPID APPEARANCE OF MUDSTONE COMPONENT
CONTINUATION FROM THE TOP OF THE PREVIOUS COLUMN
Load casts
Calcareous nodules up to 14 cm in thickness
PL parting lineation
CS large scale cross-strata
RP ripple cross-laminae
PL
CS
n=57
δ=163
%
20
10
RP
n=34
δ=63
Facies
E3&E2
E1
C1
C S VFG
E2
C S
S

7.2.6. Sedimentary characteristics of the Glen Loth Formation

7.2.6.1. Main sedimentary facies

Six new facies has been recognized in the Glen Loth Formation: **E1, E2, E3, F1, F2, G2. Facies G1** occurs in the Badbea basin

Although the facies E1, E2 and F1 share significant structural signatures (widespread shear layering), and although they are consequently interpreted to have formed in a very similar fashion, they are discussed separately. This is in order to demonstrate variability in the nature of the sedimentary structure, which has not been so far thoroughly documented (this is except for the features described by Cowan (1982,85), whose sedimentary origin is debatable). The discrimination of these three individual facies helps to elucidate textural aspects of the sedimentary evolution of the involved sediments. The nature of the associated, subordinate deposits of facies E3 and F2 has been treated as a additional criterion for making the designation of the facies, as these laminated and stratified beds carry important information regarding a broader palaeoenvironmantal context of the sedimentation(subaerial vs. subaqueous).

The structural and textural features have been considered, while designating Facies G1 and G2.

7.2.6.1.1. Facies E1: Massive and shear-layered conglomerates, muddy conglomerates and pebbly mudstones

Facies E1 is confined to the lowest portion of the Beinn Dhorain Member and represents deposits, which are transitional between the underlying conglomerates of Facies C1 (Ousdale Arkose Conglomerate, Beinn Lunndaidh Formation) and the overlying mudstones and muddy sandstones of Facies E2 & E3.

Analysis of Facies E1 is mostly based on data collected from the stream section in Glen Sletdale, before it joins Glen Loth [NH 935 127] (Fig. 7.2.1.). The one-dimensional nature of this outcrop does not allow a study of the lateral aspect of facies distribution. Additional information comes from cliff exposures at Ceann Ousdale (Fig. 7.2.2. & 7.2.22.), where analogous deposits of the same lithostratigraphic horizon (Ousdale Mudstones, Crampton *et al.*, 1914) are exposed. These latter sediments belong to a separate sedimentary basin, which will be further in the text referred to as Badbea basin (*Berriedale Outlier* in Crampton *et al.*, 1914). The deposits Facies E1 are also, although poorly exposed in the stream section of Allt Smeorail (north of Beinn Smeorail).

Many sedimentary features of Facies E1 have been described from the cut and polished large slabs, up to 30 cm in size, and from the thin sections; selected thin sections have been examined under a cathodoluminescence microscope.

Description

Conglomerates, muddy conglomerates and pebbly mudstones of Facies E1 are generally very poorly sorted and display no stratification. Gravel fraction of these deposits is composed of the same, arkosic material which makes up Facies C1(chapter 7.1.5.1.5.). The maximum particle size(MPS) ranges between 0.4 - 4.3 cm and it is governed by the size of the orthoclase feldspar phenocrysts in the Helmsdale granite, from which the detritus has been derived (Plate 7.2.1., 7.2.2, 7.2.3.).

Matrix is represented by two components: micaceous mudstone and micritic/dismicritic calcite, which occur in variable proportions. Although the mudstone-dominated matrix is most abundant, in a few instances, however, the matrix is almost entirely represented by the carbonate component (Plate 7.2.5. & 7.2.6.).

The mudstone phase consists predominantly of silt and clay. Proportion of the latter material ranges from around 30 - 40%. XRD analyses of the clay fraction from four representative samples have revealed, apart from a dominant quartz, feldspars and muscovite, presence of illite and chlorite (Fig. App.2.F-I). Results of petrographic analyses of the very fine- to fine-grained sand fraction from the samples of the mudstone matrix are given in Fig. 7.2.21. (see also chapter 7.2.6.1.12.). The mudstone matrix is petrographically and texturally identical to that in Facies E2 (chapter 7.2.6.1.2.). In the

Plate 7.2.1. Conglomerates of Facies E1.

A & B: Both photographs show sections parallel to each other and spaced 10 cm apart. In **B** the arrow points to a possible boundary between the lower and the upper bed. The boundary becomes unrecognizable in the area where the streaky muddy interbedding pinches out. Note a dramatic change in structure and texture in the lower bed from structureless and clast-supported (**B**), to shear-layered and clast to matrix-supported (**A**). In **A** the upper bed displays an "inverse grading" on the left, lack of grading in the middle and a "normal grading" on the right. These effects of "grading" are thought to be only a manifestation of non-uniform dispersion of particles in poorly remoulded mass flow deposit. (Locality: Glen Sletdale section, Bed 2, Fig. 7.2.1.B);

C: Well defined clast-supported to coarse sand matrix-supported bed of Facies E1, underlain and capped by the muddy Facies E2. Note loading and flame structures at the base of the bed. The bed appears to be ungraded (Locality: Bed 4, Fig. 7.2.1.B);

D: Another very well defined clast-supported bed of Facies E1. The base of the bed is irregular and possibly erosional. Facies E2 deposits at the top and at the bottom. Note crude shear-layering (?) (Locality: Bed 1a, Fig. 7.2.1.B).

On the photographs **A-D** largest clasts are orthoclase feldspars derived from Halmsdale granite (see also **Plate** 7.2. 2. and 7.2.3.)

Plate 7.2.1.

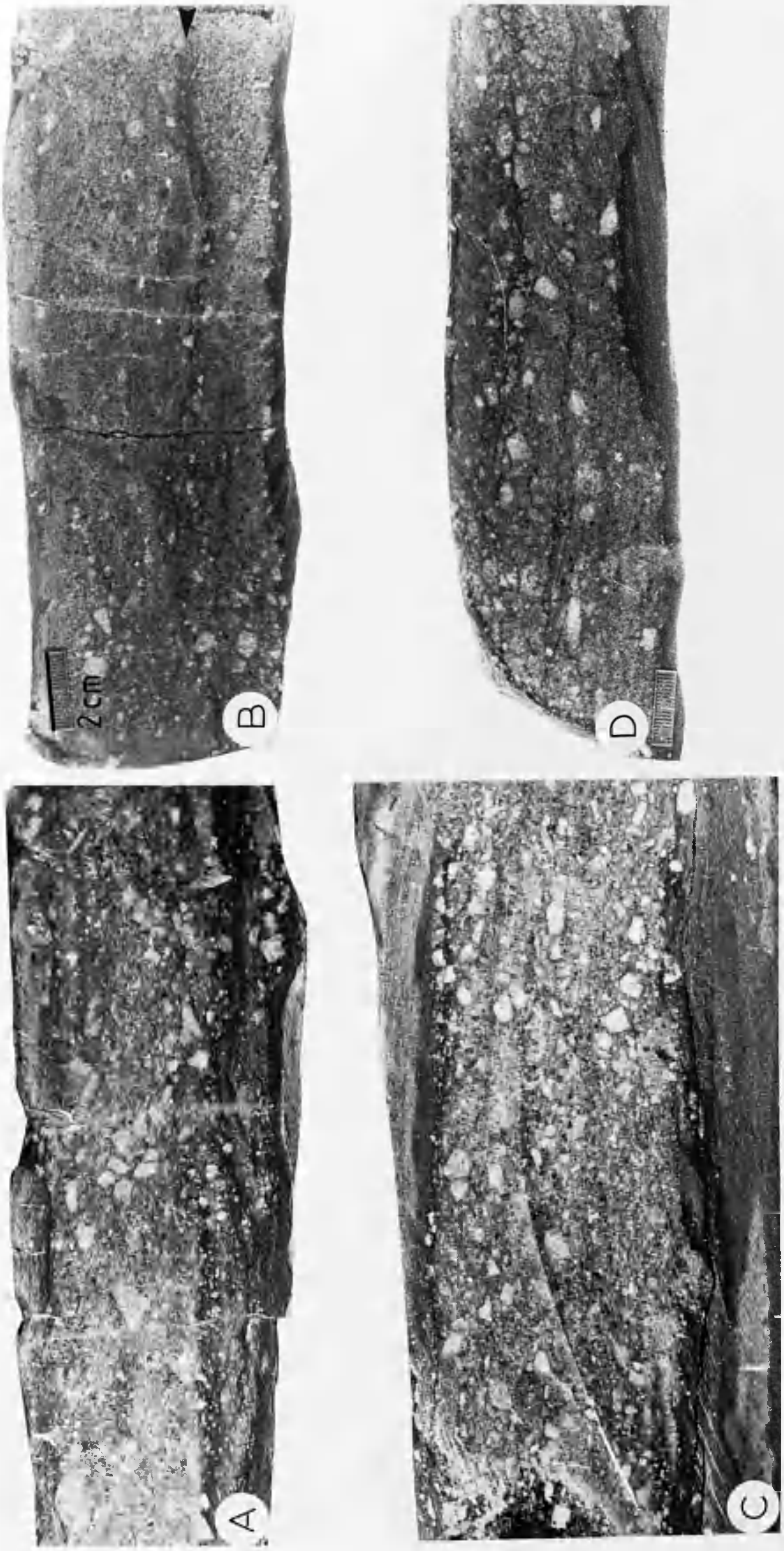


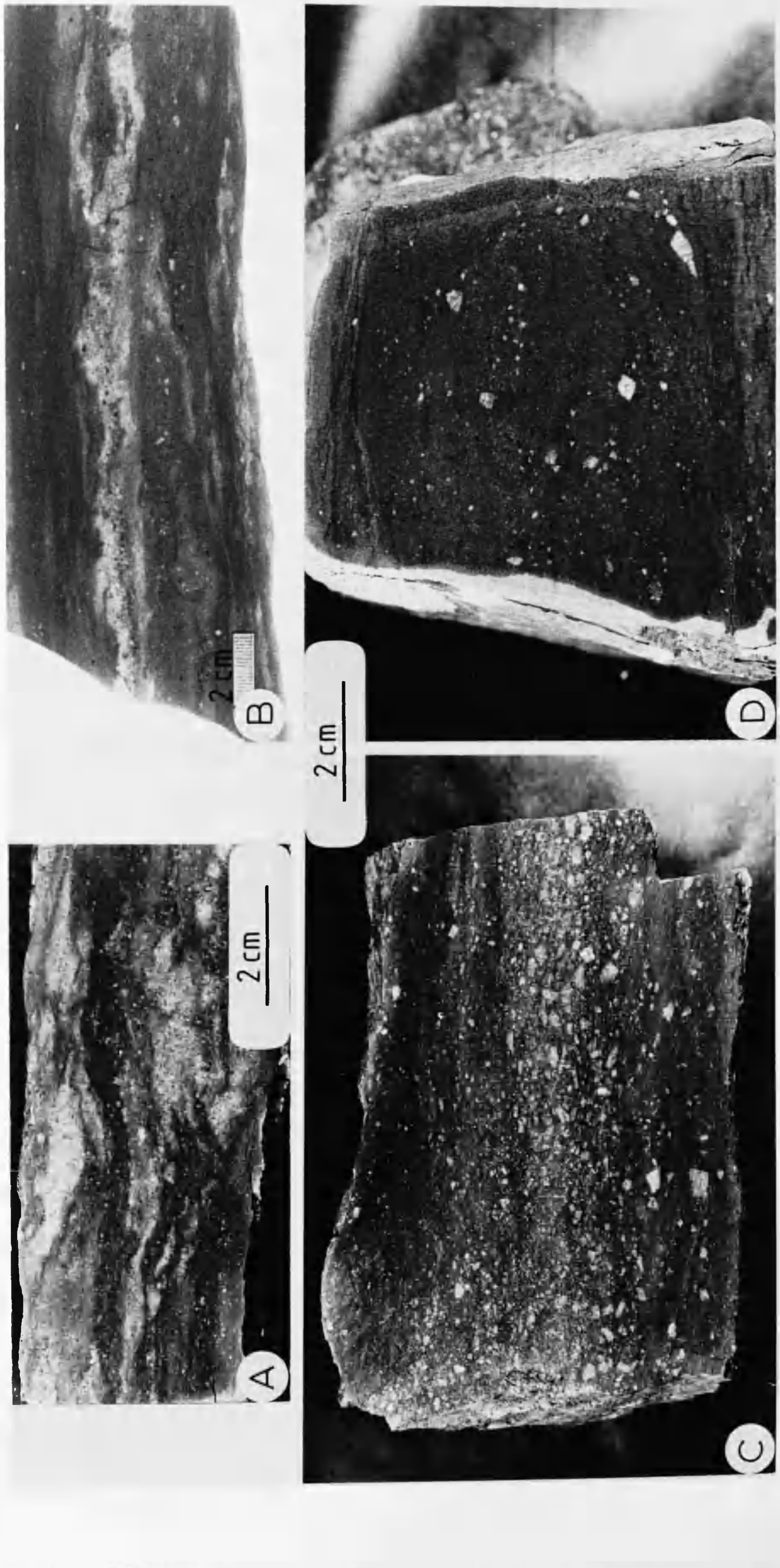
Plate 7.2.2. Clast-supported conglomerates of Facies E1; the deposits are somewhat transitional to Facies E2)

A & B: Shear-layering in the majority of the Facies E1 deposits is manifested by jagged streaks and phacoids of the arkosic detritus which are aligned parallel to the bedding. In the phot. **B** the middle, clast-rich horizon may represent an early individal gravelly layer enveloped by the muddy sediments and later sheared and smeared out in result of layer-parallel extension during the mass flowage. (Locality: **A** - Ceann Ousdale, Fig. 7.2.2.; **B** - Bed 10, Fig. 7.2.1.C);

C: Shear-layered muddy conglomerate and pebbly, calcareous mudstone. The middle clast-rich horizon may either represent an individual depositional event with merged boundaries or is a remnant of gravelly layer which has been considerably remoulded during transport with the surrounding sediments The small-scale, bright streaks represent sheared out calcareous mud. (Locality: Bed 6, Fig. 7.2.1.B);

D: Structureless, pebbly mudstone, enveloped by the shear-layered mudstones of Facies E2. Note a faint, disappearing upwards shear-layering, inclined tangentionally at the base of the massive bed - a "swirl" feature (?).(Locality: Bed 6a, Fig. 7.2.1.B)

Plate 7.2.2.



Ceann Ousdale section(Badbea basin) the mudstone matrix is petrographically similar to the equivalent material in the Beinn Dhorain Member (Fig. 7.2.21. & 7.2.22.).

The opaque to brownish, haematite-stained clay appears either as irregular "specks", scattered chaotically in the rock, or as long streaks aligned parallel to the local trend of the shear-layering(see chapter 7.2.6.1.2. for definition), and in places "wrapping around" the larger clasts (Plate 7.2.4.B). The clay material has developed also between sheets of muscovite flakes and commonly forms coatings on the detrital grains.

The micritic calcite component is generally much less abundant and its proportion varies from 0.0 - 100%. The micrite has been in many places neomorphically transformed into microsparry and sparry calcite. The neomorphic origin of, at least a proportion, of the sparry calcite is indicated by common relicts of the micrite enclosed in the sparr and by a patchy grain-size distribution of the latter (Plate 7.2.5.C & Fig. 7.2.9.B) (Bathurst, 1975; Adams *et al.*, 1984). Sparry calcite cement is probably also present, considering presence of "bird's eye" structures with well developed spar crystals (Plate 7.2.9.B) and common calcite replacement of plagioclase feldspars (see chapter 7.2.6.1.12.). The calcite cement is abundant in the subjacent deposits of the Ousdale Arkose Conglomerate (BLF). Consequently, it appears impossible to determine the exact amount of the primary carbonate mud matrix, present during the sedimentation of Facies E1.

The conglomerates range texturally from being clast- to coarse sand matrix-supported. In some there are minor amounts of finer-grained (mainly carbonate) primary matrix (Fig. 7.2.3.), and in others, fully mudstone/carbonate matrix-supported, the matrix constitutes as much as 80% of the rock (Plate 7.2.2., 7.2.3.A-C). The clast-supported beds are restricted to the basal part of the BDM (Glen Sletdale section, Fig. 7.2.1.) and are absent in the Ceann Ousdale section of the Badbea basin (Fig. 7.2.2).

There is a continuum between Facies E1 and E2 and a boundary, drawn between them, is arbitrary (Plate 7.2.2.).

The deposits of Facies E1 show no stratification, of the conventional sense, that is a grain size or fabric differences within them, indicative of either vertical or/and lateral accretion (Harms *et al.*, 1982) A few well defined beds do not display any form of

Plate 7.2.3. A-C: Deposits of Facies E1.

A: Well defined, shear-layered throughout pebbly mudstone bed of Facies E1, enveloped by thin layers of Facies E2 (arrowed). Note a distinctive "streaky" distribution of the coarse detritus. (Locality: Bed 5, Fig. 7.2.1.B);

B & C: Details of internal structure of the Bed 5;

D: Anglesey melange - quartzite phacoidal inclusions in "scaly clay" matrix. Origin of the fabric (tectonic vs. sedimentary) remains essentially unsolved. Compare with the fabrics in Plate 7.2.2. Lens cap is 5 cm wide.

Plate 7.2.3.

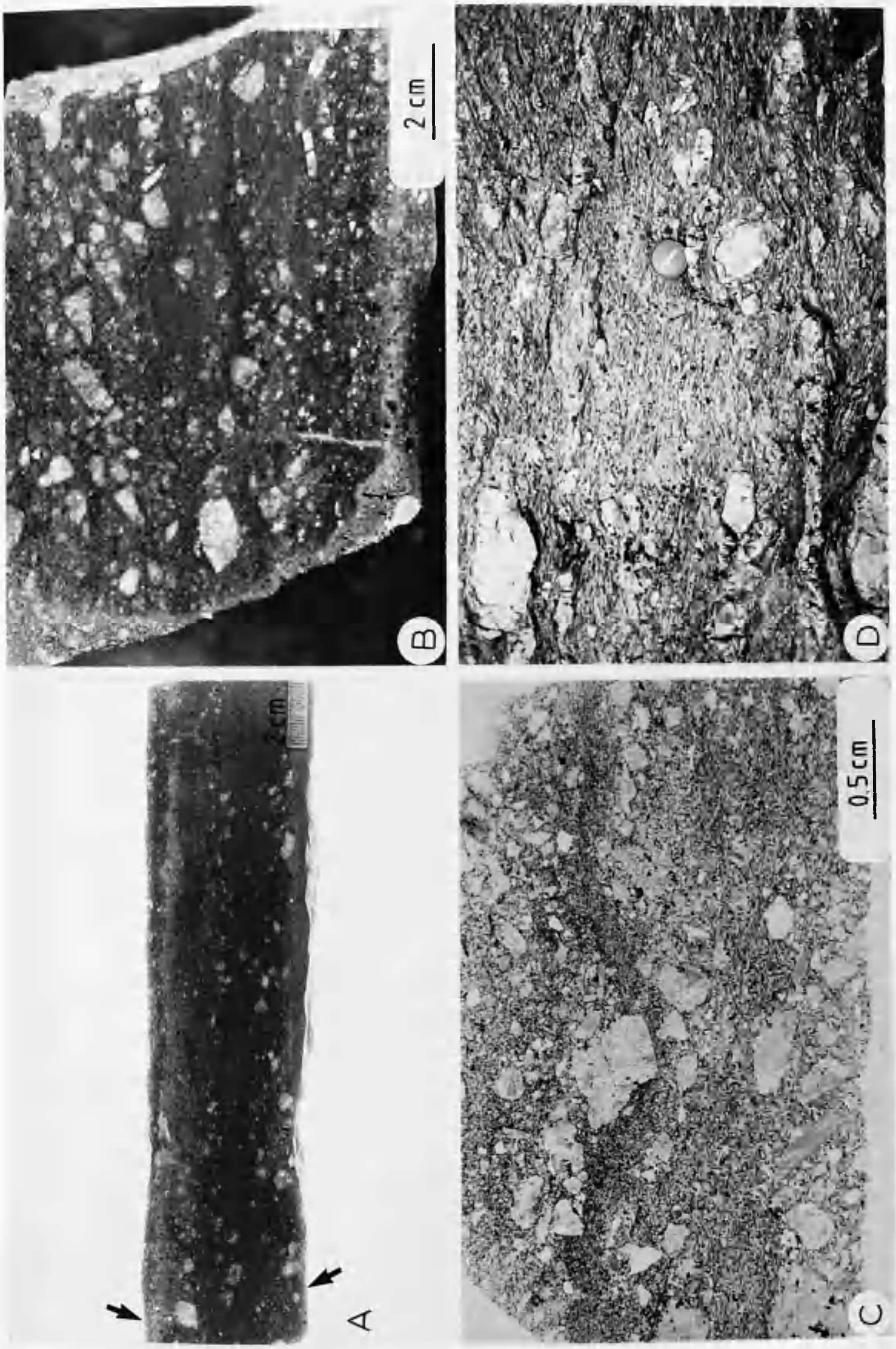
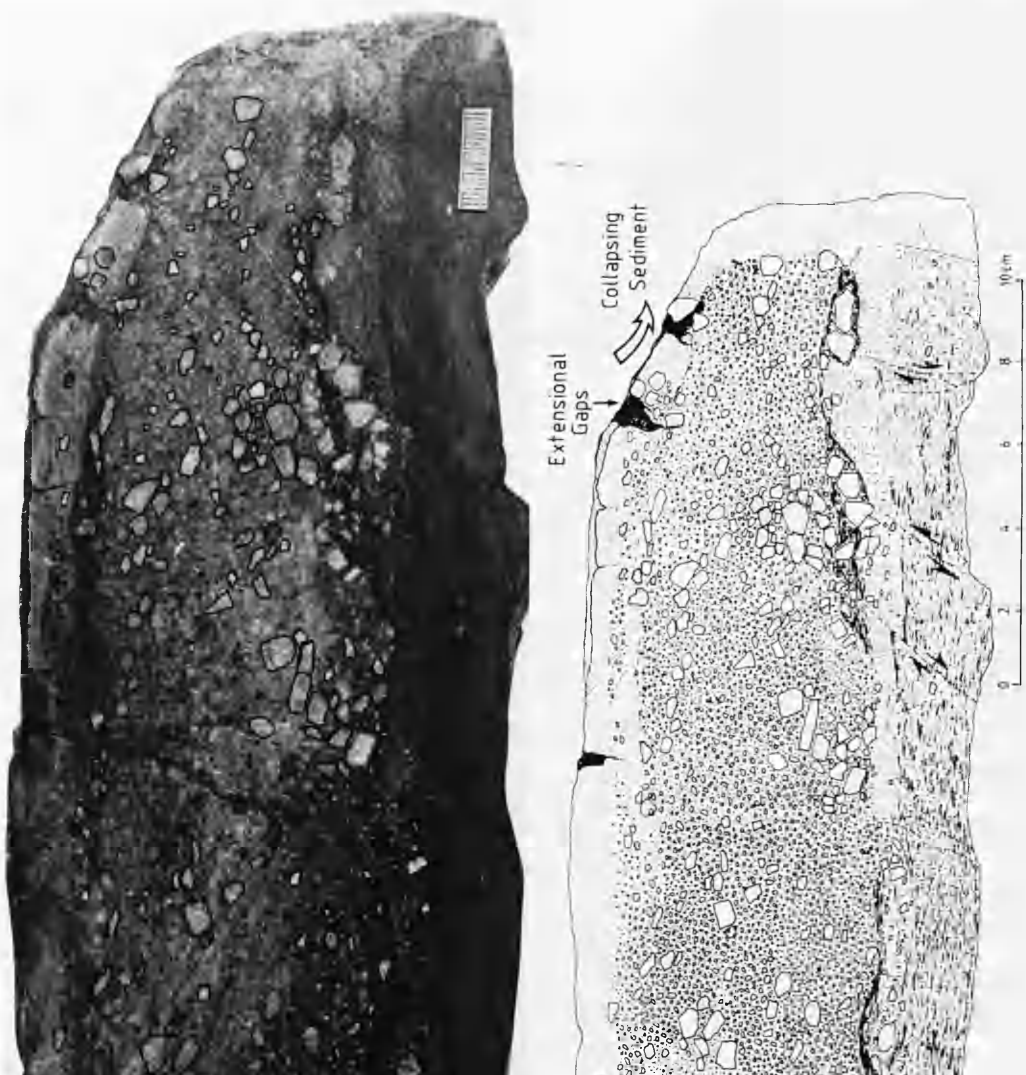


Figure 7.2.3. Cut and polished slab from the clast-rich Bed 1 of Facies E1 (Fig. 7.2.1.B). The framework is filled with micrite/dismicrite matrix. Note a sheared basal contact of the bed and streaks of mudstone, incorporated from the underlying bed during the emplacement. The bed shows incipient, extensional at the top and compressional at the base, features of gravity collapse (see also Fig. 7.2.5.).


Collapsing
Sediment
Extensional
Gaps
10cm
0
2
4
6
8

grading, considered here as a consistent trend in a vertical clast-size distribution in a bed. Typically, these trends have a very variable attitude over a very short distance (Plate 7.2.1.A).

Clast- to matrix-supported and matrix-supported-only varieties of Facies E1 show a very distinctive, pervasively developed **shear-layering** which makes the latter muddy conglomerates and pebbly mudstones rather difficult to classify as "structurless" or "disorganized". Generally the structure is manifested by jagged, pinch-and-swell streaks and lenticular inclusions(phacoids) of predominantly coarser-grained, often better sorted and clast-supported arkosic material (Plate 7.2.1.A & 7.2.2.A-B). They appear boudinaged, torn apart and smeared out parallel/subparallel with the bedding. In the localities at Ceann Ousdale the clast-rich streaks and lenses, containing a considerable proportion of yellowish calcite matrix, stand out against the red-brown mudstone background and thus highlight the nature of the shear-layering.

Some of them have been found to be folded into an S-shape forms. In spite of drastic deformation and smearing out of primary layers and intraclasts, samples examined petrographically show no evidence for cataclasis or granulation of individual clasts.

The shear-layering has been subdivided into three categories, depending on scale of the structure, that is on thickness of the thickest streaks or inclusions:

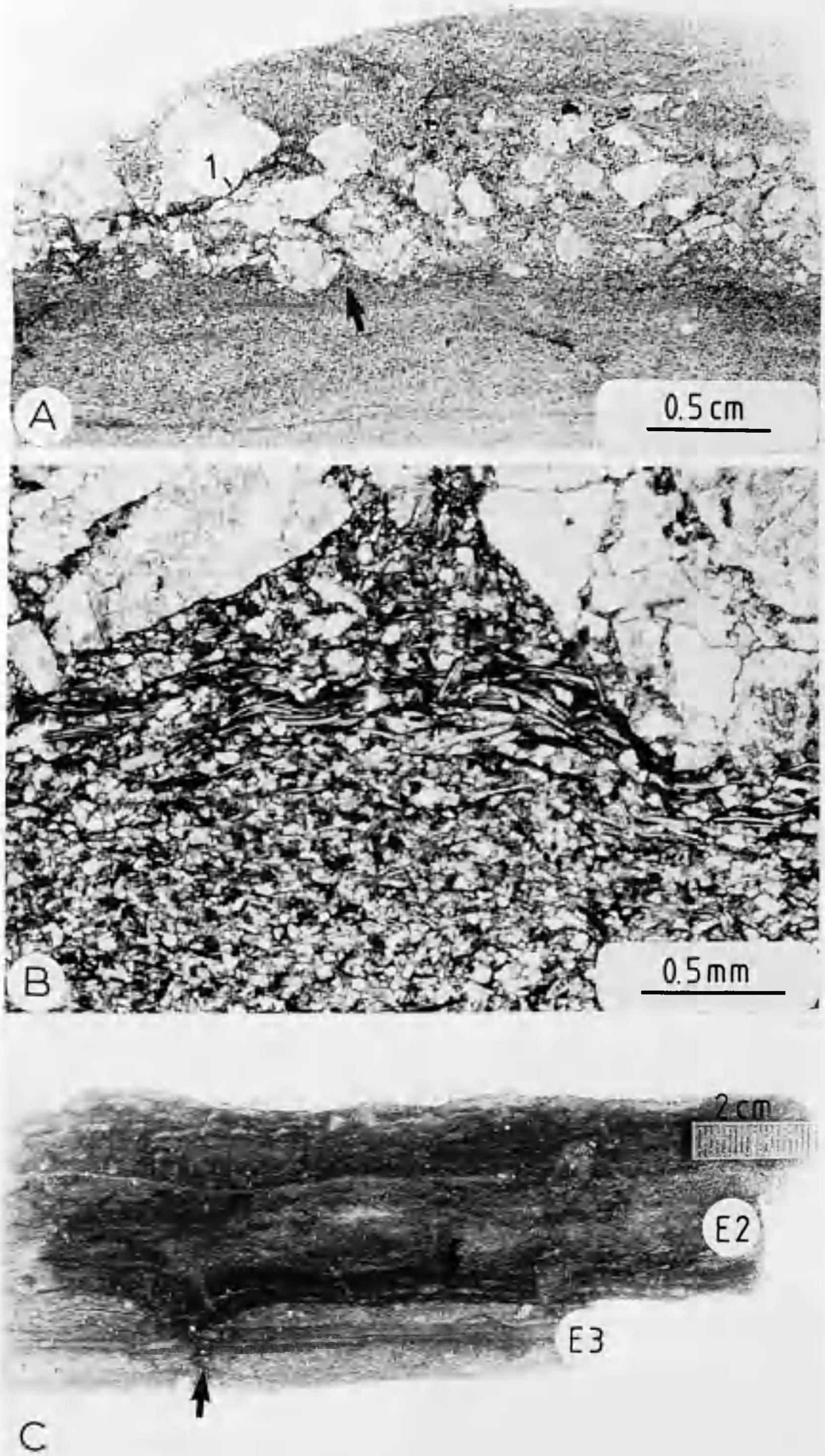
- very large scale shear-layering	>100 cm;
- large scale shear-layering	100 - 5 cm;
- medium scale shear-layering	5 - 0.5 cm;
- small scale shear-layering[1]	< 0.5 cm.

The shear-layering of Facies E1 falls into the categories of the medium to small scale structures as the thickness of the thickest streaks/inclusions varies between 0.2 - 1.3 cm. The longest of them has been found to be over 20 cm long (Plate 7.2.2.B). The very large and large scale shear-layering have not been found in the studied deposits, though it is believed that the structure of this scale is developed in the recent mudslide in Stonebarrow (Dorset, England), in which thickness of lensoid inclusions of clay and sand exceeds 100

[1]The term "shear-lamination" is proposed for this category in order to emphasize the fine scale of the structure.

Plate 7.2.4. A: Section through a lenticular "micro-bed" or a phacoid (Facies E1) surrounded by the deposits of Facies E2. The arrows point to the areas, where micas and clay streaks (microstylolites?) are strongly aligned along the base of the micro-bed. Note that some of the micro clay seams run obliquely to the general trend of the bedding (1);
B: Close up photomicrograph of the area arrowed on the phot. **A** shows alignment of the muscovite flakes and the dark clay streaks along the base of the micro-bed. The effect of "wrapping" the large clasts might be a result of post-depositional compaction (PPL);
C: Shear-layered calcareous mudstones of Facies E2, underlain by the parallel-laminated deposits of Facies E3. The lamination is disrupted along the contact by shearing and boudinage (arrowed).
(Locality: **A-C** - Bed 3a, Fig. 7.2.1.B)

Plate 7.2.4.



cm (Brunsden, 1984, Fig. 7.2.7.B; see also for example Cowan, 1982, 1985 and Bell, 1987 for analogous structures).

The streaks and the lenticular inclusions are regarded as intrabasinal clasts (or intraclasts; see also next chapter 7.2.6.1.1.).

The clast-supported conglomerates appear either totally massive or show a crude shear-layering(?) (Plate 7.2.1.). The structureless, clast-supported Bed 2a (Plate 7.2.1.A&B) has been found passing laterally, over the distance of ten centimeters into matrix-supported shear-layered part.

Three beds of Facies E1 have a markedly different textural features of the intraclasts. In beds 11 & 11a (Fig. 7.2.4.; Plate 7.2.6.A&B) the phacoidal, smeared out, calcareous olive-green and non-calcareous, haematite/clay rich dark intraclasts are partly remoulded with the arkosic, extrabasinal (extraclastic) detritus and micrite/sparry calcite material. The majority of the intraclasts do not show any primary lamination. Some display very subtle parallel lamination, enhanced by an alignment of mica flakes. Single, haematite/clay rich, muddy intraclasts have a very good roundness (Plate 7.2.6.C).

The "inversely graded" Bed 9 (Plate 7.2.5.), composed mainly of the arkosic, gravelly detritus and micrite/dismicrite matrix, shows considerable differences between the streaky layers with regard to sorting of the gravel fraction and in carbonate matrix content.

Only a very few pebbly mudstone beds have been found to be structureless and contacts between the truly massive and the shear-layered parts of such beds are relatively sharp (Plate 7.2.2.D).

The deposits of Facies E1 deposits have generally a form of sheets with mainly flat, parallel-sided boundaries. At Ceann Ousdale they have been found to be laterally continuous through a several meters (across the entire exposure).

Boundaries between the beds seem to be well defined only in a case of presence of finer-grained interbeddings of Facies E2 & E3 (Plate 7.2.1.B&D, 7.2.3.A&B). In the Glen Sletdale section the clast-rich beds clearly stand out against the shear-layered mudstone interbeddings of Facies E2 (Fig. 7.2.1., Plate 7.2.1.). In case of the mud-rich beds of Facies E1 there is usually an uncertainty with respect to whether they represent a single

Plate 7.2.5. A: Polished section through the upper part of the Bed 9, Fig. 7.2.1.C. The bed gives an impression of being inversely graded. The uppermost, the coarsest member of the bed, however, contains mainly mudstone matrix unlike the underlying, carbonate matrix-rich portion of the bed. The entire unit may either represent an allochthonous, primarily layered package of diverse sediments, that has been smeared out and partly mutually remoulded during the redeposition, or a composite bed, made up of thin mass flow surges. The author prefers a former interpretation for the individual layers/streaks show a considerable degree of intermixing; **B**: Photograph of thin section cut from of the carbonate matrix-rich area (arrowed in **A**) (layering is perpendicular to the base of the phot.) . The coarser-grained, extremely poorly sorted streaks are particularly rich in matrix, though the distribution of the carbonate (micrite/dismicrite) is patchy. Some of the matrix-rich patches display bimodal texture (**2**) and have a form of marginally remoulded intraclasts (arrowed); **C**: Close up photomicrograph of the area **1** from the phot. **B**; the finer-grained streaks are well sorted and locally strongly bimodal, though with less carbonate matrix; **D**: Close up photomicrograph of the area **2**, phot. **B**; the dominant micritic calcite matrix is locally neomorpically transformed into spar . Note a patchy distribution of the formed spar and micro-spar ; (**1**) large sparr crystal, enclosing micrite relicts and micro-spar crystals.

Plate 7.2.5.

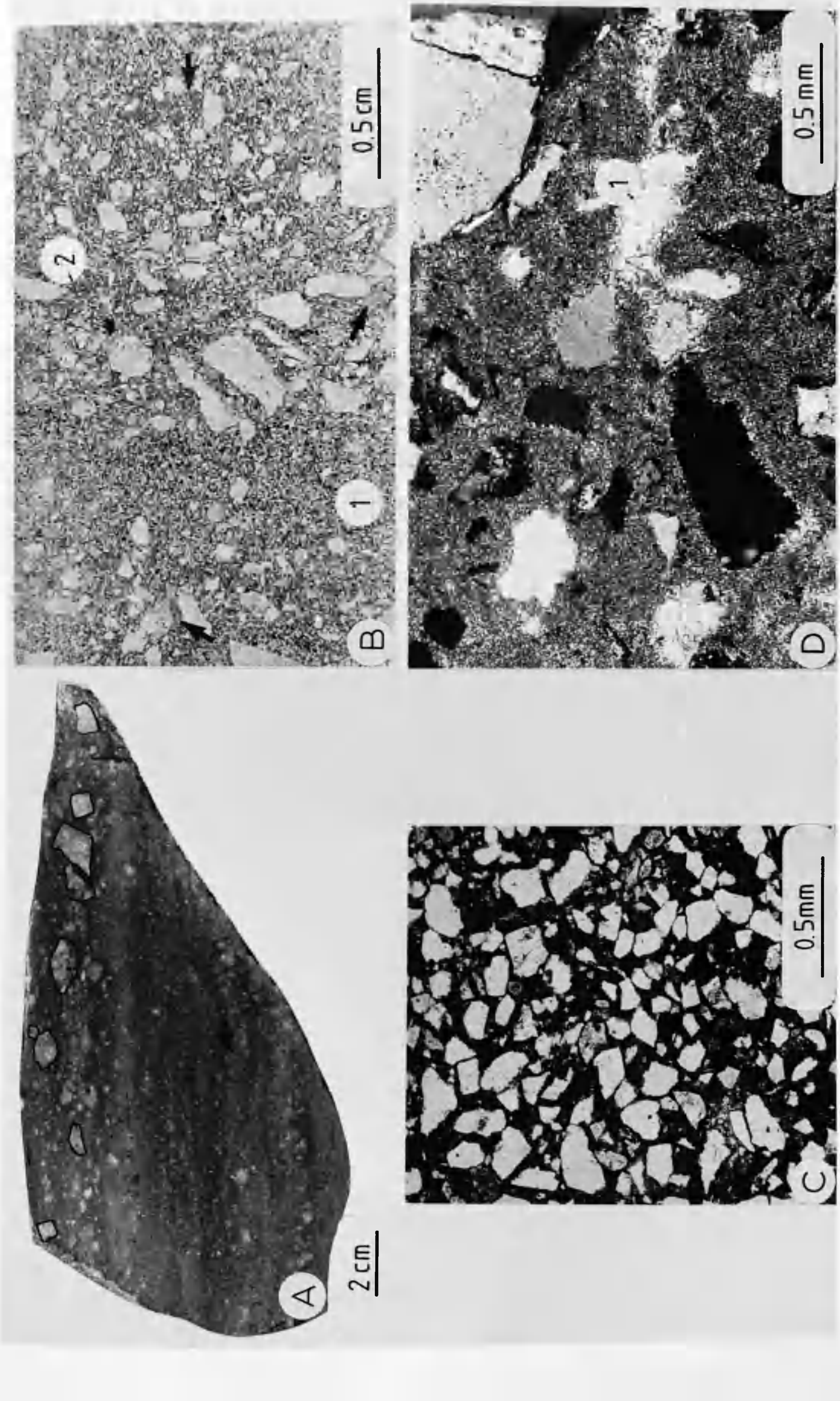
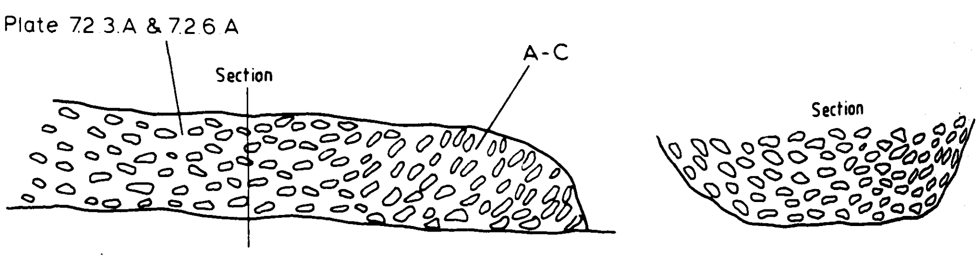
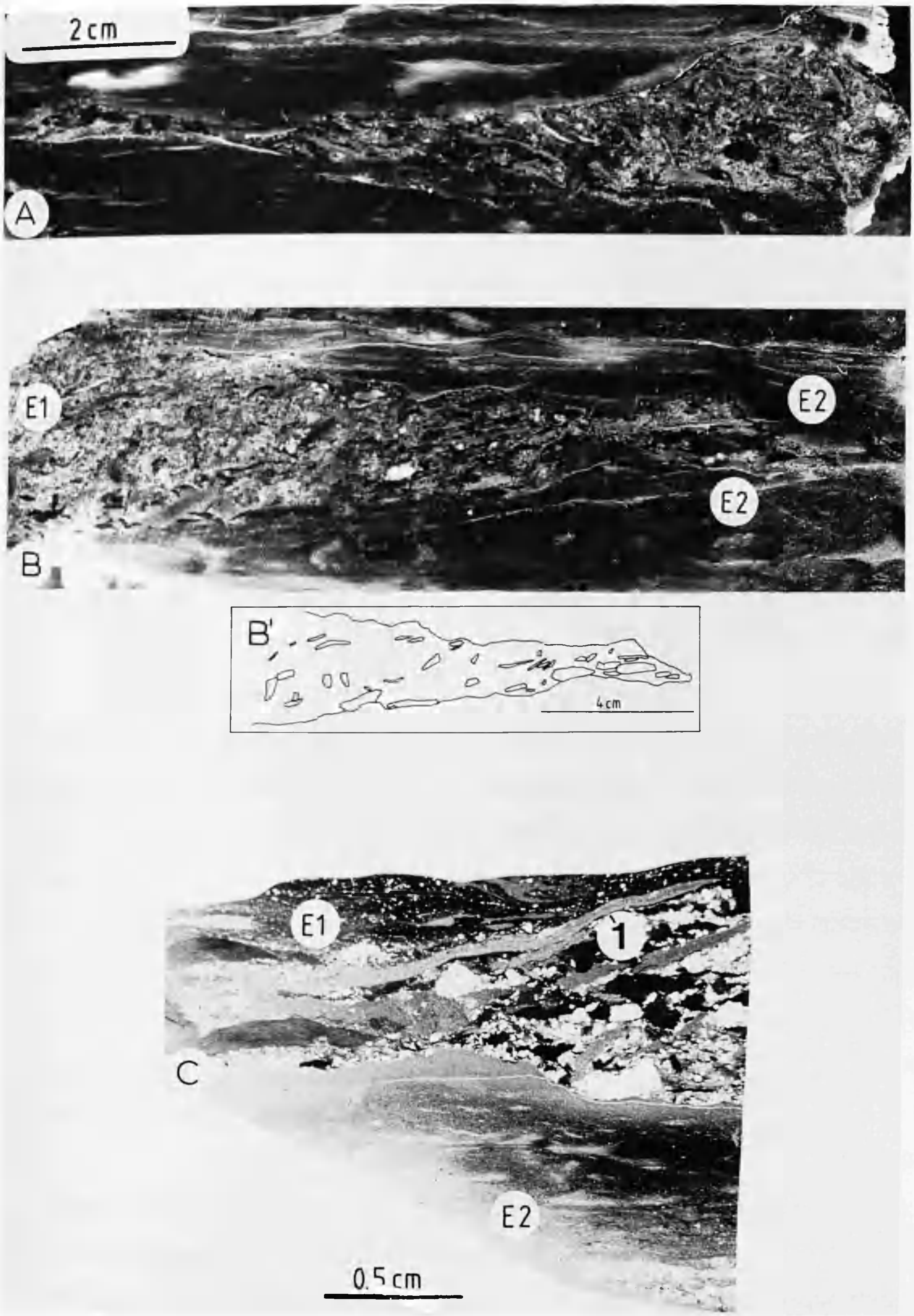


Figure 7.2.4. A & B: Photographs of polished sections from the same bed (approx. mirror images) showing snout terminus of a small debris flow (Facies E1, Bed 11a, Fig. 7.2.1.). The underlying and overlying mudstones belong to Facies E2. Note a preferential clast orientation in the debris flow bed. The diagram below (**B'**) accentuates the clast orientation in the section **B**; **A B:** Photographs of polished sections from the same bed (aprox. mirror images) showing snout terminus of a small debris flow bed (Facies E1, Bed 11a, Fig. 7.2.1.C). The underlying and overlying mudstones are Facies E2. Note a preferential clast orientation in the debris flow bed. The diagram below(**B'**) accentuates the clast orientation in the section **B**;

C: Close up photograph of thin section cut from the basal part from the Bed 11 (A & B). Some of the calcareous intraclasts show evidence of having been smeared out and torn apart during transport in the laminar flow regime. Note a subtle character of the shear lamination in the underlying deposits of Facies E2. (**1**) pseudo-lamination developed in the long, calcareous intraclast (see Plate 7.2.6.C).

The schematic diagram below shows a possible distribution of layer-parallel fabric and dipping "push-fabric" within a mass flow body.




2 cm
A
E1
E2
E2
B
B'
4cm
E1
1
C
E2
0.5 cm

depositional event or they are composite beds. The photographs B & C (Plate 7.2.2.) demonstrate the problem of interpretation of some of the more extensive, clast- or mud-rich streaks. Should they be identified with individual depositional events or still regarded only as smeared out early layers ? The present author favors the latter interpretation as the streaks and the phacoidal inclusions appear to be transitional to, and partly "remoulded" with the overlying and underlying deposits. Some of the very well defined beds display subboundaries, manifested by the shear-layering (Plate 7.2.3.A&B), and even in such, seemingly simple cases, there remains a question, whether these beds represent of single acts of deposition or are amalgamated units, though possibly formed during one major depositional event.

In the lower 3 m thick part of the Ceann Ousdale section, the pervasively shear-layered, pebbly mudstone "beds", 3 - 30 cm thick, are separated by shear-layered and parallel- and ripple-laminated mudstone interbeddings (Facies E2 & E3, Fig. 7.2.2.). Some of the bed boundaries have also been identified with continuous, flat parting planes. The upper part of the section consists of much thicker "beds", of over 100 cm in thickness. At Ceann Ousdale the only clear bed boundaries have been identified as the contacts of the beds of Facies E1 with the deposits of Facies E2 and E3. No definite bed boundaries are visible within the texturally and structurally monotonous beds of Facies E1 and it is thought that this is due to the welded nature of the contacts. Consequently, it is believed that most of the Facies E1 deposits are represented by amalgamated, composite beds. Such conclusion is also based on analyses of Facies E2 and F1 where the amalgamated nature of the beds is much more conspicuous (see chapters 7.2.6.1.2. & 7.2.6.1.7.). The minimum, true bed thickness might be as low as 0.8 cm (Plate 7.2.4.A, 7.2.6.).

Two, parallel polished sections from the Bed 2 (Plate 7.2.1.A&B) demonstrate that the problem of the identification of the bed boundaries applies also to clast-rich beds.

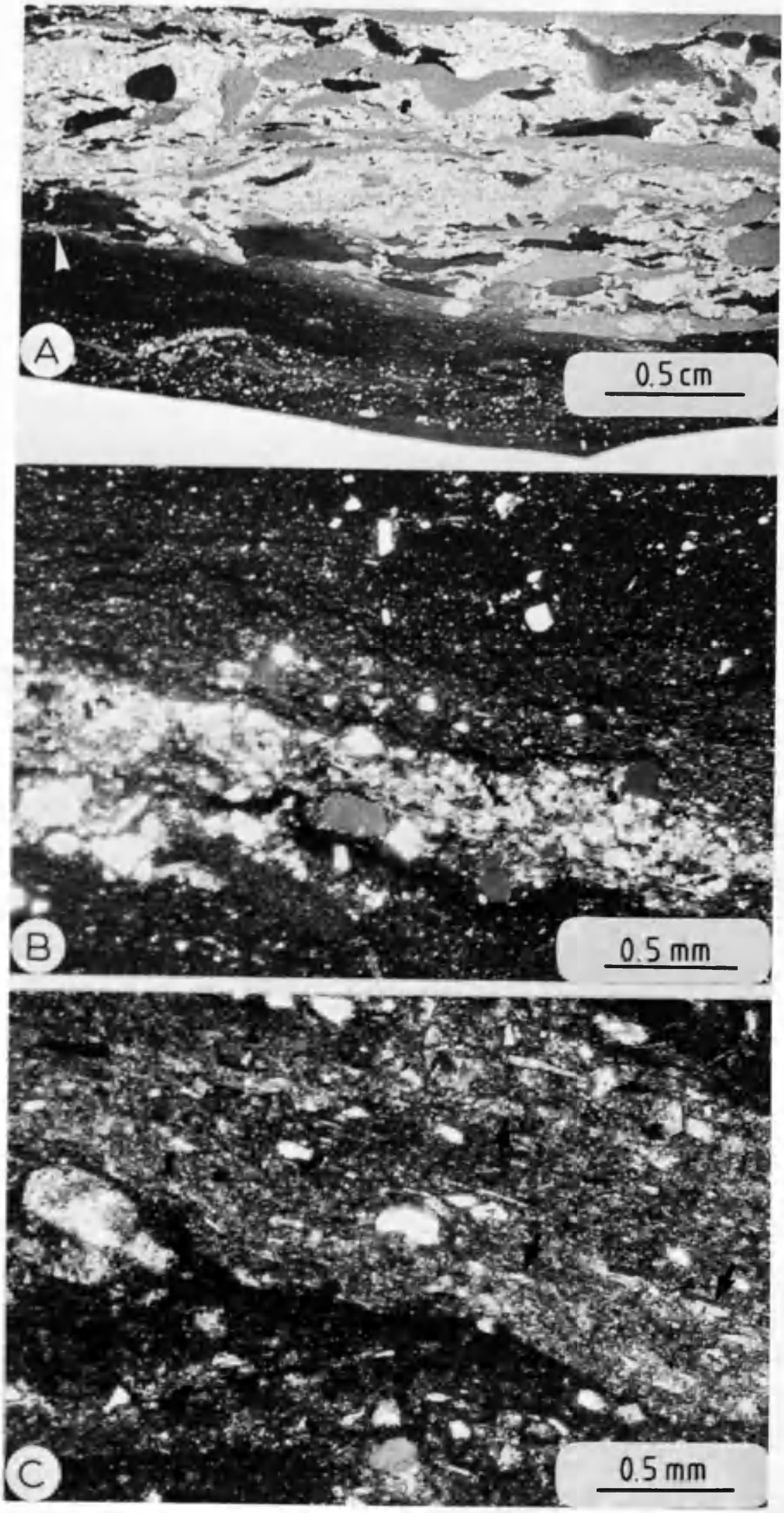
The recognized sharp, basal contacts of the beds of Facies E1 are planar to undulatory and either smooth or irregular. It is thought that some erosion of the underlying deposits was associated with the deposition of these beds (Fig. 7.2.3., Plate 7.2.1.A&D). In a few instances it seems that the finer-grained material at the base was partly incorporated by the overriding flow (Plate 7.2.1.A, Fig. 7.2.3.). A polished slab from Bed 4 (Plate 7.2.1.c)

Plate 7.2.6. A: Photograph of thin section. "micro-bed" of Facies E1 (mixture of arkosic extrabasinal detritus and intrabasinal material) underlain by the Facies E2 deposits dominated by the calcareous mud component. The shear-layering is visible in both beds. Single calcareous intraclasts in the Facies E1 bed are folded and the inferred dextral sense of shear is consistent with the inclination of the intraclasts. Note a good roundness of some of the mudstone intraclasts, achieved possibly by shear related abrasion during laminar flow transport (Bed 11, Fig. 7.2.1.C);

B: Close up photomicrograph of the arrowed area from the phot. A. Wispy, anastomosing clay streaks, wrapping around larger clasts may represent microstylolites;

C: Close up photomicrograph of the area (**1**) from the long, inclined intraclast from Fig. 7.2.4.C. Arrows point to elongate micrite and micro-sparr crystals and their aggregates oriented concordant with the inclination of the host intraclast, giving rise to pseudo-lamination. Orientation of the intraclast in the phot. **C** is opposite than in Fig. 7.2.4.C due to inverted print.

Plate 7.2.6.



reveals a presence of mudstone "flame structures". Load casts of the gravelly material in the finer-grained, mudstone interbeddings are common.

An interesting feature of Facies E1 is a relatively constant maximum particle size (0.5 - 2.5 cm) of the arkosic extraclastic detritus. In the Ceann Ousdale section, in all the examined deposits of Facies E1 the MPS is around 0.5 cm and there appears to be no relationship between the MPS and the bed thickness, though it is impossible to evaluate this statistically, as the bed boundaries are generally very poorly defined.

Although the streaks and phacoids are typically aligned parallel with the bedding, the arkosic, angular extraclasts normally show no obvious preferential orientation. Only in beds 11 & 11a (Plate 7.2.6.A & Fig. 7.2.4.) the intraclasts and the long extraclasts are consistently inclined against the point where the bed rapidly terminates. The termination has a snout-like shape. In the Bed nr.11 (Plate 7.2.6.A) single intraclasts are folded and the inferred sense of shear is consistent with the general clast orientation.

The mica flakes, similarly as the clay streaks, show locally a strong alignment (Plate 7.2.4.B.).

7.2.6.1.2. Facies E2: Massive and shear-layered mudstones and muddy sandstones

Deposits of Facies E2 dominate the Beinn Dhorain Member (BDM) and the following description is primarily based on data from Glen Sletdale section (Fig. 7.2.1.) and from exposures on the eastern slope of Beinn Dhorain (Plate 7.2.10.B), where the deposits in question are best exposed. The deposits of Facies E2 outcrop also in places on the eastern slope of Creag a' Chrionaich and in the stream section in Glen Loth just above the point of junction with Glen Sletdale [NH 935 131]. At the base of the BDM some of the Facies E2 deposits interbed with the muddy conglomerates and pebbly mudstones of Facies E1(Fig. 7.2.1.), but most of them appear higher up in the sequence. A small proportion of Facies E2 has been recognized in the Badbea basin (Ceann Ousdale section, Fig. 7.2.2.).

Similarly as in the case of Facies E1, cut and polished slabs, sampled from the measured sections, as well as thin sections, provided most of the data regarding textural and structural features of Facies E2.

Description

As has already been pointed out earlier in the chapter 7.2.6.1.1., the division between Facies E2 and E1 is arbitrary and Facies E2 is composed of over 80% dark-red mudstone and olive-green micritic/dismicritic calcite. The carbonate component is particularly abundant in the lower part of the succession of Facies E2, Fig. 7.2.1..

Extrabasinal, arkosic detritus (<20%) occurs mainly as silt to sand grade (occasionally as granules). The granules gradually disappear in the lower part of the BDM, with an increasing distance from the underlying, conglomeratic deposits of Facies E1 (Fig. 7.2.1.).

The mudstone component is predominantly represented by silty mudstones that contain > 80% mud fraction (> 40% silt) and 0 - 20% sand. Muddy sandstones containing 20 - 80% sand grade and < 80% mud grade (mostly silt), and mudstones - claystones with > 95% mud grade, < 40% silt and < 5% sand and coarser (mostly very fine-grained sand), are subordinate.

Plate 7.2.7. A-C: Muddy sandstones of Facies E2.

A & B: Shear-layering in muddy sandstones. Note a primary lamination, preserved in the sandy phacoidal intraclast (arrowed in phot. **A**);

B: Cavities, possibly representing air bubbles trapped by the depositing mudflow;

C: Swirled sandy inclusions (*whirl balls* (Dzulynski & Watson, 1965)) and shear-layering at the base;

D: Close up photomicrograph of the *whirl* feature (PPL).

(Locality: **A-D** - Beinn Dhorain [NH 935 127], BDM)

Plate 7.2.7.

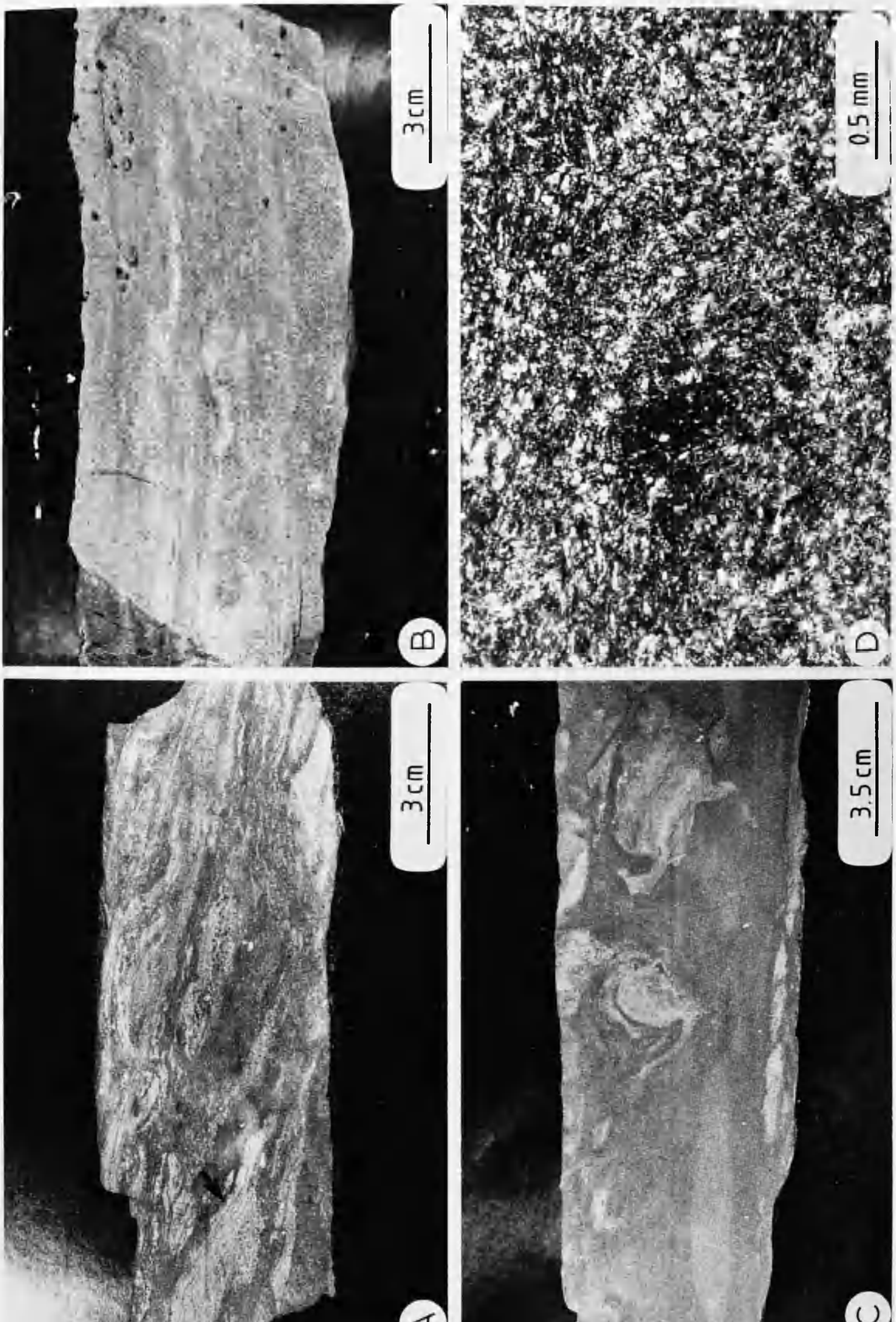


Plate 7.2.8. A-C: Facies E2.

A: The bedding is normally very well pronounced by discontinuous parting planes. The beds are amalgamated units. Ruler is 50 cm long;

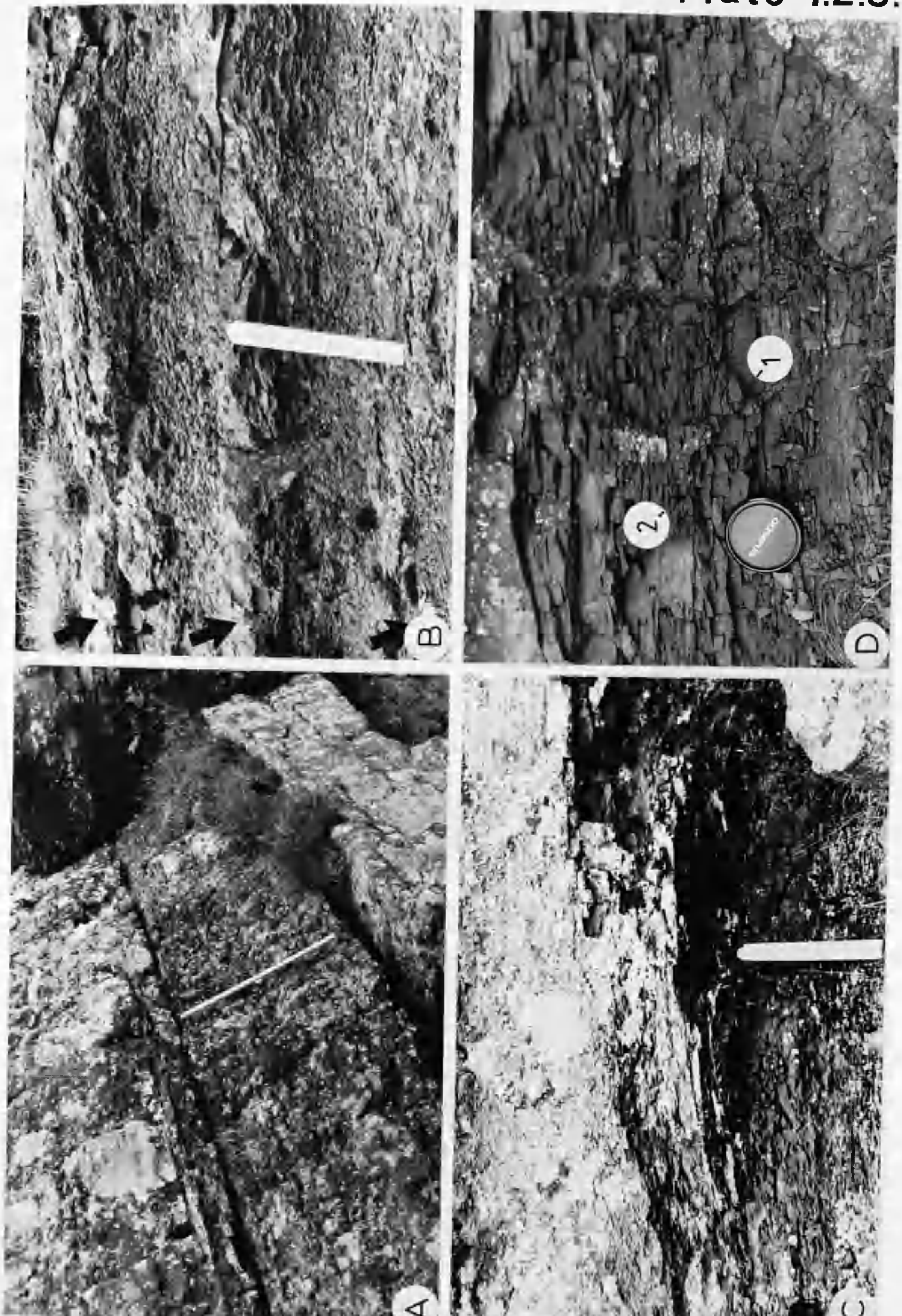
B: The bedding is again well defined through interbeddings of mudstones (fine fissility) and muddy sandstones(larger scale, blocky fissilty). Note "fused" contacts between the lithologically different beds. Ruler is 25 cm long;

C: Gradational contact between the structureless mudstones and mudy sandstones. The latter deposits closely resemble Facies F1 (Bed 23, Fig. 7.2.8.);

D: Close up photograph of the structureless mudstone/claystone deposits of Facies E2. Variability in fissility reflects the textural heterogeneity of the mud flow deposits: (**1**) muddy sandstone area, (**2**) claystone area. Lense cap is 5 cm wide.

(Locality: **A-D** - Beinn Dhorain, BDM)

Plate 7.2.8.



The presence of streaks and phacoids, displaying a variety of composition, grain sizes and sorting, and whose size ranges from over 10 cm to a few mm gives rise to a grain-size distribution and texture in the Facies E2 deposits is typically non-uniform and "patchy". In most cases the phacoids are partly "remoulded" with the surrounding material, and therefore their boundaries are diffuse, and rather poorly defined in the exposures. A few centimeters large inclusions of fine- and medium-grained sand and calcareous intraclasts of a similar size are well identifiable in the field only in the muddy sandstones (Plate 7.2.7.) and in the Bed 7/8 (Plate 7.2.9.). Thin sections from any category of Facies E2 deposits reveal clearly the smallest scale inclusions and their remoulded margins (Fig. 7.2.6., 7.2.9., 7.2.11., 7.2.12.).

A variability in fissility of the sediments allows recognition of the presence and a nature of such an textural heterogeneity, especially when it occurs on a larger scale. The muddy sandstones display a distinctive "blocky" pattern of fissility, whereas the weathering mudstones produce much finer-scale blocky type of fissility (Plate 7.2.8.B&D). The claystones display a fine, subtle fissility, trending subparallel to the bedding and characterized by a conchoidal fracture. All the sediments in question split indefinitely and the splitting planes have not been found to correspond to alignment of mica flakes. However, fine conchoidal fracture in the claystones is thought to be due to a preferential, parallel to the bedding alignment of clay particles, caused by compaction (Collinson & Thompson, 1982). The fine scale fissility may also be controlled by the shear-layering though significance of the latter factor is difficult to demonstrate and distinguish from the role played by the compaction-related alignment of the clay particles.

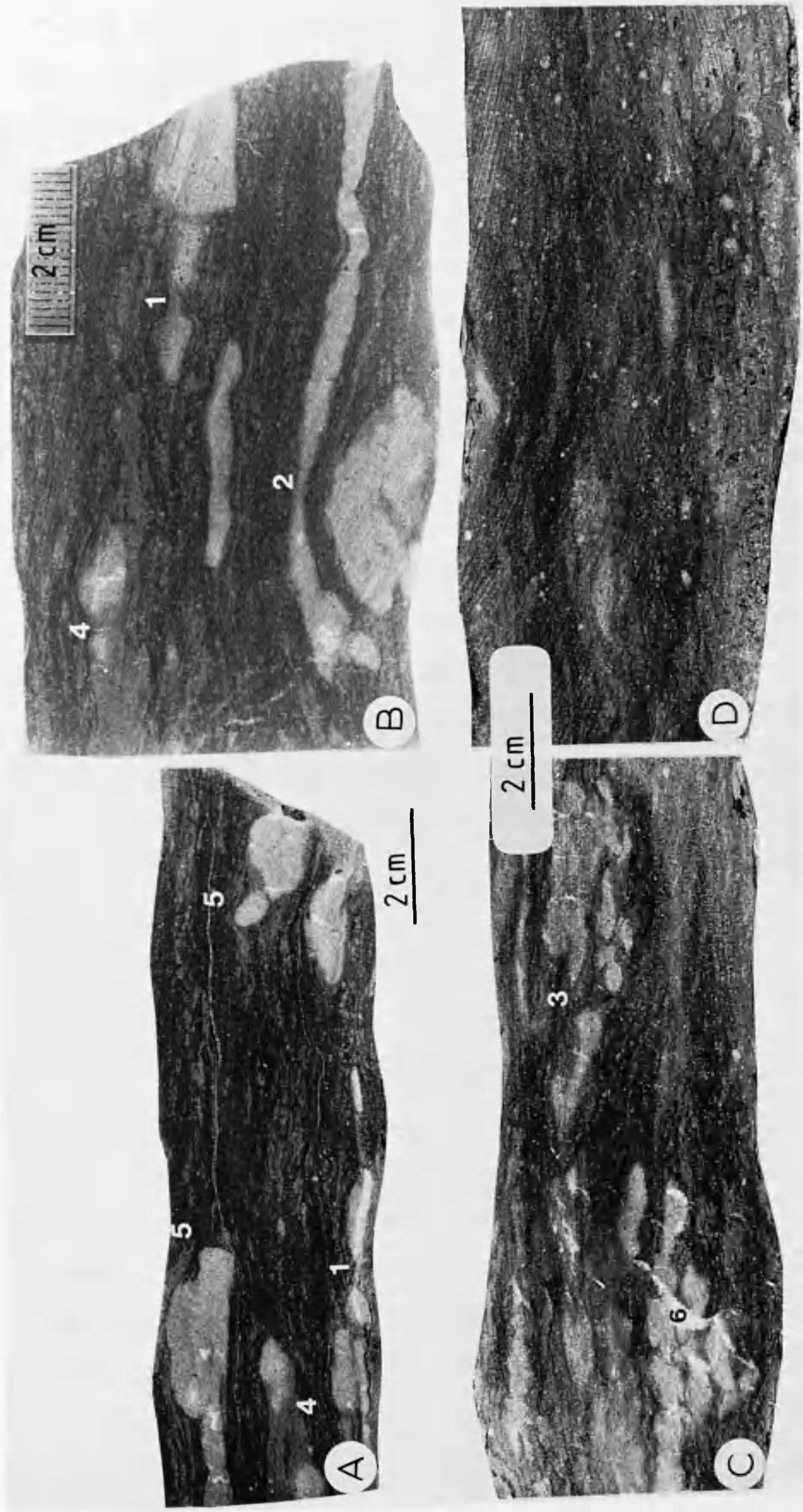
Clay material occurs in similar two forms as described for Facies E1(see the previous chapter). In the carbonate or mudstone material the opaque to dark-red clay may appear also as oblate, irregular patches and concentrations (Fig. 7.2.9. & Plate 7.2.13., 7.2.14.). Proportion of clay varies considerably within these features. The oblate clay concentrations are normally elongated parallel to the bedding and appear to be marginally mixed with the surrounding sediment. The latter form of clay is present only in the moderately to strongly remoulded deposits. Compositionally the analised clay fraction is identical as in the matrix of the Facies E1 deposits. Similar material fills also cracks, that cut highly calcareous

Plate 7.2.9. A-D: Calcareous mudstones and pebbly mudstones of Facies E2. The pebbly mudstones are transitional to the deposits of Facies E1. Photographs of polished slabs showing features of shear-layering developed in the Bed 7/8, Fig. 7.2.1.C.

A-C: Carbonate-rich intraclasts display a considerable diversity of shapes. Some are quite angular to very well rounded. (**1**) boudinage affecting the carbonate-rich primary layer; (**2**) necking; (**3**) clusters of the carbonate-rich intraclasts "linked" by the carbonate-depleted material. The latter appears typically as jagged streaks and wisps, occasionally forming asymmetric "tails" behind the intraclasts (**4**) or wrapping around them(**5**); (**6**) sparry calcite oblique veining;

D: The rock is dominated by the shear-layered, carbonate-depleted material, which is thought to be a result of layer-parallel extension related shearing, smearing out and remoulding of the carbonate-rich intraclasts with the muddy, carbonate-free material and arkosic detritus. The latter component is uniformly dispersed in the sediment.

Plate 7.2.9.



varieties of Facies E2 (see further in this chapter).

The carbonate constituent is particularly abundant in the lower part of the BDM succession (Fig. 7.2.1.). It is represented by a micritic and dismicritic calcite. Sparry calcite appears both as a product of neomorphic transformation of micrite (Fig. 7.2.9.B & Plate 7.2.5.9.) and probably also às a cement. Proportion of the sparry calcite typically increases with an increasing amount of the extraclasts. In micritic carbonates that contain no extraclasts the sparrite appears in deformed portions of the sediments as "bird's eye" structures (Fig. 7.2.9.B & Plate 7.2.13.A).

The carbonate component has been found mainly to be in a allochtonous position, that is detached from the area of the primary deposition. It occurs either as intraclasts of up to 8 cm in size or as a remoulded sediment (Fig.7.2.9., 7.2.11., 7.2.12.). In the latter case there is usually a certain proportion of clay to granule grade extra- or intraclasts, introduced during the remoulding. Some of the carbonate intraclasts have been found to reveal an original parallel lamination (Fig. 7.2.9. & Plate 7.2.13.).

Silty mudstones and muddy sandstones contain chaotically distributed small cavities, which might be entirely or partly filled with calcite (Fig. 7.2.8. & Plate 7.2.7.B). They are irregular in form, though generally spherical and some of them appear to by moderately flattened parallel to the bedding. In the muddy sandstones the cavities are particularly abundant and largest, up to 1.2 cm in diameter. In the silty mudstone horizons they are only a few millimeter in size and much less numerous. The cavities are absent in the claystones.

The deposits the Facies E2 deposits commonly display shear-layering and shear-lamination. The structures are analogous to the features described in the previous chapter(Facies E1), though in the case considered here, they are developed in a much wider variety of sediments and thus geometry and scale of the structures vary correspondingly. Structureless, massive deposits are subordinate.

While the Facies E1 deposits are characterized mainly by the medium scale shear-layering, the Facies E2 mudstones are dominated by the small scale structures - shear-lamination.

The medium scale shear-layered(max. thickness of inclusions is 5 - 0.5 cm) deposits of Facies E2 have been recognized only in a few muddy sandstone horizons (Plate 7.2.7.A&B) and in the Bed 7/8 (Plate 7.2.9.), which is calcareous silty mudstone with 1 - 3% of extrabasinal arkosic granules.

In the muddy sandstones, appearing in beds approximately 10 - 53 cm thick, the intraclasts are represented by very fine- to medium-grained sandstones. The intraclasts have a lenticular, jagged outline and are up to 1.5 cm thick and more than 8 cm long. They are set in silty mudstone matrix and are stretched and smeared out parallel and subparallel to the bedding. In spite of the advanced deformation and remoulding, some of the intraclasts show an original lamination. Occasionally, the shear-layered deposits are in contact with horizons in which the intraclasts have an irregular, though generally spherical, form and seem to have been "swirled" rather than smeared out at some stage during the sedimentation (*whirl balls* in Dzulynski *et al.*, 1957; Dzulynski & Walton, 1965)(Plate 7.2.7.C).

The Bed 7/8 (Plate 7.2.9. & Fig. 7.2.14.) is 53 cm thick and is shear-layered throughout. Thickness of the largest intraclasts increases from 0.5 cm in the lower part of the bed to 1.5 cm at the top. The extraclastic granules are most abundant in the lower portion of the bed. The carbonate-rich intraclasts are composed in around 15% of sand and silt, 15% of clay and in 75% of dismicrite. They display a diversity of form, though they are generally disc-shaped and oriented parallel with the bedding. Some of the intraclasts have partly subangular to angular contours and some have been found to be well rounded and roughly spherical in shape. Many of the intraclasts have a form of boudinage as they appear to have been stretched out and torn apart. The intraclasts occur either isolated or clustered into two or more. The clusters typically consist of a few carbonate-rich intraclasts "linked" by the silty mudstone material which contains a much higher, than the intraclasts, proportion of clay, silt and sand and a considerably reduced carbonate content. The sediment depleted in the carbonate is clearly visible as a darker material, being somewhat transitional between the carbonate-rich(white intraclasts) and the carbonate-free darkest background. It either forms asymmetric "tails" behind the intraclasts or occurs as 3 - 1 mm thick, jagged streaks that are normally parallel to the bedding but occasionally they wrap around the intraclasts (Fig. 7.2.10.A&A'). The shape of these carbonate-depleted streaks is clearly different from the carbonate-rich intraclasts, though there is a continuum between

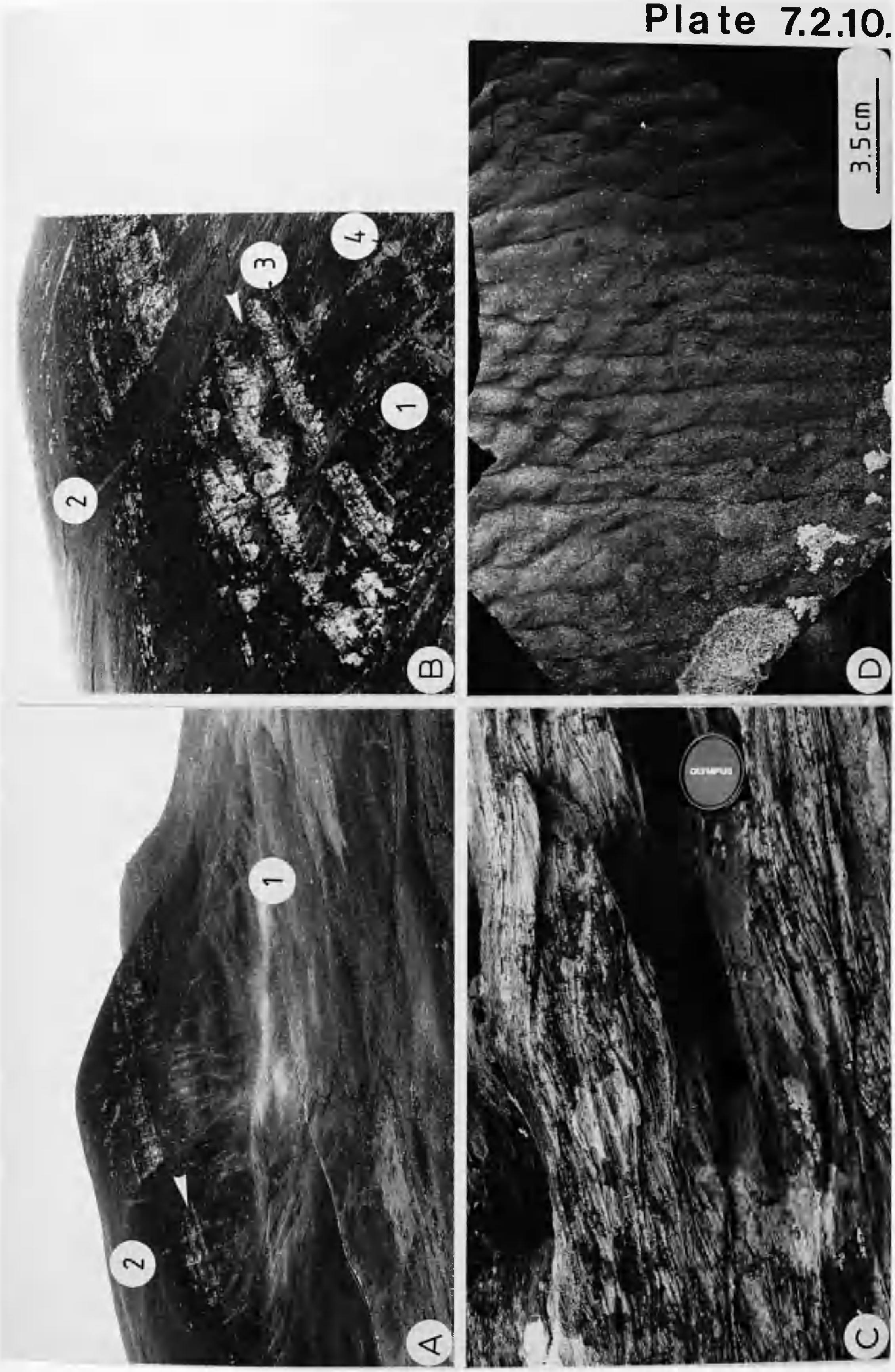
Plate 7.2.10. A: Photograph of the eastern face of Beinn Dhorain with the exposed section of the upper part of the Beinn Dhorain Member (BDM), dominated by the deposits of Facies E2 and E3 (**1**), and lower part of the Ben Uarie Member (BUM), composed of Facies F1 and F2 (**2**). The arrow shows the boundary between the two members (see also B for close up). Faults are marked. Ben Uarie in the background;

B: Close up from the phot. **A**. (**1**) BDM (**2**) BUM (**3**) sheet-like, laterally extensive sets of the current ripple cross-laminated beds (Facies E3) (see **C** below); (**4**) note a distinctive sheet-like attitude of the mudflow deposits (Facies E2);

C: Current ripple cross-laminated fine-grained muddy sandstone from the horizon marked on the phot. **3**. Note locally developed climbing ripples;

D: Wave interference ripples from the Bed 23, Fig. 7.2.8..

Plate 7.2.10.



them.

Examinations of the carbonate-rich inclusions from the Bed 7/8 under cathodoluminescence microscope have reveled no particular "stratigraphy" or zoning (Fig. 7.2.10.B). Muscovite mica flakes have been found in places to be strongly aligned parallel to the margins of the intraclasts, though the dominant, surrounding silty mudstone material generally shows no preferential mica orientation.

The small scale shear-lamination(maximum thickness of inclusions < 0.5 cm) Fig. 7.2.4., 7.2.11.B, 7.2.12.) seem to characterize a majority of the Facies E2 deposits, though reliable observations have been somewhat limited as the structure is normally best recognizable only on polished slabs and on thin sections. The structure has been recorded only from the calcareous sediments that is pure limestones, calcareous silty mudstones, siltstones and subordinately from calcareous very fine-grained sandstones. The phacoidal inclusions(intraclasts) have an analogous composition and occur both, as strongly remoulded with the matrix, having rather poorly defined margins, and as well defined forms in spite of some recognizable mixing with the background. They are normally strongly aligned parallel to the bedding. In the thinest recorded (0.3 cm thick) horizon, the shear-lamination wraps around the elevations of underlying, deformed carbonate laminae (Fig. 7.2.9.A-A').

The minimum recorded thickness of beds (or horizons) with the shear-lamination is 1.5 cm. The maximum thickness is unknown, though basing on the examinations of the polished slabs, it is thought to be more than 10 cm.

Although the Facies E2 deposits are well bedded, individual, generally sheet-like beds, are never clearly defined (Plate 7.2.8.). The bedding is pronounced by presence of well defined beds of parallel- to ripple-laminated deposits of Facies E3, by variations in grain size within Facies E2 (fissility) and by discontinuous parting planes.

While bed boundaries of Facies E3 are sharp and very well defined (chapter 7.2.6.1.3.), this is never the case with regard to the deposits of Facies E2. The grain-size changes, when occur, are gradational and a position of the actual contacts between the beds is uncertain (Plate 7.2.8.B). Discontinuous parting planes are strongly developed in some of the Facies E2 horizons, though they have been found to be unrelated to any significant

Plate 7.2.11. A, C &D: Mudstones of Facies E2 affected by cracks and brecciation. This "brittle" form of deformation is interpreted as a result of the secondary downslope, gravity driven creep of the partly lithified calcareous mudflow deposits.

A: View of the planar bed plane shows a complex pattern of cracks which is incompatible with a relatively regular geometry of desiccation cracks (phot. **B**);

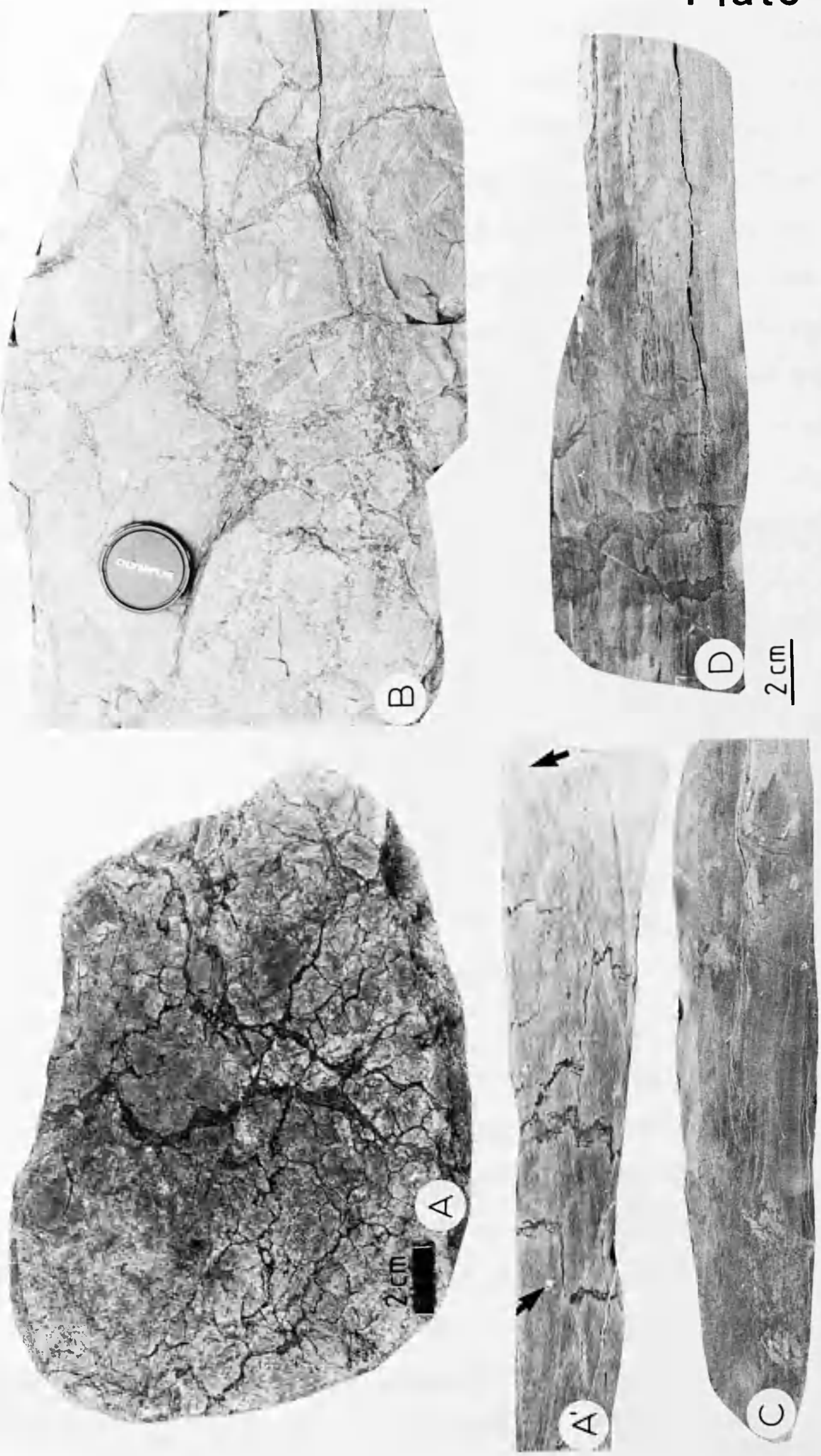
A': View of the section normal to the bedding plane. Some of the cracks have horizontal orientation over a certain distance. Note single scattered arkosic granules (arrowed);

C: Another view of the vertical section shows cracking and brecciation developed predominantly in the calcareous(bright) portion of the mudstone;

D: Section normal to the bedding plane shows an overlap of two generations of cracks indicating reactivation of mass flowage and bracciation.

(Samples **A, C & D** come from Glen Seltdale section)

Plate 7.2.11.



structural are textural features in the deposits. The parting planes are associated with the blocky fracture and typically pass laterally into completely massive portions of the deposits.

Thin, inpersistent laminated intercalations of Facies E3, occurring occasionally within the structurally and texturally monotonous Facies E2 deposits, clearly suggest their amalgamated nature. The Bed 7/8, having a unique composition and structure (Plate 7.2.9.), is atypically well defined among the surrounding sediments, and it is tempting to regard it as a product of a single depositional event. However, in the light of the overall characteristics of Facies E2, it is difficult to reject a scepticism and not to suspect even this bed of being a composite unit, especially when the minimum bed thickness, determined from the thin sections and from examination of the polished slabs is 1.5 cm. The present author believes that individual sedimentary episodes, produced beds not much thicker than 10 cm.

In the upper part of the BDM (Fig. 7.2.8.B) a several horizons with desiccation are present (Plate 7.2.11.B).

Pseudo-lamination

An interesting feature of the calcareous deposits of Facies E1, E2 and E3(parallel-laminated variety) is a discontinuous, anastomosing subtle pseudo-lamination (or veinlets), made up of calcite micrite and subordinately of micro-spar (Plate 7.2.12.A-C, Fig. 7.2.11.C & 7.2.15.). The pseudo-lamination is generally concordant with the bedding, but occasionally the veinlets have been found running obliquely to the bedding at the angle of up to 40 degrees. The crystals of the micrite and the micro-spar are elongated subparallel to the orientation of the host pseudo-laminae or form elongate aggregates (Plate 7.2.6.C & Fig. 7.2.4.C). Locally the micrite particles are aggregated into distinctive sigmoidal forms (Fig. 7.2.11.C & 7.2.15). Note, that micrite particles, making up the parallel-laminated limestones(Facies E3) show no such elongation or aggregate arrangement (Plate 7.2.13.B&C).

The veinlets branch locally, forming sigmoidal or rhomb-shape patterns (Fig. 7.2.15.C). Cathodoluminescence examinations of these features reveal secondary sigmoidal openings, sealed with a new generation of calcite.

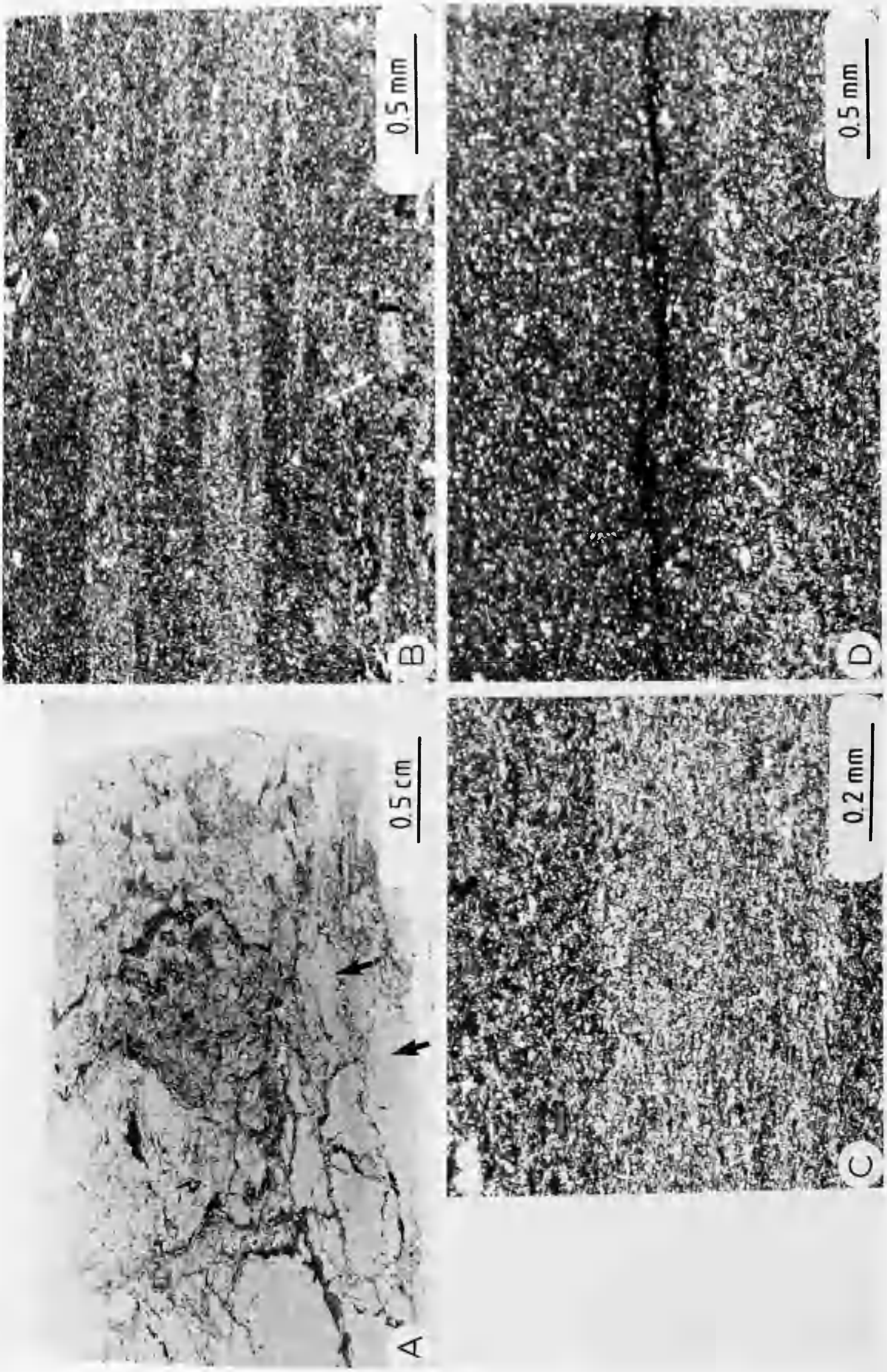
Plate 7.2.12. A: Photograph of thin section from Bed 15, Fig. 7.2.1.C. Brecciated fragment of Facies E2. Arrows points to the areas with faint pseudo-lamination, developed in the calcareous mudstones (Facies E2) in result of recrysallisation of micrite under conditions of simple shear stress. The pseudo-lamination is post-dated by the cracking and the brecciation. Note that the latter deformation has led in places to a considerable remoulding of the affected sediments;

B: Close up microphotograph of the pseudo-lamination arrowed on phot. **A**. Note a discontinuous and anastomosing nature of the structure (XPL);

C: Close up of the pseudo-laminae from phot. B. Note layer-parallel elongation of the micrite crystals and their aggregates (XPL) (see Plate 7.2.13.B & C for comparison with the true lamination of Facies E3);

D: *En echelon*, clay-sealed cracks in calcareous mudstone of Facies E2 possibly represent gaps and fissures created mainly due to excess pore water pressure, generated locally during lateral compression at the incipient creep movement (Schwartz, 1982).

Plate 7.2.12.



The pseudo-laminae have been locally found following closely the early true laminations (Fig. 7.2.11.C), wrapping around the extraclasts but never cutting them. In the clay rich host deposits the calcite crystals are considerably stained with iron-oxide. In one instance, in the Bed11a (Facies E1, Plate 7.2.6.C), the pseudo-lamination has been found to be restricted to a long, calcareous intraclast, closely following its orientation (Plate 7.2.6.C).

Thickness of the individual pseudo-laminae can be as small as the minimum size of micrite crystal.

Brecciation

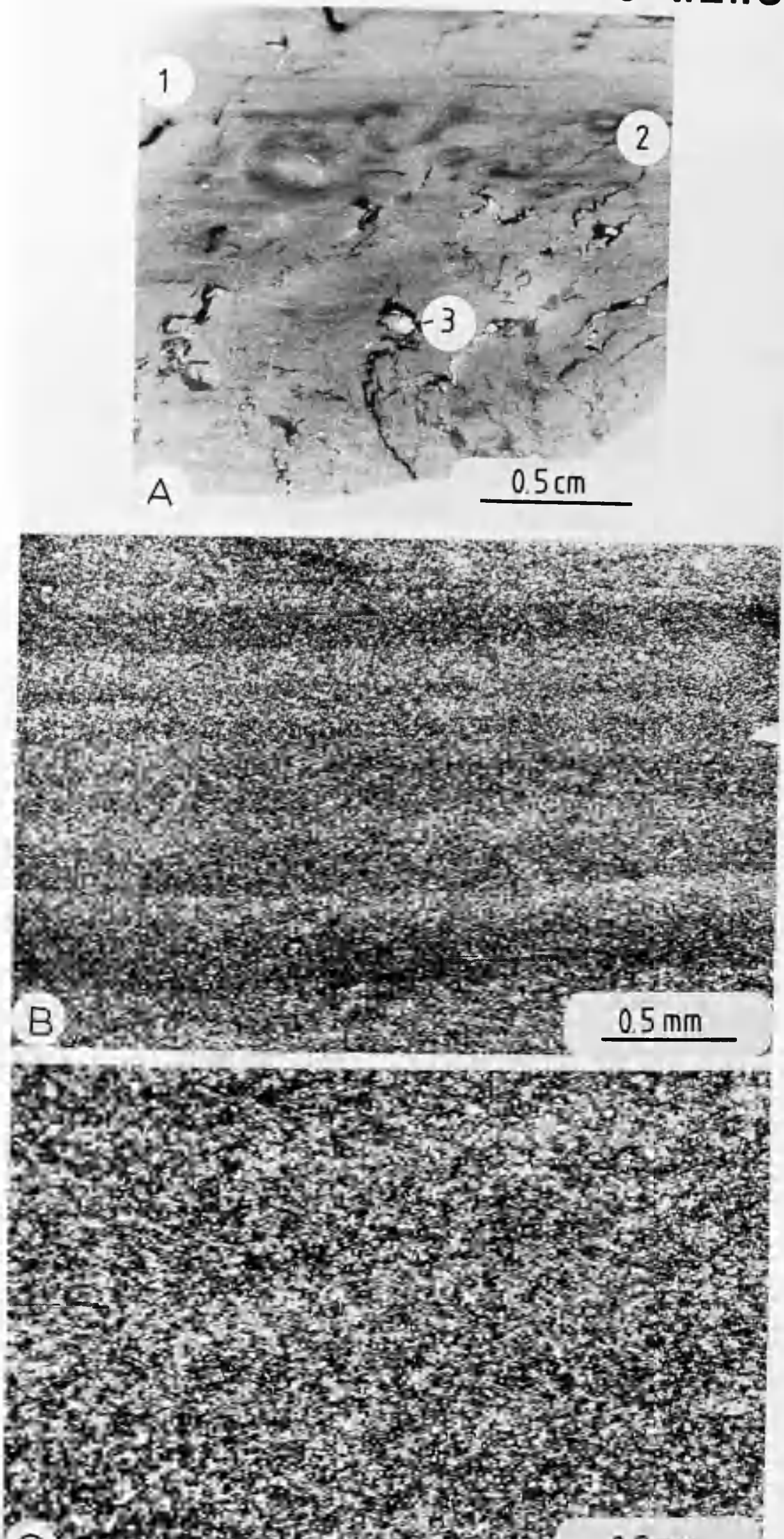
The calcareous varieties of the Facies E2 and E3 are commonly found showing a complex pattern of cracks which postdate the described above pseudo-lamination (Plate 7.2.11. & 7.2.12.A-C). They may occur in horizons as thin as a few centimeters, being overlaid by deposits unaffected by the cracks (Fig. 7.2.11.A&A'). The cracking often passes into strongly brecciated areas (Plate 7.2.12.A). Geometry of the cracks, their scale and distribution are incompatible with the features that characterise desiccation cracks. The cracks being described here have an anastomosing pattern in sections parallel and normal to the bedding, with no polygons developed (Plate 7.2.11.A). In the vertical sections the cracks show often a very similar pattern and they generally display no particular orientation (Plate 7.2.11.A', C&D). However, in places they appear running parallel to the bedding, being occasionally arranged in *en echelon* systems (Plate 7.2.12.). The horizontal cracks are either isolated or connected with the oblique/vertical cracks.

The width of the cracks is up to 2 cm. They are filled with a mixture of the material which has collapsed from the walls of the cracks and dark-red to opaque clay. The small cracks appear to be filled only with haematite-stained clay. In carbonate sediments the cracks, have been found occasionally filled in the center by sparry calcite ("bird's eye" structures) (Plate 7.2.13.A) and the cracks frequently display forms, which are somewhat transitional to oblate patches of concentrated dark clay mixed with micrite.

Unlike the desiccation mud cracks, the features described above are confined in their occurrence to the calcareous mudstones/claystones and limestones.

Plate 7.2.13. A: Photograph of thin section, taken from carbonate intraclast (PPL). **(1)** locally preserved parallel lamination in micrite (Facies E3); **(2)** structureless, remoulded carbonate, enriched in clay which concentrated as insoluble residue in the post-remoulding available pore spaces in a form of oblate patches or fillings of the cracks; **(3)** some of the remaining cavities are sealed centrally by sparry calcite ("bird's eye" structure);
B: Close up photomicrograph of the parallel-laminated micrite from the phot. **A** (XPL);
C: Close up of one of the laminae from phot. **B**. demonstrates uniform dimensions of micrite particles (XPL). (Locality: Glen Sletdale section [NH 935 127], BDM)

Plate 7.2.13.



7.2.6.1.3. Facies E3: Ripple cross-laminated and parallel-laminated sandstones and mudstones

Deposits of Facies E3 are particularly abundant in the uppermost part of the Beinn Dhorain Member, where they occur in association with the mudstones of Facies E2 (Fig. 7.2.8.). The lower part of the sequence contains a very small proportion of parallel-laminated sediments (Fig. 7.2.1.). At Ceann Ousdale (Badbea basin) Facies E3 appears in association with the pebbly mudstones of Facies E1 (Fig. 7.2.2.).

Description

The Facies E3 deposits form very well defined beds by the contrast with the massive and structureless on the surface mudstones of Facies E2.

The ripple cross-laminated beds, that make up to around 92% of Facies E3, are represented by sediments ranging from very fine grained sandstones to muddy siltstones. Geometry of the cross lamination clearly indicates that the structure is a product of migration of unidirectional current ripples (Plate 7.2.10.B&C). In fact orientation of the cross laminae has a strongly unimodal distribution (Fig. 7.2.21.). A climbing, ripple cross-lamination is locally developed with either erosional surfaces between the sets or with preserved stoss-side laminae. Thickness of sets varies from 0.5 - 5 cm and averages 1.9 cm. Set forms have been found, preserved in Bed 22, (Fig. 7.2.8.) and they are 3 - 3.5 cm thick. Muddy sediments occur often as thin laminae which drape ripple forms, producing a flaser lamination. In Facies E2 Bed 23 (Fig. 7.2.8.B) a thin, discontinuous horizon have been found, which shows a positive of wave interference ripples (Plate 7.2.10.D).

The ripple cross-laminated beds of Facies E3 are very well defined beds and a form of parallel-sided, erosionally or non-erosionally based sheets (Plate 7.2.10.B). Muddy intraclasts occasionally appear right above the erosional bases. Bed thickness ranges from 1.5 - 66.5 cm, averaging 11 cm, and the data display a log-normal number frequency distribution (Fig. 7.2.13.). Lateral continuity of the beds (or sets of beds) increases with their increasing thickness. In the section oblique to the inferred local palaeotransport, the sets of current ripple cross-laminated beds have been found continuous for over 50 m

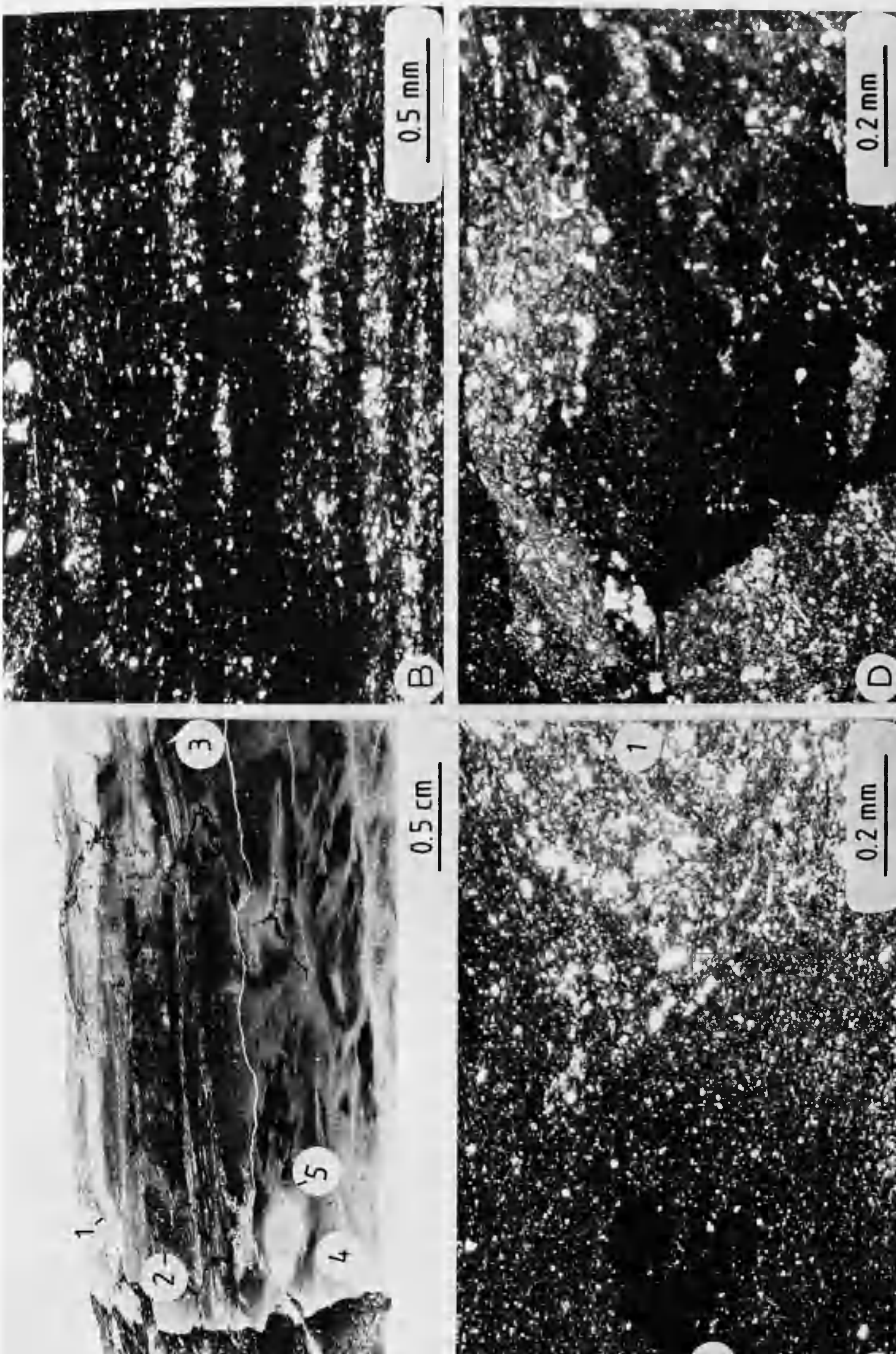
Plate 7.2.14. **A**: Photomicrograph of thin section from the Bed 19, Fig. 7.2.1.C (PPL): (**1**) moderately deformed calcareous silty laminae; the darker laminae below consists mainly of micrite (some clay and fine/very fine silt); (**2**) sediment in this horizon has been considerably remoulded and clay-enriched; the primary lamination has been almost completely destroyed; (**3**) horizon where the primary parallel lamination has been disrupted (see phot. **B**); (**4**) totally remoulded shear-layered sediments; the dominant, bright material is micrite (some clay and fine/very fine silt); (**5**) oblate calcareous silt intraclast (see the phot. **C** for close up);

B: Close up photomicrograph of the parallel lamination (Facies E3) from the horizon **3**, phot. **A** (PPL). The lamination has only been moderately disrupted; the coarser, bright laminae consist of medium silt and micrite; the darker, finer-grained laminae are made up of fine silt and a mixture of clay, organic matter and micrite;

C: Close up photomicrograph of the area (**5**), phot. A (XPL); (**1**) calcareous silt intraclast partly remoulded with the background; (**2**) haematite-stained clay patch appears to be partly remoulded with surrounding sediment; the latter feature, however, is seen as a secondary clay (insoluble residue) sealing the available pore spaces in the remoulded, carbonate-rich sediments;

D: Close up of the crack infill from phot.**A** consisting of collapsed fragments and insoluble clay residue (opaque matter).

Plate 7.2.14.



(Plate 7.2.10.B). The thinnest beds appear as discontinuous interbeddings within the generally finer grained deposits of Facies E2 and, in case of the Ceann Ousdale sequence, within the considerably coarser-grained pebbly mudstones (Fig. 7.2.2.).

The ripple cross-laminated beds of Facies E3 show very seldom any significant vertical trends in the grain-size distribution. If such an coarsening- or fining-upwards does occur, it is restricted to the uppermost portions of the beds.

The **parallel-laminated variety of Facies E3** forms an insignificant proportion of the Glen Loth sequence and makes up as little as 8.6% of the total of the deposits of Facies E3. It is slightly more abundant in the lower part of the Ceann Ousdale section (Fig. 7.2.2.).

The lamination appears to be developed in two forms:

1) lamination developed in clastic material and manifested by interlamination of clay, silt and very fine sand;

2) lamination manifested by carbonate and clay/organic laminae.

While the both types of the parallel lamination have been recorded from the Glen Loth sequence, the Ceann Ousdale section contains only the first, "clastic" type of the lamination.

The parallel-laminated beds range from 0.5 - 7.0 cm in thickness, with an average 3.3 cm (Fig. 7.2.13.), and are generally very discontinuous.

In the clastic variety of the parallel lamination the coarsest(coarse silt to very fine sand), grayish laminae are generally thicker (0.5 - 0.1 cm). Thickness of the clay to medium silt, dark-brown laminae ranges from 0.3 - 0.1 cm. Basal boundaries of the coarser laminae are sharp, whereas the finer-grained once often occur either in a gradational relationship with the former or have sharply outlined boundaries.

The carbonate-rich parallel lamination is basically represented by two main components. The carbonate(micrite/dismicrite) laminae, are olive-greenish and regardless of the proportion of the extraclastic and intraclastic silt and clay, which can be as high as 50%(calcareaous silt), their thickness ranges from 0.25 - 0.004 mm (Fig. 7.2.11.B&C, Plate 7.2.13.A & 7.2.14A&B). Rapid pinch-outs of the laminae are common. The silty mud to clay/organic laminae have a similar thickness range and are dark-brown to opaque. The carbonate-rich latter structure strongly resembles the parallel lamination which is common in the Achanarras lacustrine sequences (Donovan, 1971; Donovan, *et al.*, 1974; Trevin, 1986).

As has been mentioned above the parallel-laminated deposits are negligible in the Beinn Dhorain Member and in all the examined occurrences the laminations have been found considerably deformed by loading of the overlying sediments as well as by shearing, boudinage and brecciation.

7.2.6.1.4. Facies E1 - Interpretation

The deposits of Facies E1 are in the majority rich in the fine-grained mudstone and/or carbonate(primary) matrix and this feature together with the lack of current structures suggest that these muddy conglomerates and pebbly mudstones formed in result of **mudflow** transport and deposition. The term "mudflow" is commonly regarded as a synonym for "debris flow", "cohesive debris flow" (Lowe, 1979; Nemec *et al.*, 1984) or "true debris flows" (Middleton & Hampton, 1973, 1976), though it the present context it is primarily used in order to emphasize the textural distinction between the mud-rich flows of Facies E1 (and Facies E2 - see further in text) and the debris flows of Facies B and B1 (chapters 7.1.5.1.2. & 7.4.5.1.1.), containing sandy matrix (see also Lowe, 1979, p.77).

An approach toward the analysis of Facies E1 (similarly as in case of Facies E2, F1, B1) is somewhat affected by the fact that the individual beds, seen as representative of single acts of deposition, are generally unrecognizable. The existing approach toward describing and interpreting the mass flow deposits is strongly based on such, defined above, concept of a bed (Walker, 1975, 1977; Aalto, 1976; Lowe, 1982; Surlyk, 1984 and many others). However, in the present case distinct structural and textural characteristics of Facies E1 and E2 do allow a number of considerations, regarding: (1) mechanism(-s) of emplacement of the mudflows, (2) palaeoenvironmental setting of the mudflow sedimentation and (3) textural evolution of the involved sediments.

The deposits of Facies E display a very distinctive internal structure, described and defined earlier in the text as a shear-layering. The geometry of this feature - the lenticular and jagged form of the intraclasts, and their consistent, parallel/subparallel to the bedding orientation, is explained herein as being a result of shearing, which took place at some stage within the flow, along planes parallel/subparallel to the base of the flow (general bedding trend). This consequently indicates a laminar flow regime (Lindsay, 1966, 1968; Fisher, 1971; Enos, 1977). In these conditions the "soft", semi-lithified intraclasts are thought to have become strongly aligned, smeared out and torn apart (boudinaged) along the shearing planes. Sporadically they became folded and S-shaped.

Very similar features have been produced experimentally by Schwartz (1982) (Fig. 7.2.5. & 7.2.7.A), though it is not clear whether the boudinaged layers in Schwartz's

Figure 7.2.5. Block-diagrams A-D demonstrate the inferred steps in development of the shear-layering in pebbly mudstones (Facies E1) in result of axially symmetrical, layer-parallel extension. All features depicted on the block-diagrams have been observed in polished slabs of rocks (see also Plate 7.2.2. & 7.2.6.). Note a considerable homogenization of the involved deposits, corresponding to the progressive deformation. The drawing below serves as a possible analog, though in the case studied here the autochthonous, layered sediments have not been found. The diagram above left (after Cowan, 1982) shows that unlike uniaxial compaction the studied shear-layered sediments were laterally unconfined and able to extend in all directions parallel to layering, while shortening in a direction normal to layering.

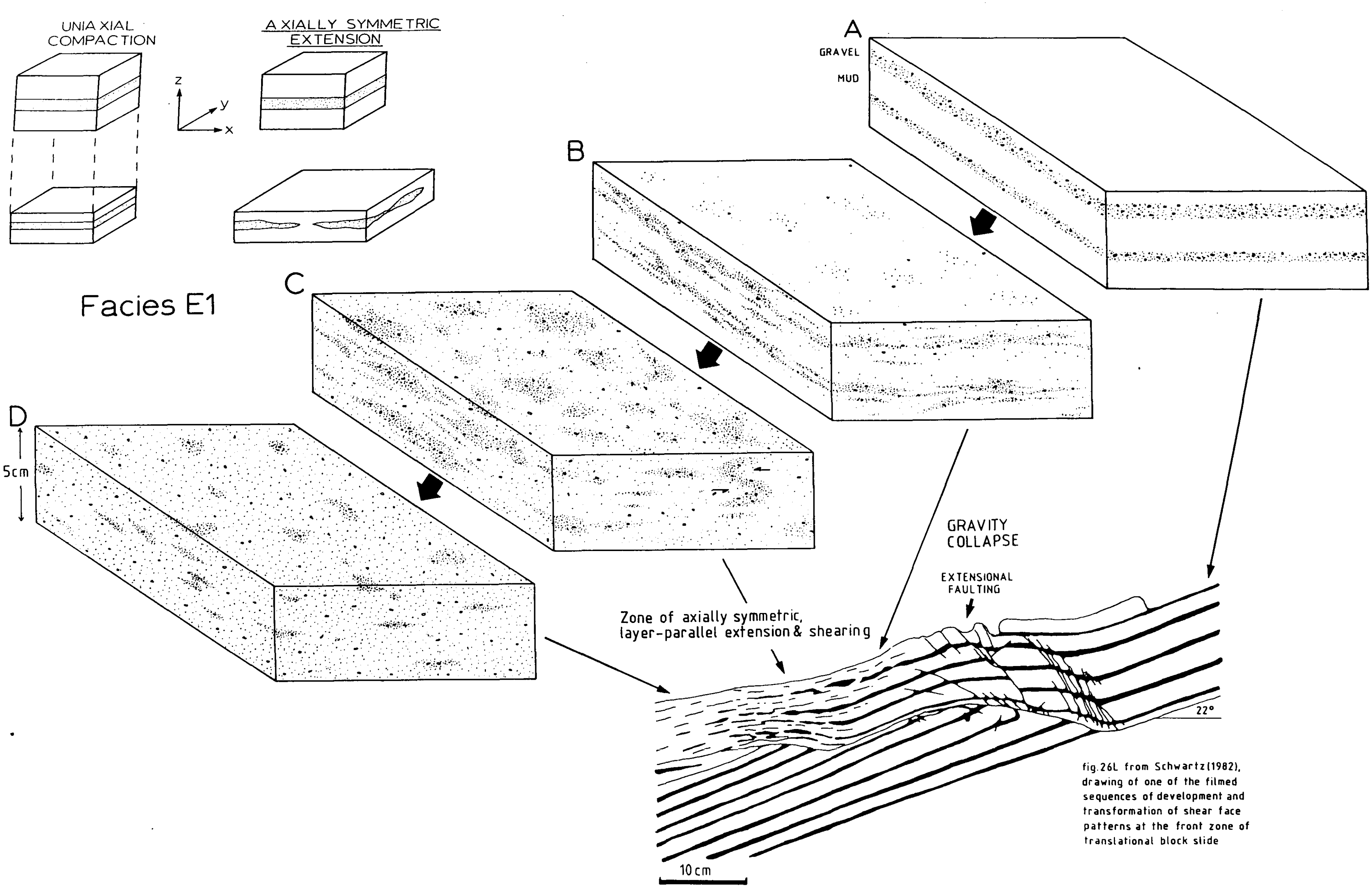
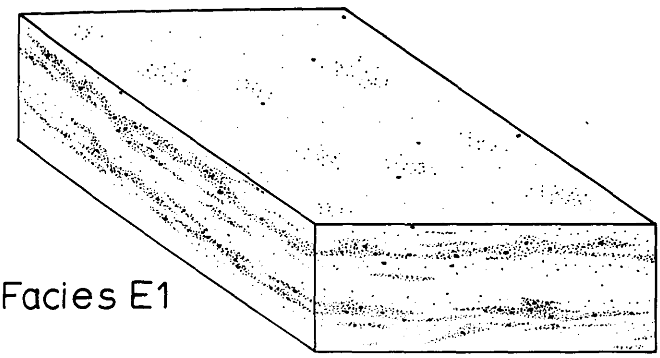


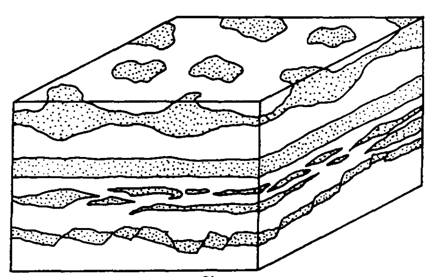
fig.26L from Schwartz (1982), drawing of one of the filmed sequences of development and transformation of shear face patterns at the front zone of translational block slide

Figure 7.2.5a. The figure demonstrates strong similarity between the nature of the shear-layering recognized in Facies E1, E2 and F1 and the mesoscopic structures described by Cowan (1982, fig.2) from partly dewatered and consolidated sediments of the Fraciscan melange (Piedras Blancas Point, California).

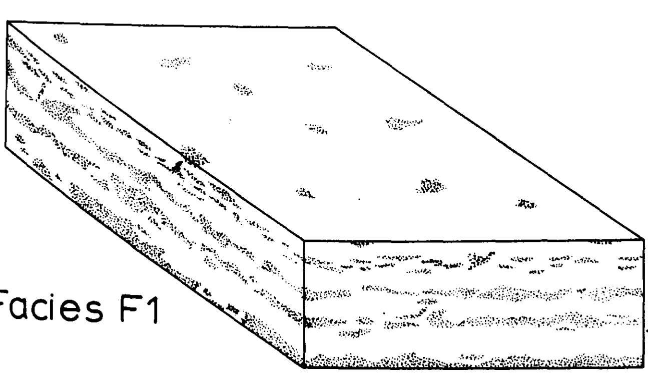


Facies E1

Facies E2
(BED 7/8)



(after Cowan, 1982)



Facies F1

experiment have been ellipsoidal or prolate in form.

The pinch-and-swell, ellipsoidal geometry of the intraclasts, common necking and boudinage in Facies E1 indicate a deformation of the primary sediments in a process of layer-parallel extension (Fig. 7.2.5.; Cowan, 1982, 1985). For there is no detectable preferential direction of extension in the discussed deposits, extension apparently acted with equal ease in all directions in the plane of the layering (XY) and was therefore axially symmetric with respect to the normal to the layering. The bulk mesoscopic coaxial progressive strain is qualitatively recorded by the distortion of the intraclasts which were deformed into flattened oblate ellipsoids (Cowan, 1982).

While the extensional signatures are so wide-spread, there is a near absence of folds (typical slump features) and other evidence for layer-parallel shortening. The preponderance of shear-lamination, recording layer-parallel extension and the general absence of folds in both incipient and intensely deformed primary deposits suggest that the original layering was oriented at low angles, or possibly parallel to the XY planes of both infinitesimal and finite strain ellipsoids through the deformation. The delicately thinned inclusions in regions of extreme necking do not appear to have rotated with respect to their parent layers or nearby intraclasts. If this is the case, this relationship between the XY plane and layering would additionally indicate a coaxial strain path (Cowan, 1982).

Zones of shearing, displaying occasionally a "*pseudo-lamination*" (Nemec *et al.*, 1984), have been reported from recent and ancient debris flow deposits. They have always been found to be restricted to the basal portions of the debris flow beds (Johnson, 1970; Johnson, 1984; Hampton, 1972; Middleton & Hampton, 1973; Lawson, 1982; Visser, 1983) and occasionally associated with an inverse grading (Walker, 1975; Gloppen & Steel, 1981; Nemec & Muszynski, 1982). These observations appear to be consistent with a classical, rheological model of a debris flow (plug flow) proposed by Johnson (1965, 1970, 1984) in which a non-deforming (or non-sheared) rigid plug "slides" above the basal zone of shearing (laminar flow). The non-sheared rigid plug conditions propagate downwards until the entire flow ceases to move (Fig. 7.2.6.C).

In the majority of the deposits of Facies E1 the shear-layering, representing the laminar flow conditions, is pervasive and has not been found to be confined to particular horizons.

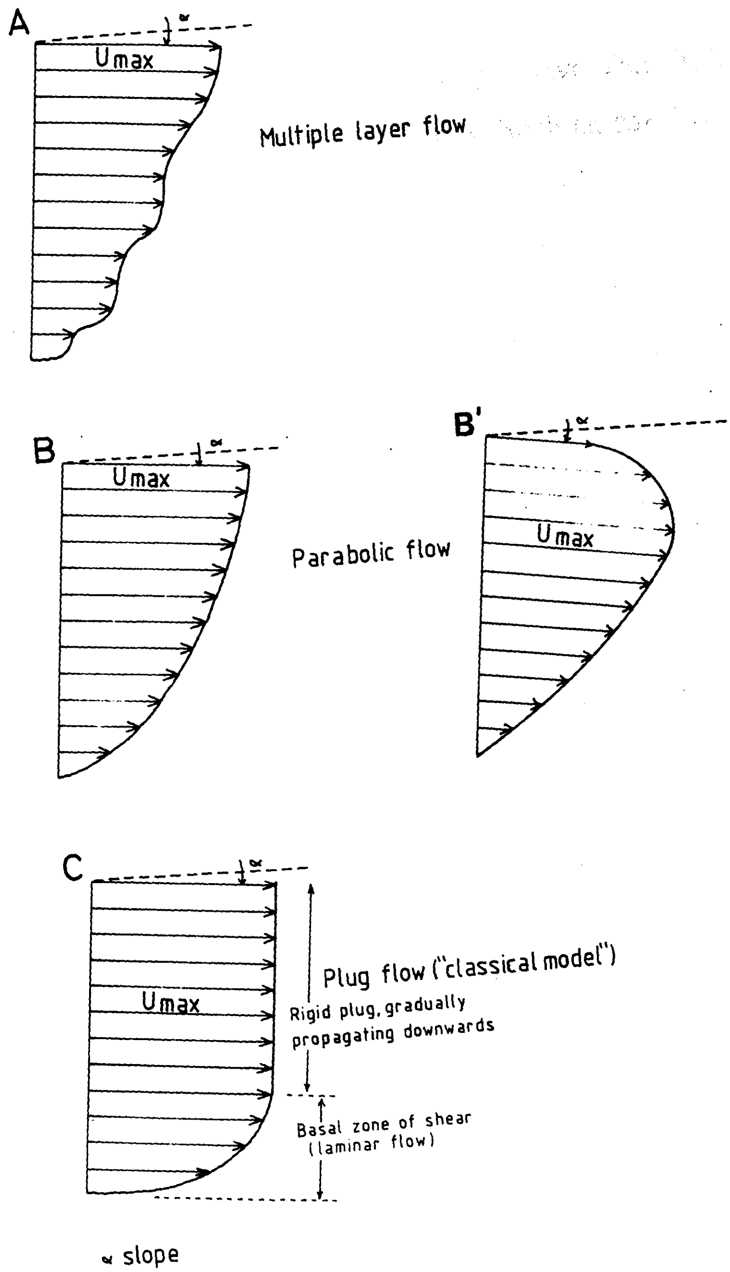


Figure 7.2.6. Velocity profiles in mass flows after: **A & B**: Takada (1969), Craig (1979, 1981) and Brunsden (1984); **B'**: Middleton and Southard (1984) (for subaqueous debris flow); **C**: Johnson (1965, 1970, 1984).

Only the beds 1 and 6a (Fig. 7.2.3. & Plate 7.2.2.D) seem to show the "classical" features, being massive throughout with a shearing zone developed at the base; individual beds are generally unrecognizable anyway.

It is thought that the depositing mudflows might have been, at least at some stage, entirely dominated by the laminar flow conditions. Such an conclusion finds support in works of Sharp (1938), Takada (1968), Craig(1979, 1981), Lawson (1982), Schwartz(1982), Brunsden(1984) and Middleton & Southard (1984) from which it is clear that some low viscosity ("wet") mudflows or Lawsons's Type 3 flows may move, being continuously internally sheared (Fig. 7.2.6.A-B'). Hence, the Johnson's (1965,1970) debris flow model (Fig. 7.2.6.C) may be complicated by presence of multiple shear planes within the debris flow body. These may occur during the main phase of the mass flow movement or during its initiation or cessation (Brunsden, 1984) (Fig. 7.2.6.A,B&B').

The interpreted mudflows of Facies E1 appear to fall into at least four, possibly genetically related, primary categories - stages of mass movement.

1 - The Bed nr.1 (Fig. 7.2.1 .& 7.2.3.) displays signs of a possible gravity "collapse" and mobilisation of the interlayered gravelly and muddy sediments, which could have transformed into the second, main stage of the mudflow evolution (Fig. 7.2.5.) (see also Schwartz, 1982, fig. 26). Cowan (1982,p.454) argued for the same mechanism, as responsible for horizontal spreading of the partly consolidated sediments.

2 - It is thought that in the second stage, immediately post-dating the mobilisation, the multiple layer (or mixed layer) type of mudflow or parabolic flow has developed (Takada, 1968; Craig, 1979, 1981; Schwartz, 1982; Brunsden, 1984) (Fig. 7.2.6.A,B&B'). This phase would be represented by the strongly texturally heterogeneous deposits of Facies E1 in which the individual, variable lithologically layers are still recognizable, though they are clearly affected by shearing associated with the layer-parallel extension (Plate 7.2.2.B & 7.2.5.A).

3 - Continuous downslope flowage and layer-parallel extension and shearing would have led to a further remoulding of the layers. In the process the sediments would have achieved a considerable degree of homogenisation, though with still detectable shear-lamination (Lawson, 1982) (Plate 7.2.2.A&C, Fig. 7.2.5.).

4 - The wide-spread presence of the shear-layering, diagnostic of the multiple shear planes within the mudflows, certainly does not eliminate a possibility of a plug flow type of movement (Fig. 7.2.6.C) in the final stage of the mudflow transport. In the light of the present understanding of the rheology of the debris flows (Johnson, 1965, 1970, 1984) it is thought that the upper, non-sheared portion of the flow (rigid plug) was most likely to develop through a gradual, downward propagation through a frictional and cohesive freezing of the flow. It is important to realize that the evidence of the laminar flow conditions, dominating at some stage the entire mudflow, could have eventually become preserved within the non-deformed, rigid plug. Thus, it is clear that the observed sedimentary features of the mass flow deposits do not always reflect the final mass flow behavior, for at this stage it is usually the rigid plug, sliding on a thin, sheared layer.

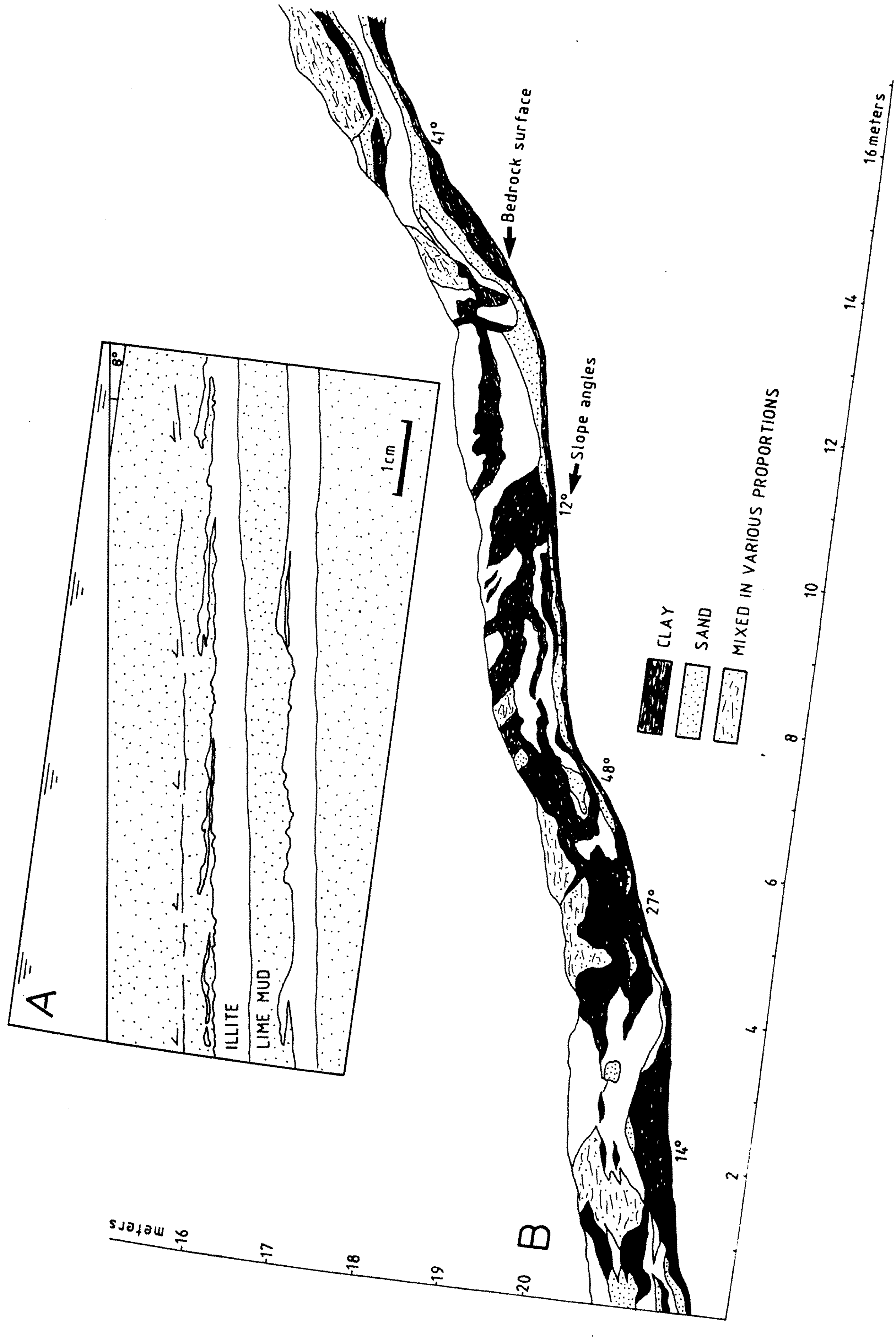
Fabric and structure of mass flow deposits may, however, record the prevailing flow regime (laminar or turbulent) prior to the moment of development of the rigid plug. One also ought to take into account that they may reflect the pre-transport sedimentary features of the source sediment (Enos, 1977).

The Bed 11a (Fig. 7.2.4.) unlike the Bed 11 and the other deposits of Facies E1 exhibits a strong inclination of the long intraclasts in the opposite direction than the snout-shaped terminus of the "micro-mudflow" bed. It is thought that in this particular case the fabric developed in response to the overthrusting of the mudflow body in the snout area. Such inference is supported by the Schwartz's (1982, fig. 42b) experimental works, as well as by observations of the recent submarine (Prior et al., 1984; Prior & Coleman, 1984) and subaerial debris flows (Rust, 1981; Lawson, 1982; Wells & Harvey, 1987) in which an analogous "push-fabric" can form in pressure ridges within the mass flow bodies (see also chapter 7.4.5.1.1.). Hence it is apparent that the evolution of the Facies E1 mudflows could have proceeded in radically different ways depending on the sector of the mudflow body and consequently, the resulting deposits are expected to display distinctly different structures and fabrics (Fig. 7.2.4.).

The recognized in places massive to chaotic with "whirl balls" horizons suggest locally developing "turbulent flow" conditions preceding formation of the rigid plug.

In the Lawson's (1982) fully sheared sediment flows of (his type 3), containing 25-

Figure 7.2.7. A: Effects of strong drag forces beneath shear planes, initiated by a shallow sediment flow, are indicated by substratal flow and fold structures at the upper interfaces of the illite layers (after Schwartz, 1982, fig.16);
B: large-scale shear-layering in a recent mudslide, Stonebarrow, Dorset (England) (after Brunsden,1984, fig 9.11).


A
8°
1cm
ILLITE
LIME MUD
B
16 meters
17
18
19
20
2
4
6
8
10
12
14
16 meters
14°
27°
48°
12°
41°
Slope angles
Bedrock surface
CLAY
SAND
MIXED IN VARIOUS PROPORTIONS

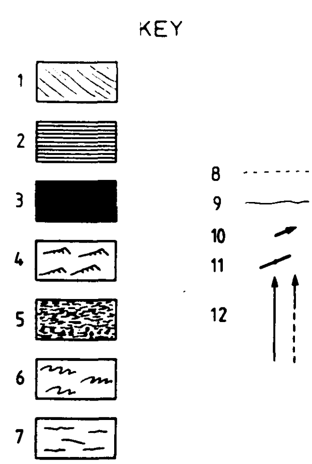
30% water (dry wt.), particles of all sizes, excluding cobbles and boulders, appeared uniformly distributed within the mudflows. This is entirely consistent with the lack of grading in the deposits of Facies E1.

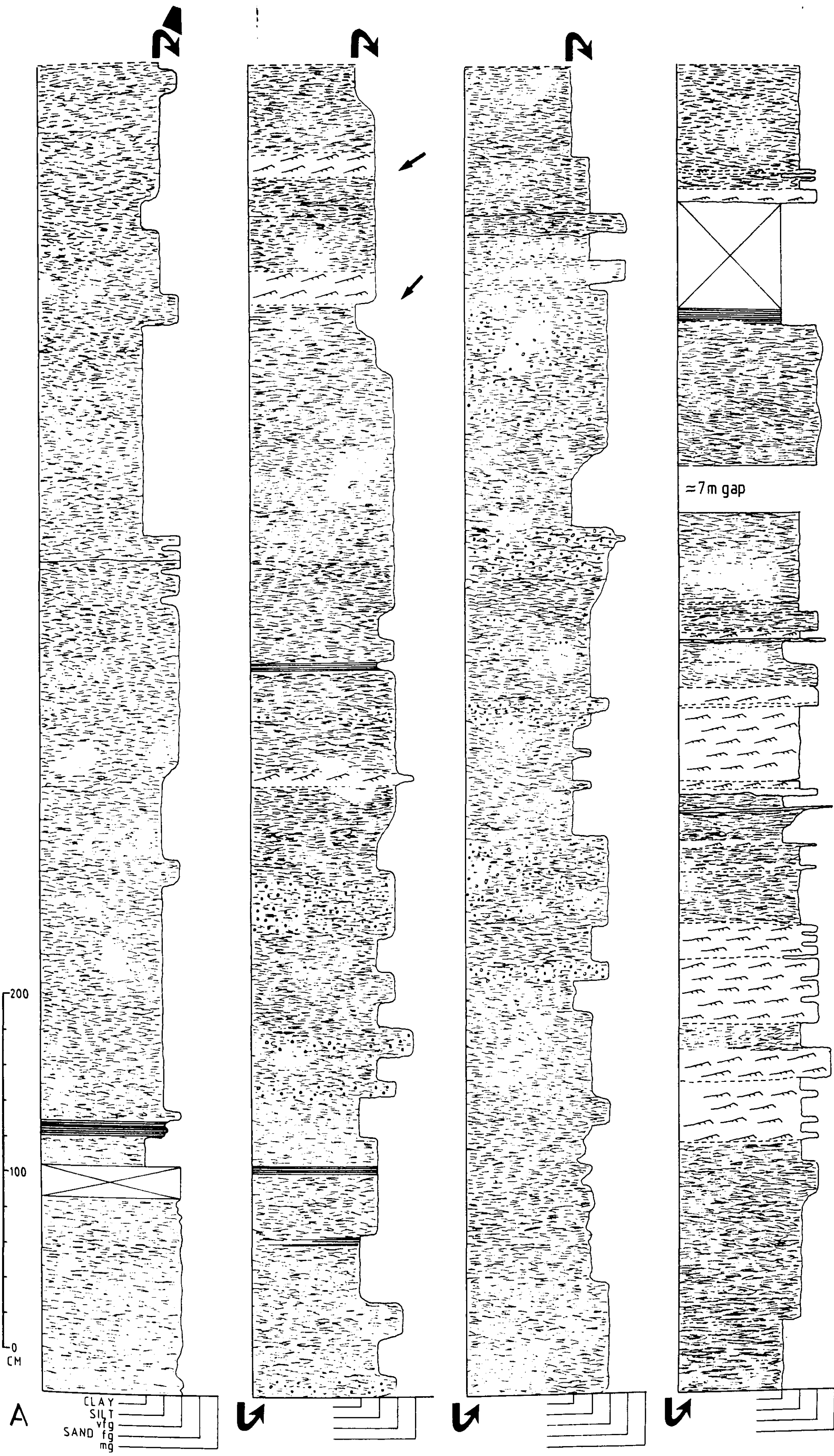
Abundance of the clay-rich finer-grained matrix in the mass flow deposits has been commonly regarded as an unequivocal evidence of a significant if not a key role played by cohesive properties of the clay-water mixture (cohesive matrix strength) in supporting larger clasts in suspension, at least during last stages of the mass flow movement (Lowe, 1979,1982; Nemec *et al.*, 1984; Postma, 1986). The deposits of Facies E1 are predominantly matrix-supported though the muddy component is usually accompanied by the primary carbonate material, occurring in the form of soft intraclasts or in the totally remoulded state. Some of the beds of Facies E1 beds are almost entirely carbonate matrix-supported. Following the reasoning laid out in the chapter 7.1.5.1.2. it is understood that in the case of the mudflows of Facies E1, the dominant cohesive strength component was imparted by the chemical bonds, developed between micrite particles and between micrite and other clasts. The textural features of the carbonate material - presence of "plastically" to "brittley" deformed intraclasts - indicate a significant, though variable degree of cohesion of the carbonate material, during the sedimentation. The cohesion was most likely and primarily a resultant of a cemenation of early carbonate mud, rather than due to electrostatic/electromagnetic forces acting between the clay particles (Ingels, 1962; Mitchell, 1976; Bathurst, 1975). In the scenario of the significant or the dominant role played by the carbonate matrix, the cohesive strength component produced by the attraction forces between clay particles, would be clearly negligible (Mitchell, 1976).

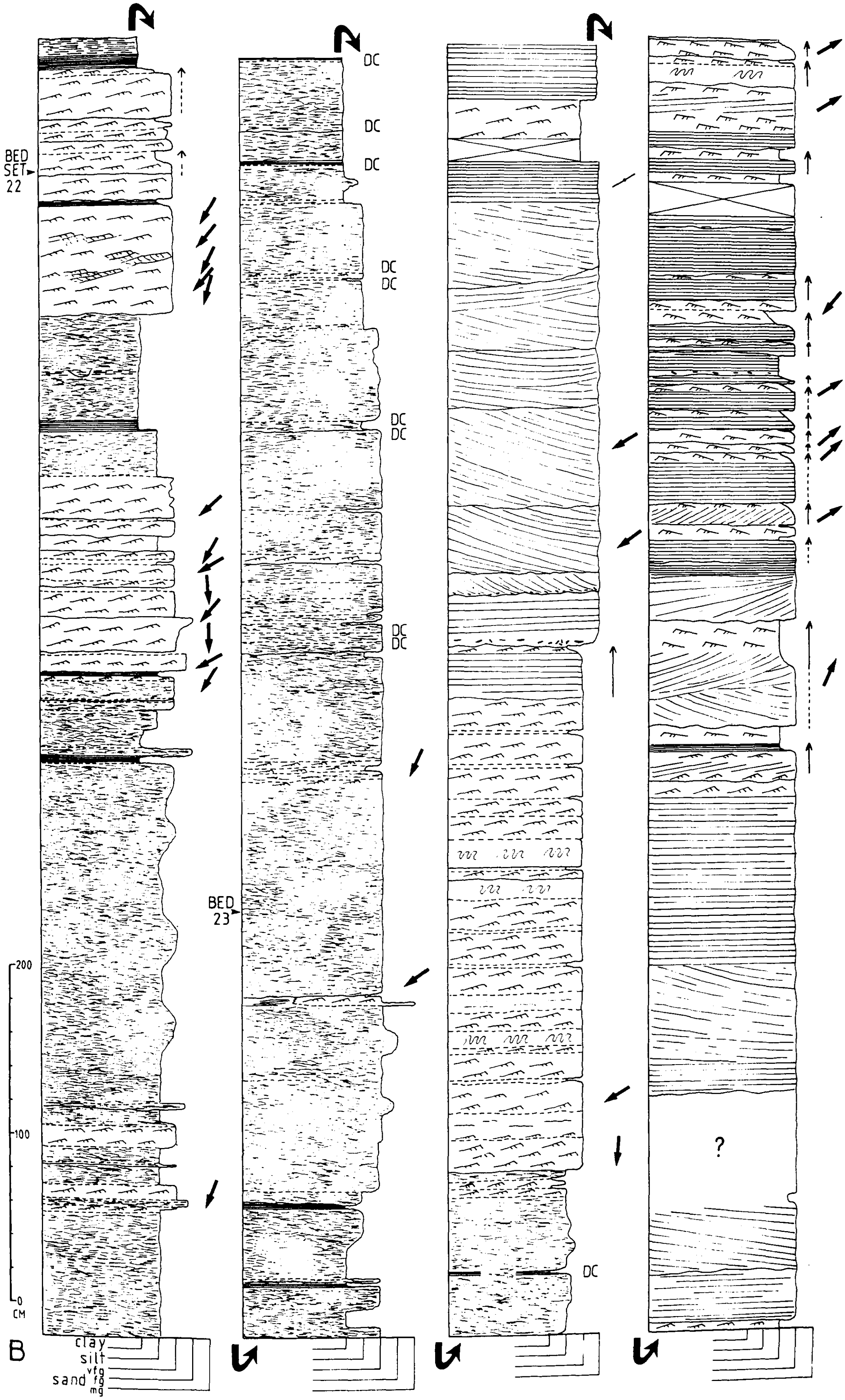
The inferred considerable differences in cohesive strength between semi-lithfied carbonate mud and clay matrix are followed by significant structural differences. The cracks and brecciation as well as the irregular patchy concentrations of clay are restricted to calcareous mudstones and calcilutites. The shear-layering/lamination in carbonate component rich mudstones (see Facies E2) has been found much more pervasive than in the non- or little calcareous deposits (Fig. 7.2.11. & 7.2.12.).

The clast-supported (carbonate matrix filled framework) varieties of the Facies E1, occurring in the form of atypically well defined beds, and being massive to crudely shear-

Figure 7.2.8. Graphic logs through the upper part of the Beinn Dhorain Member, dominated by Facies E2 and E3 (**A**) and through the transition into the Ben Uarie Member (Facies F2) (**B**). Note a dramatic change in palaeotransport directions associated with the transition into the BUM (Locality: Beinn Dhorain). **Key**: **1** - cross stratification; **2** - planar stratification; **3** - parallel lamination; **4** - current ripple cross lamination; **5** - shear-layered/massive deposits of Facies E2 (muddy sandstone variety with cavities); **6** - convolute lamination; **7** - shear-layered/massive deposits of Facies F1; **8** - non-erosional contact; **9** - erosional contact; **10** - palaeocurrent direction; **11** - strike of parting lineation; **12** - fining upwards throughout and at the top only.




≈7m gap
200
100
0
CM
A
CLAY
SILT
vfg
SAND fg
mg


BED SET 22
DC
DC
DC
DC
DC
DC
DC
DC
DC
BED 23
DC
?
200
100
0
CM
B
clay
silt
vfg
sand fg
mg

layered (Plate 7.2.1. & Fig. 7.2.3.), do not show any particular features that could indicate a significantly different mode of transport and deposition than the one discussed above. The disspersive pressure which is normally thought to be effective in the clast-rich mass flows (Lowe, 1979; Nemec *et al.*, 1984) does not manifest through an inverse grading. It is thought that the exceptionally effective carbonate cohesive matrix strength, might have significantly inhibited the action of dispersive pressure.

The shear-layered base of the Bed 1, Fig. 7.2.3. indicates a plug flow type of mass flow movement. Faint shear-layering observed in the Bed 1a (Plate 7.2.1.D) and the high cohesive strength of the carbonate matrix may independently suggest laminar flow conditions during the transport of these gravelly mass flows (Enos,1977).

7.2.6.1.5. Facies E2 - Interpretation

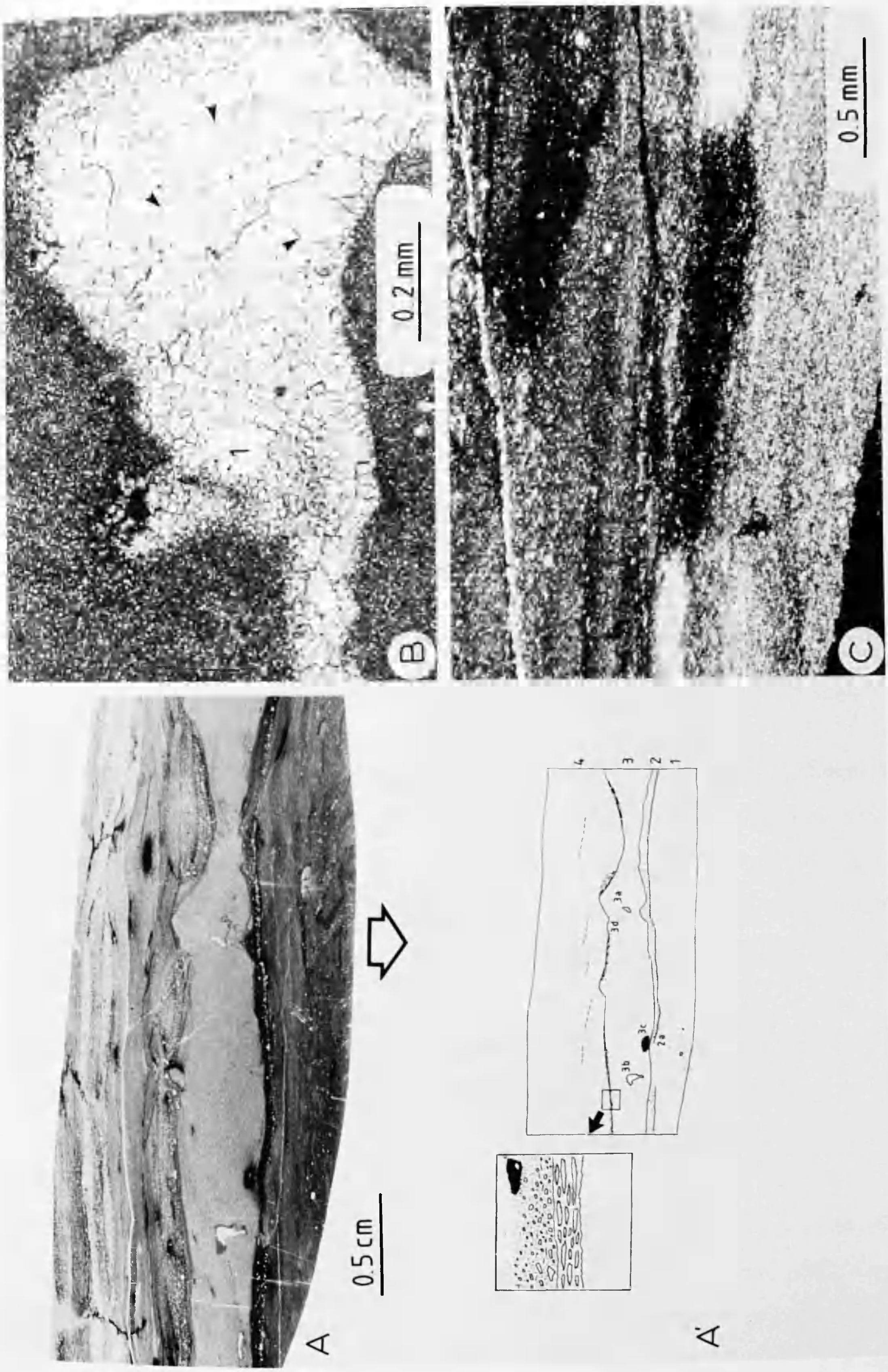
There is clearly a continuum between Facies E1 and E2 though the transition from muddy conglomerates and pebbly mudstones into muddy sandstones and mudstones is not accompanied by emergence of distinctly new structural features, which might indicate a significantly different mechanism(-s) of sedimentation of the latter deposits. Hence, they are also interpreted as a product of deposition from cohesive mudflows, characterised by pervasive internal shearing (laminar flow conditions), operating at some stage during the mudflow emplacement. The inferred stages of the mudflow transformation, and associated structural/textural evolution of the involved sediments are analogous to those depicted in Figure 7.2.14.

The Figure 7.2.14.5 applies in particular to the formation of the Bed 7/8, and shows some new elements of the development of the shear-layering. It clearly illustrates, however, the proposed concept of the formation of the structures in the deposits of Facies E2. There is an obvious analogy with the model for Facies E1 and F1 (Fig. 7.2.5. & 7.2.18). In the laminar flow conditions the carbonate-rich intraclasts were continuously boudinaged, torn apart and abraded. Thus, in the process of the mudflow transport the originally layered sediments achieved variable degrees of homogenisation, depending on duration of the laminar flow regime they were subjected to. The smaller, jagged, carbonate-depleted and mud-enriched streaks are regarded as a product of such shear-related

Figure 7.2.9. A: Photograph of thin section cut from of a 8 cm large intraclast, taken from shear-layered calcareous mudstone (Facies E2) (see **A'** for explanation); (**1**) shear-laminated extramicrite/dismicrite; (**2**) silty mud laminae torn apart (**2a**); (**3**) boudinaged dismicrite laminae; (**3a**) neomorphic and cement "bird's eye" sparr; (**3c**) concentration of clay residue with sparr in the center; shear-lamination is developed locally along the interface between layers **3** and **4** (see attached diagram); (**3d**) the carbonate layer has been locally remoulded along the margins with the surrounding sediments; (**4**) moderately deformed laminae of calcareous silt and dismicrite;

B: "Bird's eye" structure from phot. **A**. The arrows point to well developed crystal faces of sparry calcite cement; (**1**) micrite enclosed by microsparr and sparr suggests that some of the latter material is of neomorphic origin.

C: Boudinaged micrite layer from the horizon **4**. The extensional gap has been filled with haematite-stained clay residue and micrite (phot. **C** is not covered by phot. **A**).



A
0.5 cm
A'
4
3
2
1
3a
3b
3c
3d
2a
B
0.2 mm
C
0.5 mm

diminution of the primary carbonate layers and remoulding with the surrounding muddy sediment (Plate 7.2.9. & Fig. 7.2.10.). Locally, the carbonate-depleted product of the intraclasts abrasion has been concentrated behind them in a form of "tails". The angular contours of some of the intraclasts may suggest a considerable degree of their lithification during the mudflow emplacement.

The cohesive strength of the mudflows of Facies E2, similarly as in the case of Facies E1, is thought to have been generated by the attraction forces acting between the clay particles though in the flows with a significant carbonate component, the sediment cohesion was primarily due to the cementation factor of the semi-lithified carbonate sediments. Considering the mentioned earlier, highly effective, primary carbonate matrix-derived cohesion factor operating during the sedimentation, it seems unlikely that the increasing or decreasing content of the gravel fraction should have a significant influence on the mechanism of the discussed here mass flows. At least the observed rocks do not reveal features which might suggest to the contrary (see also interpretation of Facies B1, chapter 7.4.5.1.1.)

The very small thickness of some of the individual shear-laminated horizons(0.3 mm) as well as their discontinuity are incompatible with the concept of them having been a result of a deposition of one mudflow. It is thought that many of the observed zones of shearing could have formed locally at the interface between laminae during the multilayer flowage. The Figure 7.2.9. demonstrates a significant degree of deformation of the involved deposits.

The minimum thickness of the interpreted mudflows of both Facies E1 and E2 was in a range of a few cm. The maximum thickness of the flows remains unknown.

Pseudo-lamination

The pseudo-lamination is interpreted as a result of primary recrystallisation of micrite under conditions of simple shear stress (Bathurst, 1975; Wardlaw, 1962; Durney & Ramsay,1973). In such regime the new micrite and micro-sparr crystals grew almost parallel to the shear plane, in the direction of minimum compressive stress. The process is seen as an analogous to the formation of crystal fibers along the fault surface (Durney &

Figure 7.2.10. **A & A'**: Photograph and diagram of thin section from the Bed 7, Fig. 7.2.1.C. Lenticular, carbonate-rich phacoid has a tail of carbonate-depleted material, which formed in result of mechanical abrasion associated with layer-parallel extension and shearing during the mass flowage (see also Plate 7.2.9.). Note that locally micas are aligned along the margins of the phacoid;

B: Cathodoluminescence photomicrograph of the arrowed in **A'** part of the margin of the carbonate-rich phacoid shows no zoning nor particular "stratigraphy"; **(1)** orange-brown represents the early carbonate material; **(2)** bright yellow is the neomorphic/cement sparr and microsparr. The dark material represents carbonate-free muddy matrix.

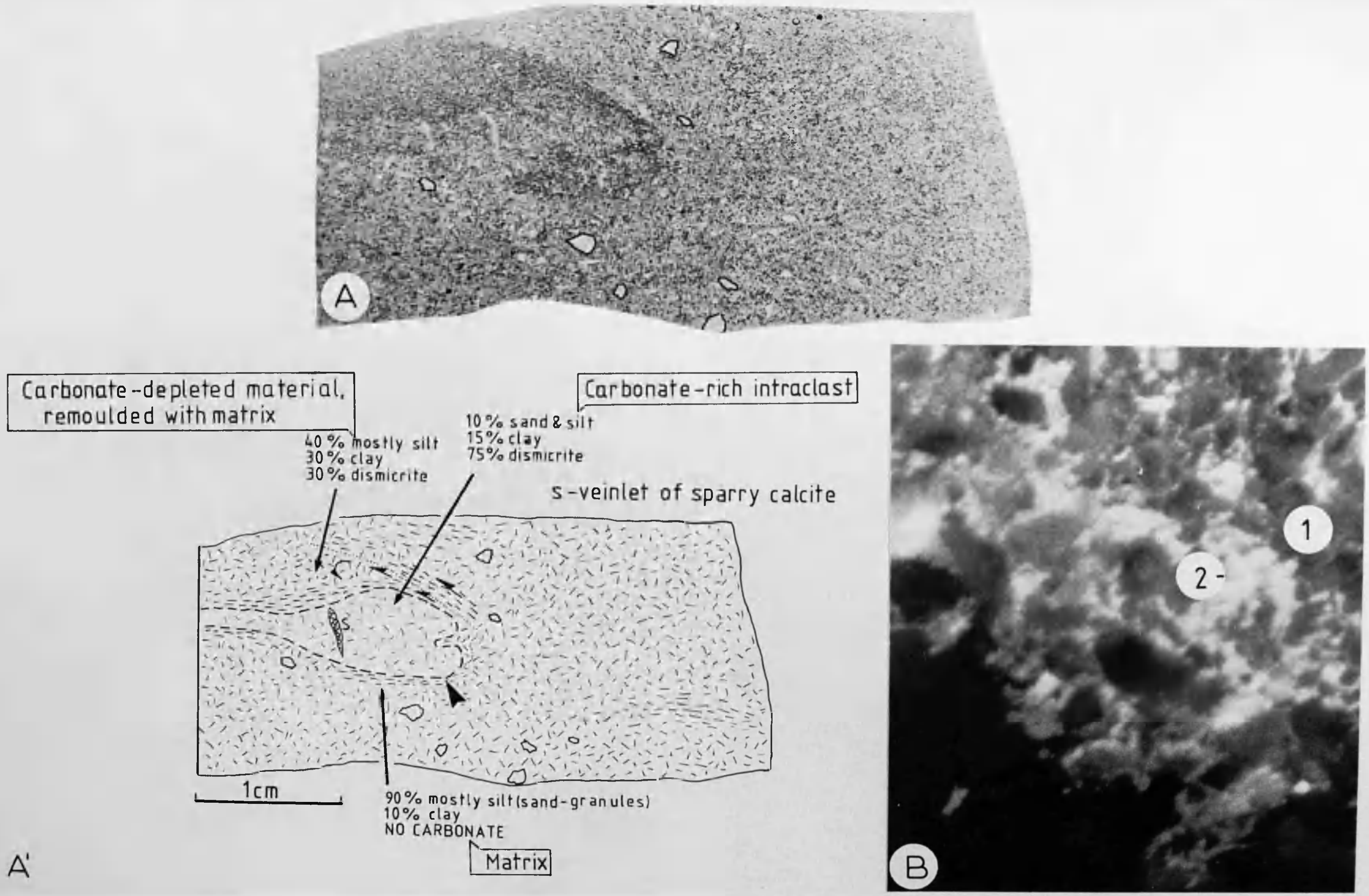
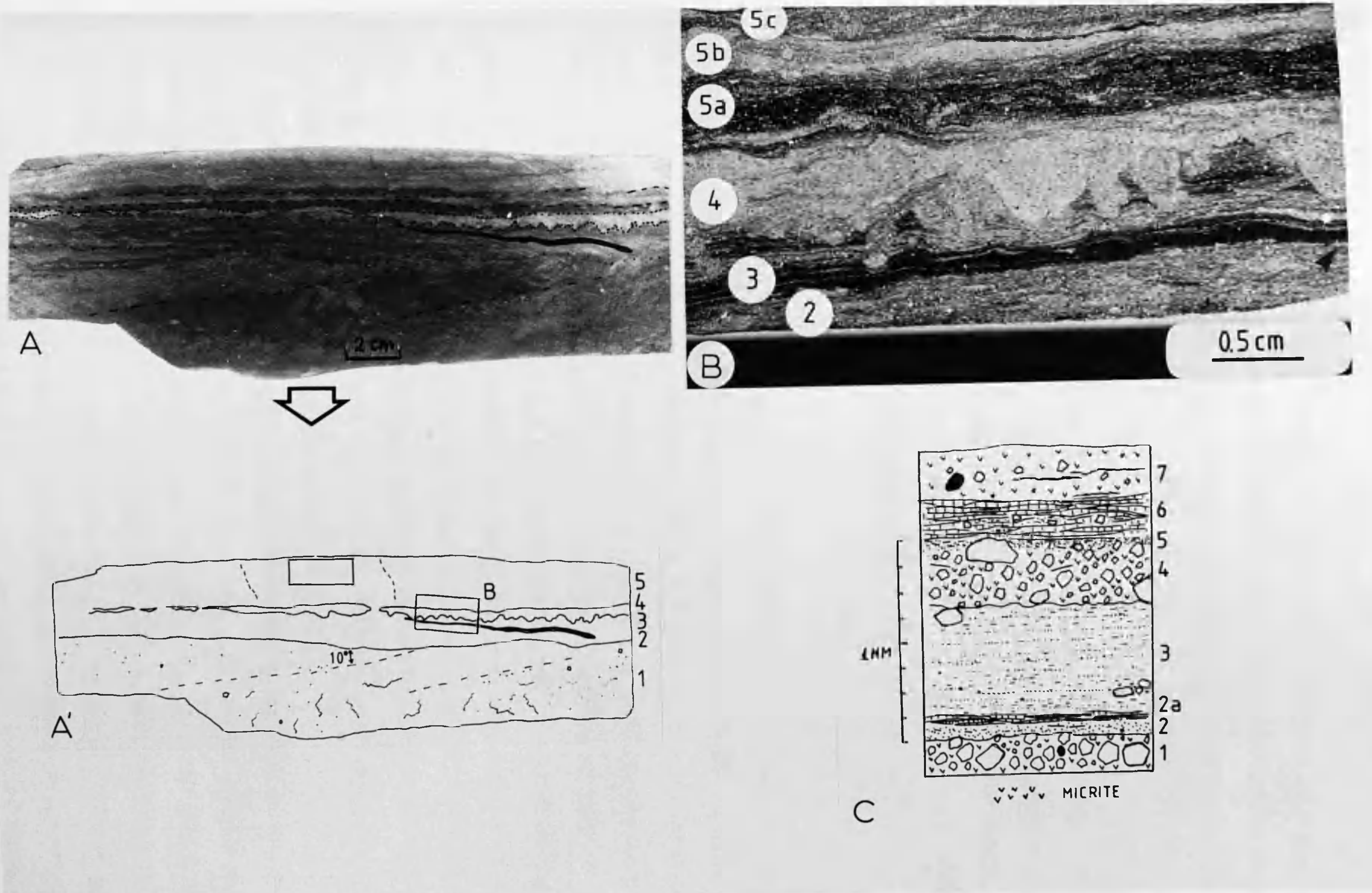

A
Carbonate-depleted material, remoulded with matrix
40 % mostly silt
30 % clay
30 % dismicrite
Carbonate-rich intraclast
10 % sand & silt
15 % clay
75 % dismicrite
s-veinlet of sparry calcite
s
1cm
90 % mostly silt (sand-granules)
10 % clay
NO CARBONATE
Matrix
A'
1
2
B

Figure 7.2.11. Figure demonstrates complexity of the structural and textural characteristics of Facies E2 and E3 (Bed 20, Fig. 7.2.1.C).

A & **A'**: (**1**) Medium-scale shear-layered calcareous silty mud with scattered granules. The layering is inclined with relation to the general bedding trend and it is truncated by the overlying sediments. Note faint, chaotic clay-sealed cracks; they are absent in the upper sediments;

B: Close up photgraph of thin section, taken from the horizon marked on the attached diagram **A'**; (**2**) shear-layered, calcareous, muddy fine sand; (**3**) parallel-lamination (Facies E3): darker laminae are composed of haematite-stained clay, probably organic matter and very fine silt with minor carbonate content (single "dropped" grains of fine silt to very fine sand). The coarser laminae are up to 0.2 cm thick. They tend to be discontinuous and often load into the darker laminae. They are clay-free and composed of silt to very fine sand with micrite matrix (50/50) (see also **C** for details); (**4**) very poorly sorted calcareous, silty medium sand with single micrite intraclasts pervasively loading into the horizon **3** (note also boudinage affecting this layer); (**5**) originally, probably parallel-laminated sediments (Facies E3) have been considerably disrupted by layer-parallel extension and shearing and minor synsedimentary faults. Marked area is shown on the photograph of thin section, Fig. 7.2.12.; (**5a**) remoulded, shear-layered mixture of calcareous silty mud and calcareous mud with intraclasts of extramicrite; (**5b**) calcareous very fine sand remoulded locally with mud and silty mud (single scattered clasts of very coarse sand). Note a long intraclast of calcareous mud, partly remoulded with the surrounding sediments. (**5c**) calcareous silty mud;

C: Detail section through the horizon **3** from phot. **B** (arrowed); (**1**) calcareous silt with sporadic carbonate intraclasts; (**2**) calcareous silty mud with micas aligned parallel to the bedding; (**2a**) discontinuous calcite veining (pseudo-lamination); (**3**) parallel-laminated, weakly calcareous silty mud. The darker, clay/organic matter-dominated laminae are up to 0.05 mm thick. The coarser, brighter laminae are normally one clast of silt grade thick. Scattered outsize grains of very fine sand to coarse silt appear along some of the laminae. The outsize particles occasionally form cemented by micrite clusters. The boundary between **3** and **4** is sharp and undulating; (**4**) calcareous silt (mainly extraclasts, 5% of inraclasts), generally ungraded with outsize particles projecting locally into **5**; the laminae is in places deformed and loads locally into **3** (not visible on the diagram). In places the laminae shows at the top a dramatic fining into **5**; (**6**) pseudo-lamination similar as in **2a** and confined to the boundary between **6** & **7**; (**7**) calcareous (micrite only) mud (3% of silt & single carbonate intraclasts); discontinuous, undulating clay streaks (microstylolites ?).


A
2 cm
A'
B
5
4
3
2
1
10°
5c
5b
5a
4
3
2
B
0.5 cm
7
6
5
4
3
2a
2
1
1MM
MICRITE
C

Ramsay, 1973) and to the growth of micro-size calcite mosaic parallel to shear fractures in large deformed crystals of calcite and along the interfaces between twin lamellae (Bathurst, 1975,p.478; Wardlaw, 1962). The conditions of bed-parallel shear stress are also indicated independently by the sigmoidal ("fish-like") and rhomb-shape micro-pull-apart structures (Fig. 7.2.15.).

In the case discussed here, however, no shear planes with a significant horizontal displacement have been recorded. This can be explained by conditions of **sediment creep** in which material reacts to shear stresses by deformation without visible failure. This represents the sum of particle displacements within a microfabric (Schwartz, 1982). A strong increase of shear stress appears just before failure (Hobbs *et al.*, 1976).

Cracks and brecciation

The complex system of cracks and brecciation, affecting the calcareous varieties of Facies E2 and E3, post-date the formation of the pseudo-lamination. However, even though they evidently appear as post-depositional features they unquestionably formed during the sedimentation of the discussed deposits. This is clearly indicated by the fact that very often the sediments overlying the cracked and brecciated horizons are intact.

The organised or chaotic system of cracks and brecciation are interpreted as gravity induced deformations, related to processes ranging from perceptible creep movements to some translation on shear faces or even slumping (Schwartz, 1982). Geometry of the cracks as well as their scale are incompatible with the characteristics of desiccation features (Plate 7.2.11.). They also appear only in the calcareous mudstones, whereas the desiccation polygons have been found in various lithologies.

The bedding-parallel/subparallel, planar to undulose, *en echelon* to anastomosing cracks (Plate 7.2.4.A&B, 7.2.6.B, 7.2.12.D) may either represent bed-parallel gaps and fissures created mainly due to excess pore water pressures, generated during gravity induced lateral compression (Schwartz, 1982, fig. 17) or non-sutured microstylolites(micro clay seams) (Wanless, 1979). According to the former interpretation, the layer-parallel micro-cracks would be representative of the incipient creep movement ,when no significant deformation of the sediments takes place. Non-sutured microstylolites are regarded as a

Figure 7.2.12. Drawing depicts another section from the Bed 20. Note an essentially extensional nature of disruption of the layer **2**. The numbers correspond to the once in Fig. 7.2.11. The marked area from the horizon **5** is shown below: the photoraph of thin section shows pervasive shear-layering in the poorly sorted calcareous medium/fine sand. Content of carbonate (micrite/dismicrite) varies between streaks and ranges from 40-90%. The darker streaks have the highest carbonate content. Note scattered single clasts of very coarse sand. Smeared out extramicritic intraclast (arrowed) is partly remoulded with the surrounding sediments.

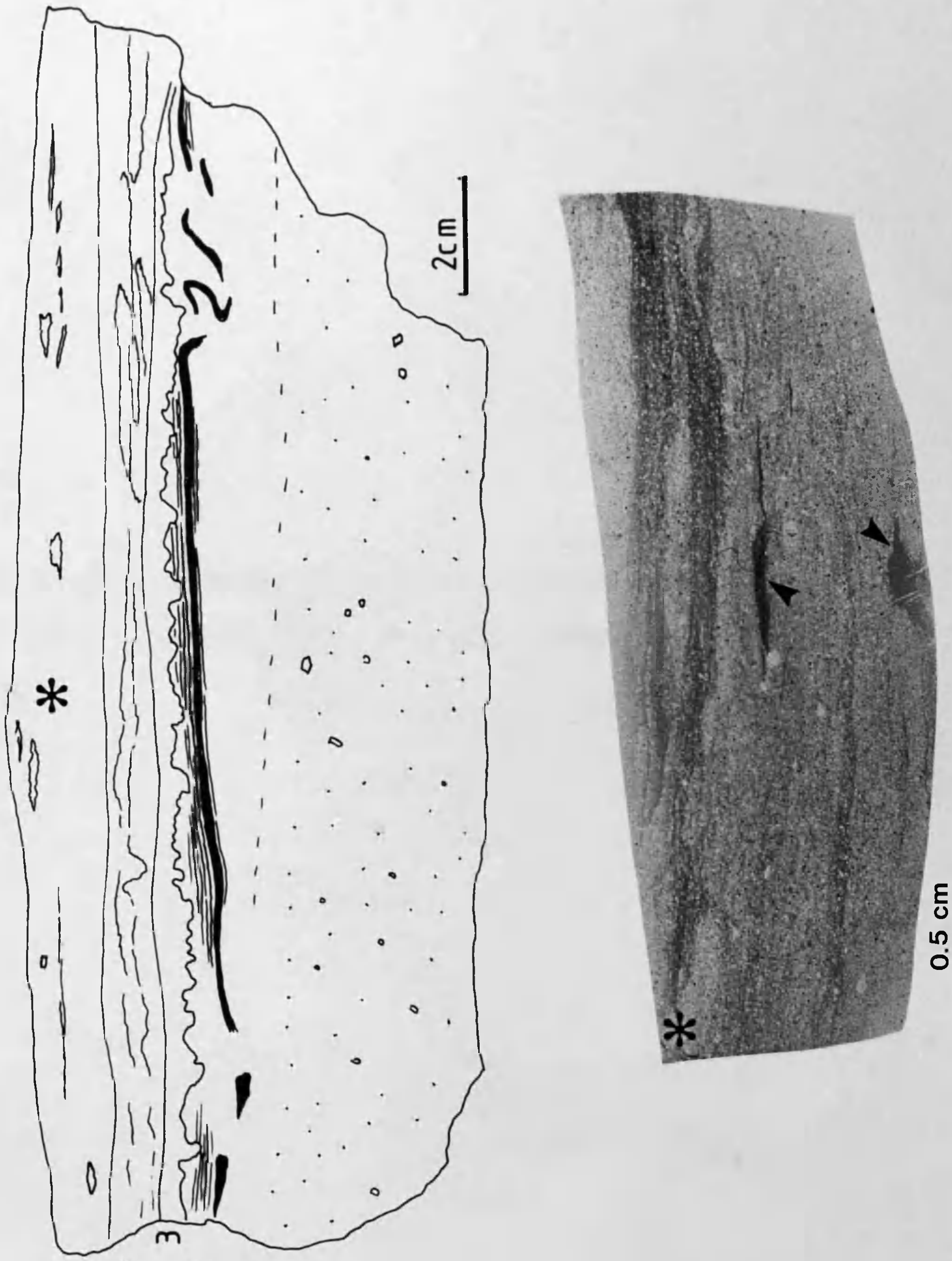
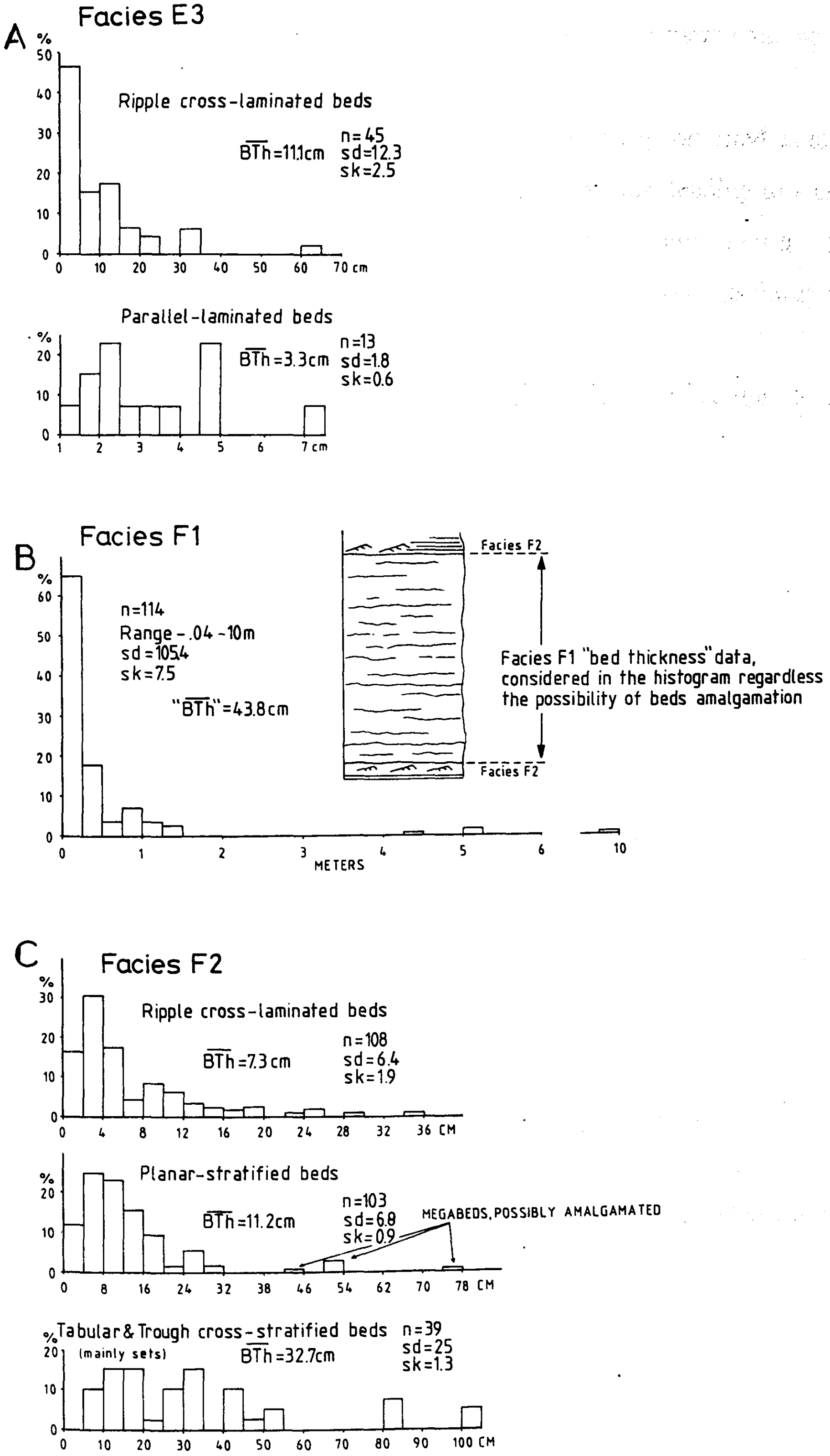

5
4
3
2
1
*
2cm
*
0.5 cm

Figure 7.2.13. Number frequency distribution of bed thickness for: **A** - Facies E3; **B** - Facies F1 and **C** - Facies F2. $\overline{\mathbf{BTh}}$ - mean bed thickness, **sd** - standard deviation, **sk** - skewness.


A
Facies E3
%
Ripple cross-laminated beds
BTh=11.1cm
n=45
sd=12.3
sk=2.5
0 10 20 30 40 50 60 70 cm
Parallel-laminated beds
BTh=3.3cm
n=13
sd=1.8
sk=0.6
1 2 3 4 5 6 7 cm
B
Facies F1
n=114
Range-.04-10m
sd=105.4
sk=7.5
"BTh"=43.8cm
Facies F2
Facies F1 "bed thickness" data, considered in the histogram regardless the possibility of beds amalgamation
Facies F2
METERS
C
Facies F2
Ripple cross-laminated beds
BTh=7.3cm
n=108
sd=6.4
sk=1.9
0 4 8 12 16 20 24 28 32 36 CM
Planar-stratified beds
BTh=11.2cm
n=103
sd=6.8
sk=0.9
MEGABEDS, POSSIBLY AMALGAMATED
0 8 16 24 32 38 46 54 62 70 78 CM
Tabular & Trough cross-stratified beds
(mainly sets)
BTh=32.7cm
n=39
sd=25
sk=1.3
0 10 20 30 40 50 60 70 80 90 100 CM

result of pressure solution in clay-rich limestones. According to Wanless (1979) platy material chokes the seam as an effective pathway for fluid migration and acts as a glide surface along the solution surfaces.

The wider, complex in geometry and more chaotically oriented cracks indicate probably some perceptible translations along the shear planes, leading to a considerable fragmentation of the involved deposits. The most intense fragmentation - brecciation, combined with remoulding, is likely to represent a form of slumping (Schwartz, 1982, fig. 25b,37).

The "brittle" character of the cracking and brecciation in the calcareous deposits(Facies E2 and E3) indicates a significant degree of lithification of the sediments, achieved mainly due to the carbonate cementation. Identical diversity in fabric in carbonate mass flows, corresponding to the variable degree of lithification in the remobilised sediments(flowage vs. brecciation) has been documented from the European Creataceous chalk (Bromley & Ekdale, 1987).

Apart from the cited above flume experimental work by Schwartz, mudcracks which formed in the result of downslope sediment creep have been reported from ancient deposits by Potter *et al.*,(1980, p.33). Blocky fragmentation of the semi-lithified sediments in modern subaerial and subaqueous mass flows is a common phenomena (e.g. Brunsden, 1984; Prior *et al.*,1984).

Gravity-driven brecciation has been interpreted from ancient carbonate slope settings in association with other mass flow deposits (slumps, debris flows, turbidites) (Fuchtbauer & Richter, 1983; Kennedy, 1980, 1987).

The cracks commonly exhibit forms transitional to oblate patchy concentrations of clay and the latter features are always associated with variously deformed and remoulded deposits. In the latter case the calcareous material seems to have reacted to lateral stress in a "plastic", rather than "brittle" fashion. Hence, the oblate clay concentrations are seen as equivalent features to the cracks, developed in much less lithified sediments.

The cracks, often cutting the plastically deformed carbonate material reflect an evolving style of response of the calcareous sediments to lateral stresses ("plastic" --> "brittle"), corresponding to their increasing degree of lithification.

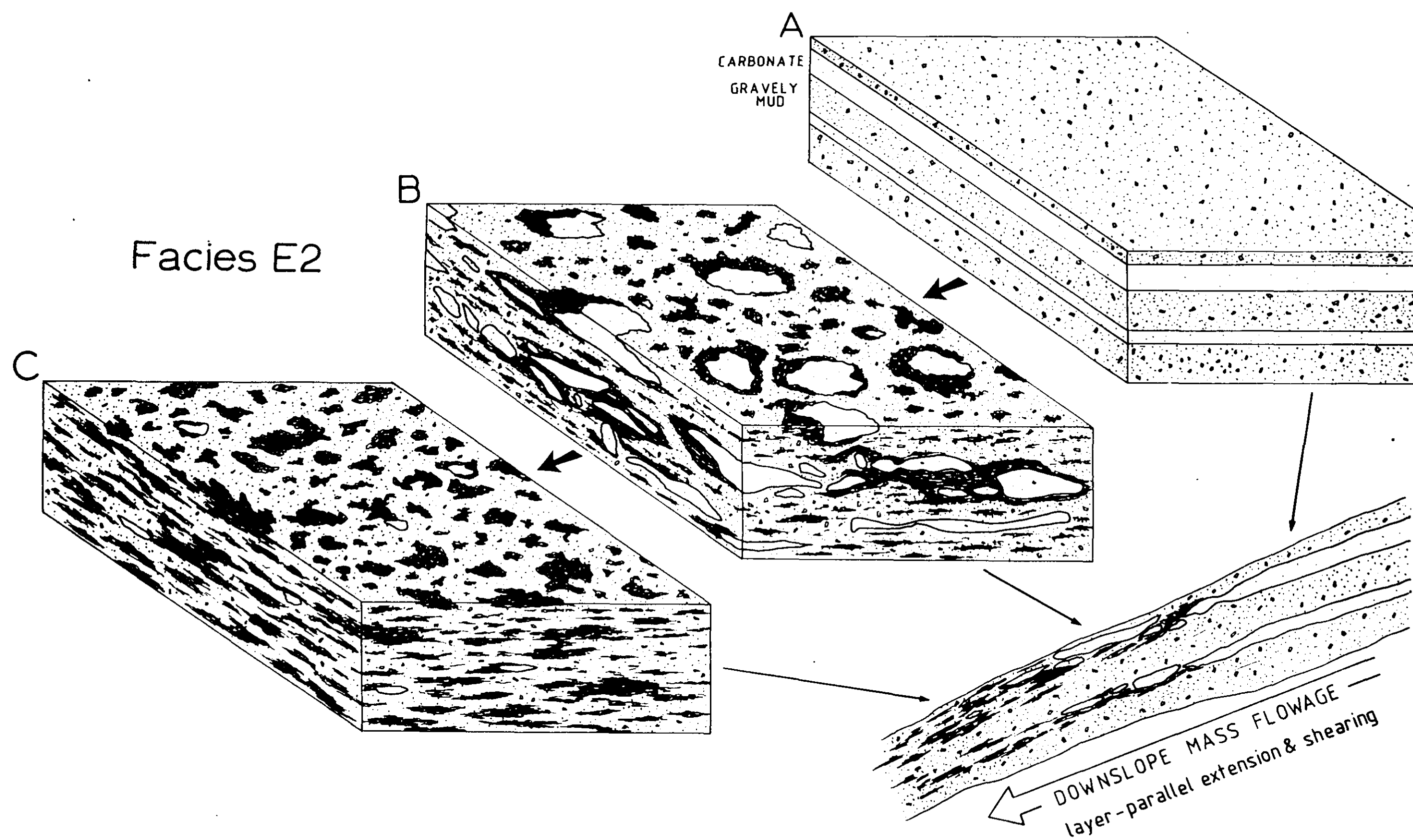
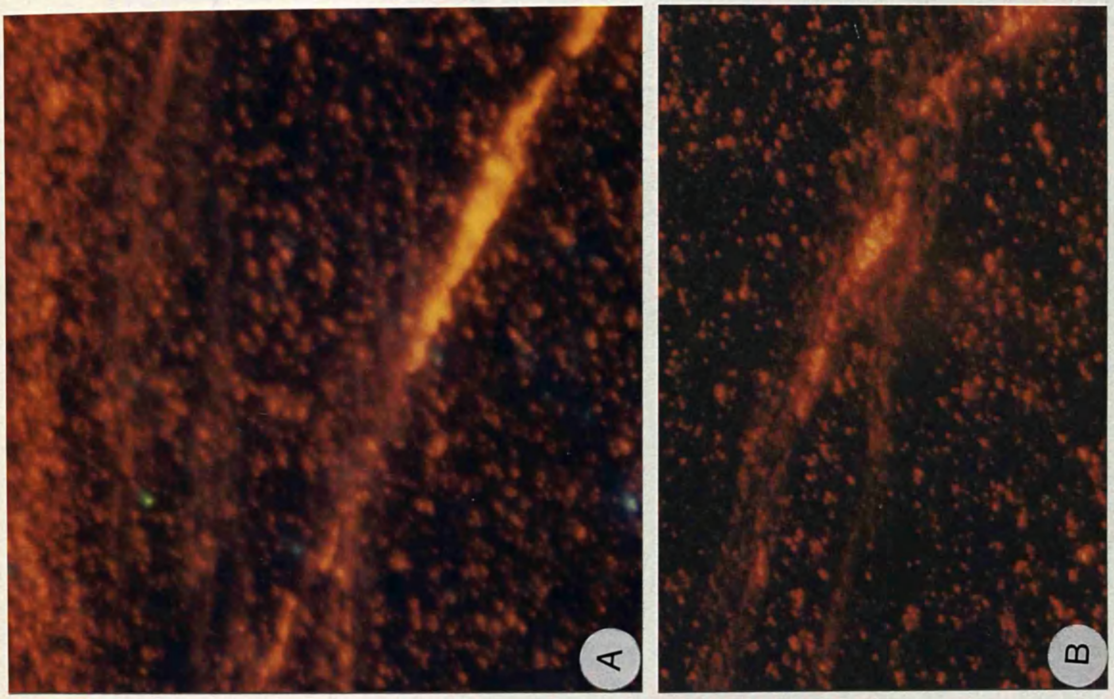


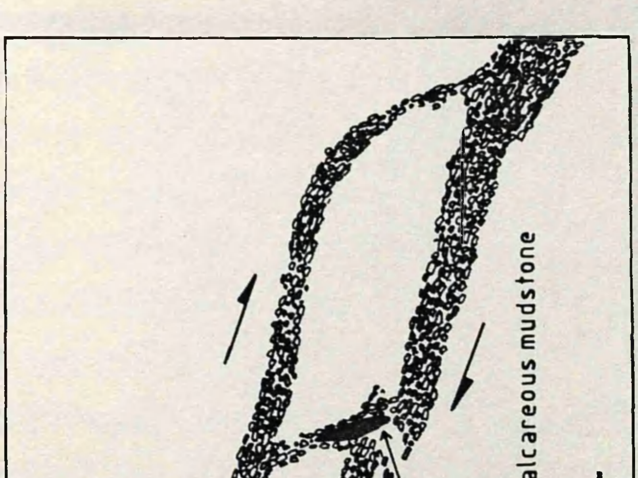
Figure 7.2.14. Inferred model of development of shear-layering in the sediments of Bed 8/7, Fig. 7.2.1.C. Progressive deformation and shear-related remoulding lead to gradual homgenisation of the involved sediments (see also Plate 7.2.9.). The structures generated in an experimental tank by Schwartz (1982) (see Fig. 7.2.5.) are regarded as a possible analog. The autochthonous deposits have not been found in the studied case (**A** - inferred state).

Figure 7.2.15. Details of pseudo-lamination.

A & B: Cathodoluminescence photomicrographs show two generations of calcite (micrite/dismicrite) involved in formation of pseudo-lamination; **(1)** early pseudo-lamination (orange-brown carbonate); **(2)** later, bright yellow carbonate fills sigmoidal openings along the earlier pseudo-laminae, as well as crystallizes in the surrounding calcreous sediments;

C: Drawing from the cathodoluminescence photomicrograph shows rhomb-shape, micro-pull apart features, associated with the development of the pseudo-lamination.


A
B


Calcareous mudstone
S
0.2 mm

The creep movement related grain-to-grain micro-shear translations as well as the more advanced remoulding are responsible for an increase in porosity of the discussed mass flow deposits (see also Taylor & Lapre, 1986). In process of migration of fluids the clay material was concentrated in the created pore spaces, oblate cavities and cracks, as an insoluble residue (Bathurst, 1975). In the cracks and oblate cavities the clay is locally mixed with the material that collapsed from their walls (Plate 7.2.14.). Later on the sparry calcite of the neomorphic and the cement phase crystallized in the remaining pore spaces creating bired's eye structures (Plate 7.2.9.B, 7.2.13A).

7.2.6.1.6. Subaqueous versus subaerial aspect of the mudflow deposition - significance of the Facies E3 deposits

Facies E1 and E2 are locally accompanied by ripple cross-laminated and parallel-laminated deposits of Facies E3. The parallel-laminated, calcareous to non-calcareous mudstones and calcilutites are negligible in the lower part of the Beinn Dhorain Member (BDM) (Fig. 7.2.1.) and subordinate in its upper part (Fig. 7.2.8.). They are also minor in the lowest portion of the Ousdale Mudstones (Fig. 7.2.2.).

Rapid appearance of the mud-rich(including carbonate mud) Facies E1, E2, and E3 above the mud-free conglomerates of Facies C1 (Fig.7.2.1. & 7.2.2.) is difficult to interpret in the way other than involving an existence of a **lake** or a **flood-basin**, an environment characterised by sedimentation of muds and carbonates (see also Nemec *et al.*, 1984; Larsen & Steel, 1978). The intimate association of Facies E1 and E2 with the parallel-laminated sediments of Facies E3 independently suggest a **subaqueous setting**, of the discussed above, mudflow deposition. Carbonate precipitation (most likely non-organic) was probably a background sedimentary process, for the fall out from suspension of the clastic material (mainly silt and clay) derived either by wind and depositing through the water column or by diluted density currents. The formation of the carbonate laminae was probably the result of increased pH due to photosynthesis followed by carbonate precipitation. The clay/organic-rich laminae might have originated through a seasonal decay of algal phytoplancton (Donovan, 1971; Trevin, 1986). The wind action and the possible depositing turbidity currents are thought to have led to the development of the "clastic" variety of the parallel-laminated Facies E3 deposits. It is likely that the some of these turbidity currents could have directly followed the mudflow episodes, or represent their distal equivalents (Hampton, 1972; Kelts & Hsu, 1980).

The scarcity of the deposits of Facies E3 and the poor state of their preservation (they typically occur in a allochthonous position) are thought to have been due to a considerable instability of the subaqueous depositional slope - the conditions which favored mass movements - generation of mudflows and later remobilisation of the resulted deposits. The very small thickness of some of the depositing individual mudfows is difficult to reconcile with a subaerial environment of their emplacement.

Total absence within the deposits of Facies E1, E2 and E3 of larger scale erosional features, like channels or scours, that could be seen as a result of dissecting of the mudflow lobes by stream flows, as well as lack of associated stream flow deposits are additional arguments against the subaerial setting of the mudflow sedimentation. The processes of dissecting and reworking of the mudflow/debris flow deposits are extremely common in the subaerial (alluvial fan) environment (Beaty, 1963; Bull, 1977; Johnson, 1984) (see also chapter 7.1.5.1.4., 7.2.6.1.10. & 7.4.5.1.1.), and in the subaerial setting the muddy gravels, gravelly muds and muds(Facies E1, E2, E3) would be highly susceptible to rill-wash and or sheet-wash erosion, reworking and winnowing of the fines. No features have been found in the discussed deposits which might indicate such processes.

In the upper part of the BDM several horizons with desiccation cracks have been found in association with Facies E2 and E3. These findings, however, do not *per se* imply an subaerial aspect of the deposition of the mudflows in question. The horizons with desiccation cracks may only mark changes of the water level in the lake, leading to periodic emergence of the in fact subqueously deposited mudflows.

It is difficult to exclude categorically a possibility, that some of the discussed here mudflows were deposited subaerially. In fact the oblate cavities, particularly abundant in the muddy sandstone beds (Fig. 7.2.8.), may represent air bubbles trapped in the more sandy mudflows, spreading over a dry depositional surface (Sharp & Nobles, 1953; Crandell & Waldron, 1956; Bull, 1964). However, there are no other, more convincing, independent evidence to suggest that particular mudflow deposits formed in such a way.

The ripple cross-laminated beds of Facies E3, which formed in the result of migration of current ripples (Fig. 7.2.8.), are certainly not diagnostic in any way with regard to this problem, though they are very likely to be genetically related to the mudflow depositional events, and possibly represent lower flow regime currents following the mudflow emplacement (low density turbidity currents (?), *C Bouma Devision*, Hampton, 1972) and depositing the extensive sheets (Plate 7.2.10.B).

The current ripples palaeotransport data have a unimodal frequency distribution (Fig. 7.2.21.), and this might indirectly suggest a strongly unidirectional pattern of the emplacement of the mudflows.

The climbing ripples, developed locally, indicate a high sediment supply and an efficient vertical accretion of some of the beds (Collinson & Thompson, 1982).

7.2.6.1.7. Facies F1: Massive and shear-layered muddy sandstones and sandstones

These rocks constitute a proportion of the deposits of the Ben Uarie Member(BUM) (upper part of the Glen Loth Formation). The BUM covers most of the area of the N sector of the Golspie basin. The sandstones, 150 m thick, appear above the pebbly mudstones and mudstones of the Beinn Dhorain Member(BDM) (Plate 7.2.10.A&B & Fig. 7.2.8.B) and above the conglomerates of Beinn Lunndaidh Formation(BLF). They are well exposed in Glen Loth on the eastern slopes the Beinn Dhorain and Ben Uarie. At least 230 m thick sequence of the deposits Facies F1 outcrop in the stream section of Allt Smeorail, where it rests directly on the conglomerates of the BLF. In the latter site Facies F1 makes up the total of the exposed deposits of the Glen Loth Formation.

The following analysis of Facies F1 is also based on data from sandstones that appear in the lower portion of the Col-bheinn Formation. They are best exposed south of Loch Brora at Duchary Rock and Leadoch Rock (Fig. 7.2.20., 7.5.1., 7.5.2.). Some exposures of the same deposits can also be found on the SW slope of Cagar Feosaig [NH 831 032].

Description

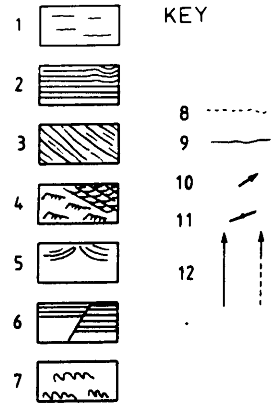
The sandstones of Facies F1 are subarkosic wacke with non-matrix constituents being generally very fine- to fine-grained and relatively well sorted, the best sorting being seen in the deposits in the area of Beinn Dhorain and Ben Uarie (Plate 7.2.15.A&B & 7.2.16.A&B). They contain around 20% of iron-oxide/clay matrix. The sandstones exposed in Allt Smeorail are less sorted with common scattered clasts of up to very coarse sand grade and with clay matrix from 43 - 47% (Plate 7.2.15.C). The sandstones from Duchary Rock are fine- to very fine-grained and essentially well sorted with regard to the sand fraction, though occasionally scattered clasts as coarse as granules can be found (Plate 7.2.19.B). Content of the clay matrix in the latter deposits varies between 19 - 60%.

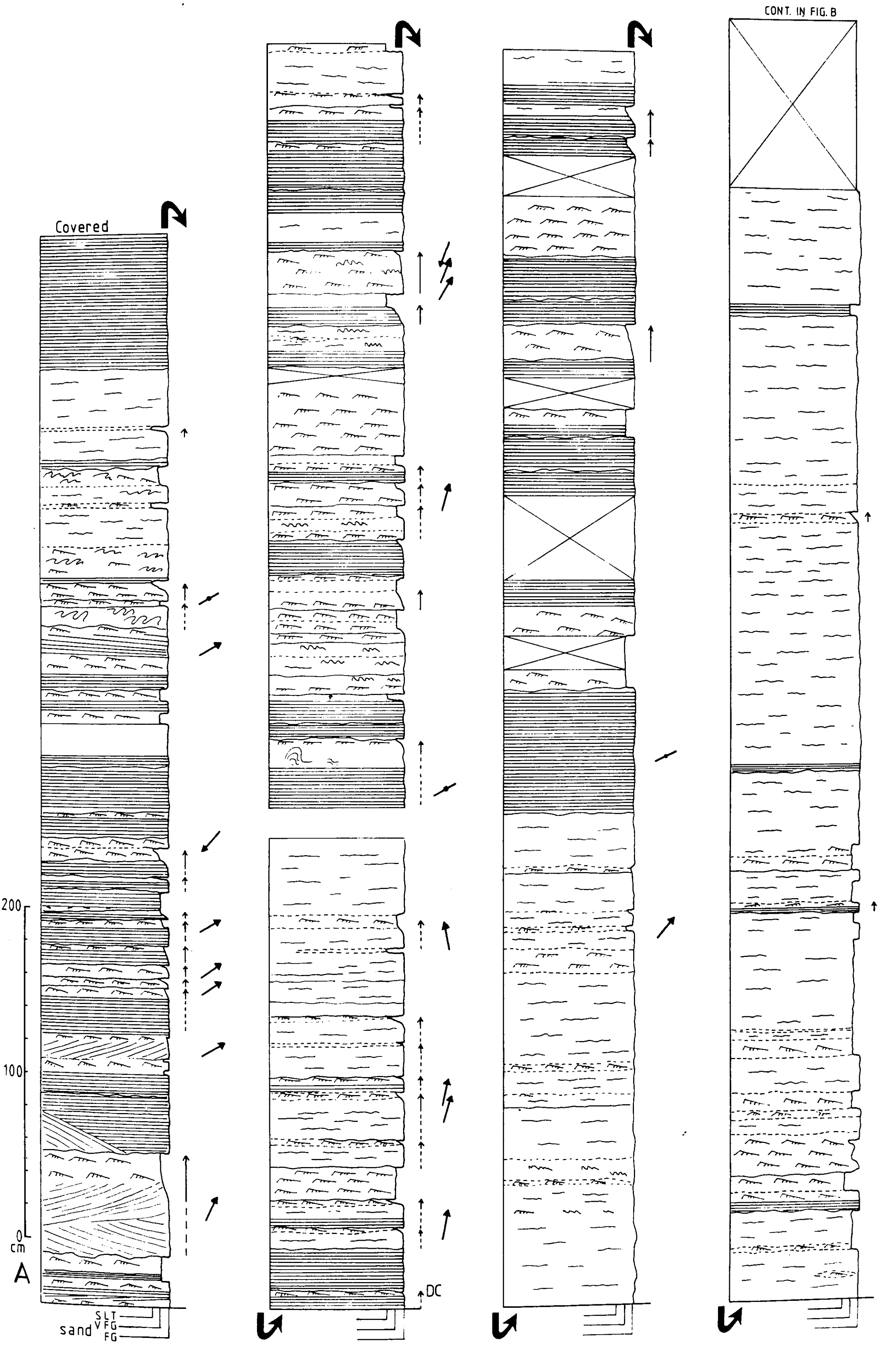
In all three occurrences, the sandstones of Facies F1 consist mostly of angular to subangular grains.

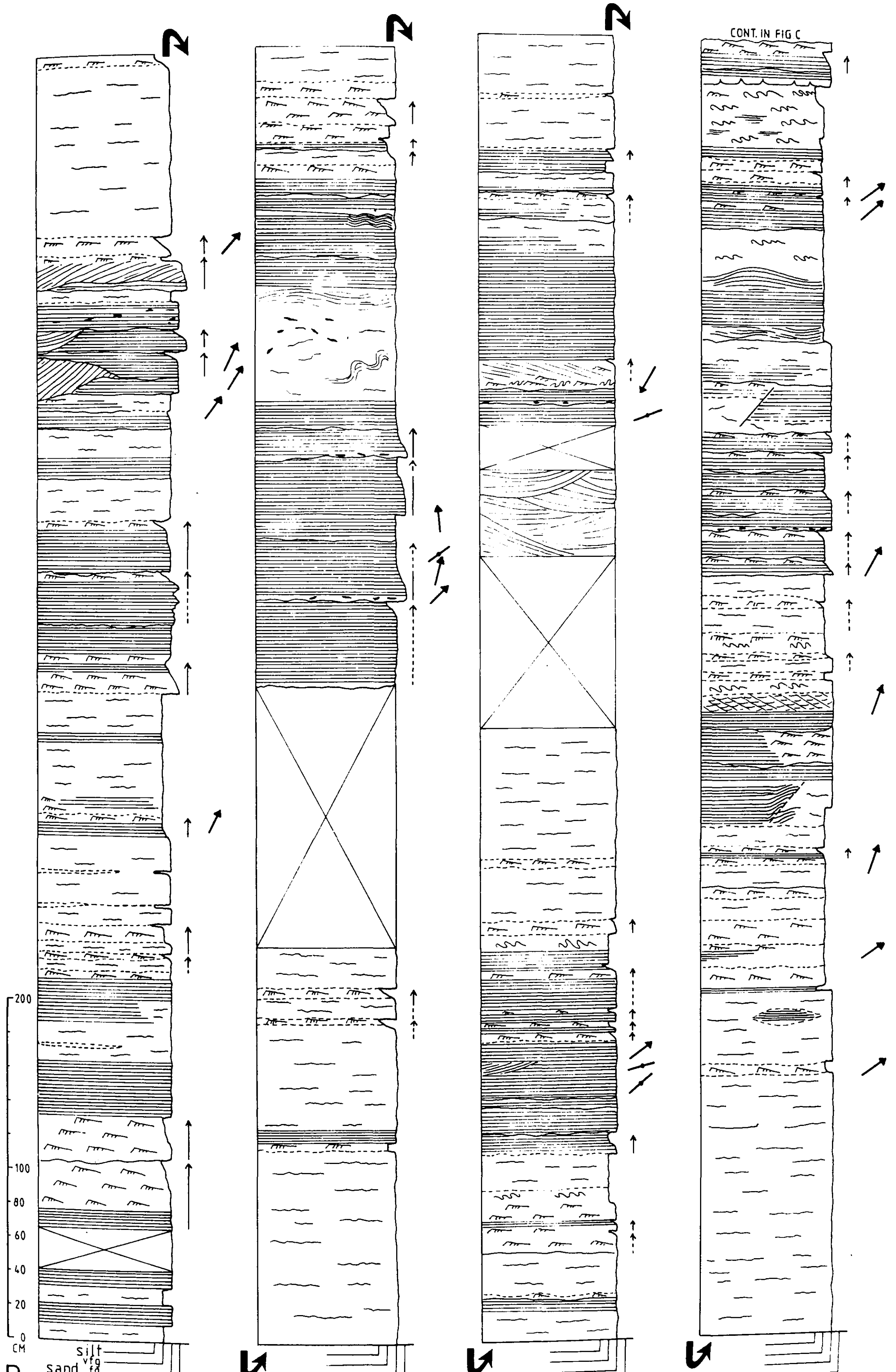
The sandstones of Facies F1 deposits appear either fairly massive and homogeneous

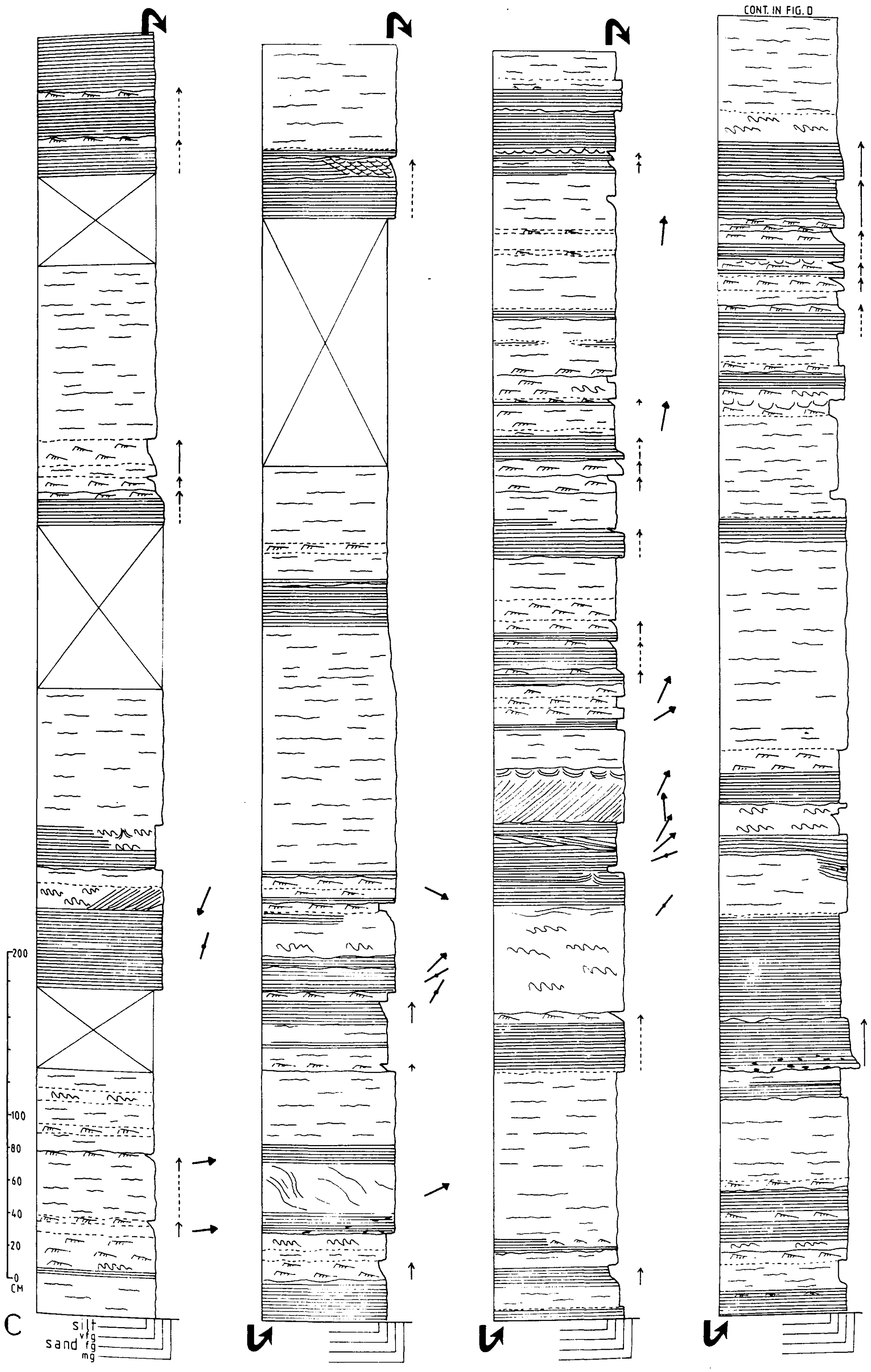
Figure 7.2.16. A-D: Graphic logs showing vertical distribution of Facies F1 and F2. (Locality: Beinn Dhorain and Ben Uarie (**A-D**), and Ben Uarie (**D**)).

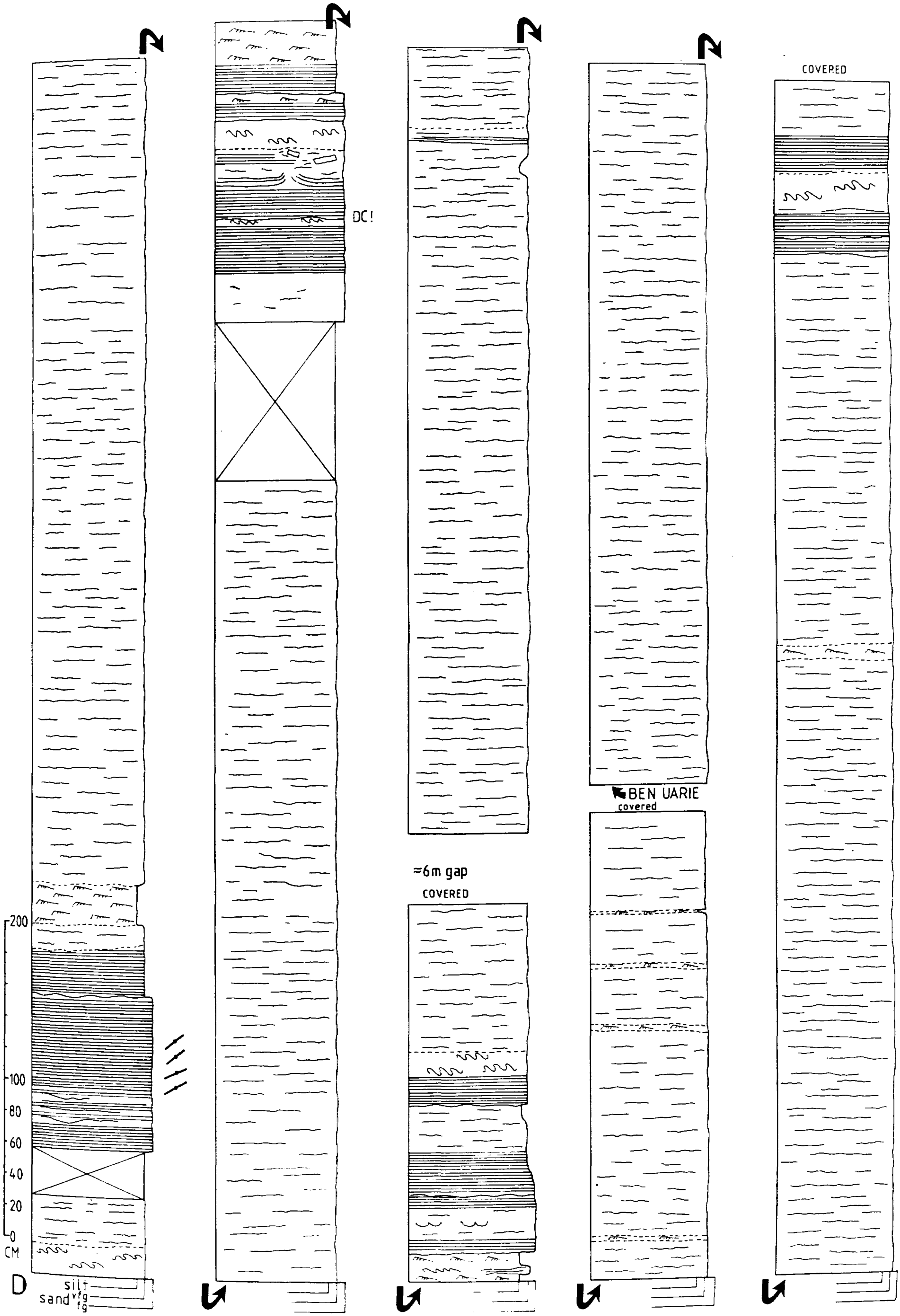
Key: **1** - shear-layered to massive deposits (Facies F1); **2** - planar stratification and wavy lamination; **3** - cross stratification; **4** - current ripple (climbing ripple) cross lamination; **5** - water escape pillars; **6** - synsedimentary faults; **7** - convolute lamination; **8** - non-erosional contact; **9** - erosional contact; **10** - palaeocurrent directions; **11** - strike of parting lineation; **12** - fining upwards and fining upwards at the top only; **DC** - desiccation cracks.




CONT. IN FIG. B
Covered
200
100
0
cm
A
SLT
VFG
FG
sand
DC


CONT. IN FIG C
200
100
80
60
40
20
0
CM
silt
vfg
sand fg
mg
B


CONT. IN FIG. D
200
100
80
60
40
20
0
CM
C
silt
vfg
sand
fg
mg


DC!
≈6m gap
COVERED
BEN UARIE
covered
COVERED
200
100
80
60
40
20
0
CM
D
silt
sand vfg
fg

(Plate 7.2.19.A&B) or, while being still rather structureless, display a distinctive textural heterogeneity. The latter feature is expressed in a form of abundance of partially remoulded intraclasts with different grain size distributions and variable amounts of clay matrix. They are basically whitish, sandy inclusions (or intraclasts) with none to low clay matrix content and dark-brown muddy material (Plate 7.2.15.A&B, 7.2.17.B-D). These both forms of sediment show various stages of mutual admixing, which, at a most advanced stage is total homogenisation.

The intraclasts may reach up to 30 cm in size (Plate 7.2.17.C), though they are generally smaller than 2 cm. Both muddy and sandy sediments are arranged into medium to small scale shear-layering and shear-lamination (for the definition see chapter 7.2.6.1.2.). The structures have an analogous form as in the case of Facies E1 and E2 and are typically pronounced by layer-parallel smeared out and boudinaged layers and phacoidal inclusions (Plate 7.2.15., 7.2.16., 7.2.17., 7.2.18., 7.2.19.). In the field the deposits in question may often appear completely structureless and only a polished slab or a thin section may reveal a faint shear-layering or shear-lamination. Although most of the intraclasts have an ellipsoidal form and are strongly aligned parallel to the bedding, many of them display very irregular outlines (Plate 7.2.17.B&C). Some appear as they have been "swirled" (Plate 7.2.15.A). In the sections parallel to the bedding, the sandy inclusions reveal no particular organised arrangement or alignment (Plate 7.2.18.B). Mica flakes and other long clasts appear to show no preferred orientation.

Syndepositional faults have been occasionally found cutting the shear-layered deposits of Facies F1 (Plate 7.2.19.D).

Regardless, whether the sandstones of Facies F1 appear massive or shear-layered, the rock typically displays horizontal to subhorizontal, undulatory parting planes. These features have not been found to be related to any textural nor structural facets of the sediments (Plate 7.2.17.A, 7.2.19.A&B). Their continuity and spacing vary considerably. In the deposits from the Ben Uarie Member the undulating parting features are from a few centimeters to a few meters long and a distance between them varies between 2 - 20 cm. No particular hierarchy of these structures have been recognized. The sandstones from Duchary Rock (Col-Bheinn Formation) show much less pervasive parting planes (Plate

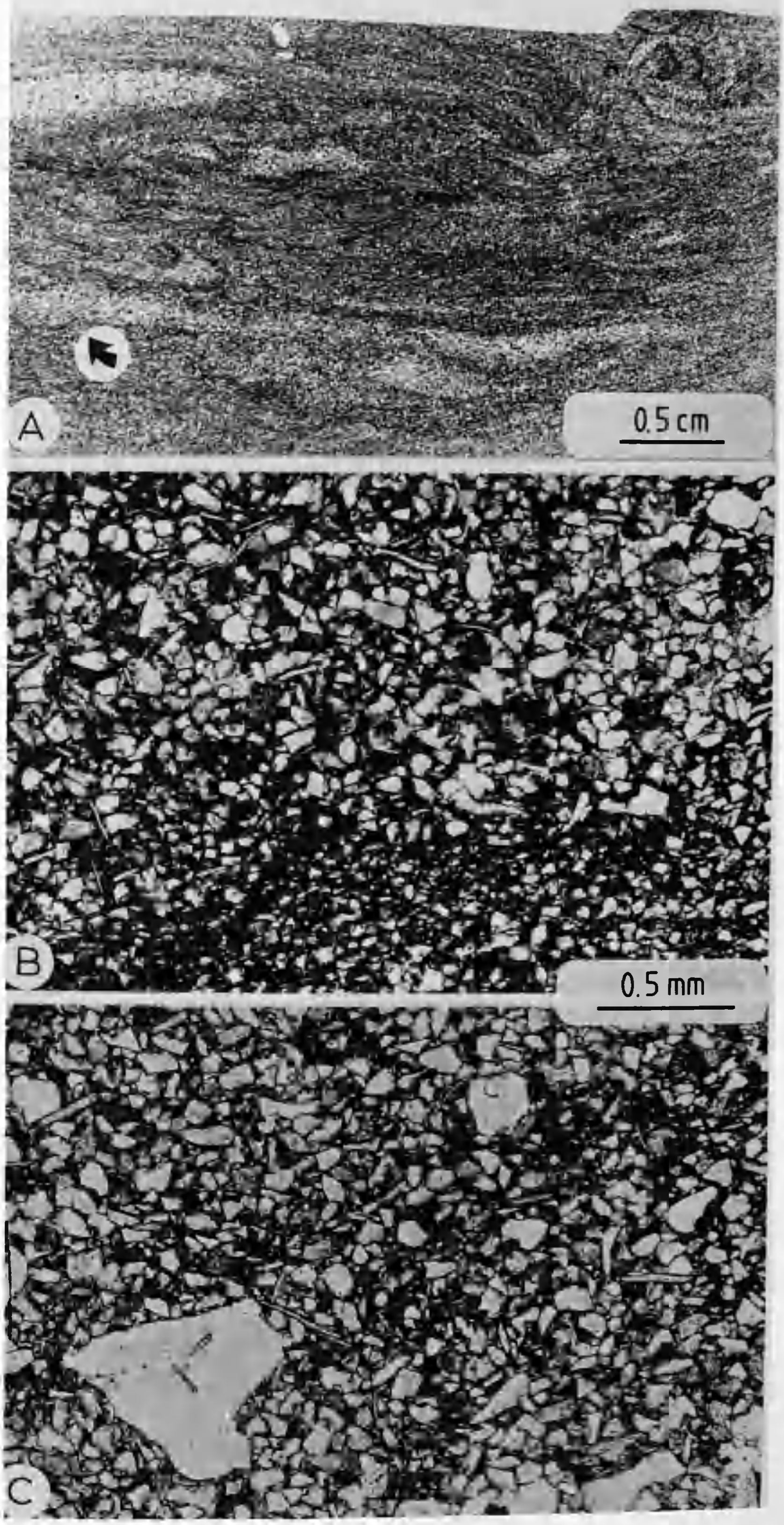
Plate 7.2.15. A-C: Deposits of Facies F1.

A: Photograph of thin section shows shear-layered muddy sandstone. Note folding of some of the intraclasts and a swirled feature in the lower left corner (PPL). (Locality: Duchary Rock, Col-bheinn Formation);

B: Close up photomicrograph of the area arrowed on the phot **A** (PPL). Note a good sorting of the sand fraction and a considerable amount of clay;

C: Photomicrograph shows textural details of the poorly sorted variety of Facies F1 (PPL). (Locality: Allt Smeorail (north of Beinn Smeorail), BUM)

Plate 7.2.15.



7.2.19.A & Fig. 7.2.20.). Planar parting surfaces are prominent and can be traced for tens of meters. The sandstones, separated by them are either totally massive or display much less conspicuous and much more discontinuous, undulating parting planes with a spacing in a range of a few centimeters. The planar surfaces of the parting planes display an irregular pattern of platy parting.

Locally, the massive sandstones have been found to contain oblate cavities, which are less then 2 cm in size and appear flattened parallel with the bedding (Plate 7.2.19.C).

Bed boundaries in the deposits of Facies F1 are unrecognizable and a significance of the parting planes with regard to this problem remains unknown. The Figure 7.2.13. shows a histogram of a number-frequency distribution of bed thickness data for 114 "beds" of Facies F1(data from the section at Beinn Dhorain, Fig. 7.2.16). In this particular case "beds" have been defined as deposits bounded from the top and from the bottom by the well defined beds of Facies F2 (see chapter 7.2.4.1.8.), regardless a possibility of them being amalgamated units. The data show an extremely broad, log-normal scatter, from 0.04 - 11 m. For the 80.7% of the data fall in the range between 0.04 - 1 m, with the "beds" from 0.04 - 0.25 m thick representing 67.2% of the entire population, it is believed that most of the Facies F1"beds" are composite amalgamated sedimentary units, made up of beds in a range of thickness from 0.04 - 0.25 m.

The basal contacts of the deposits of Facies F1 beds of Facies F2 (see the next chapter) are mainly abruptly gradational and either flat or moderately undulated. Facies F1 manifests in a form of sheets, with lateral extent increasing with increasing thickness and ranging from tens of centimeters to probably hundreds of meters (Duchary Rock, Fig. 7.2.20.).

A number of the "beds" of Facies F1 have been found to fine upwards in their uppermost parts into ripple cross-laminated deposits(Facies F2). Such couplets make up 23% of the entire examined population of the fining-upward beds and bed-couplets (Fig. 7.2.19.)

Plate 7.2.16. A & B: Deposits Facies F1.

A: Photomicrograph of thin section shows crude shear-layering in well sorted, very fine-grained sandstone. Muddy intraclasts have been smeared out along the horizontal shear plane; dextral sense of movement is inferred from the shape of the deformed intraclasts (see close up **B**) (PPL). (Locality: Allt Smeorail, BUM);

B: Close up photomicrograph of the central remoulded intraclast from the phot. **A**. Note a chaotic orientation of micas and other grains (PPL);

C: Photomicrograph showing well sorted, very fine-grained sandstone - the sample taken from the planar-stratified bed (Facies F2). Note a consistent alignment of the mica flakes unlike in Facies F1 above (PPL). (Locality: Beinn Dhorain, BUM)

Plate 7.2.16.

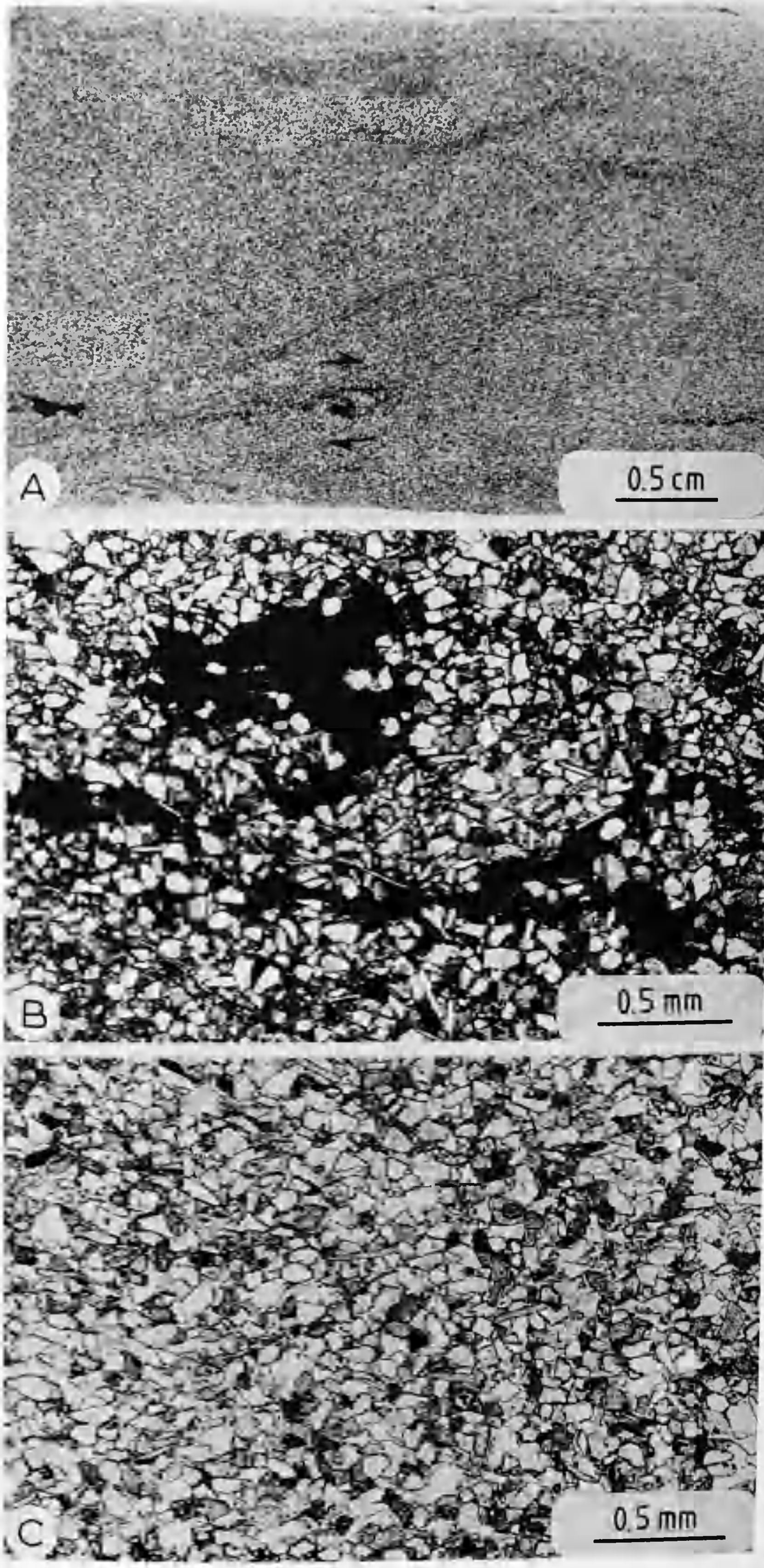


Plate 7.2.17. A-C: Deposits of Facies F1.

A: Pervasively shear-layered muddy sandstone. Discontinuous parting planes appear to be unrelated to any structural or textural features in the sandstones; they may represent some of the shear planes. Lense cap is 5 cm wide;

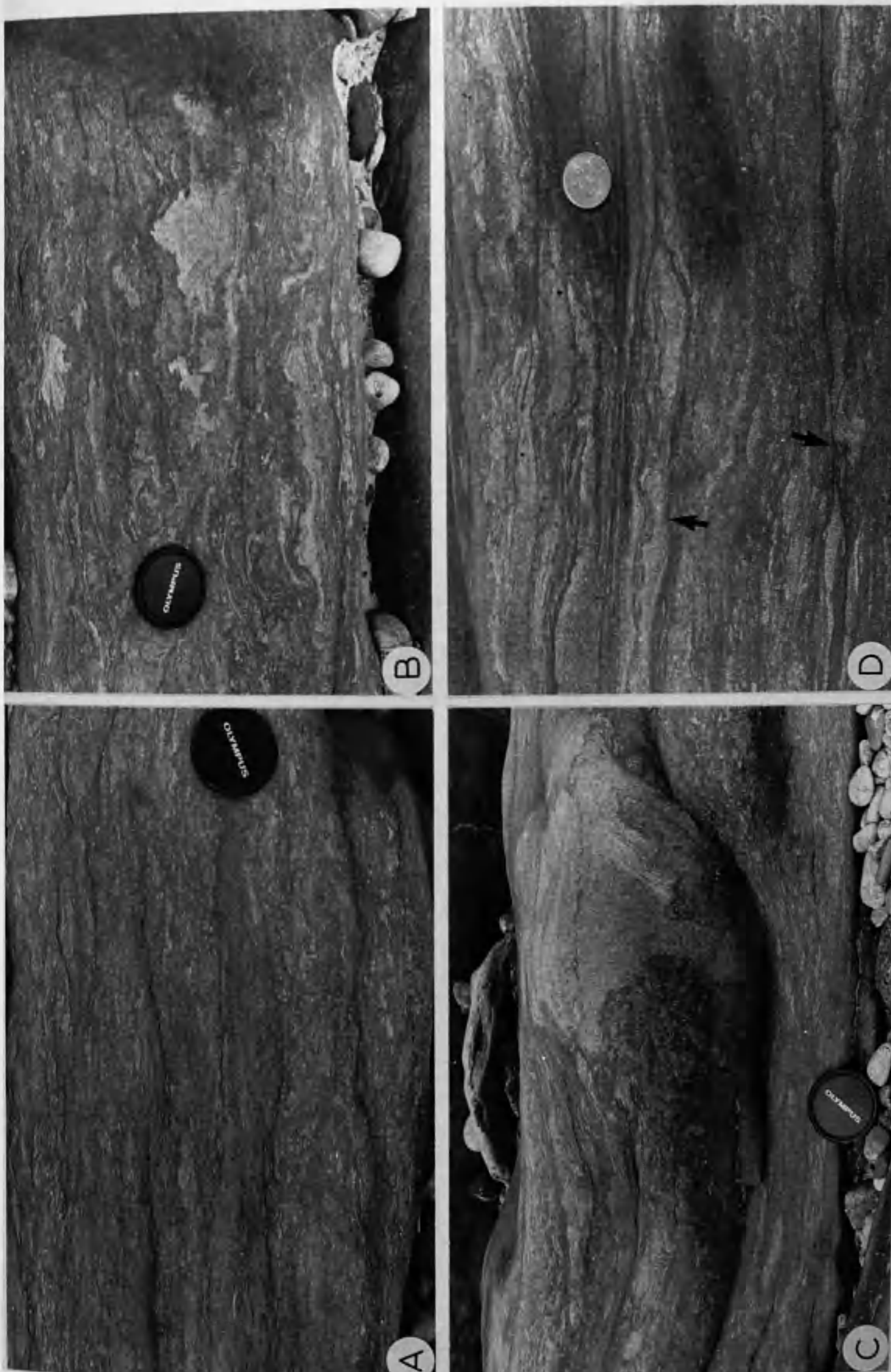
B: Another example of massive to shear-layered muddy sandstones. Note a much more irregular form of the intraclasts;

C: Exceptionally large sandy intraclast within the shear-layered deposits;

D: Boudinage and smearing out of the layers (intraclasts) (arrowed). The planar-stratified interbedding(Facies F2) is drapping the underlying boudinaged layer.

(Locality: **A-D** - SW of Cagar Feosaig [NH 831 032], Col-bheinn Formation)

Plate 7.2.17.



7.2.6.1.8. Facies F2: Planar-stratified, tabular/trough cross-stratified and ripple cross-laminated sandstones(siltstones)

In the Ben Uarie Member(BUM), exposed on the eastern slopes of Beinn Dhorain and Ben Uarie (Plate 7.2.10.), the stratified and laminated sandstones of Facies F2 accompany the massive and shear-layered sandstones of Facies F1 (Fig. 7.2.16.). In the stream section of Allt Smeorail, however, the minimum 230 m thick sandstone sequence is entirely represented by Facies F1.

The planar-stratified, trough cross-stratified and ripple cross-stratified sandstones and conglomerates, that accompany Facies F1 at Duchary Rock (Col-bheinn Formation) will be discussed in chapter 7.5.4.1. These deposits have been designated as a variety of Facies F2.

Description

Planar-stratified sandstones are predominantly very fine- to fine-grained and well sorted. They form beds in a range of thickness from 1 - 78 cm, with average 11.2 cm (Fig. 7.2.13.C). The bed thickness data display a log-normal number frequency distribution. It seems likely that some of the recorded "mega-beds" are products of amalgamation of thinner units.

The beds have a form of sheets and lensoid sheets with either erosional or rapidly gradational bases. The basal contacts are smooth to irregular and planar to broadly channelised. In the section oblique to the inferred palaeocurrent transport the lateral extent of the beds exceeds a several meters, but the maximum is unknown.

Abundant mudstone intraclasts are occasionally found above the bases of the beds (Plate 7.2.16.).

Individual laminae within the beds have a discontinuous attitude and their planar surfaces reveal parting lineation. Orientation of the latter, linear structures shows a very consistent SW-NE cluster (Fig. 7.2.21.). Mica minerals are typically oriented sub-parallel/parallel to the laminae (Plate 7.2.16.C). Locally, the planar laminae have been found "wrapping" irregularities of the underlying strata (Plate 7.2.17.D).

Asymmetric current ripple cross-lamination is generally developed in slightly finer-grained sandstones than the planar-stratification. Individual, well defined beds are 0.5 - 36 cm thick, averaging 7.3 cm, and the bed thickness data are characterised by a log-normal number frequency distribution (Fig. 7.2.13.C). Thickness of form sets thickness is between 1 - 3 cm.

The beds are generally sheet-like and lensoid in form. Their basal contacts are either erosional, flat to undulating or planar and abruptly gradational. A climbing ripple cross-lamination is locally developed with either erosional surfaces between the sets or with preserved stoss-side laminae. A climb angle varies between 5 - 10°.

Large scale trough cross-stratified sandstones form a marker horizon at the base of the Ben Uarie Member (Fig. 7.2.8.B & 7.2.17.). The large scale trough and tabular cross-stratified beds are, however, very rare higher up in the sequence (Fig. 7.2.16.). The large scale cross-stratification is developed in sandstones of a similar grade and sorting as the planar stratification. The beds are 5-100 cm thick, averaging 37.7 cm (Fig. 7.2.13.C), and the bed thickness data seem to approximate a normal number frequency distribution. They are usually erosionally based, though no major downcutting has been recognized. Some of the beds show reactivation surfaces (Fig. 7.2.17.). Mudstone intraclasts are common above the bases of the beds.

The beds of Facies F2 commonly show fining-upwards, which is normally restricted to their uppermost parts (Fig. 7.2.16., 7.2.17., 7.2.19.). The planar-stratified and large scale cross-stratified beds commonly pass upwards into finer-grained current ripple cross-laminated deposits. The planar-stratified beds passing into the "ripple-marked" members are clearly most abundant among such fining-upwards "couplets" (40.7% of the examined population of 81) (Fig. 7.2.19.). In one locality the planar-stratified beds fine upwards into parallel-laminated mudstones (Fig. 7.2.17.).

The mentioned above vertical transitions of the planar and cross-stratified sandstones into the ripple cross-laminated sandstones and siltstones have often been found to be associated with analogous trends in the down-current direction. The lateral structural transitions, however, do not always involve the grain-size change. Unfortunately no diagrams are available to demonstrate these lateral relationships.

Plate 7.2.18. A-C: Deposits of Facies F1 and F2.

A: Shear-layered muddy sandstones are seen at the base and at the top. Planar-stratified, fining-upward beds of Facies F2 with abundant intraclastic material are in the center of the photograph. Note flat and broadly scoured, erosional bases of the beds of Facies F2. Lense cap is 5 cm wide.;

B: On the planar bed surfaces the intraclasts (phacoids) in the shear-layered deposits appear chaotic and irregular (compare with the view of the plane normal to the bedding - A & C);

C: Planar-stratified sandy layer has been torn apart (boudinaged) within the pervasively; shear-layered muddy sandstones.

(Locality: **A-C** - SW of Cagar Feosaig [NH 831 032], Col-bheinn Formation)

Plate 7.2.18.

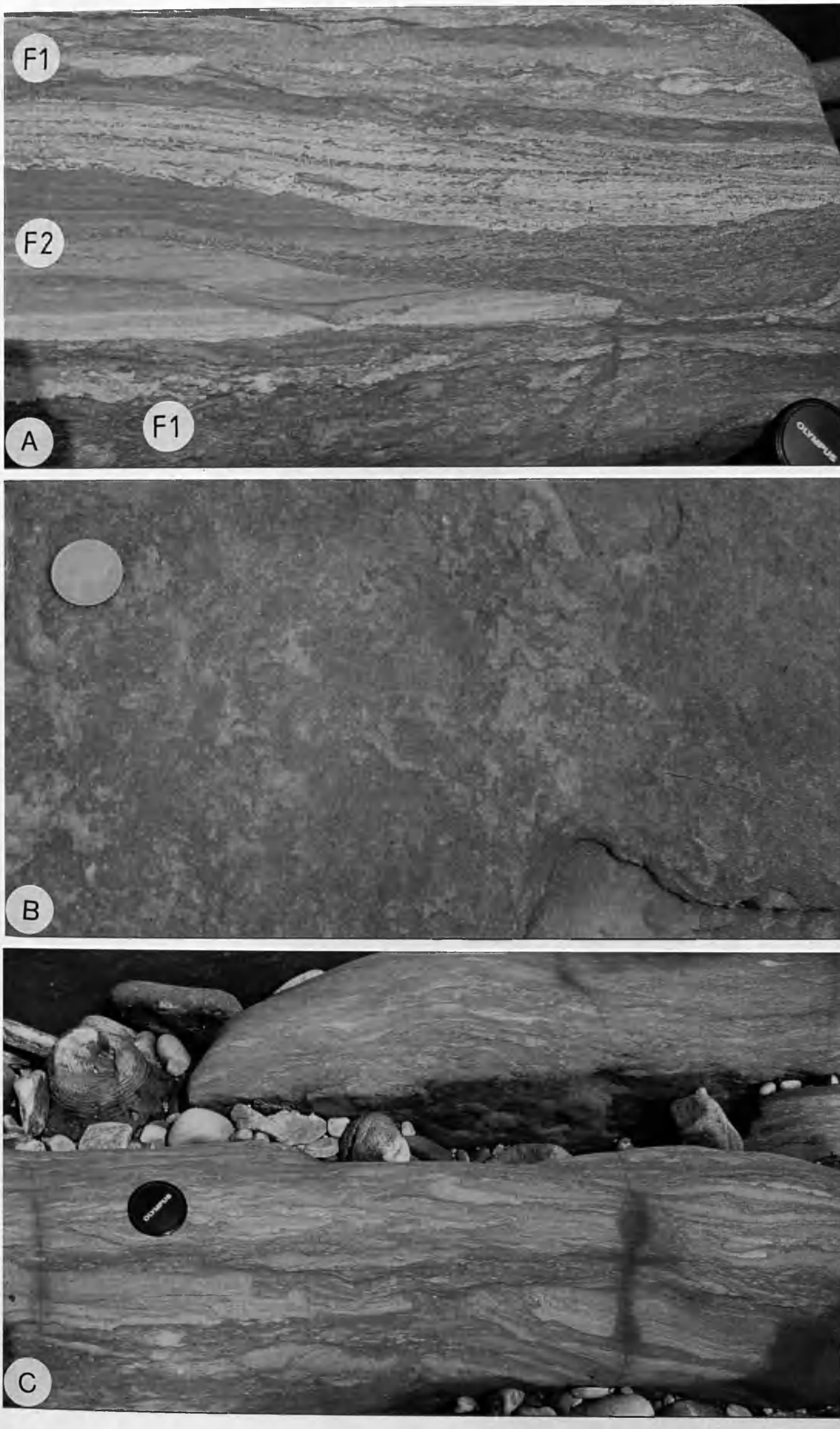


Plate 7.2.19. A-C: Muddy sandstones of Facies F1 from Duchary Rock (Col-bheinn Formation).

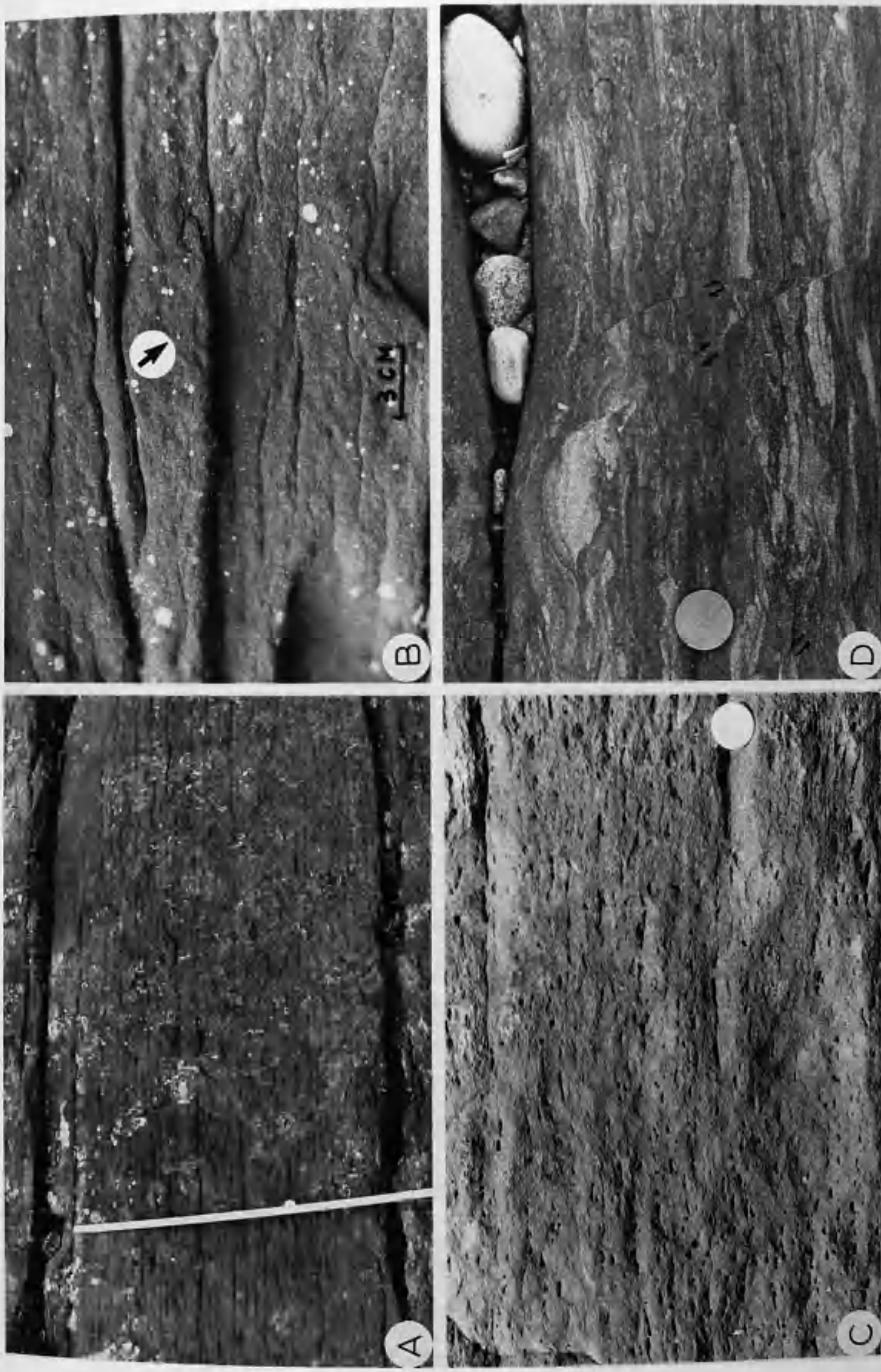
A: Here Facies F1 is represented by fairly massive and monotonous sandstones with pervasive, discontinuous parting planes. There is also a set of much more prominent and continuous planar parting planes (see also Fig. 7.2.20.). Ruler is 0.75 m long;

B: Close up of the nature of the parting features. The sandstone appears to be structureless with scattered sporadic granules (arrowed);

C: Shear-layered/massive muddy sandstones with abundant oblate cavities;

D: Syndepositional faults affecting the shear-layered muddy sandstones (Locality: SW of Cagar Feosaig [NH 831 032], Col-bheinn Formation).

Plate 7.2.19.



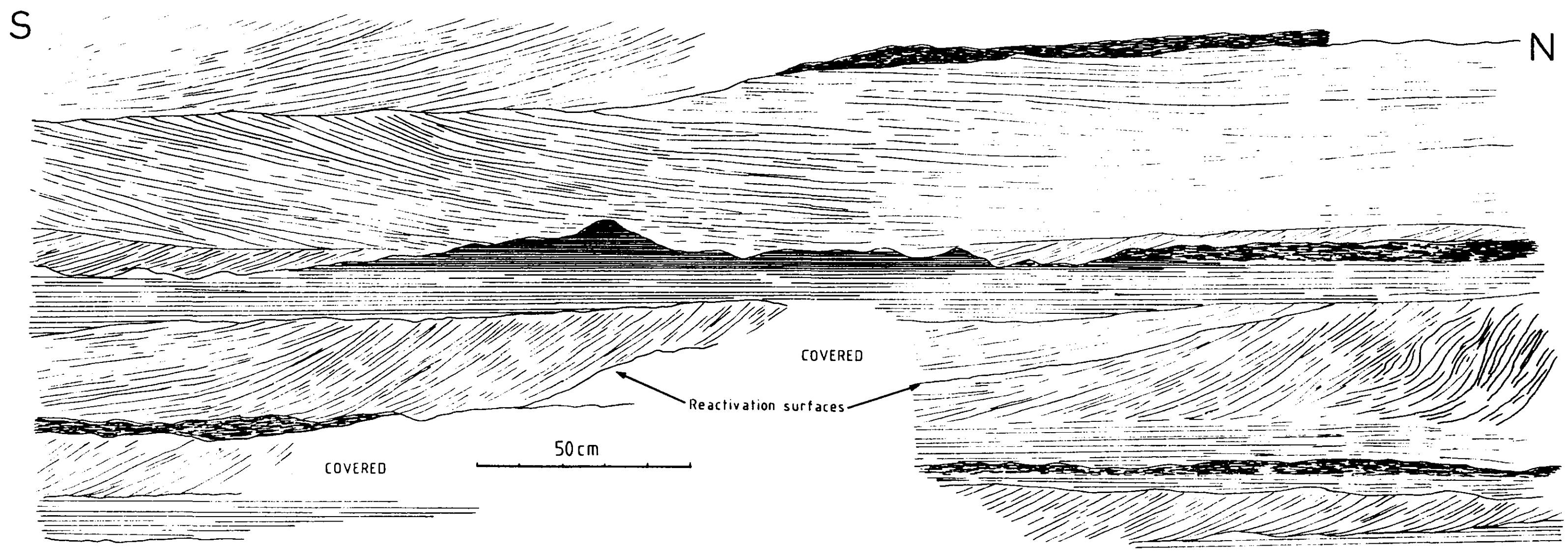


Figure 7.2.17. Drawing depicts trough cross-stratified sandstones of Facies F2 from the base of the Ben Uarie Member. The arrows indicate fining-upwards. (Locality: Beinn Dhorain).

The Facies F2 deposits frequently reveal features of soft-sediment deformations. A convolute lamination is most abundant, and appears to be mainly developed in the ripple cross-laminated and planar cross-stratified sandstones. The deformation is often so pervasive that the type of the original structure is unrecognizable. In a number of instances the degree of deformation decreases upwards into totally undeformed structured sandstones (Fig. 7.2.16.B&D). No dish structures (Lowe & LoPiccolo, 1974; Lowe, 1975) have been recorded. In a few beds water escape structures - Type A pillars *sensu* Lowe(1975) - have been found (Fig. 7.2.16.C). Load casts are occasionally present. The large scale cross-stratified beds display in places oversteepened laminae (Fig. 7.2.17.).

A considerable soft-sediment deformation, and sediment remoulding have locally been found to accompany syndepositional faults (Fig. 7.2.16.B).

It has to be emphasized that there is clearly a continuum between the beds with the convolute lamination and the massive to shear-layered sandstones of Facies F1. The deposits classified as Facies F1 have often been found in a transitional - vertically as well as laterally - relationship with Facies F2. The transition is usually relatively rapid, but the divide between the beds with strongly convolute lamination and the deposits of Facies F1 has often been drawn arbitrarily.

7.2.6.1.9. Facies F1 - Interpretation

Texturally and structurally the sandstones of Facies F1 resemble the muddy deposits of Facies E2 and there is in fact a number of beds, which though classified as Facies F2, seem to fall into a transitional category (Plate 7.2.8.B&C). Muddy sandstones exposed in the upper part of the Beinn Dhorain Member (BDM) contain only slightly more of the clay grade fraction than the Facies F1 sediments, that appear higher up in the sequence (Ben Uarie Member (BUM)). However, the deposits of Facies F1 from the Allt Smeorail section, as well as some of them exposed at Duchary Rock, Leadoch Rock (Col-bheinn Formation) have almost identical proportion of the clay content (Plate 7.2.15.) to that recorded in the muddy sandstones of Facies E2.

The shear-layering, passing often into massive, strongly homogeneous sediments, is common in both Facies F1 and E2 and the division between the two facies is arbitrary but based mainly on the differences in grain size distribution. Consequently, it is logical to account for a similar *en mass* mode of transport and deposition (see interpretation of Facies E2).

It is apparent that some of the deposits, classified as Facies F1, formed in a result of *in situ* liquefaction, possibly combined with fluidisation, of the previously laid down sands of Facies F2. This is strongly indicated by the convolute lamination, gradually disappearing upwards in some of the beds, and by the presence of water escape structures (Type A pillars, Lowe,1975). The formation of some of the convolute laminations might have, however, involved some downslope mass flowage (slumping).

It is very difficult to envisage, however, that most of the composite "beds" of Facies F1, up to 11 m thick at Beinn Dhorain and Ben Uarie, minimum 230 m thick in the Allt Smeorail section and at least 15 m thick at Duchary Rock, are a product of complete *in situ* liquefaction and fluidisation (Lowe,1976a). Evident water escape structures (dishes or pillars) have not been found in any of the deposits of Facies F1 and the jagged edges of the characteristic elongate intraclasts do not show a consistent upward bending, which could indicate an upward movement of fluid.

The overall geometry of the shear-layering and the shear-lamination in Facies F1 - the distinctive ellipsoidal, boudinaged form of the sandy and the muddy inclusions

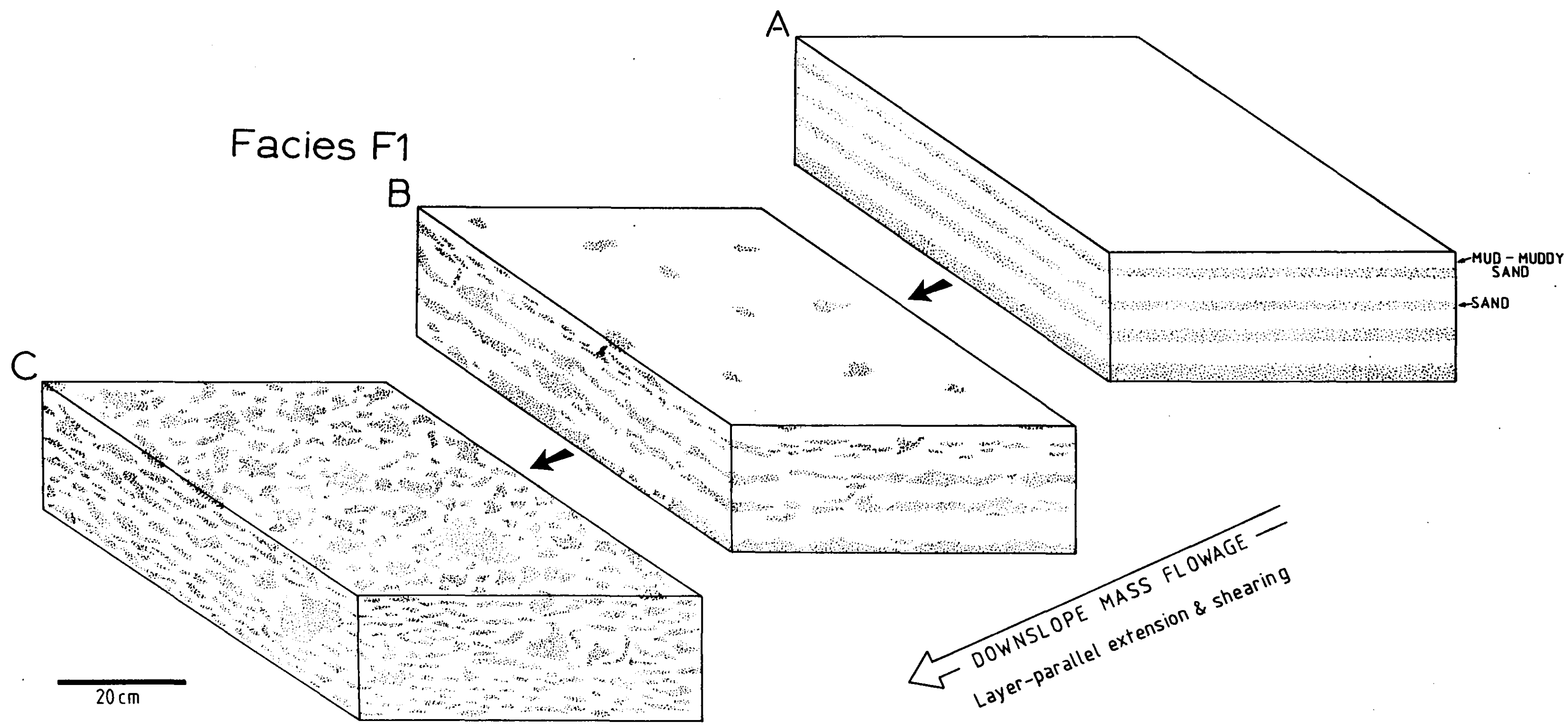


Figure 7.2.18. Inferred model of development of shear-layering in the muddy sandstones of Facies F1. The model is analogous to the one for Facies E1(Fig. 7.2.5.) and E2(Fig. 7.2.14.).

(intraclasts), presence of extensional synsedimentary faults combined with the general scarcity of folds and other compressional features, indicate an axially symmetrical, layer-parallel extension and shearing - the mechanisms analogous to the once proposed as responsible for development of Facies E1 and E2 (see also Cowan, 1982, 1985). Such an hydroplastic deformation is thought to have accompanied the mass flow emplacement of the muddy sandstones and sandstones.

The sandstones of Facies F1 are interpreted as a product of deposition from **sandy debris flows** in which some cohesive strength might have been imparted by the interstitial mixture of clay and water (Lowe, 1976a). The adjective "sandy" emphasizes the dominant fraction of the clastic material.

The strongly log-normal number frequency distribution of the Facies F1 "beds" from Beinn Dhorain (Fig. 7.2.13.B) suggests, that in the case of this particular section, thickness of individual flows was in the range of a few to 50 cm and that the thick "beds" represent a product of accumulation and amalgamation of many flows, rather than a result of emplacement of a few catastrophic *megaflows* (Lowe, 1976a). Poor definition of the bed boundaries may be a result of foundering of superimposed layers due to density instablities (Lowe, 1976a) or due to basal intermixing during the sandy debris fow deposition.

The sections in Allt Smeorail and at Duchary Rock provide no indicators regarding the thickness of the depositing sandy mass flows. Significance of the characteristic, discontinuous parting planes with regard to the latter problem remains essentially unknown though they may represent shear planes.

The widespread presence of the shear-layering within the deposits of Facies F1 suggests that the sandy debris flows were essentially thoroughly sheared at some stage during transport (laminar flow conditions). Mobilisation and evolution of the flows might have proceeded in a similar fashion as in case of the mudflows of Facies E1 and E2 (see chapters 7.2.6.1.4. & 7.2.6.1.5.). The trigger mechanism, however, might have been different (see discussion below).

The texture of the Facies F1 deposits suggests that sands in the source were relatively well sorted and only slightly lithified. Such sediments seem to have been prone to liquefaction (and possibly fluidisation) (Seed & Lee, 1966; Seed, 1968; Lowe, 1976a, Allen, 1982). These processes could have either acted as mechanism(-s) that triggered failure (*spontaneous liquefaction*), and could have consequently initiated mobilization of the sandy debris flows, or followed the failure. In either scenarios the liquefaction - collapse of the grain-framework - could have considerably improved mobility of the sandy debris flows, by reducing their internal, frictional resistance, and hence, could have increased their travel distance (Lowe, 1976a). No evident water escape structures have been recorded from the deposits of Facies F1, though these subtle features might have been destroyed during the mass flow transport. Pore fluid expulsion from the shear zones of active subaerial sediment gravity flows has been reported by Lawson (1982, p. 292).

A late stage thixotropy and the cohesiveness of the sediments might have acted in a reverse direction - shortening the travel distance of the sandy debris flows (Lowe, 1976a). It is thought that the cohesive strength, on the other hand, operated also as an important factor in supporting the coarser grains as well in reducing a dissipation rate of excess pore pressure (Pierson, 1981; see also chapter 7.1.5.1.4.). The later agent would again have improved the mobility of the sandy debris flows, by diminishing the frictional strength of the flows.

It is argued here that the development of the hydroplastic laminar shearing does not necessarily have to take place at the last stages of the mass flow movement, as has been indicated by Lowe, (1976a) and Enos, (1977). The observed in Facies F1 shear-induced features, the boudinaged or swirled intraclasts may well reflect the earlier stages of the mass flow transport, but became preserved - "frozen" - in the relatively non-deforming rigid plug (Fisher, 1982, see also chapters 7.2.6.1.4. & 7.2.6.1.5.). The progressive mass flowage and associated internal shear would have gradually led to a textural homogenisation of the deposited sands (Fig. 7.2.18.). In spite of the pervasive internal deformation, dispersive pressure, resulting from collisions and/or near approaches between silt to fine-grained sand particles, was probably negligible (Lowe, 1976b), and the sediment dispersion within the flows was maintained mainly by combined action of buoyant effect of the interstitial clay and water mixture, cohesion and possibly lift forces of the escaping pore fluid (Lowe, 1976b; Pierson, 1981; Lawson, 1982).

It is noteworthy that the deposits of Facies F1 display remarkable similarities with the sandstones of Jackfork Group and Atoka Formation (Pennsylwanian) Ouachita Mountains,USA, which according to Lowe(1976a, fig.4,5,6) may represent short traveled deep-sea liquefied flow deposits. The common sedimentary features are: (1) dominant silt to fine-grained sand fraction;(2) common thick composite sandstone beds consisting of thin sedimentation units without grading or other intervening deposits (3) lack of current structures; (4) massiveness or presence of lamination, caused by hydroplastic shear and (5) accompanying current generated deposits with water escape pillars and convolute lamination.

As has already been mentioned above, the term "sandy debris flow" has been introduced, instead of "liquefied flow", in order to stress the interpreted active role of the cohesive shear strength within the majority of the discussed Facies F1 sediment flows. Some of the clay depleted varieties of Facies F1 might, however, match the category of liquefied flows (Lowe, 1976a), in which the cohesive strength is generally negligible.

Some of the deposits designated as Facies F1 bear some superficial resemblance to a faint planar/wavy lamination produced by development of adhesion ripples in sebhka/playa environment (Glennie, 1970; fig 62). They are also similar to *contorted structures* and *brecciated laminae*, associated with interdune deposits (Kocurek, 1981).

Beds entirely produced by accretion of adhesion ripples have been found to be maximum 20 cm thick, averaging 8 cm (Upper Cambrian Galesville Sandstone; Kocurek & Fiedler, 1982). Hence, it appears that the deposition of dry sand by adhering to the wet land surface is grossly ineffective in producing thick sedimentary units, comparable to the once of Facies F1.

Adhesion ripples, which accrete most efficiently, produce a distinctive *pseudo-cross-lamination* (Kocurek & Fiedler, 1982). This structure has not been recorded from any of the deposits Facies F1. On bedding planes the adhesion ripples occur in a form of subparallel ridges and such features have not been observed in the studied case.

Sand accumulation during formation of *adhesion-plane-bed* is extremely slow and could not possibly have been responsible for the generation of the thick beds of Facies F1. Moreover, the accretion of the adhesion ripples takes place over a very narrow range of water contents, beginning on a totally saturated, just emergent surface, and ending when saturation level falls below 80%. Such an depositional cycle typically produces drying-upward units which begin with pseudo-cross-lamination passing into adhesion-plane-bed-lamination (Kocurek & Fielder, 1982). Such units are absent in Facies F1. It is also difficult to envisage that the conditions of "just emergent" wet depositional surface could be sustained for a longer period of time in the hot, arid climate (Rahn, 1967; Glennie, 1970; Williams, 1970, 1971; Picard & High, 1973; Frostic & Reid, 1977) with continuous deposition of air-borne sand.

In the light of the arguments presented above the "adhesion ripple option" - as an alternative possibility of the formation of the Facies F1 - has to be rejected. The features of Facies F1 like: the shear-layering, the size of some of the intraclsts, the irregular and roughly spherical shape of of some of them as well as the significant clay/silt content are incompatible with the aeolian origin.

A possibility that some of the beds of Facies F1 represent contorted and brecciated laminae of the interdune areas has to be also discarded for the are no dune deposits present (Kocurek, 1981).

Facies F1(similarly as Facies E1 and E2) displays no structures which might be identified as trace fossils (Ekdale *et al.*,1984), and consequently there are no evidence that the features of the sediments in question were produced by borrowing of organisms. The general regularity in geometry of the shear-layering additionally eliminates the possibility of bioturbations. The intraclasts, although roughly ellipsoidal, are far more irregular and do not resemble elliptical or circular cross-sections of randomly oriented borrows.

7.2.6.1.10. Subaqueous versus subaerial aspect of deposition of sandy debris flows - significance of the deposits of Facies F2

Although all the possible ancient analogs of the Facies F1 deposits, known to the present author, represent a subaqueous setting (Lowe, 1976a; Steel *et al.*, 1985), the corresponding modern sandy debris flows have been reported from the

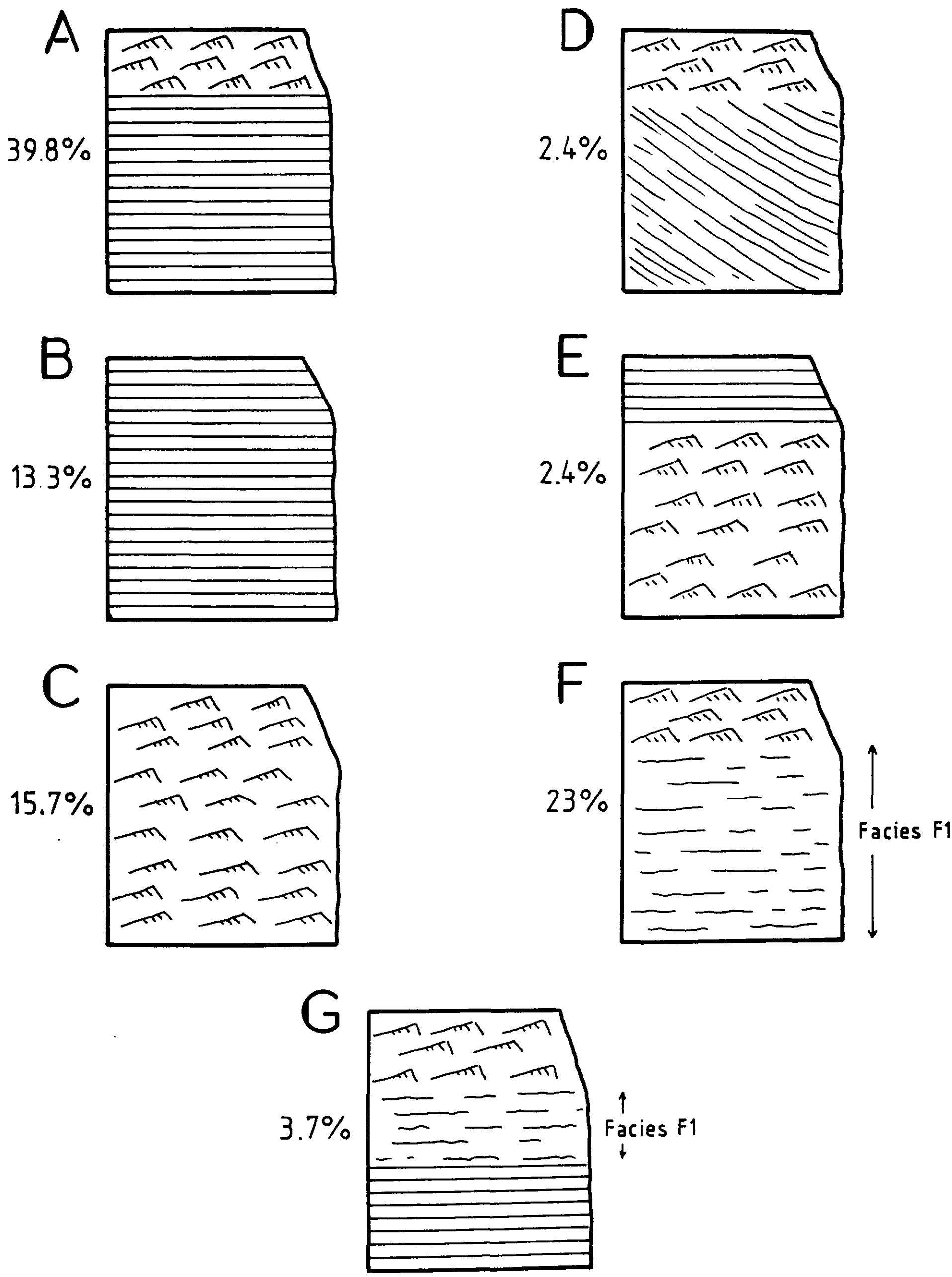


Figure 7.2.19. Types of fining-upward beds and bed-couplets (Facies F2 & F1) and their frequency in the measured sections.

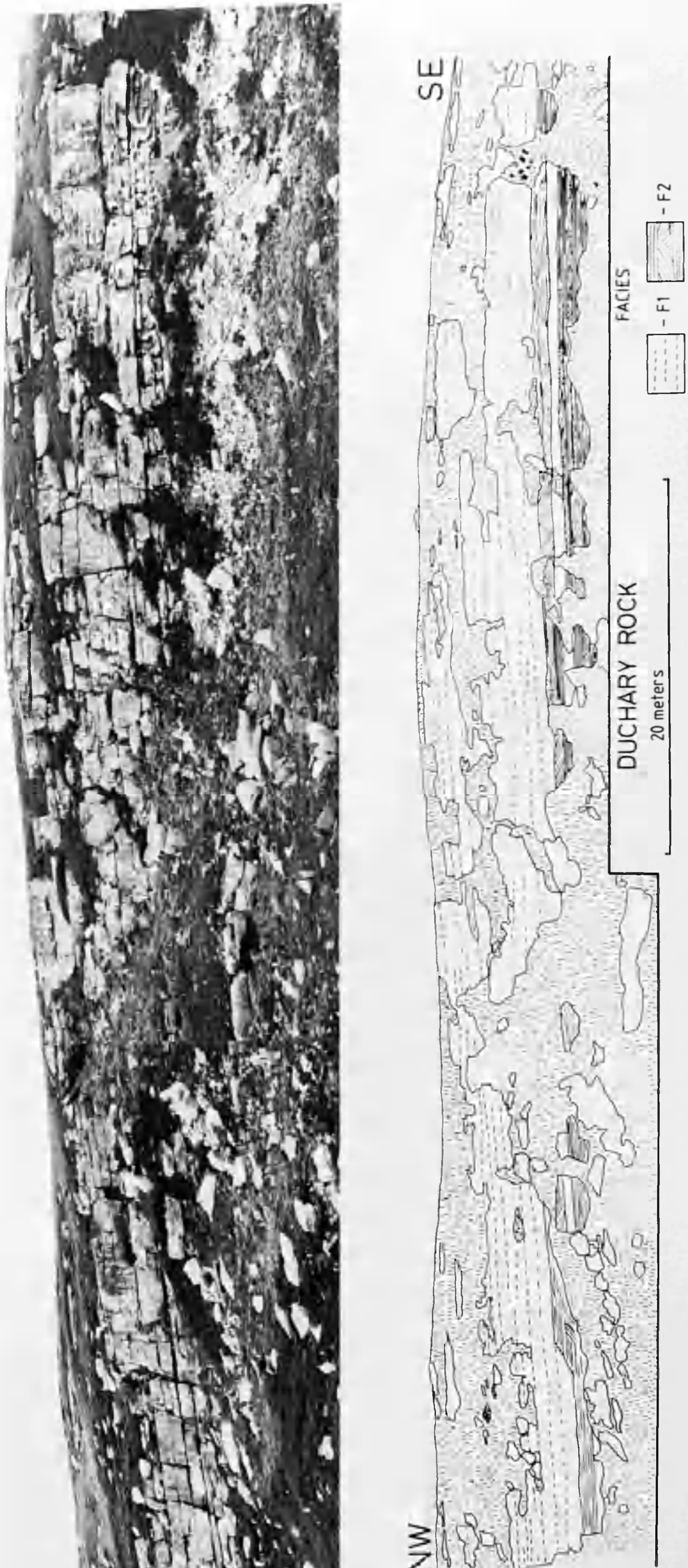
subaqueous(marine) (Tertzaghi, 1956; Bjerrum, 1971; Andresen & Bjerrum, 1967; Morgenstern, 1967 ; Field & Hall, 1982; Field *et al.*, 1982) as well as from the subaerial settings (Seed & Lee, 1966; Seed, 1967; Seed, 1968; Peackoc & Seed, 1968).

At Beinn Dhorain the deposits of Facies F1 are often interbedded with the planar-stratified and asymmetric, current ripple cross-laminated sandstones. The large scale, trough and tabular cross-stratification is rare and mainly confined to the basal portion of the Beinn Dhorain Member(BDM) (mostly trough cross-stratification) (Fig. 7.2.8.B & 7.2.16.). The beds of Facies F2 are ungraded, fining-upwards (mainly at the top) or form the fining-upward couplets (Fig. 7.2.19.). The discontinuous nature of the planar stratification, common erosional bases of the beds, their considerable thicknesses, the associated asymmetric, current ripple cross-lamination (including climbing ripples) and widespread presence of the parting lineation indicate conditions of the upper-stage flow regime (upper-stage plane bed) during deposition of the planar-stratified sands (Pickard & High, 1973; Harms et al., 1982). It is likely that some of the sporadic thin planar-stratified beds, do represent the lower-stage flow conditions (Fig. 7.2.17.). The orientation of the parting lineation shows a strong cluster, which is in accord with the unimodal orientation of the ripple cross-laminae and the large scale cross-strata. This suggests that in the Beinn Dhorain - Ben Uarie area, apart from the basal part of the BUM, the sands of Facies F2 were deposited from predominantly unidirectional currents flowing to the NE (see also chapter 7.2.6.16.). No palaeocurrent data are available from the Allt Smeorail section and from Duchary Rock and Leadoch Rock.

In view of the presence of the desiccation cracks, found in the Beinn Dhorain section (Fig. 7.2.16.A,D) and, on the other hand, lack of any evidence that could directly indicate a subaqueous setting of the sedimentation of the Facies F1 and F2, the both facies are believed to have formed in a **subaerial environment.** The oblate cavities, elongated parallel to the bedding (Plate 7.2.19.C), found in some of the Facies F1 deposits in all three main localities, may represent air bubbles, trapped by the sandy debris flows, travelling on a dry land surface (?) (Sharp & Nobles, 1953; Crandell & Waldron, 1956; Bull, 1964).

The generally flat based, sheet-like beds of Facies F2 are thought to have been deposited from short-lived, unconfined, sand-laden **sheetfloods** (McKee *et al.*, 1967;

Figure 7.2.20. Photograph and attached diagram of the SW face of Duchary Rock (Col-bheinn Formation) demonstrates a considerable continuity of the Facies F1 sandstone sheets as well as their impressive thickness.


SE
NW
DUCHARY ROCK
20 meters
FACIES
- F1
- F2

Scott *et al.*, 1969; Williams, 1970; Stear, 1983,85; Tunbridge, 1981a,b; Graham, 1983), that operated during or/and between the periods of the sandy mass flow activity.

Planar-stratification commonly occurs in deposits of meandering and braided streams (Harms & Fahnestock,1965; McGowen & Garner, 1970; Harms *et al.*, 1982 and others) but the structure is invariably subordinate to a large scale, tabular and trough cross-stratification. The scarcity of the latter structures in the studied deposits - apart from the lower part of the BUM (see chapter 7.2.6.1.16.) - and absence of channel features, do eliminate a possibility of interpretation of Facies F2 as deposits of channelised, stream flows.

The fining-upward beds and couplets, as well as the ungraded beds, represent conditions of rapidly waning flow stage (McKee *et al.*, 1967; Scott *et al.*, 1969). The most common among them (40%), the planar-stratified -> ripple cross-laminated couplets (Fig. 7.2.19.) represent a transition from the upper- to the lower-stage flow conditions, followed by a drop in competence. The planar-stratified or ripple cross-laminated only, fining-upward beds (15.7%) reflect a reduction in current velocity and in the competence within the range of either upper or lower-stage flow regime. The lack of fining-upward trends in many of the beds of Facies F2 as well as the absence of ripple cross-lamination above many of the planar-stratified beds may indicate a very sudden decline in the flow strength with no deposition at the lower-stage regime (McKee, *et al.*, 1967; Scott *et al.*, 1969; Jones, 1977). Such dramatic changes in the flow conditions are understandable, considering the tendency of the sheetfloods to a rapid, lateral spreading on the land surface.

The absence of the pronounced vertical grain-size segregation may also be due to the fact, that the sheetfloods of Facies F2 generally carried a very narrow range of clast sizes (very fine- to fine-grained sand). A possibility of erosion of the thin, fining-upward tops should also be taken into account.

The planar-stratified and ripple cross-stratified deposits may possibly be genetically related, and hence, the latter would represent distal equivalents of the former. In fact the planar-stratified deposits have been commonly found passing laterally in the downcurrent direction into the ripple cross-laminated beds (unfortunately except of the Fig. 7.2.16. no more detailed diagrams are available to demonstrate this). It is also noteworthy that the planar-stratified and ripple cross-laminated beds are characterised by similar number frequency distributions (Fig. 7.2.13.C) and that the former beds are generally thinner than the latter. Scott *et al.* (1969) documented similar proximal -> distal structural relationships from the deposits of the recent, hurricane generated, sandy sheetfloods (see also Tunbridge, 1981a, fig.9c).

The sheetfloods of Facies F2 originated probably through a surficial winnowing of the underlying, sheetflood and mass flow sands (McKee *et al.*, 1967; Williams, 1971). There is little evidence, however, to suggest that the laminar sandy debris flows evolved, through dilution, into the turbulent, upper/lower-stage, tractive currents. Although, the 23% of the examined, fining-upward beds and couplets do consist in the lower portion of the sandy debris flow member of Facies F1, fining rapidly into ripple cross-laminated deposits of Facies F2 (Fig. 7.2.19.), no two-dimensional exposures demonstrate unequivocally the corresponding, lateral trend. Neither there are any sufficient data nor published works regarding the lateral variability of the internal structure in the recent as well as the ancient analogs for the discussed here deposits. Therefore, it is safer at the present stage to suggest only that the finer-grained, ripple cross-laminated members of the F1 -> F2 couplets may be a product of deposition from tractive currents, directly following the emplacement of the sandy debris flows and possibly surficially reworking their deposits (Lowe, 1976a). The fact that no beds of Facies F2 have been found, as intervening in many thick, composite beds of Facies F1, may indicate that the action of tractive currents was not an intrinsic phenomena of the sandy debris flow sedimentation.

The well sorted very fine to fine grained sands of Facies F2 were deposited fairly rapidly and for being loose, containing little clay, and hence, very porous, they must have been particularly susceptible to the liquefaction (Kolbuszewski, 1950; Seed, 1968; Peacock & Seed, 1968; Seed, 1968; Tunbridge, 1981a; Allan, 1982). In fact the beds of Facies F2 commonly display the soft-sediment deformations. In is believed that the liquefaction could have led to a failure and to a remobilisation of the sheetflood deposits and consequently to an initiation of a secondary generation of sandy debris flows. The syndepositional faults, associated convolute lamination, as well as the rapid lateral transitions of the Facies F2 beds into Facies F1, occasionally with a zone of the soft-sediment-deformed deposits between them, may represent of the latter processes of remobilisation. The remoulded, clay-enriched mass flow sands, being considerably more compacted and less porous than the source sediments, would have been much less prone to liquefaction (Seed & Lee, 1966; Lowe, 1976a; Allen, 1982). The liquefaction of these deposits would have been more likely to occur, if aided by water, squeezed out of the subjacent sediment during loading (Lowe, 1976a); though again no water escape features have been found in the deposits of Facies F1, and the synsedimentary faults, recorded in one locality (Plate 7.2.19.D), are not accompanied by liquefaction features.

The large scale cross-stratified beds(mainly trough cross-stratified) of Facies F2 are most abundant in the basal part of the Ben Uarie Member (BUM). They are occasionally arranged in fining-upward units, with ripple cross-laminated or parallel-laminated deposits at the top. In the upper part of the BUM the large scale trough and tabular cross-sets are much less common and have smaller thicknesses. Limited outcrops permit only to conclude that these beds formed in a process of migration of megaripples (three-dimensional large ripples, dunes) or two-dimensional large ripples (Harms *et al.*, 1982), within a network of possibly more channelised, though still ephemeral unidirectional flows, whose depths were sufficient for development of bedforms with minimum hight of 1 m (Fig. 7.2.13.C). The locally developed reactivation surfaces (Fig. 7.2.17.) mark changes in flow stage over the bedforms (Collinson, 1970). The opposite palaeocurrents between the basal part of the BUM (Fig. 7.2.8.B & 7.2.21.) and the remaining, upper portion of the sequence are discussed further in chapter 7.2.6.1.16.

7.2.6.1.11. Facies E1, E2 and F1 and some features of melanges associated with accretionary wedges

The shear-layering and shear-lamination, characterizing the deposists of Facies E1, E2 and F1 do strikingly resemble style of deformation of layer-parallel sheard and disrupted sediments in some of the melange units *(Type 1* melange in Cowan, 1985) that occur in a setting of an accretionary wedge of active convergent margins (Helwing & Emmet, 1981; Sakai, 1981; Aalto, 1982; Bachman, 1982; Cowan, 1982, 1985; Byrne, 1985).

There is a number of motifs which are common in both suites of rocks (Fig. 7.2.5a.):

(1) boudinage of primary layers;

(2) pinch-and-swell structures;

(3) roughly ellipsoidal, rather than prolate form of the resulted inclusions;

(4) absence of folds or other compressional features, that could indicate a layer-parallel shortening;

(5) local intrastratal extensional faulting.

Significant differences between the two groups of sediments are:

(1) absence of cataclasis and granulation in the deposits of Facies E1, E2 and F1 while scarcity of the minor deformation of grains has been reported by Cowan (1982) from Franciscan sediments near Piedras Blancas, California; much more significant cataclasis characterizes the Ghost Rocks melange (Byrne,1985);

(2) zones of disrupted deposits may reach hundreds of meters in thickness, though these units can be as thin as a few centimeters.

While purely sedimentary - mass flow genesis of the layer-parallel extension and shearing appears to be rather troublesome to document in the melange context for arising difficulties in separating sedimentary signatures from tectonic imprints (Cowan, 1982, 1985; Underwood, 1984; Bell, 1987), in the case of Facies E1,E2 and F1 the sedimentary origin of the shear-layering and shear-lamination is evident and a possibility of the tectonic impact upon the development of these structures has to be discarded on the following grounds:

(1) slight overall, post-depositional deformation: the shear-layered strata occur within a

broad syncline and their dip varies from 70 - 0^{o} (Fig. 3.3.);

(2) the facies in question are interbedded in places with laminated/stratified deposits(Facies E3 and F2) and the deposition of some of them was preceded by erosion and reworking of the underlying shear-layered substrate (Plate 7.2.17.D);

(3) lack of either cataclasis or granulation of the particles;

(4) textural features of the deposits does independently indicate mass flow emplacement (chaotic mudstones and pebbly mudstones).

At present no unequivocal evidence are available for the purely sedimentary genesis of layer-parallel extension and shearing, with regard to some of the accretionary prism related melange units, especially to the Type 1 of Cowan (1985). The documentation of the shear-layering and the shear-lamination (Facies E1, E2 and F1) and the recognition of its entirely sedimentary origin, offer a useful tool which may help to elucidate the evolution of some of the problematic melange units in accretionary prisms and in particular it may help to distinguish sedimentary and tectonic signatures.

7.2.6.1.12. Petrographic characteristics of the Glen Loth Formation (Beinn Dhorain Member and Ben Uarie Member)

Beinn Dhorain Member (BDM)

The BDM is characterised by the presence of three main textural-petrographic components:

(1) The **arkosic detritus** is confined to the lowermost part of of the BUM (Glen Sletdale section) and it forms primarily the gravel fraction of the conglomerates and muddy conglomerates of Facies E1. It occurs also in the subordinate proportions in some of the deposits of Facies E2. It is present in a similar context in the Ceann Ousdale section(Badbea basin) (Fig. 7.2.21. & 7.2.22.).

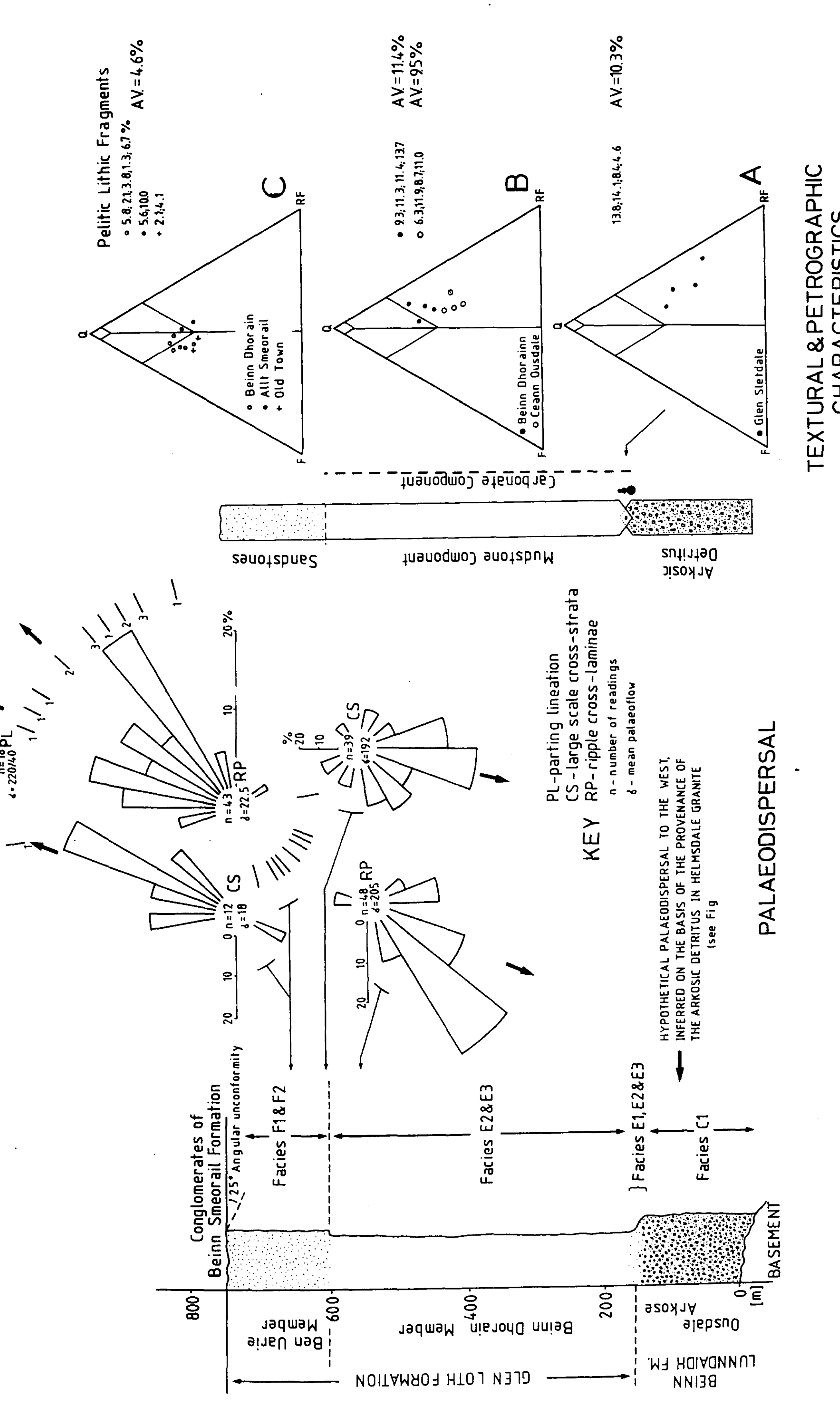
The arkosic component appears petrographically identical to the material which makes up the Ousdale Arkose conglomerate (Beinn Lunndaidh Formation), and it has been evidently derived from the Helmsdale granite, and probably mainly from its porphyritic part. There are no evidence for the fine-grained type of the Helmdsale granite contributing the detritus. Orthoclase is the most distinctive constituent of the arkosic detritus and forms the largest particles. It shows little alteration and only occasionally calcite appears in narrow cleavage-related cracks. The plagioclase, albite - oligoclase, is usually altered to calcite, fine-grained mica and aggregates of iron-oxides and chlorite. The calcite tends to penetrate the crystals along the twining planes.

Quartz clasts are generally smaller and often marginally replaced by calcite. Quartz and K-feldspar overgrowths are extremely scarce or absent in the muddy deposits.

It is likely that along the base of the BDM the arkosic material is gradually "substituted" by the Moine clasts, depending on the lithological nature of the underlying conglomerates and the basement.

(2) The **mudstone component** appears rapidly in the profile of the BDM (Fig. 7.2.1.). It typifies Facies E2, though it also occurs subordinately as matrix in some of the conglomerates and pebbly mudstones of Facies E1. In the latter facies the mudstone component, apart from being petrographically distinct from the coarser material (see below), it is usually very well defined, due to the gap in grain size between gravel and silt

Figure 7.2.21. Summary diagram of sedimentary and petrographic characteristics for the Beinn Lunndaidh and the Glen Loth formations in the NE part of the Golspie basin.


PALAEODISPERSAL
TEXTURAL & PETROGRAPHIC CHARACTERISTICS
Pelitic Lithic Fragments
AV.=4.6%
AV.=11.4%
AV.=95%
AV.=10.3%
C
B
A
Beinn Dhorain
Allt Smeorail
Old Town
Ceann Ousdale
Glen Sletdale
Carbonate Component
Sandstones
Mudstone Component
Arkosic Detritus
KEY
PL-parting lineation
CS-large scale cross-strata
RP-ripple cross-laminae
n - number of readings
δ - mean palaeoflow
HYPOTHETICAL PALAEODISPERSAL TO THE WEST, INFERRED ON THE BASIS OF THE PROVENANCE OF THE ARKOSIC DETRITUS IN HELMSDALE GRANITE (see Fig
Conglomerates of Beinn Smeorail Formation
25° Angular unconformity
Facies F1&F2
Facies E2&E3
Facies E1,E2&E3
Facies C1
BASEMENT
Ben Uarie Member
Beinn Dhorain Member
Ousdale Arkose
GLEN LOTH FORMATION
BEINN LUNNDAIDH FM.

to finer fractions. This creates a strong bimodality of the pebbly mudstones of Facies E2 and E1.

In the Ceann Ousdale section(Fig. 7.2.2.) the mudstone component occurs mainly as matrix in the muddy conglomerates and pebbly mudstones of Facies E1. The bimodality, however, is here much less conspicuous.

In the BDM(Golspie basin), the introduction of the muddy material (rapid transition into Facies E2-dominated part of the member) is associated with a dramatic, though gradual, disappearance of the arkosic coarse-grained detritus (Fig. 7.2.21.). In the Ceann Ousdale section(Badbea basin) no such significant changes in composition are apparent, though there is a dramatic "switch" in an environment of deposition, represented by the transition into the conglomerates, sandstones, mudstones and limestones of Facies G1 (see chapter 7.2.6.1.14.).

The most distinctive petrographic signature of the mudstone component is particularly high proportion of low-grade metamorphic, pelitic lithic fragments (PLF) (for details see chapter 7.4.5.1.3.) in the analysed very fine to fine-grained sand fraction. It ranges from 4.6 - 14.1% and averages 10.3 and 11.4% for analysed pebbly mudstones and muddy sandstones respectively (Fig. 7.2.21.C) . They appear as angular to well rounded clasts. Granulite, mica-schists and granitoid, angular rock fragments constitute 13.8 - 5.5% of the total sampling target (400). The two, exceptionally low PLF values (4.6 and 8.4%), obtained from the pebbly mudstones (Fig. 7.2.21.C), are due to a high proportion of the counted granitic, and Moine rock fragments. The mudstone component is rich in muscovite (3.0 - 7.3%). The muscovite shows often iron-oxide-stained clay alterations developed between the sheets of mica flakes. Biotite is present as relatively large grains, normally altered to chlorite and iron-oxide. Feldspars are also considerably altered; mostly through fine-grained mica, clay and calcite replacement. They are represented by K-feldspar (15.8 - 7.8%) and plagioclase (0.5 - 2.5%). Quartz is mainly monocrystalline, and similarly as feldspars, occurs as angular to subangular clasts. Garnet, rutile, zircon, apatite and detrital chlorite have been found in trace amounts. The amount of clay in the mudstone component ranges between 30 - 100%. XRD analyses of the clay fraction from four representative samples revealed, apart from quartz, fedspars and muscovite, presence of illite and chlorite

(Fig. App.2.F-I).

(3) The **carbonate component** is represented by micritic/dismicritic calcite and it appears mixed in widely variable proportions with the arkosic detritus and mudstone component . It is present in the BDM as well as in the equivalent deposits in the Badbea basin(Ceann Ousdale section). In the BDM the carbonate is most abundant in Facies E2, whereas in the Ceann Ousdale section it is apparent mainly in Facies E1 (for details see description of Facies E1, E2 and E3).

Ben Uarie Member (BUM)

Sandstones - The very fine to fine-grained sandstones from the area of Beinn Dhorain and Ben Uarie are generally well sorted with regard to the sand fraction. The Facies F1 deposits contain higher proportion of clay fraction than the stratified associated sediments (Facies F2). The sandstones exposed in the section of Allt Smeorail and in Oldtown are less sorted and contain more argillaceous material than the sandstones in the former area.

The BUM sandstones display a fairly consistent petrographic characteristics (Fig. 7.2.21.C). They are significantly different with regard to the content of the pelitic lithic fragments (PLF) from the mudstone component of the Beinn Dhorain Member(BDM). It varies from 1.3 - 6.7% and averages 4.6 %. Proportion of high-grade metamorphic (Moine?) and granitoid rock fragments ranges between 12.0 - 7.8%(av. 10.5%). Muscovite is abundant and its average proportion in the Beinn Dhorain - Ben Uarie area is 2.6%. Biotite occurs in trace amounts. The sandstones from Oldtown and Allt Smeorail contain a higher proportion of muscovite (av. 4.3%). Biotite is also more abundant (av.2.2%). The micas have similar features as described above for the mudstone component.

Monocrystalline quartz is dominant. The polycrystalline variety appears in trace amounts.

K-feldspars (mostly orthoclase, trace microcline) (17.7 - 27.0%, av. 23.2%) and plagioclases(albite-oligoclase) (2.3 - 0.3%, av. 2.3%) display variable degrees of alteration, normally to fine-grained mica and clays. The plagioclase is occasionally affected by calcite replacement.

Detrital chlorite, garnet, rutile, quartz with vermicular chlorite, andalusite and rutile have been found in trace amounts.

The detrital grains are unevenly coated by mixture of iron-oxide and clay. Quartz overgrowths are the most common form of cement, particularly in the less muddy sandstones from the Beinn Dhorain - Ben Uarie area. Content of the silica cement varies there from 16.8 - 8.2% (av. 11.3%). Calcite cement, postdating the formation of the quartz overgrowths, is locally present in proportion of up to 11.5%. The calcite cement is much more abundant (up to 14.0%) in the more argillaceous sandstones in Old Town and Allt Smeorail. In the latter localities the quartz overgrowths are much less common and in some of the analyed samples are virtually negligible.

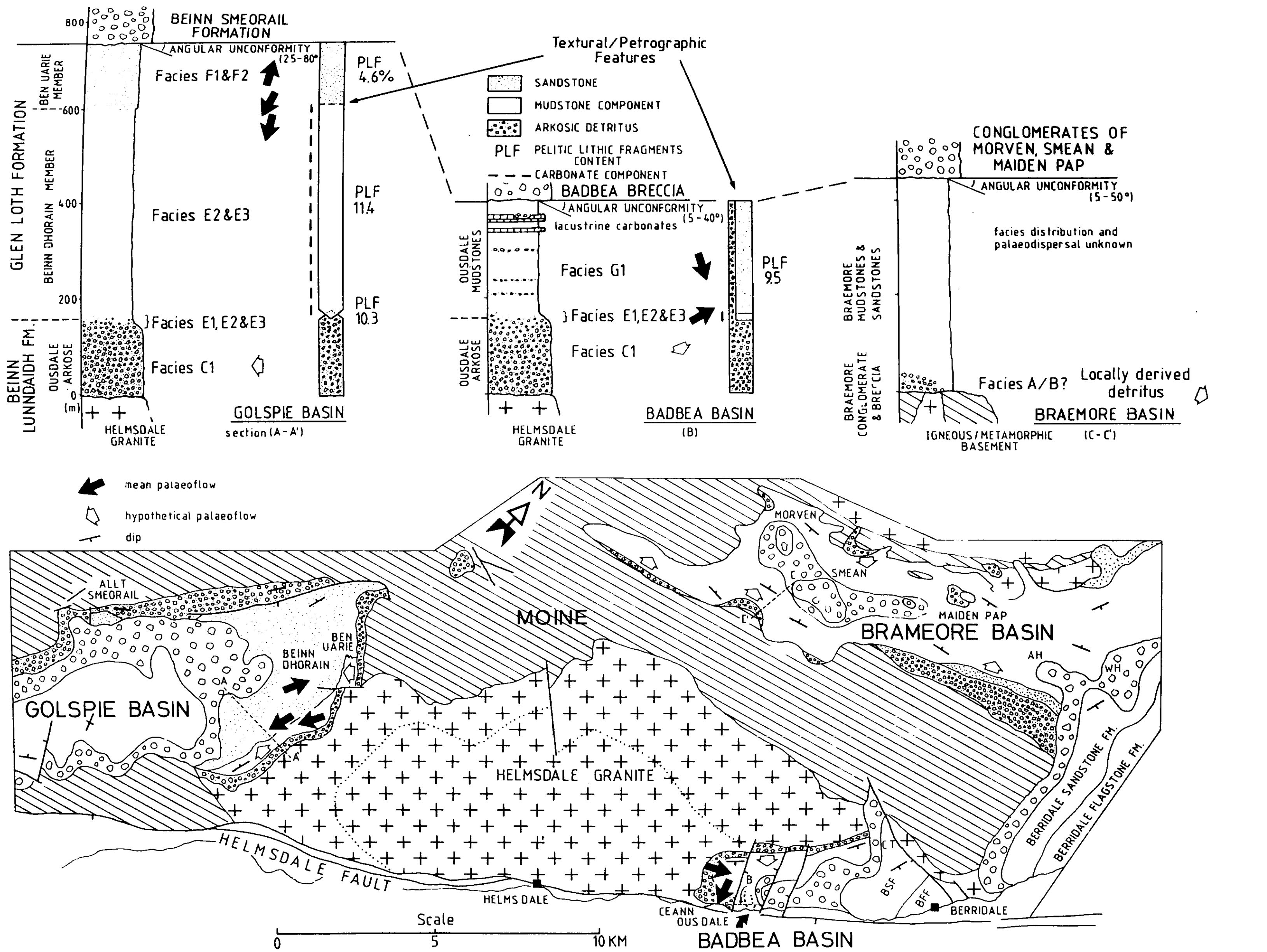
7.2.6.1.13. Palaeodispersal data for the Beinn Dhorain Member and the Ben Uarie Member

The basal part of the Beinn Dhorain Member (BDM), similarly as the underlying conglomerates of the Beinn Lunndaidh Formation (Ousdale Arkose) do not offer any direct palaeoflow indicators. The definite source of the arkosic detritus in the adjacent Helmsdale granite is taken as a basis for the inference of a hypothetical general dispersal of the arkosic material to the W (Fig. 7.2.21.).

Unfortunately no palaeoflow data are available from the most of the remaining section of the BDM. Only the numerous current ripple cross-laminated interbeddings(Facies E3) at the very top of the sequence, exposed on the eastern slope of Creag a' Chrionaich and Beinn Dhorain (Fig. 7.2.8.B) yield a unimodal palaeoflow pattern, which indicates the SW direction of emplacement of the muds of the BDM (Fig. 7.2.21.).

Dip azimuths of the large scale trough cross-strata from the basal portion of the Ben Uarie Member, measured at Creag a' Chrionaich and at Beinn Dhorain, strongly suggest the SSW-S dispersal, similar to that in the underlying mudstones (Fig. 7.2.21.).

Figure 7.2.22. Comparison of vertical facies distribution, palaeodispersal and petrographic signatures between Golspie and Badbea basins. Little information is available from Braemore basin. The dotted line marks gradational boundary between the outer coarse-grained and inner fine-grained parts of the Helmsdale granite (after Tweedie, 1979).


BEINN SMEORAIL FORMATION
ANGULAR UNCONFORMITY (25-80°)
Facies F1&F2
Facies E2&E3
Facies E1, E2&E3
Facies C1
GLEN LOTH FORMATION
BEN UARIE MEMBER
BEINN DHORAIN MEMBER
BEINN LUNNDAIDH FM.
OUSDALE ARKOSE
800
600
400
200
0
(m)
HELMSDALE GRANITE
PLF 4.6%
PLF 11.4
PLF 10.3
GOLSPIE BASIN
section (A-A')
Textural/Petrographic Features
SANDSTONE
MUDSTONE COMPONENT
ARKOSIC DETRITUS
PLF PELITIC LITHIC FRAGMENTS CONTENT
CARBONATE COMPONENT
BADBEA BRECCIA
ANGULAR UNCONFORMITY (5-40°)
lacustrine carbonates
Facies G1
Facies E1, E2&E3
Facies C1
OUSDALE MUDSTONES
OUSDALE ARKOSE
HELMSDALE GRANITE
PLF 9.5
BADBEA BASIN
(B)
CONGLOMERATES OF MORVEN, SMEAN & MAIDEN PAP
ANGULAR UNCONFORMITY (5-50°)
facies distribution and palaeodispersal unknown
BRAEMORE MUDSTONES & SANDSTONES
BRAEMORE CONGLOMERATE & BRECCIA
Facies A/B?
Locally derived detritus
IGNEOUS/METAMORPHIC BASEMENT
BRAEMORE BASIN
(C-C')
mean palaeoflow
hypothetical palaeoflow
dip
N
ALLT SMEORAIL
BEN UARIE
BEINN DHORAIN
GOLSPIE BASIN
MOINE
MORVEN
SMEAN
MAIDEN PAP
BRAMEORE BASIN
AH
WH
HELMSDALE GRANITE
HELMSDALE FAULT
HELMSDALE
CEANN OUSDALE
BADBEA BASIN
BSF
BFF
BERRIDALE
BERRIDALE SANDSTONE FM.
BERRIDALE FLAGSTONE FM.
Scale
0
5
10 KM

Change in palaeotransport appears to be extremely dramatic (Fig. 7.2.8. & 7.2.21.). The NE palaeoflow directions, inferred for the Ben Uarie Member in the Beinn Dhorain - Ben Uarie area, are based on the dip azimuths of the large scale trough and tabular cross-strata and current ripple cross laminae. These fairly unimodal distributions are in accord with the mean NE-SW strike of parting lineations, associated with the planar-stratification (upper plane bed).

For the absence of current structures, no palaeotransport data are available from the Allt Smeorail section and from the Oldtown outlier.

7.2.6.1.14. Facies G1: Assemblage of large scale, trough cross-stratified and planar-stratified sandstones and conglomerates and structureless to ripple cross-laminated and parallel-laminated sandstones and mudstones (Ousdale Mudstones, Badbea basin)

Facies G1 represents the majority of the deposits of the Ousdale Mudstones. The strata in question appear above the pebbly mudstones and mudstones of Facies E1, E2 and E3 (Ceann Ousdale section, Fig. 7.2.2.). Colour of the rock is gray to gray-green with a few red units, in contrast to the underlying entirely red rocks. The succession is 210 - 240 m.

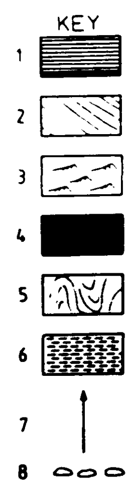
The following description of Facies G1 is based on sections measured in cliff exposures at Ceann Ousdale, in the quarry located by the road A9 between Helmsdale and Berriedale (Fig. 7.2.22. [ND 065 195]) and in the road cut in the vicinity of the quarry. In all localities the limited lateral extent of the exposures does not permit a satisfactory identification of the two-dimensional relationships between various types of strata, that make up Facies G1.

In the upper part of the sequence, the deposits in question are intervened by a number of a few meters thick units of lacustrine limestones with numerous horizons with desiccation cracks. The latter deposits have not been studied in detail, though in preliminary examinations they closely resemble the carbonates of Facies E3 (see chapter 7.2.6.1.3.).

Description

The sediments exposed at Ceann Ousdale (Fig. 7.2.23.) are dominated by large scale trough cross-stratified sandstones, pebbly sandstones and sandy conglomerates and by planar-stratified sandstones. The maximum particle size (MPS) of the conglomeratic deposits oscillates within a relatively narrow range between 0.5 - 2.3 cm and the gravel fraction is represented by the angular, arkosic material, derived from Helmsdale granite. Similarly as in the case of Facies C1, C2 and E1, the MPS is "dictated" by the size of the orthoclase feldspar phenocrysts. The conglomeratic deposits are typically rich in sandstone/mudstone intraclasts which are a few centimeters in size.

Figure 7.2.23. Graphic log of the deposits of Facies G1. **S** - slump/debris flow beds; **CS** - crevasse splays. (Locality: **1-4** - Ceann Ousdale, **5** - Quarry by road A9 [ND 065 195], Ousdale Mudstones). For further explanation see Fig. 7.2.8.. **KEY: 1** - planar stratification; **2** - cross stratification; **3** - ripple cross stratification; **4** - parallel lamination; **5** - convolute stratification; **6** - no structure visible; **7** - fining upwards; **8** - calcareous nodules.



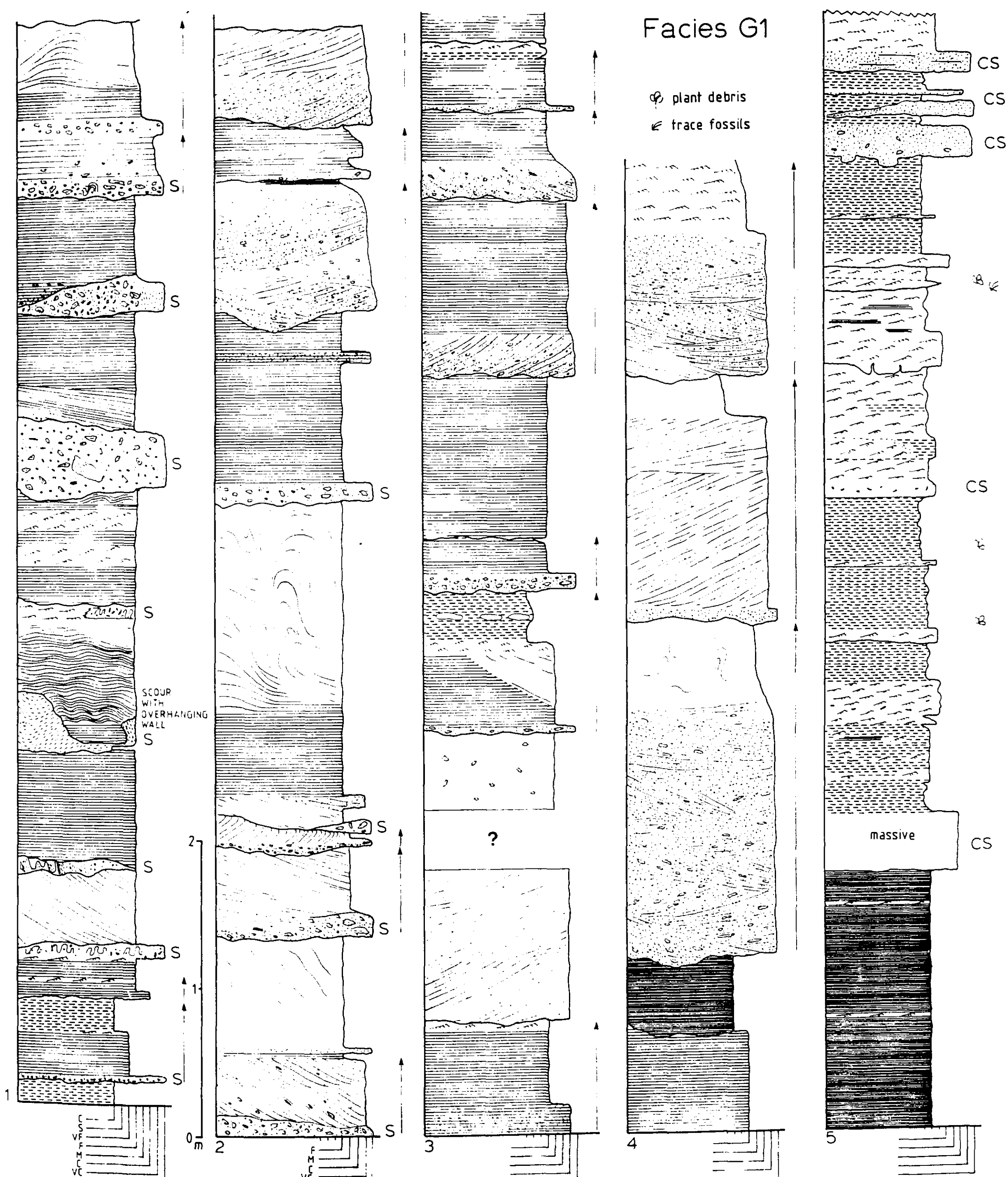
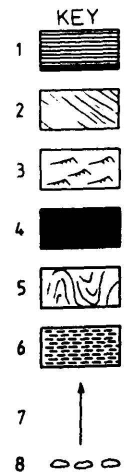

Facies G1
plant debris
trace fossils
S
S
S
S
SCOUR WITH OVERHANGING WALL
S
S
S
S
S
S
S
?
CS
CS
CS
CS
massive
CS
1
2
3
4
5
0 m
1
2
C
S
VF
F
M
C
VC
CG

Figure 7.2.23. Graphic log of the deposits of Facies G1. **S** - slump/debris flow beds; CS - crevasse splays. (Locality: **1-4** - Ceann Ousdale, **5** - Quarry by road A9 [ND 065 195], Ousdale Mudstones). For further explanation see Fig. 7.2.8.. **KEY: 1** - planar stratification; **2** - cross stratification; **3** - ripple cross stratification; **4** - parallel lamination; **5** - convolute stratification; **6** - no structure visible; **7** - fining upwards; **8** - calcareous nodules.



Thickness of the trough cross-stratified beds (sets and cosets) ranges from 7 - 170 cm(av. 66.4 cm). Thickness of the individual trough sets varies from 7 - 115 cm(av. 38 cm). The beds are erosionally based with common scours. The top bed boundaries are usually rapidly gradational into fine- or medium-grained sandstones with planar stratification or ripple cross-lamination, giving rise to fining-upward units with thicknness in a range from 0.24 - 2.36 m(av. 1.53 m).

The sandstones are predominantly fine-grained, well sorted and very micaceous. They are mostly planar-stratified and the parting lineation has been often found on surfaces of the laminae. The beds are 12 - 200 cm thick(av. 55 cm). and have erosional irregular to flat bases. One scour, 0.5 m deep and 1m wide, shows evidence of a lateral undercutting of the underlying mudstone strata (Fig. 7.2.23.).

Scattered pebbles, granules or mudstone intraclasts are occasionally present in the sandstone beds and tend to concentrate directly above the bases of the beds, forming basal conglomeratic lags. The stratification is normally poorly defined in these horizons. The planar-stratified beds pass vertically in places into asymmetric ripple cross-laminated sandstones and mudstones.

The planar-stratified as well as trough cross-stratified sandstones beds are often affected by water escape structures i.e. by large scale convolute lamination and water escape pillars (Type A, Lowe, 1975). Some of the beds have been found almost entirely structureless, and might represent a product of advanced, post-depositional sediment deformation and churning related to the upward water expulsion. It is also possible that some of the massive beds formed in result of bank collapse related sandy mass flows into the channels (Turner & Monro, 1987; see also further in the text).

Very fine-grained sandstones, siltstones and claystones are generally scarce at Ceann Ousdale but they have been found much more abundant in the quarry by the A9 and in the road cut outcrops. In the former locality they appear in a particularly thick packet (Fig. 7.2.23.). They are either structureless, splitting indefinitely with a conchoidal fracture, or finely parallel-laminated to ripple cross-laminated. Some of the ripple-marked very fine-grained sandstone beds have a form of erosinally based lenses, enveloped by the mudstones.

Plant debris (*Psilophyton and Pachytheca*), *Porolepis* scales and a variety of trace fossils (*Merostomichnites, Acripes, Diplocraterion* and others) have been recorded from the mudstones (road cuts and the quarries[ND 065 195]) (Friend & Williams, 1978; Tre in, 1986).

The argillaceous deposits comprise locally sheet-like to lenticular conglomeratic beds, ranging in thickness from 12 - 22 cm. They are structureless to crudely planar-stratified, clast-supported, often with open framework, and with MPS from 1.3 - 0.8 cm. The beds have flat, non-channelised erosional bases, and sharp to rapidly gradational tops, being capped by the finer-grained sediments.

A very distinctive feature of the deposits of Facies G1 at Ceann Ousdale, is presence of intraclast-rich, massive and chaotic conglomerates, muddy conglomerates as well as pebbly mudstones and mudstones. They form, erosionally based lenticular beds in range of thickness from 20 - 50 cm. The upper boundaries of the beds are either sharp and erosional or rapidly gradational into the overlying stratified deposits. An analogous, rapid transition can be in places traced laterally. The intraclasts are up to 20 cm in size and some of them are folded. Moreover, a number of mudstone and pebbly mudstone beds display features that are characteristic of slumps. They are composed of a predominant claystone/siltstone material deformed into tight isoclinal folds and often remoulded with the gravely detritus (Fig. 7.2.23. & Plate 7.2.20.). The folded parts of the beds may grade rapidly into totally massive and disorganised pebbly mudstones or conglomerates. The folds have been found in some of the beds to be erosionally cut from above.

Interpretation

A proportion of Facies G1 displays features that appear to be typical of **stream flow depsits**, sediments so extensively documented in the sedimentological literature (Allen, 1965, 1970; Bluck, 1967, 1980; Cant & Walker, 1976, 1978; Miall, 1977 and many others). The trough cross-stratified and planar-stratified conglomerates and sandstones represent infills of fluvial channels. Their features like: generally narrowly spaced main erosinal surfaces, relatively small thickness of the individual fining-upward units and lack of major, deeply incised channels suggest an ephemeral nature ~~that~~ the fluvial episodes.

Such mode of stream flow sedimentation is typical in semi-arid climatic conditions (Rahn, 1967; Glennie, 1970; Williams, 1970, 1971; Picard & High, 1973; Frostic & Reid, 1977), that in fact characterised the studied region during the Devonian (Burgess, 1961; Allen, 1974).

Friend and Williams (1978) have interpreted the discussed deposits as infills of braided river channels.

It is thought that the stream flow discharge, at least as some stage, was moderaty channelised and responsible for the formation of the broad scoures. This erosional action of the stream flows might have yielded a great proportion of the intraformational detritus and the channelised discharge provided a particularly suitable setting for development and migration of mega-ripples, and hence deposition of the large scale cross-stratified gravels and sands. The trough cross-stratification is, however, generally scarce in the dominant fine-grained sandstones. This is understandable in view of lack of megaripple formation in flume experiments for fraction 0.1 - 0.15 mm (Harms *et al.*, 1982). Large scale cross-stratification have generally been reported to be virtually completely absent in this size range (Harms *et al.*, 1982).

The sandstones displaying predominantly planar stratification, associated with parting lineation, were most likely deposited during upper-stage plane-bed transport (Harms *et al.*, 1982). The recurring rapid jump in the grain size from the gravel to the fine-grained sand and *vice versa* indicates that sediments finer than medium-grained sand were the most abundant form of detrirus available in the source area (see also McKee, *et al.*, 1967). The upper-stage, planar-stratified sandstones and conglomerates could have been deposited either within alluvial channel or on bars. Some of the planar-stratified deposits may also represent a product of an unchannelised, **sheetflood** discharge, occurring during peak flood events (McKee, *et al.*, 1967; Tunbridge, 1981; Graham, 1983; Stear, 1983,85; Blair, 1987a,b). The limited lateral extent of the exposures precludes, however, a detail evaluation of the possible settings of the formation of the planar-stratified sediments.

The rapid deposition of the well sorted sands was often followed by upward escape of fluids, squeezed from the sediments and causing the intense, large scale soft-sediment deformations (e.g. McKee *et al.*, 1967).

The structureless, ripple cross-laminated and finely parallel-laminated very fine-grained sandstones, siltstones and claystones might have accumulated on tops of bars, within abandoned channels or on **flood plain**. The latter setting is thought to be represented by the relatively thick packet of mudstones, exposed in the quarry by the road A9 and in the road cut (Fig. 7.2.23.). The sheet-like, erosionally based conglomeratic beds enveloped within mudstones may be interpreted as deposits of **crevasse splays**, invading the flood plain at peak discharges (Stear, 1983; Van Dijk *et al.*, 1978). The lenticular, also erosionally based ripple cross-laminated very fine sandstones, grading laterally into siltstones and claystones, may represent distal toes of the crevasse splay bodies. It is striking, however, that the conglomeratic sheet-like beds do not grade into sandstone members, the sediments which dominate the channel infills. Friend and Williams (1978) have postulated that these arkosic gravelly sheets represent product of sheet-wash sedimentation (sheetfloods). Such unchannelised depositional events might have been intrinsic processes of the gravely alluvial fans, fringing the Helmsdale granite highland in the E (see also chapter 7.2.6.1.16.) and interfingering with the independent fluvial system, depositing predominantly fine sandy fraction of distinctly different provenance (see chapter 7.2.6.3.).

An intrigueing facet of Facies G1 are the slump beds and the related massive, chaotic pebbly mudstones, muddy conglomerates and conglomerates. The tight folding in the slump mudstoness could not have been produced by a water escape related liquefaction or fluidisation, for the impermeable nature of the sediments (Lowe,1975; Allen, 1982). Furthermore, the basal boundaries of the slump beds are always sharp and erosional, with the undeformed sandstones resting below. This in no way resembles the characteristic gradational contact of the convolute laminated sandstones with the underlying intact deposits.

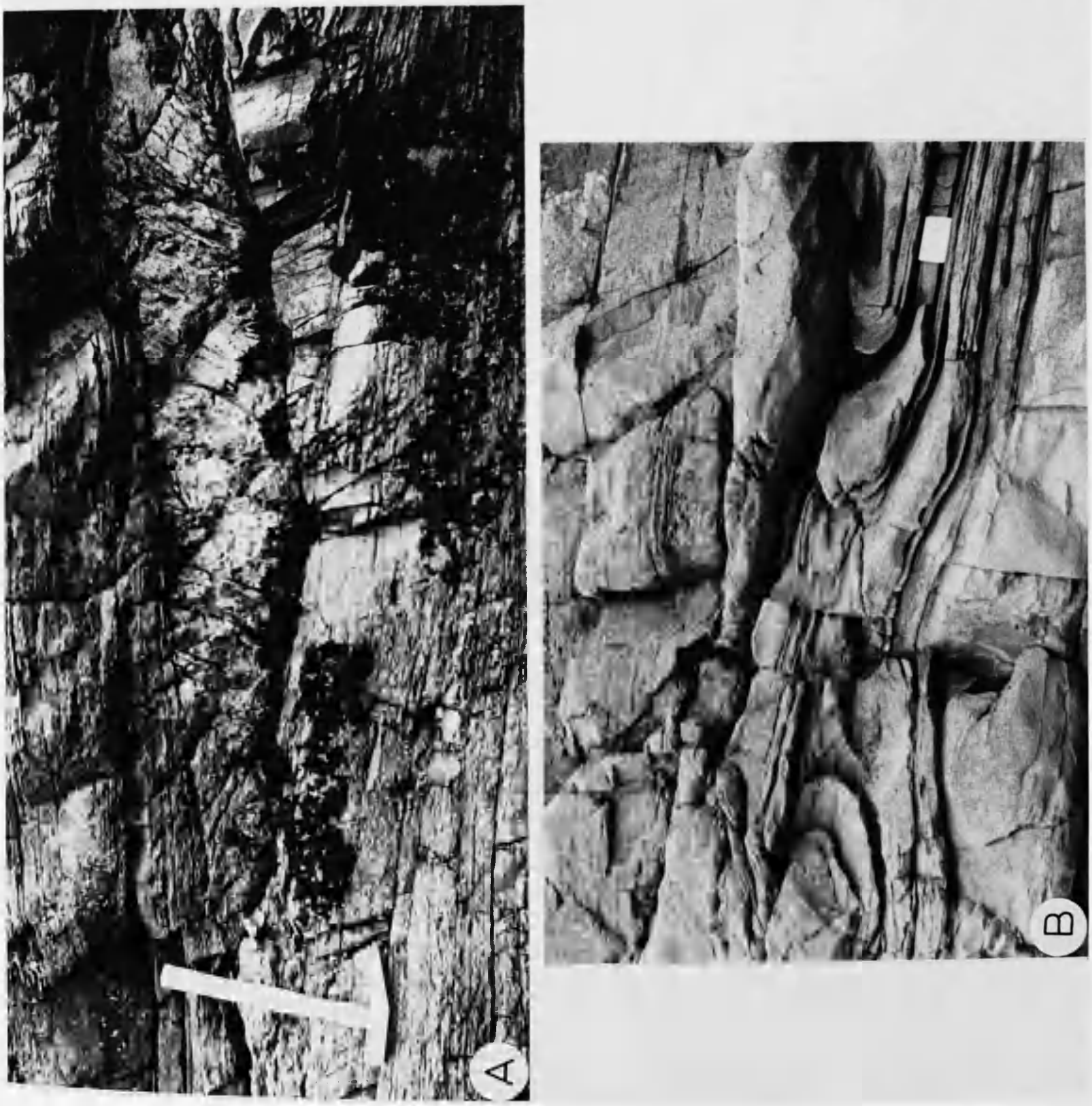
It is proposed that the slump beds formed in a result of **collapse of banks** of the channels caused by undercutting (Stanley, *et al.*, 1966; Coleman, 1969; Karch, 1969; Laury, 1971; Klimek, 1974; Gibling & Rust, 1984; Allen, 1985; Turner & Monro, 1987). Aspects of river bank collapse, relevant to the discussed deposits, are listed below and some are quoted from (Gibling & Rust, 1984):

Plate 7.2.20. A & B: Deposits of Facies G1.

A: Wedge-shaped mudstone slump bed, well defined among planar- and cross-stratified sandstones, it is interpreted as a result of channel bank collapse. The slump bed becomes massive to the left as it wedges out. Hammer is 40 cm long. (Locality: Ceann Ousdale, Ousdale Mudstones);

B: Water escape structures are common in the sandstones of Facies G1. The structureless sandstones (below) formed probably in a result of vigorous passage of the escaping fluid through the sands, which destroyed early stratification. Some of the massive sandstone beds, however, might have originated through en mass emplacement of the collapsed sandy channel banks (see Fig. 7.2.23). (Locality is the same as **A**)

Plate 7.2.20.



(1) Bank collapse occurs in meandering, braided and ephemeral, rivers. The collapse takes place by small-scale caving, resulting from normal river erosion and by large-scale rotational slumping (Gibling & Rust, 1984);

(2) The surfaces of the rotational slips may range downward at least to the level of channel bottoms (Allen, 1985);

(3) The rotational slips may grade into more remoulded mudflows (debris flows), and movement on rotational slips may reactivate any associated mudflows (Allen, 1985);

(4) The bank collapse is a rapid and widespread process. More than 15 bank failures per mile where encountered locally in the Brahmaputra River (Coleman, 1969, p.165), hence large amounts of semiconsolidated mud in blocks of variable size are added to the channels over short periods (Gibling & Rust, 1984);

(5) The bank collapse is promoted by many factors. The magnitude and frequency of water-level fluctuations is a highly significant factor. The collapse normally occurs as banks dry out during periods of falling water level. The type of bank sediment, its thickness, cohesion, porosity and frost action additionally influence the nature and rate of collapse;

(6) The site of bank collapse may be controlled by incipient fractures, commonly by desiccation cracks (Stanley *et al.*, 1966; Karch, 1969; Allen, 1985).

Gibbling & Rust (1984) described products of bank collapse from the Carboniferous braided stream deposits (Morien Group, Nova Scotia). While in the Gibbling and Rust's case the resulted sediments have a form of blocks up to 2 m in diameter and rubble, forming lensoid lags, the massive chaotic beds described herein are seen as representative a variety of **mass flows (slumps/debris flows)** rather than sliding into the channels of individual coherent bloks. During the bank collapse and mass flow transport a variety of sediments could have been incorporated and remoulded, and produced muds, gravelly muds, muddy gravels and gravels accumulated on the bottoms of the channels. These sediments must have been highly susceptible to erosion and reworking by the stream flows and this is indicated by sharp to rapid gradational contacts of the mass flow beds with stratified infills of the channels. This might have been an alternative way of producing the intraclastic detritus. Some proportion of the intaclastic material could have also been yielded directly in the result of bank collapse (Gibling & Rust, 1984).

Petrographic features of Facies G1

The conglomeratic deposits of Facies G1 are represented by the arkosic detritus which has its source in the porphyritic portion of Helmsdale granite. It has identical petrographic characteristics as described in chapter 7.2.6.1.12..

The dominant sandstones/claystones display distinctly different petrographic and textural signatures. The sandstones are mainly fine-grained and there is some gap in grain-size distribution between the gravel and the dominant fine-grained sand and the finer fractions. The sandstones are normally well sorted with clasts being angular to subangular.

Petrographically they are sublithic arenites with negligible amount of fine-grained matrix (Fig. 7.2.21. & Plate 7.2.22.D). Rock fragments are represented by low-grade metmorphic pelitic lithic fragments(PLF), whose content ranges between 6.3 - 11.9%(av. 9.5%). The rocks are very micaceous with average muscovite content 7.3%. Biotite appears negligible. Average proportion of detrital chlorite is 2.6%. Potassium and plagioclase feldspars appear weakly altered to fine-grained mica and calcite. Garnet and zircon have been found in trace amounts.

XRF analyses of two samples of claystones have revealed presence of mica, illite and chlorite.

Palaeodispersal

At Ceann Ousdale the trough cross-strata and the parting lineations serve as indicators of palaeodispersal of the discussed sediments to the S (Fig. 7.2.27.B).

7.2.6.1.15. Facies G2: Assemblage of planar-stratified and large scale trough/tabular cross-stratified sandstones and pebbly sandstones (Beinn a' Bhragaidh Member)

The deposits of Facies G2 have been described from the fragmentarily exposed, approximately 63 m thick, lowest portion of the Beinn a' Bhragaidh Member (BBM), whose minimum thickness in the area of Beinn a' Bhragaidh is around 530 m. This assemblage of brown-red sandstones and pebbly sandstones crops out on the southern slopes of Beinn a' Bhragaidh above the conglomerates of the Mound Rock Conglomerate (BLF) (Fig. 7.1.24. & Plate 7.2.21.A). The contact is rapid and transitional and pebbly sandstones gradually disappear in the upper part of the BBM.

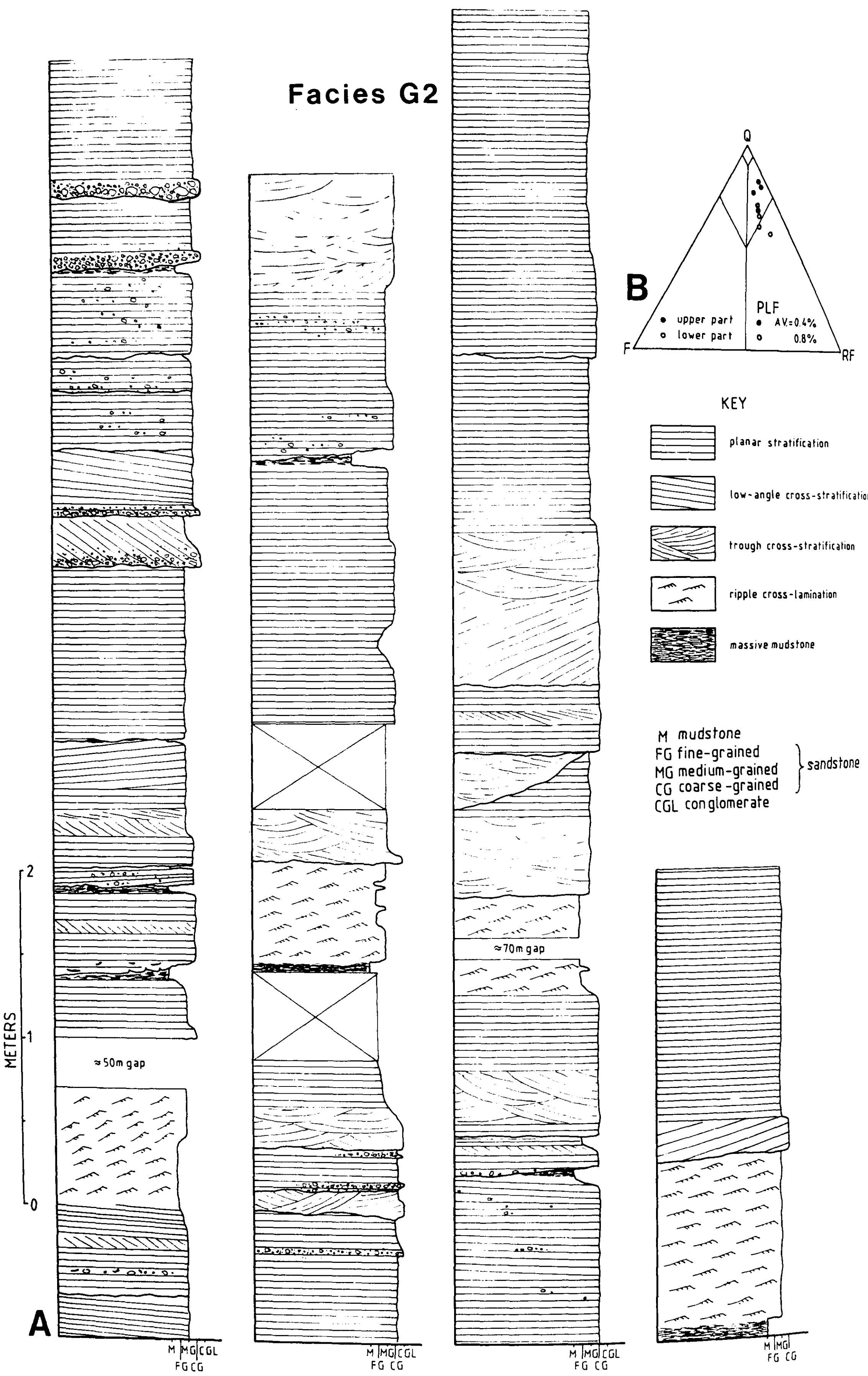
The deposits from the upper part of the BBM, that is from its portion approximately between 200 - 300 m above the base, are poorly exposed in two quarries, located between Mound Rock and Culmaily. The nature of the exposures, however, does not permit an extraction of data that could allow to infer an environment of deposition or palaeotransport directions.

Description

The deposits of Facies G2 deposits are dominated by planar-stratified and low angle cross-stratified sandstones, which occur in beds, ranging in thickness between 10 to over 200 cm. A three-dimensional quarry outcrop on the summit of Beinn a' Bhragaidh reveals a parallel-sided, sheet-like geometry of some of the planar-stratified beds as well as their considerable continuity (over 20 m) (Plate 7.2.21.B). Bases of the planar-stratified beds are typically flat and erosional, with common basal conglomeratic horizons, with angular to subangular clasts up to 15 cm in size (Fig. 7.2.24.A). The clasts of gravel fraction appear also either scattered within the beds or form discontinuous stringers, highlighting the nature of the stratification.

The large scale trough/tabular cross-stratified sandstone and pebbly sandstone beds have erosional bases, and often appear as infills of scours and channel-like forms up to 50 cm deep. The front face of the quarry (Plate 7.2.21.B) shows that the cross-stratified and

Figure. 7.2.24. A: Graphic log from the lower part of the Beinn a' Bhragaidh Member (BBM); **B**: Petrographic features of the BBM; **PLF** - low-grade pelitic lithic fragments; AV - average content.


Facies G2
A
B
METERS
0
1
2
≈50m gap
≈70m gap
M MG CGL
FG CG
M MG
FG CG
Q
F
RF
upper part
lower part
PLF
AV=0.4%
0.8%
KEY
planar stratification
low-angle cross-stratification
trough cross-stratification
ripple cross-lamination
massive mudstone
M mudstone
FG fine-grained
MG medium-grained
CG coarse-grained
sandstone
CGL conglomerate

planar-stratified sandstones may also form complex units, infilling larger channels. These are enveloped by sheet-like, mostly planar-stratified beds.

Ripple cross-laminated fine- to medium-grained sandstones and structureless mudstones are subordinate in the described assemblage.

The rocks representing the exposed upper part of the BBM are poorly exposed and appear to be predominantly fine- to medium-grained well to moderately sorted sandstones. They appear to be mostly planar-stratified; with some parting lineation. Large scale cross-stratification and ripple cross-lamination have also been recorded. The conglomeratic interbeddings, so abundant in the lower part of the BBM, are absent here. The nature of the quarry exposures has not allowed to measure section.

Interpretation

The planar- to cross-stratified sandstones (and some minor conglomerates), making up the majority of Facies G2, are thought to represent **stream flow** and possibly **sheetflood** deposits. The generally poor exposure of the rocks rules out making more specific inferences regarding nature of the alluvial sedimentation. Only the quarry outcrop, located on the summit of Beinn a' Bhragaidh (lower part of the BBM), gives a general idea of possibly two main types of discharge, that were responsible for formation of Facies G2.

The distinctly sheet-like in form, flat based and internally planar-stratified sandstone beds may represent proximal overbank deposits which originated in result of extensive sheetflooding outside the channels, and were characterised mainly by upper-plane bed flow conditions (McKee, *et al.*, 1967; Tunbridge, 1981; Stear, 1983,85; Blair, 1987a,b). These sediments are intervened by cross- and planar-stratified channel infills, produced by confined pre- or post-sheetflood straem flows (Bull, 1977; Stear, 1983,85; Blair, 1987a,b).

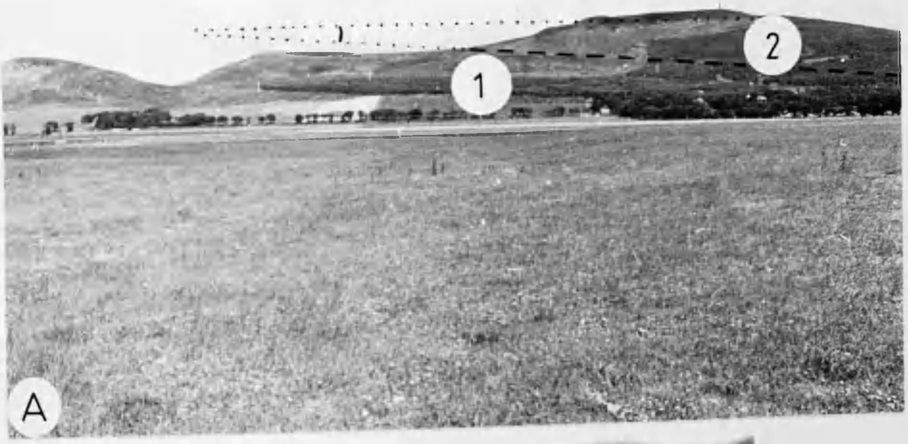
Petrographic features of the Beinn a' Bhragaidh Member

Texturally as well as petrographically the sandstones from the lower part of the Beinn a' Bhragaidh Member closely resemble the sandstone matrix from the underlying conglomerates of the Beinn Lunndaidh Formation. They are poorly - moderately sorted,

Plate 7.2.21 A: View of the southern slope of Beinn a' Bhragaidh; (**1**) conglomerates of the Mound Rock Conglomerate (Beinn Lunndaidh Formation); (**2**) sandstones and pebbly sandstones of the Beinn a' Bhragaidh Member (Glen Loth Formation) - Facies G2. Slight angular disconformity is apparent between the base of the Beinn a' Bhragaidh Member and the strata at the top of Beinn a' Bhragaidh. The base of the member may represent an original depositional alluvial fan surface of the Mound Rock fan;

B: Facies G2 - (**1**) parallel-sided, planar-stratified beds possibly of sheetflood origin; (2) complex assemblage of channel infills: cross- to planar-stratified sandstones. Major erosional surface - base of the channel is arrowed. (Locality: quarry on the summit of Beinn a' Bhragaidh, Beinn a' Bhragaidh Member, GLF)

Plate 7.2.21.



sublitihic wacke (Plate 7.2.22.A & Fig. 7.2.24.B). The clasts are mostly angular and subangular. The rock fragments component is represented mainly by high-grade metamorphic and granitoid clasts. The low-grade metamorphic, pelitic lithic fragments(PLF), which were so distinctive of the Glen Loth Formation in the northern part of the Golspie basin (see chapter 7.2.6.1.12.), are either scarce or absent in the Beinn a' Bhragaidh Member in the south (Fig. 7.2.24.B). K-feldspar(orthoclase, microcline) is dominant and its content varies from 9.4 - 7.6%(av.8.4%). Proportion of plagioclase feldspar ranges between 2.4 - 0.0%(av.0.9%). Fine-grained mica and carbonate replacement are most common alterations, affecting the both types of feldspars, though microcline always appears unaltered. Muscovite and biotite are present in approximately equal proportions and constitute 7.9 - 2.8%(av.4.5%). The biotite is typically altered to clay and iron-oxide. The muscovite appears locally replaced by a secondary, fine-grained mica. Quartz is represented by a monocrystalline variety.

The detrital grains are unevenly coated by clay/iron-oxide material. Authigenic quartz is the most widespread form of cement and its content varies between 22.3 - 5.0%(av.11.1%). Calcite cement is present only locally in proportion of 10 - 11%. Authigenic chlorite, feldspar(mainly potassium) and mica represent subordinate cement phases. Garnet and opaque grains have been recorded in trace amounts.

The clast composition and textural characteristics of the gravel fraction of the conglomeratic interbeddings correspond closely to the features in the underlying conglomerates of the Mound Rock Conglomerate(BLF). The main difference, apart from the smaller size of the clasts, lies in the absence of the coarse detritus derived from the Rogart Central Granodirite Complex (RCGC), the component which is so distinctive of the Mound Rock Conglomerate (Fig. 7.1.24.).

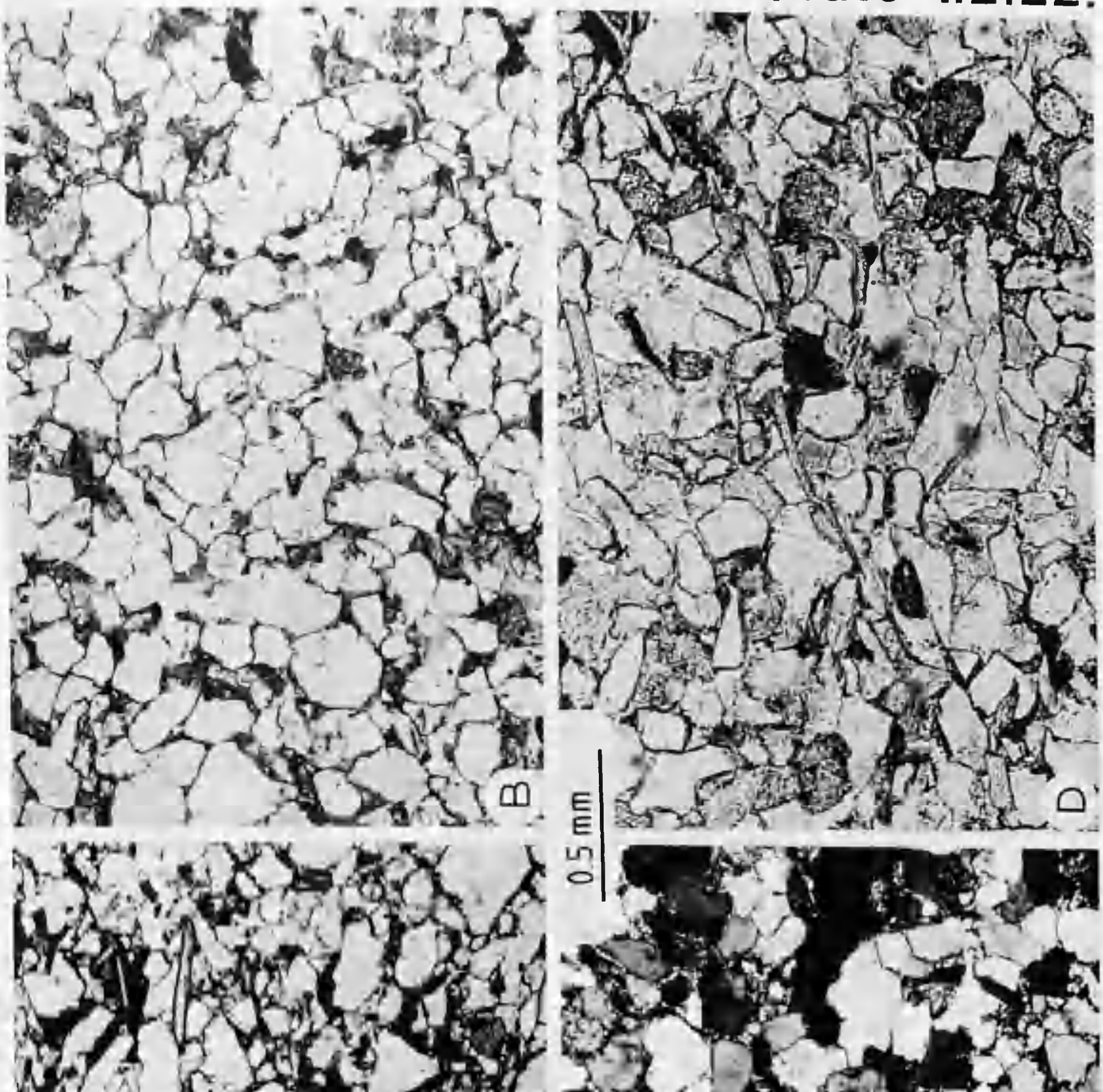
The sandstones from the upper part of the BBM (200 - 300 m above the base) are medium to coarse-grained and generally well to moderately sorted with majority of the grains being angular to subangular. They appear to be mineralogically slightly more mature, than the underlying rocks of the lower part (Fig. 7.2.24.B & Plate 7.2.22.B&C). The lithic fragments are represented predominantly by high-grade metamorphic and granitoid clasts. Muscovite and biotite are present in about equal proportions and constitute

Plate 7.2.22. A: Photomicrograph of the poorly sorted sandstone from the lower part of the Beinn a' Bhragaidh Member. Biotite flakes have been partly or entirely replaced by haematite and clay (arrowed). (PPL) (Locality: Beinn a' Bhragaidh, GLF);

B & C: Photomicrographs of well sorted, and mineralogically more mature sandstone from the upper part of the Beinn a' Bhragaidh Member (Locality: Culmaily, GLF). Authigenic mica and chert are the dominant cement. **B** - PPL, **C** - XPL.;

D: Photomicrograph of well sorted, micaceous sandstone of Facies G1 (Locality: Ceann Ousdale, Ousdale Mudstones)

Plate 7.2.22.



6.7 - 1.3%(av.4.2%). Rare, subrounded micritic carbonate intraclasts have been found.

Zircon, garnet, rutile and opaque minerals appear as accessory components.

Authigenic quartz(overgrowths) is present locally in proportions from 15 - 12.5%. Calcite cement is also present, though also only locally in amounts of up to 3.5%. The most widespread form of cement in the upper portion of the BBM is a mixture of secondary fine-grained mica, intergrown with chert and microcrystaline quartz (Plate 7.2.22.B&C). Authigenic chlorite occures in clusters, "floating" in the groundmass of mica and chert, and often displays spherulitic to variolitic texture. The chert and microcrystaline quartz have often been found as marginal replacements of the detrital, mainly monocrystaline quartz grains. Feldspar overgrowths are present in negligible proportions.

Palaeodispersal

The paleotransport data are available only from the lowest part of the BBM. The plot of azimuth of dip of large scale cross-strata indicates a bimodal palaeodispersal in the area of Beinn a' Bhragaidh (Fig. 7.2.30.).

7.2.6.2. Sedimentary environment of the Glen Loth Formation and Ousdale Mudstones

7.2.6.2.1. Beinn Dhorain Member (BDM) and Ousdale Mudstones

There is a rapid and gradational, upward transition from the Ousdale Arkose Conglomerate (Beinn Lunndaidh Formation) into mud and primary carbonate matrix-enriched muddy conglomerates, pebbly mudstones and mudstones of the Beinn Dhorain Member (Fig. 7.2.1. & 7.2.21.). This transition reflects a dramatic passage from the sheetflood-dominated alluvial fan environment(Facies C1) into subaqueous sedimentary setting, characterized by a variety of mass flow processes(Facies E1, E2 and E3, see chapters 7.2.6.1.4. & 7.2.6.1.5.). The transitional trend is manifested by a gradual fining- and disappearing upwards of the conglomeratic arkosic component (Fig. 7.2.21.). There is a relatively sharp boundary below which the mudstone/carbonate material is not found and above which it constitutes a significant, increasing upwards proportion of the deposits (Fig. 7.2.1. & 7.2.21.. The transition from the Ousdale Arkose(Facies C1) to Ousdale Mudstones (Facies E1, E2, E3 at Ceann Ousdale(Badbea basin)) is also marked by a rapid introduction of the mudstone component but in the latter case its amount remains constant up the succession and so does the proportion of the arkosic detritus (Fig. 7.2.2. & 7.2.22.).

Because of the limited exposure the corresponding lateral facies trends could not have been examined. However, it is reasonable to infer that the mentioned above upward transitions from Facies C1 into Facies E1, E2 and E3, in the Golspie basin as well as in the Badbea basin, mirror lateral facies interdigitations, that represent interaction between sedimentary processes at a subaerial/subaqueous interface on the alluvial fans whose toes became at some stage inundated by a standing body of water. Such an **fan-delta** setting (Holmes, 1965; Larsen & Steel, 1978; Gloppen & Steel, 1981; Nemec *et al.*, 1984; McPherson *et al.*, 1986 McPherson *et al.*, 1987; Nemec, 1987) is strongly indicated by an intimate association of almost matrix-free arkosic clast-supported beds (Facies C1 & E1) with pebbly mudstones and mudstones (Facies E1, E2 & E3) and by mixing of the former, fan-derived, extrabasinal material with the lake deposited, intrabasinal muds and carbonate sediments. In the Ceann Ousdale section, except for one Facies C1 bed, only the mixed, pebbly mudstones are present (Facies E1, Plate 7.2.2.A) with absence of individual, clast-supported, matrix-poor beds. The clast-supported material appears in the shear-layered pebbly mudstones in a form of smeared out inclusions.

The above evidence for sediment mixing and the facies associations imply a dynamic interaction between the fan and the adjacent lake system (Larsen & Steel, 1978; Gloppen & Steel, 1981; Nemec *et al.*, 1984; Nemec, 1987) in the Golspie as well as in the Badbea basin. In the both localities sheetfloods were responsible for transport of the arkosic detritus onto the subaerial/subaqueous interface of the fan-deltas (Fig. 7.2.25.). At Ceann Ousdale one sheetflood bed of Facies C1 is sandwiched between the ripple cross-laminated mudstones of Facies E3 and the shear-layered pebbly mudstones of Facies E1(Fig. 7.2.2.). In the Glen Sletdale section no sheetflood deposits have been found to be directly interbedded with the lake mudstones (Fig. 7.2.1.). The clast-rich beds of Facies E1 are structureless and their sheared basal contacts, crude shear-layering and smeared out muddy wisps (Plate 7.2.1. & Fig. 7.2.3.) suggest a laminar mass flow emplacement, rather than the sheetflood deposition.

Ballance (1984, p. 355), while discussing possible sedimentary processes of an interpreted ancient fan-delta sequence(middle Cenozoic Simmler Formation, California), speculates that the alluvial fan-borne sheetfloods (his sheetflows) might have transformed into cohesive debris flows by "intake of the lake deposited sand and water"*(sic!)*. Such an alternative has to be discarded for it is clear that clast concentration in fluidal, relatively low-density/viscosity sheetflows (or sheetfloods) would have additionally diminished because of the flow dilution during entering the lake (see also Nemec & Steel, 1984).

In the case of the Glen Sletdale fan-delta, discussed herein, the clast-rich beds of Facies E1 are thought to have originated through an *en mass* mobilisation of the previously deposited sheetflood gravels, interbedded with lake sediments (Fig. 7.2.25. & 7.2.29.). The mobilisation and the downslope mass flow transport involved incorporation of the lake fine-grained sediments. It is also possible that the admixing of the fan derived gravels with the lake muds could have been achieved either as a result of vigorous passage of the sheetfloods through the blankets of the lacustrine sediments or by a postdepositional

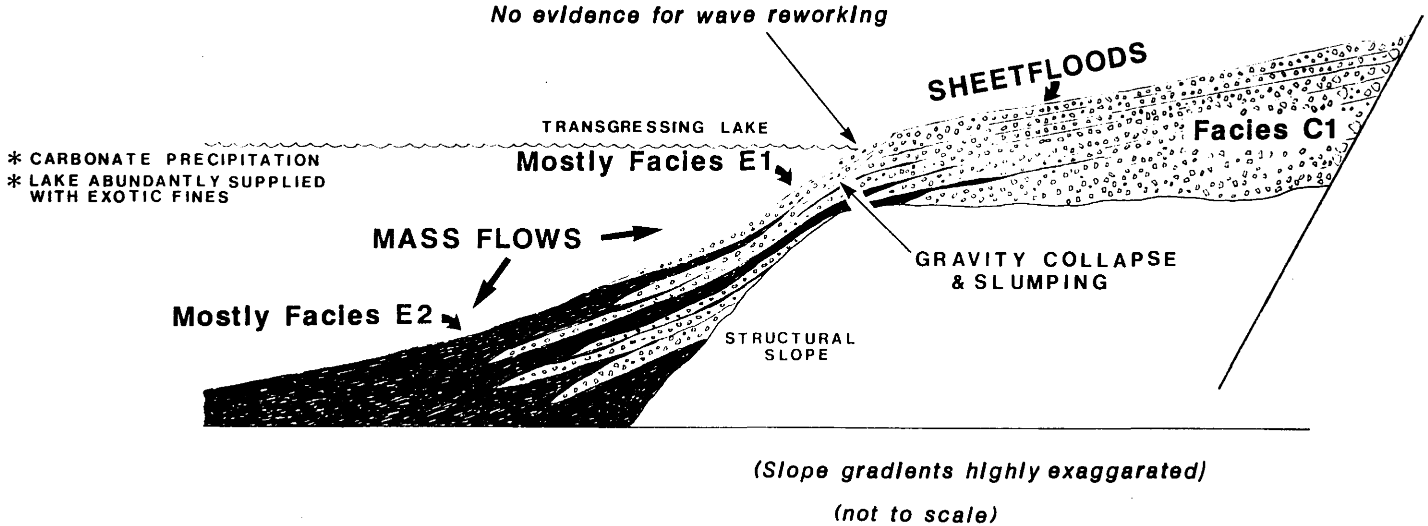


Figure 7.2.25. Schematic section shows distribution of dominant sedimentary processes and resulting facies in the interpreted fan-deltas.

loading of the gravels into the muddy layers (Fig. 7.2.29.) (Larsen & Steel, 1978; Nemec *et al.*, 1984; Nemec & Steel, 1984).

The Figure 7.2.3. demonstrates that the clast-rich mass flow deposits of Facies E1 might have later been remobilised by a gravity collapse, leading to further downslope flowage and admixing of the gravels and muds (see also Fig. 7.2.25.).

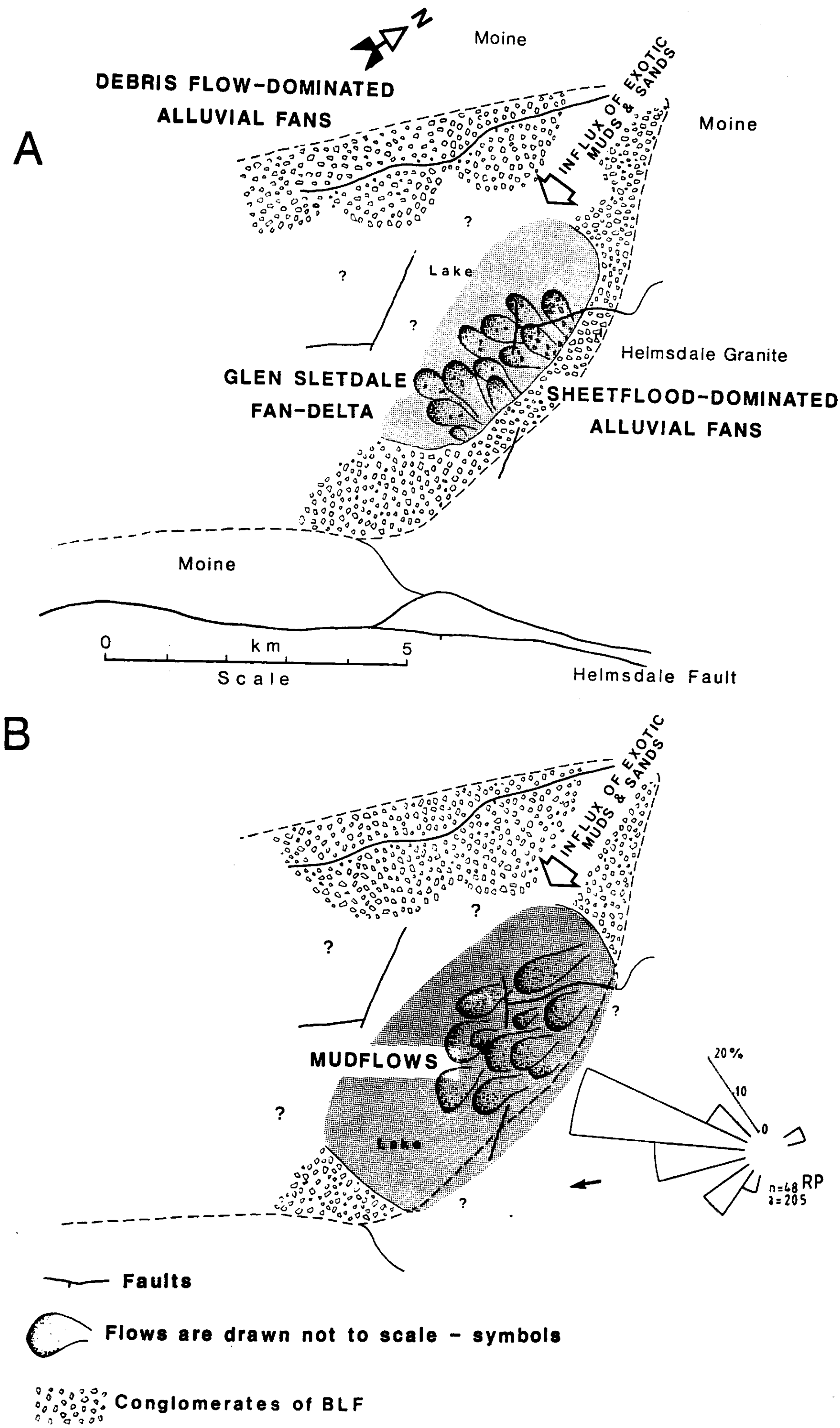
No structural/textural evidence have been found for wave reworking of the fan-borne gravels in a beach environment.

Fan-deltas (*sensu* Holmes, 1965; McPherson *et al.*, 1986; McPherson *et al.*, 1987; Nemec, 1987) form in response to a rapid subsidence along the basin margin (Holmes, 1965; Gloppen & Steel, 1981; Nemec *et al.*, 1984; McPherson *et al.*, 1987). Creating of basin margin depressions is critical for ponding adjacent to the marginal fan bodies and hence for an interplay between lacustrine/marine and alluvial fan systems (Gloppen & Steel, 1981; Blair, 1987b; McPherson *et al.*, 1987).

Development of the Glen Sletdale fan-delta along the NE margin of the Golspie basin was most likely controlled by the N-S to NNW-SSE trending faults and the resultant subsidence is thought to have been responsible for a formation of a standing body of water and for inundation of a portion of the low-gradient, alluvial fan(-s) (Fig. 7.2.25.A & 7.2.26.A). Position of the Ceann Ousdale fan-delta was probably controlled by subsidence associated with tectonic activity along the NE-SW and NNW-SSE trending faults, all possibly belonging to the Helmsdale fault system (Fig. 7.2.27.A).

There is a striking difference in a mode of sediment transport and deposition between the subaerial and the subaqueous segments in the discussed fan-deltas. While the fanglomerates are interpreted to have been deposited from sheetfloods on the low-gradient fans, the subaqueous settings of the systems were characterized by slope instability and totally governed by mass flow processes. Such an contrast appears to be best explained by employing a combination of basically two factors: (1) rapid subsidence and creating a structural slope, both responsible for the ponding - inundation of the fan toes and contributing to depositional slope instability within the subaqueous portion of the fan-delta, (2) high sedimentation rates within the subaqueous segment of the fan-delta, facilitating build up of excess pore water pressure in the underconsolidated sediments. Abundance of

Figure 7.2.26. Palaeogeography of the northern part of the Golspie basin during **(A)** development of the Glen Sletdale fan-delta and **(B)** during the formation of the main, mudstone portion of the Beinn Dhorain Member. **RP** - orientation of current ripple cross laminae (Facies E3).


A
DEBRIS FLOW-DOMINATED ALLUVIAL FANS
Moine
Moine
INFLUX OF EXOTIC MUDS & SANDS
Lake
GLEN SLETDALE FAN-DELTA
Helmsdale Granite
SHEETFLOOD-DOMINATED ALLUVIAL FANS
Moine
0 km 5
Scale
Helmsdale Fault
B
INFLUX OF EXOTIC MUDS & SANDS
MUDFLOWS
Lake
20%
10
0
n=48 RP
Faults
Flows are drawn not to scale - symbols
Conglomerates of BLF

the fines depositing in the lake must have been particularly effective in reducing capacity for drainage of pore water from the progressively buried sediments. This must have significantly promoted reduction of their shear strength (Shepard, 1955; Terzaghi, 1956; Prior & Suhayda, 1979; Gloppen & Steel, 1981; Pierson, 1981; Prior & Coleman, 1984), making them highly prone to downslope mass flowage.

As has already been mentioned, the former, tectonic factor is a necessary condition for a fan-delta development. A substantial amount of subsidence is required in order to accommodate around 450 m of the mudstones of the Beinn Dhorain Member and 150 m of the sandstones of the Ben Uarie Member in the Golspie basin and 210 - 240 m of the deposits of the Ousdale Mudstones in the Badbea basin.

For the Glen Sletdale fan-delta sequence does not offer any direct palaeocurrent indicators, it is assumed on the basis of the provenance of the arkosic detritus in the Helmsdale granite, that the dispersal pattern within the fan-delta system (including the subaqueous part) was generally to the W (Fig. 7.2.26.A). In the Ceann Ousdale fan-delta sequence (Badbea basin) the current ripple-laminations (Facies E3) indicate a palaeotransport to the NE, what in fact would be consistent with the general dispersal direction of the arkosic gravels from the Helmsdale granite (Fig. 7.2.27.A).

In the Golspie basin the arkosic detritus disappears gradually upwards (Fig. 7.2.21.) and the Beinn Dhorain Member is in the majority made up of the structureless/shear-layered mudstones and muddy sandstones of Facies E2; unfortunately with no palaeotransport indicators. Only the uppermost, around 20 m thick, portion of the member contains numerous current ripple cross-laminated beds (Facies E3), that consistently indicate a unimodal palaeotransport pattern to the SW.

The fine- to very fine-grained sand fractions of the BDM mudstones display very distinctive petrographic signatures - in particular they are characterized by a significant proportion (10.3 - 11.4%) of the low-grade metamorphic pelitic lithic fragments (PLF) (Fig. 7.2.21.). This lithic component is exotic with regard to the Golspie basin as it has clearly not been derived from the surrounding high-grade metamorphic and granitoid terrains. Provenance of these cryptic clasts, however, has not been established (chapter 7.4.5.2.). The presence of PLF fragments in the fine sand fractions must be to great extend also a function of grain size. In the case of the Glen Sletdale section distinctive bimodality is also apparent (Facies E1 and E2), what indicates that arkosic detritus, evidently derived from the Helmsdale granite, and the lake deposited fines had undergone quite independent paths of textural evolution prior to the final deposition (see also chapter 7.2.6.3.).

Basing on the palaeotransport data from the topmost portion of the BDM, it is postulated herein that the fan-delta-related lake was primarily fed, from the NE with externally derived exotic muds and fine- to very fine-grained sands (Fig. 7.2.26.A). Within the subaqueous portion of the fan-delta the depositing fines, including the precipitated carbonate mud, became *en mass* admixed with the locally derived, fan-borne gravels. No deposits of the inferred lacustrine setting are exposed, that could eventually reveal more about an autochthonous nature of the muddy and the carbonate sediments. Vigorous sediment supply into the lake, especially with regard to the fines, and high rates of sedimentation on the unstable, subaqueous segment of the fan-delta, promoted continuous mobilisation and mass flow redeposition of the slope sediments.

As has already been mentioned above, the arkosic detritus disappears gradually upwards in the lowermost part of the BDM and so does consequently the trace of the interplay between the muddy/carbonate lacustrine and gravelly fan depositional systems. The remaining, over 400 m thick, part of the BDM, being dominated by the mudstones of Facies E2 records a stage of the development of the Golspie basin, when its NE part was taken over by the mudflow deposition (Fig. 7.2.26.B). The mudflows are interpreted to have essentially been deposited in a subaqeous setting, though periodically exposed to desiccation due to changing water level in the lake (see also chapter 7.2.1.6.).

The rapid, upward passage from the fanglomerates into the subaqueous environment indicates a transgressive lake scenario. Nemec (1987) has stressed that a fan-delta setting does not directly imply a progradation of an alluvial fan. According to him there are well documented cases of fans (Nemec & Steel, 1987) which came into the direct contact with a standing body of water not because they prograded into it from a highland, but because the sea or lake itself prograded over an active fan and brought it into interplay, under overall transgressive circumstances (marine or lacustrine).

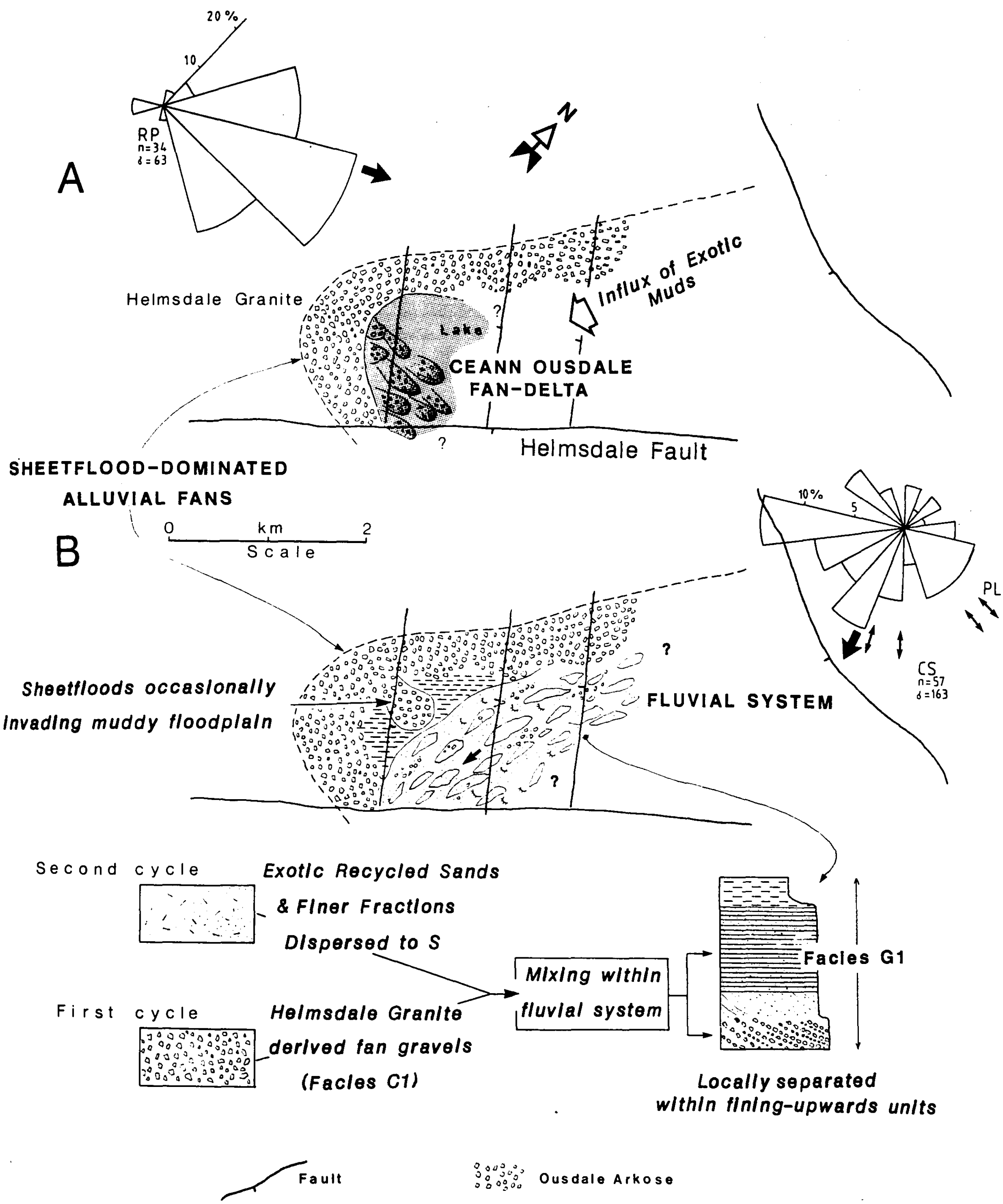
It is emphasized that the fining-upward fan-delta sequences, observed in the both basins (Golspie and Badbea) do not necessarily represent a regional transition into a period of tectonic quiescence, manifested in the cease of the alluvial fan development followed by lacustrine sedimentation. The 450 m thick Beinn Dhorain Member for example, represents a period of mass flow sedimentation, which is seen as a resultant of a combination of an abundant sediment supply (see chapter 7.2.6.3.) and the subsidence. Blair (1987b) argues that lacustrine environment may be very responsive to active tectonic subsidence and migrate over fans to occupy the basin-margin depressions.

The mudflows of Facies E2 are thought to have been emplaced to the SW, that is approximately from the postulated earlier direction of the main fine-grained sediment supply (inferred from the current ripple cross-laminations in the uppermost portion of the BDM). For the limited exposure of the discussed deposits the general palaeogeographical context of the mudflow sedimentation remains unknown. Perhaps recognition of sedimentary nature of the lithostratigraphically equivalent Berriedale Mudstones and Sandstones in the Braemore basin, located to the NE (Fig. 7.2.22.), may help to elucidate the aspect of provenance of the muddy sediments in the Beinn Dhorain Member and possibly to specify their sedimentary context.

The Ceann Ousdale fan-delta system (Badbea basin) was characterized probably by the NE dispersal (Fig. 7.2.27.A). The alluvial fan <-> lake interaction and processes of subaqeous, mass flow related mixing of the two distinctly different groups of sediments are represented by the entire 10 m thick fan-delta sequence (Fig. 7.2.2.). The sedimentary processes operating within the Ceann Ousdale fan-delta are interpreted to be essentially analogous to the once, recognized for the Glen Sletdale fan-delta, though the subaqueous segment in the former system appears to have received higher supply of the arkosic detritus. The dominant Facies E1 pebbly mudstones contain also less primary carbonate component.

The Ceann Ousdale fan-delta sequence is sharply covered by the stream flow and lacustrine deposits of Facies G1 and they make up the majority of the Ousdale Mudstones (Fig. 7.2.2.). The latter fluvial depositional system is characterized by palaeodispersal to the S. It is thought to have initially been responsible for supplying the fan-delta lake with exotic fines - rich in low-grade metamorphic pelitic lithic fragments (Fig. 7.2.27.A). It is

Figure 7.2.27. Palaeogeography of the Badbea basin during: (**A**) development of the Ceann Ousdale fan-delta; (**B**) development of the main (Facies G1) portion of Ousdale Mudstones. The diagram below illustrates the interpreted textural evolution of the deposits of Facies G1(see enclosed map in Fig.7.2.28. for location of the considered area). **RP** - orientation of current ripple cross laminae (Facies E3); **CS** & **Pl** - orientation of cross strata and parting lineation respectively (Facies G1).


20 %
10
RP
n=34
δ=63
A
N
Influx of Exotic Muds
Helmsdale Granite
Lake
CEANN OUSDALE
FAN-DELTA
?
Helmsdale Fault
SHEETFLOOD-DOMINATED
ALLUVIAL FANS
10%
5
0 km 2
Scale
B
PL
CS
n=57
δ=163
Sheetfloods occasionally
invading muddy floodplain
FLUVIAL SYSTEM
Second cycle
Exotic Recycled Sands
& Finer Fractions
Dispersed to S
First cycle
Helmsdale Granite
derived fan gravels
(Facies C1)
Mixing within
fluvial system
Facies G1
Locally separated
within fining-upwards units
Fault
Ousdale Arkose

for the sandstones of the Facies G1 display similar mineralogical characteristics (Fig. 7.2.21). They are also well sorted(dominant fine-grained fraction) and most likely represent recycled(second-cycle) sediments. The Facies G1 contains also an appreciable proportion of the arkosic detritus, mainly of the gravel fraction, which tends to concentrate in the basal portions of the fining-upward cycles (Fig. 7.2.23.1-4. & 7.2.27.B). It also forms erosionally based conglomeratic sheets, sandwiched within the floodplain mudstones (Fig. 7.2.23.5).

It is interpreted that the sandy fluvial system, dispersing the second-cycle sands to the S was additionally supplied with the first-cycle gravelly material, derived from the adjacent alluvial fans, fringing the Helmsdale granite basin margin (Fig. 7.2.27.B). The fan-related sheetflood events might have occasionally invaded the muddy floodplain, depositing isolated gravelly beds. Some of these deposits may, however, represent stream-borne crevasse splays (see chapater 7.2.6.1.14.).

From the Middle Old Red Sandstone Hornelen basin (W Norway) Gloppen and Steel (1981, p.62) have documented fan-delta sequences, which are analogous to the ones discussed above, and in which the fan-borne gravels mixed in the subaqueous setting with the lacustrine muds derived by an independent axial system.

It is noteworthy that the southern palaeodispersal of the exotic low-grade lithic clasts into the Badbea basin is consistent with the postulated earlier pattern of supply into the Golspie basin, of mineralogically very similar fine-grained sediments.

The interpreted here fan-deltas, are the first such sedimentary settings documented in detail from the Orcadian basin. They, however, do not appear to have been unique along the margins of the main Orcadian lake. Many of the marginal, lacustrine facies studied in detail by Donovan (1978), clearly display evidence of an active alluvial fan <-> lake interaction (see also Trewin , 1986).

7.2.6.2.2. Ben Uarie Member (BUM)

In the NE part of the Golspie basin, the mudstones of the Beinn Dhorain Member (BDM) pass dramatically into the sandstones of Facies F1 and F2, making up the Ben Uarie Member (BUM). The transition is associated with a remarkably dramatic (180 degrees)"switch" in the palaeotransport directions (Fig. 7.2.8.B & 7.2.21.). The sandstones of Facies F2 yield palaeocurrent data that consistently indicate a unimodal palaeodispersal to the NE and NNE.

The sandstones of the Ben Uarie Member are strikingly monotonous in terms of a grain-size characteristics, ranging between very fine to fine-grained and displaying generally good sorting. The BUM sandstones are also petrographically distinctly different from the subjacent deposits of the BDM as their content of the low-grade pelitic lithic fragments is much lower, ranging from 1.3 - 6.7% (av. 4.6%).

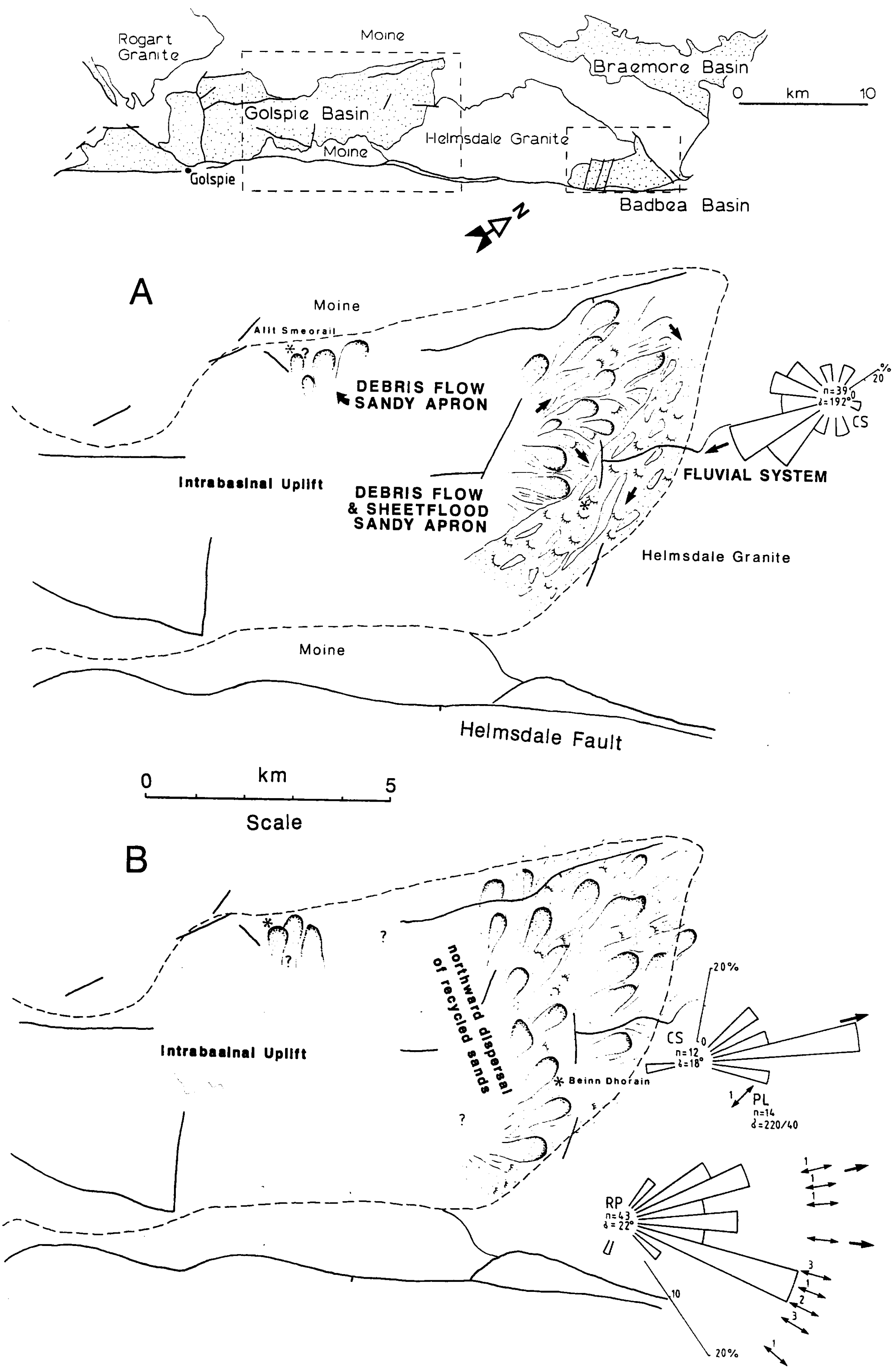
The deposits of Facies F1 have been interpreted as a product of subaerial sandy debris flow deposition, interacting with or intermitted by the sheetflood events (Facies F2) (see chapters 7.2.4.1.9. & 7.2.6.1.10.).

An overall sedimentary setting for these processes is envisaged as a **sandy aprons** (or alluvial fans) or **system of coalescent aprons** prograding to the NNE and NE (Fig. 7.2.28.). To the author's knowledge no modern, analogous sandy subaerial fans have been documented, that could match the scale and the facies characteristics characteristics of the sandy aprons of the Ben Uarie Member interpreted herein.

Carter (1975) reported a sandy "fan-bench", developed along a 4 m deep trench excavated in Quaternary sands. The fans were only 5 m wide and 1-2 m high and formed in over 36 hours through *en mass* redeposition of mobilised well-sorted, medium- to fine-grained sands in a form of micro-debris flows (*sand-fingers*). The mobilisation and emplacement of the sandy debris flows was primarily controlled by fluidisation and liquefaction of the trench sands. The scale of these "micro-fans" as well as of the size of the individual sandy debris flows are hardly compatible with the interpreted here sandy aprons and the sandy debris flows deposits of the BUM, though the small size of the Carter's fans is to some extend a function of the very short duration of their growth.

Graham (1983) has recognized fine-grained sand/silt ripple- to planar-stratified facies in the Upper Devonian Munster Basin(Ireland), and interprets them as a series of vertical accretion deposits produced by non-channaelised floods on alluvial plain (see also Tunbridge, 1981). These deposits, however, closely resemble only Facies F2 and are not accompanied by any deposits which might correspond to Facies F1.

Figure 7.2.28. Palaeogeography of the northern part of the Golspie basin during: **(A)** formation of the stream flow horizon, represented by the lowest portion of the Ben Uarie Member (Fig. 7.2.16.) and **(B)** during the main phase of development of the sandy aprons of the BUM. The direction of emplacement of the sandy debris flows at Allt Smeorail is speculative (?) and based on assumption that the deposits at Allt Smeorail belong to the same dispersal system as the sandstones in the area of Beinn Dhorain (strong textural and petrographic similarities). Generalised map above shows the extend of the area considered in diagrams **A** and **B**. **CS** - orientation of cross strata; **RP** - orientation of current ripple cross laminae; **Pl** - strike of parting lineation.


Rogart Granite
Moine
Braemore Basin
0 km 10
Golspie Basin
Helmsdale Granite
Moine
Golspie
Badbea Basin
N
A
Moine
Allt Smeorail
DEBRIS FLOW SANDY APRON
n=39
δ=192°
CS
%
20
0
FLUVIAL SYSTEM
Intrabasinal Uplift
DEBRIS FLOW & SHEETFLOOD SANDY APRON
Helmsdale Granite
Moine
Helmsdale Fault
0 km 5
Scale
B
northward dispersal of recycled sands
20%
CS
n=12
δ=18°
Intrabasinal Uplift
Beinn Dhorain
PL
n=14
δ=220/40
RP
n=43
δ=22°
10
20%

The very narrow grain-size range, the good sorting and the vastly mass flow mode of emplacement of the deposited sands of the BUM suggest their recycled origin. It is postulated herein that the BUM sandy aprons were supplied with abundant volumes of pre-existing, little lithified sands, deposited earlier in the approximately middle part of the Golspie basin. The sands must have undergone a considerable textural evolution and grain-size separation prior to the deposition, preceding the final remobilisation. Intrabasinal uplift is envisaged to have brought the sediments into a position of instability and proneness to remobilisation and redeposition into the continuously subsiding northern part of the Golspie basin (Fig. 7.2.28.).

The base of the BUM is characterized by the trough cross-stratified, around 7 m thick sandstone horizon, which, although being petrographically and texturally distinctly different from the underlying mudstones of the BDM, does show a similar, strongly unimodal southward palaeodispersal (Fig. 7.2.8.B & 7.2.21.). This palaeotransport direction is clearly opposite to the one in the overlying, petrographically and texturally identical sandstones. In order to explain this disaccord it is proposed that at initial stage of the northward NE-NNE progradation of the sandy apron, the sediments were dispersed against the S-SW inclined basin floor in the northernmost part of the Golspie basin, the one which controlled the S-SW dispersal of the BDM muds. Consequently the apron toe sediments would have been subject to reworking and further transport by southward flowing currents of the diverted apron drainage system, depositing mainly cross-stratified sands (Fig. 7.2.28.A). This fluvial system is seen to have been confined from one side by the prograding from the S sandy apron and from the NE by the basin margin. Considering the small thickness of the formed cross-stratified horizon, it is thought that the postulated drainage system was probably short lived, for soon the entire northern part of the Golspie basin became occupied by the sandy debris flow/sheetflood sedimentation, possibly overstepping the basin margin (Fig. 7.2.28.B).

The observed in the section very rapid change in the palaeotransport direction is probably a result of a very swift progradation of the sandy apron, so that the transitional in terms of palaeodispersal, probably very thin deposits are impossible to recognize in the section, especially considering its rather poor degree of exposure.

Direction of emplacement of the sandy debris flows at Allt Smeorail is purely hypothetical. It is assumed, on the basis of the textural and petrographic affinities (Fig. 7.2.21.), that the flows at Allt Smeorail and in the Beinn Dhorain area belong to the same dispersal system.

7.2.6.2.3. Beinn a' Bhragaidh Member (BBM)

A palaeogeographic picture of the BBM remains largely unknown for the very limited exposure of these deposits. The bimodal distribution of the palaeocurrent data (42 readings taken at Beinn a' Bhragaidh from the lowest portion of the member) may indicate an existence of two fluvial systems (Fig. 7.2.30.), shedding sands and minor gravels, of mostly Moine provenance, into the Golspie basin from the W and from the E and interdigitating in the axial part of the basin.

7.2.6.3. Summary of textural evolution and provenance of the Glen Loth Formation and Ousdale Mudstones

7.2.6.3.1. Beinn Dhorain Member (BDM) and Ousdale Mudstones

The interplay between the alluvial fan and lake depositional systems, during the development of the Glen Sletdale and Ceann Ousdale fan-deltas, manifested itself through vigorous, *en mass* mixing of the extrabasinal, fan-borne, first-cycle gravels with the intrabasinal, lake-related, second-cycle fines and carbonates. The admixing led to so called **textural inversion** (Folk, 1968); in other words to a downstream regress in textural maturity of the fanglomerates. The textural inversion has been reported as a distinctive phenomenon in subaqueous realm of fan-deltas (Larsen & Steel, 1978; Wescott & Ethridge, 1980; Gloppen & Steel, 1981; Nemec *et al.*, 1984).

The Figure 7.2.29. illustrates the interpreted evolutionary stages in textural development of the deposits of the Glen Sletdale fan-delta, and represents a case of a history of textural inversion.

In the Ceann Ousdale fan-delta the ratio gravel/mud was much higher than in the Glen

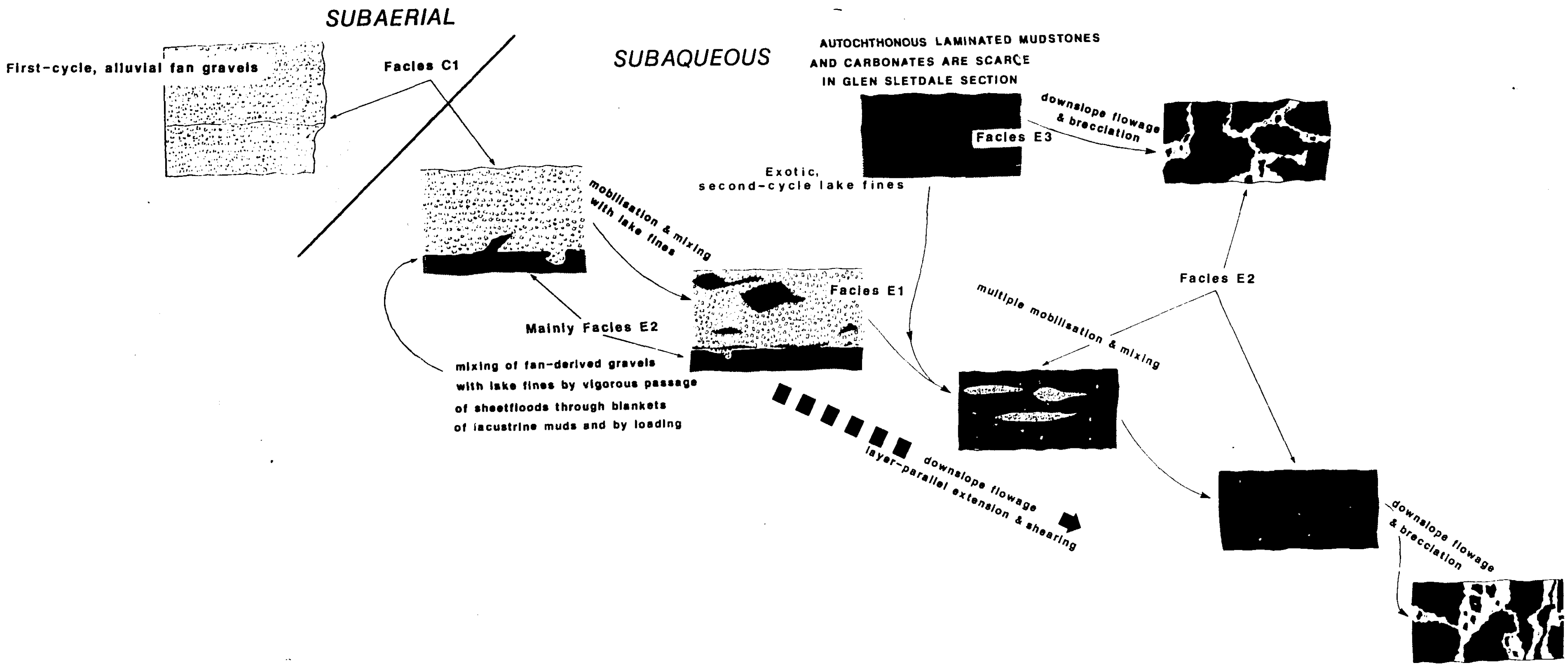


Figure 7.2.29. Schematic illustration of the textural evolution of the fan-delta deposits. The diagram is based on data from the Glen Sletdale section. The Ceann Ousdale fan-delta shows essentially the same characteristics.

Sletdale fan-delta. The former sequence displays also more abundant autochthonous, laminated deposits of Facies E3. In the Glen Sletdale section they have been found mainly in an allochthonous position as remoulded matrix and as intraclasts.

The mudstones of the Beinn Dhorain Member (BDM) are a product of resedimentation of primarily organized - laminated sediments that had achieved some degree of lithification prior to the mobilisation. The Facies E2 deposits contain abundant intracalasts, many of which show an early lamination (Fig. 7.2.9. & Plate 7.2.13.). Petrographically the BDM mudstones appear to be unrelated to the surrounding granitic and high-grade(Moine) terrains of the Caledonian basement. The provenance of the exotic, low-grade metamorphic lithic clasts has not been established (chapter 7.4.5.2.). However, regardless this mineralogical discrepancy, the BDM mudstones seem also texturally unrelated to the adjacent basin infills. In other words it appears impossible to treat them as a form of a distal, downstream equivalent(floodbasin or playa lake) of the marginal fanglomerates. The mudstones appear rapidly above the conglomerates (Fig. 7.2.1. & 7.2.2.) and there is an absence of sandstone horizons that could eventually represent link members between the gravelly(Facies B, C & C1) and muddy depositional systems (Facies E1, E2, &E3). Consequently the BDM mudstones stand out among the infills of the Golspie basin as both petrographically and texturally exotic.

An analogous concept essentially applies to the sandstones and mudstones of Facies G1 and the mudstone component of Facies E1, E2 and E3 in the Badbea basin.

The close mineralogical affinity between the mudstones of Facies E1, E2, E3 and sandstones of Facies G1(Badbea basin), together with the palaeodispersal pattern of the latter, suggest that the sandy fluvial system fed the lake during the development of the Ceann Ousdale fan-delta (Fig. 7.2.27.A). The formation of the stream flow deposits of Facies G1 serves as an alternative scenario for textural inversion (Fig. 7.2.27.B). In the latter case the recycled(or second-cycle), well sorted, predominantly fine-grained, petrographically exotic, fluvial sands, dispersing to the S mixed with the Helmsdale granite derived first-cycle, fan-borne gravels.

7.2.6.3.2. Ben Uarie Member (BUM)

The monotonous, over 150 m thick succession of relatively well sorted very fine- to fine-grained sandstones of Facies F1 and F2, occurring only in the Golspie basin and only in its northern part, appears to be texturally exotic and unrelated, in terms of a palaeogeographical context, to any deposits in the area. At Beinn Dhorain and Allt Smeorail the contacts of the sandstones with the underlying mudstones (Beinn Dhorain Member) and the coarse conglomerates(Beinn Lunndaidh Formation) respectively are transitional but very rapid and indicate no continuity nor evolutionary passage in sedimentary environment.

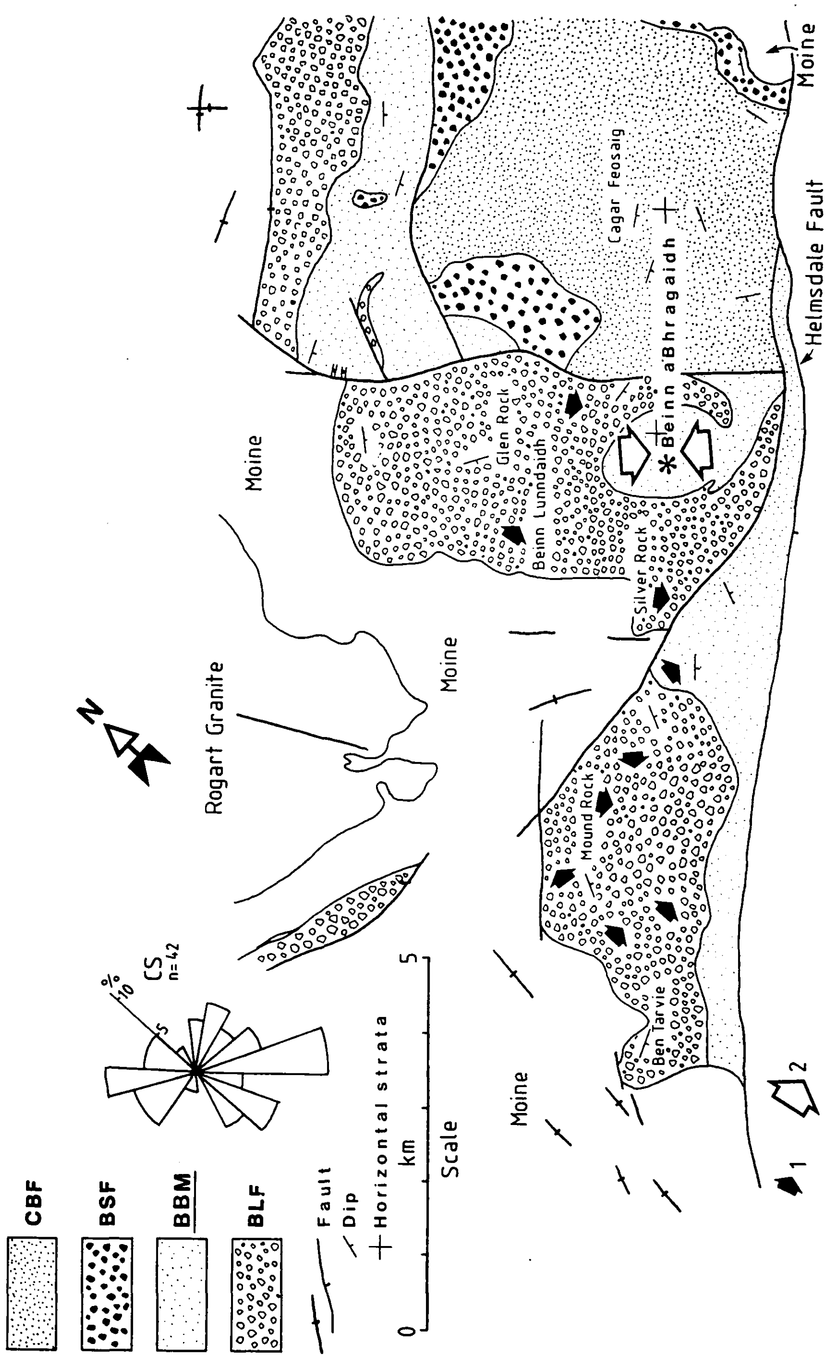
It is postulated that the BUM sandstones represent resedimented, semi-lithified deposits that had undergone a considerable textural evolution and grain-size segregation, prior to the remobilisation. These abundant well sorted fine- to very fine-grained sands are interpreted to have been derived from the S in response to intrabasinal uplift (Fig. 7.2.28.). No autochthonous, source deposits are preserved in the basin. The sandstones of BUM dramatically wedge out to the S and are absent along the SE margin of the basin.

Provenance of the BUM sandstones is difficult to establish for the very small size of the clasts in question. The identified lithic fragments are derived mainly from granitoid and high-grade metamorphic terrains. There is also a minor component of the low-grade metamorphic pelitic lithic fragments.

7.2.6.3.3. Beinn a' Bhragaidh Member (BBM)

Texturally as well as compositionally the sandstones and minor conglomerates of the BBM closely resemble the rare sandy interbeddings, present occasionally within the subjacent conglomerates of the Beinn Lunndaidh Formation. It is thought that they may represent distal equivalents of alluvial fans undergoing a phase of recession. Considering the NW component of the palaeodispersal pattern, it is tempting to speculate that the Golspie basin might have been a structure, bounded from the east during the development of the Beinn Lunndaidh Formation and the Beinn a' Bhragaidh Member. The missing half of the southern part of the basin might have been brought down along the Helmsdale fault latter in the Palaeozoic or Mesozoic times.

Figure 7.2.30. Map of the southern part of the Golspie basin shows the bimodal palaeodispersal pattern that characterised the development of the lower portion of the Beinn a' Bhragaidh Member (**BBM**) (Glen Loth Formation). **1** - mean vectors of the palaeotransport in the Beinn Lunndaidh Formation(conglomerates) (**BLF**); **2** - components of the palaeodispersal for the lower part of the **BBM** (see the enclosed above corresponding rose diagram of cross strata orientation); **BSF** - Beinn Smeorail Formation (conglomerates); **CBF** - Col-Bheinn Formation (sandstones).


CBF
BSF
BBM
BLF
Fault
Dip
Horizontal strata
0
5
km
Scale
CS
n=42
%
10
5
N
Rogart Granite
Moine
Moine
Moine
Moine
Glen Rock
Beinn Lunndaidh
Silver Rock
Beinn a'Bhragaidh
Cagar Feosaig
Helmsdale Fault
Mound Rock
Ben Tarvie
1
2

7.3. Development of the Golspie basin during the sedimentation of the Beinn Lunndaidh and Glen Loth formations - Summary

The Caledonian orogen of the Northern Highlands had undergone significant erosion prior to the initiation of the Old Red Sandstone sedimentation and around 21-30 km of the crust had been removed (Soper & Barber, 1982; Blundell, 1984; Blundell *et al.*, 1985). Consequently the conglomerates of the Beinn Lunndaidh Formation were deposited on the Caledonian lower crust (Watson, 1985) and the unroofed Newer Granites (Rogart and Helmsdale).

The debris flow-dominated alluvial fans developed along the western margin of the Golspie basin. The thickest, around 400 m thick sequence of the fanglomerates formed in the southern sector of the basin (Creag an Amalaidh - Ben Tarvie and Mound Rock fans, Fig. 7.1.27.). The palaeodispersal of the latter two fanglomeratic units concurs with the clast composition and the orientation of the faults bounding the basin. The conglomerates are locally absent along the western margin of the basin (between Oldtown and Beinn Smeorail) as well as along the opposite, eastern margin.

The sheetflood-dominated alluvial fans were fringing the NE, granitic edge of the Golspie basin and their deposits (Ousdale Arkose Conglomerate - Facies C1) are maximum 150-180 m thick. Analogous fanglomerates developed along the granitic margin of the Badbea basin (Fig. 7.1.27.). Small fans formed locally along the northern and the southern edge of the Braemore basin.

While the texturally homogeneous, sheetflood arkoses of Facies C1 represent a classical example of a first-cycle sedimentation, the textural signatures of Facies B and B1 indicate that the interpreted debris flows originated through mobilisation of the pre-existing, semi-lithified gravels and sands of possible early alluvial fans or fluvial deposits. These second-cycle sediments probably admixed to some extent with the first cycle, locally derived detritus (Fig. 7.1.26.).

In the south the development of the gravelly alluvial fans was succeeded by the sandy stream flow/sheetflood sedimentation (Facies G2), characterised by the bimodal palaeodispersal pattern (Fig. 7.2.30) (lowest, 60 m thick part of the Beinn a' Bhragaidh

Member, Glen Loth Formation). The majority of the 530 m thick succession was probably also deposited in a fluvial sandy system although more specific inferences and determination of the palaeocurrent directions have not been possible owing to the very limited exposure of the unit. It is also impossible to determine the relationship between the Beinn a' Bhragaidh Member and the deposits of the Beinn Dhorain and the Ben Uarie members.

In the northern part of the Golspie basin the transition from the alluvial fan sedimentation (Facies C1) into the mass flow-dominated lake environment (Beinn Dhorain Member - Facies E1, E2 and E3) is represented by the fan-delta sequence. It was produced in conditions of interplay between the sheetflood-dominated alluvial fan(-s) and lacustrine environment in overall transgressive circumstances. The majority of the 450 m thick Beinn Dhorain Member represents a record of the south-westward emplacement of the externally derived, exotic muds in a form of subaqueous mass flows.

An analogous fan-delta sequence characterises the succession from the Badbea basin (Fig. 7.2.2. & 7.2.27.A), although in the latter case it is succeeded by the stream flow, flood plain and lacustrine deposits of Facies G1, which make up the majority of the Ousdale Mudstones (Fig. 7.2.27.B). Similarily as in the Golspie basin the the muds of Facies E1, E2 and E3 (as well as the mudstones and sandstones of Facies G1) represent a second-cycle, exotic material containing the distinctive low-grade metamorphic, pelitic lithic fragments (PLF) of an enigmatic provenance. The same southward palaeodispersal pattern, characterising the Beinn Dhorain Member and Facies G1 of Ousdale Mudstones indicate a possible common source area of the exotic detritus.

Following the mud flow sedimentation of the Beinn Dhorain Member the continuously subsiding northern portion of the Golspie basin was filled from the S-SW with the over 150 m of resedimented sands in a form of sandy debris flows (Facies F1) and sheetfloods (Facies F2). The palaeodispersal patterns from the Ben Uarie Member suggest that the central, intrabasinal uplift contributed to the *en mass* mobilisation of the pre-existing, considerably reworked sands. Deposits of the Glen Loth Formation have not been preserved along the eastern edge of the Golspie basin i.e. between Creag a' Chrionaich and S of Duchary Rock.

The Golspie basin migth have been at least partly separated from the east during the Lower Old Red Sandstone by the NE-SW trending basement ridge of Helmsdale granite and Moine metasediments. There are, however, neither palaeocurrent indicators nor other data which might support the notion. Nevertheless, it is most likely that the fans of the BLF fringing the Helmsdale granite margin did disperse to the W and NW (Fig. 7.1.27.). The bimodal palaeodispersal pattern from the lowest part of the Beinn a' Bhragaidh Member (GLF) may suggest a westward-dipping component of the basin floor (see also chapter 7.2.6.2.).

Mykura (1983a) draws attention to the Lower Old Red Sandstone *land-locked internal basins* present between Strathpeffer and southern Orkney, but does not present evidence in support of the notion. Richards (1985b) describes a 1 km thick, Lower Old Red Sandstone lacustrine succession form the offshore (Fig. 3.2.), and interprets it as an isolated basin being a distal equivalent of the Turriff basin.

The most distinctive feature of the majority of the lower (Lower Old Red Sandstone) group of the infill of the Golspie basin is their resedimented, second-cycle origin (Facies B, B1, E1, E2, F1, F2). It is interpreted that a variety of sediments (gravels, sands and muds) had been locally blanketing the crystalline basement. They became mobilised and emplaced predominantly *en mass* into a tectonically initiated depression.

Although it seems reasonable to infer that the faults bounding the Golspie basin might have have had a profound influence on the locus of the alluvial fan sedimentation and on the palaeodispersal, and that the continuing uplift along the high-angle/vertical faults might have promoted the instability of the depositional surface and the mass flow processes, it is postulated herein that the abundance of a wide range of a relatively unconsolidated detritus in the source area was a significant if not a critical factor controlling the distribution, mode of deposition and the type of sediments emplaced into the basin.

The local absence of the BLF fanglomerates along the western and the eastern margin of the basin may be a resultant of either a scarcity or a lack of available debris in the source area and not necessarily, exclusively due to a localized tectonic "quiescence" or absence of fault controlled escarpment. The siliceous granulites, which constitute the majority of the surrounding Moine source terrain, are very resistant to denudation (uniaxial compressive strength values range from 200-300 MPa) and in a "first-cycle scenario" they would not have been capable to yield the required copious volumes of gravel and sand and feed the debris flow fans. One may speculate that in the case of lack of available, abundant source sediments the Golspie basin would have been *sediment-starved.* The textural signatures of Facies B and B1 of the Beinn Lunndaidh Formation as well as Facies E1, E2, E3, F1 and F2 of the Glen Loth Formation independently suggest the the debris flows formed from the mobilisation of the pre-existing, variously reworked gravels, sands and muds of variable provenance.

7.4. **Beinn Smeorail Formation (BSF)**

7.4.1. Introduction

The Beinn Smeorail Formation (BSF) consisting mainly of coarse conglomerates represents the lower part of the upper, Middle Old Red Sandstone group of the infill of the Golspie basin (Fig. 6.2.). This lithostratigraphic unit is named *"Massive Conglomerates and Pebbly Sandstones"* in Read *et al.* (1925). The conglomerates of the BSF are regarded as an equivalent of *"Badbea Breccia"* (Badbea basin) and *"Morven & Smean Conglomerate"* (Braemore basin) (Crampton *et al.*, 1914) (Fig. 7.2.22).

The formation was named by Mykura (1983a), after name of the summit Beinn Smeorail at the NW margin of the basin (Fig. 3.3.).

The BSF is subdivided here into five lithological units, each a conglomeratic body, differing with regard to position within the Golspie basin, clast composition, facies characteristics and palaeodispersal (see chapters 7.4.5.3. & 7.4.5.4.). They are as follows:

(1) Ben Horn Conglomerate;

(2) Old Town - Killin Rock Conglomerate;

(3) Cnoc Cragaidh Conglomerate;

(4) Creag a' Bhodaidh Conglomerate;

(5) Socach Hill Conglomerate.

The units Oldtown - Killin Rock, Cnoc Cragaidh and Socach Hill are also referred in the text as "fans" (e.g. Socach Hill fan, Fig. 7.4.11.) as they appear to represent bodies of individual alluvial fans or fan systems (see chapter 7.4.5.4.).

Similarly as in the case of the Beinn Lunndaidh Formation the conglomeratic units mentioned above have not been nominated as formal lithostratigraphic "members" because of their overall, significant compositional and sedimentological similarities (see chapter 7.1.1.). Moreover, although some of the boundaries of the conglomeratic units are easly defined in particular localities they are not mappable over the area of the basin. The BSF is clearly dominated by Oldtown - Killin Rock and Creag a' Bhodaich units whose lateral contacts area broadly gradational. Distribution of the conglomeratic units of the BSF is depicted schematically in Figure 7.4.12. (see also chapter 7.4.3. further in the text)

7.4.2. Angular unconformity - lower boundary

The lower contact of the Beinn Smeorail Formation (BSF) with the underlying deposits of the Glen Loth Formation is an angular unconformity and this relationship is most evident along the margins of the basin.

In the gorge NW of Oldtown horizontal conglomerates rest on steeply inclined sandstones of the Glen Loth Formation (Ben Uarie Member) which dip to the SE at angle of 70° (Fig. 3.3.). An analogous relationship, though less dramatic is also apparent 1.5 km SW of Oldtown, NW of Carrol Rock. The actual contact at the latter site is not exposed.

An equivalent unconformity along the NW margin of the basin is seen in Allt Smeorail (N of Beinn Smeorail), where the conglomerates of the BSF rest near horizontally upon the sandstones of the Ben Uarie Member, which dip to the SSE at angle of 40°.

Around 1.5 km SSW of Creag a' Chrionaich, close to the NE margin of the basin, the Creag a' Bhodaich Conglomerate with a dip of 5° rests upon steeply inclined sandstones and mudstones of the Glen Loth Formation, which dip to the NW at angles of over 50°. A few hundred meters to the S the same conglomerate is seen close to the Ousdale Arkose Conglomerate (Beinn Lunndaidh Formation), which dips to the NW at angle of 70°. Finally it comes to rest upon the surface of Moine siliceous schists (Read *et al.*, 1925).

A corresponding angular unconformity is evident in the Badbea basin, 2 km NE of Ceann Ousdale, where sandstones and mudstones of the Ousdale Mudstones are truncated by the Badbea Breccia (Crampton *et al.*, 1914) (Fig. 7.2.22.). In the section on Creag an Turnail (Fig. 7.2.22.), the unconformable junction of the Badbea Breccia with the steeply dipping mudstones is even more obvious.

The Badbea Breccia is about 90 m thick.

In the Braemore basin the Morven, Smean and Maiden Pap Conglomerate at Achnachavish Hill appears to rest with angular unconformity on the Braemore Mudstones and Sandstones (Crampton *et al.*, 1914). The conglomerate occupies central part of the Braemore basin, being best exposed at Morven, Smean and Maiden Pap. Its thickness diminishes form 180 m at Morven to around 75 m NE of Wag Hill (Fig. 7.2.22.).

7.4.3. Distribution and thickness

The conglomerates of the Beinn Smeorail Formation (BSF) outcrop mainly in the central and the northern part of the Golspie basin. They reach their maximum thickness of around 360 m in the area of Creag a' Bhodaich (Creag a' Bhodaich Conglomerate). The thickness of the formation diminishes to the south to 80 m and 40 m along the SE margin of the basin at Killin Rock and SE of Duchary Rock respectively.

The Ben Horn Conglomerate is located most further to the SE and is represented only by a small outcrop at the top of Ben Horn (Fig. 3.3.). Thickness of this unit is 120 m, though some proportion of the conglomerates is missing due to denudation.

The Oldtown - Killin Rock Conglomerate occupies the central part of the basin, where at Oldtown it rests unconformably of the sandstones of GLF and at Killin Rock comformably on the deposits of the Socach Hill Conglomerate. The Oldtown - Killin Rock Conglomerate seems to continue to the NE beyond Cnoc Cragaidh and Beinn Smeorail, possibly interfingering with the Creag a' Bhodaich Conglomerate. Thickness of the Oldtown - Killin Rock unit decreases from around 200 m at the NW basin margin (Oldtown) to 70 m and 30 m at the SE basin margin(Killin Rock and SE of Duchary Rock respectively) (Fig. 7.4.11.). In the area of Cnoc Cragaidh thickness of the conglomerate is around 100 m and the unit is underlaid by a lenticular body of the Cnoc Cragaidh Conglomerate (Plate 7.4.1.B). Width of the latter unit is around 450 m and considering its palaeodispersal characteristics (Fig. 7.4.1.) the conglomerates probably wedge out to the SE.

The Socach Hill Conglomerate is 11 - 12 m thick and underlies the Oldtown - Killin Rock unit along the SE margin of the Golspie basin (Fig. 7.4.11.). Both conglomeratic units differ in terms of clast composition and palaeodispersal (Fig. 7.4.11.). Taking into account the general NW palaeotransport direction established for the Socach Hill Conglomerate (Fig. 7.4.8. & 7.4.11.; see also chapter 7.4.5.4.) and absence of this unit at the western basin margin, it probably thins out in the corresponding direction. It is not exactly clear, however, whether the Socach Hill Conglomerate does indeed belong to the BSF or represents the Lower Old Red Sandstone Beinn Lunndaidh Formation. The dramatic - "bed-to-bed" - changes in clast composition (Fig. 7.4.8.) may for example only reflect swift shifts or progradations of active segments of alluvial fans, fed by a source of distinctly different lithology than the subjacent fans (see chapter 7.4.5.3.).

The Creag a' Bhodaich Conglomerate, the thickest unit of the Beinn Smeorail Formation occurs in the NE part of the Golspie basin and probably coalesces in the SW direction with the Oldtown - Killin Rock unit (see chapter 7.4.5.5.).

Distribution of the BSF conglomeratic units is schematically shown in Figure 7.2.12.

7.5.4. Upper boundary

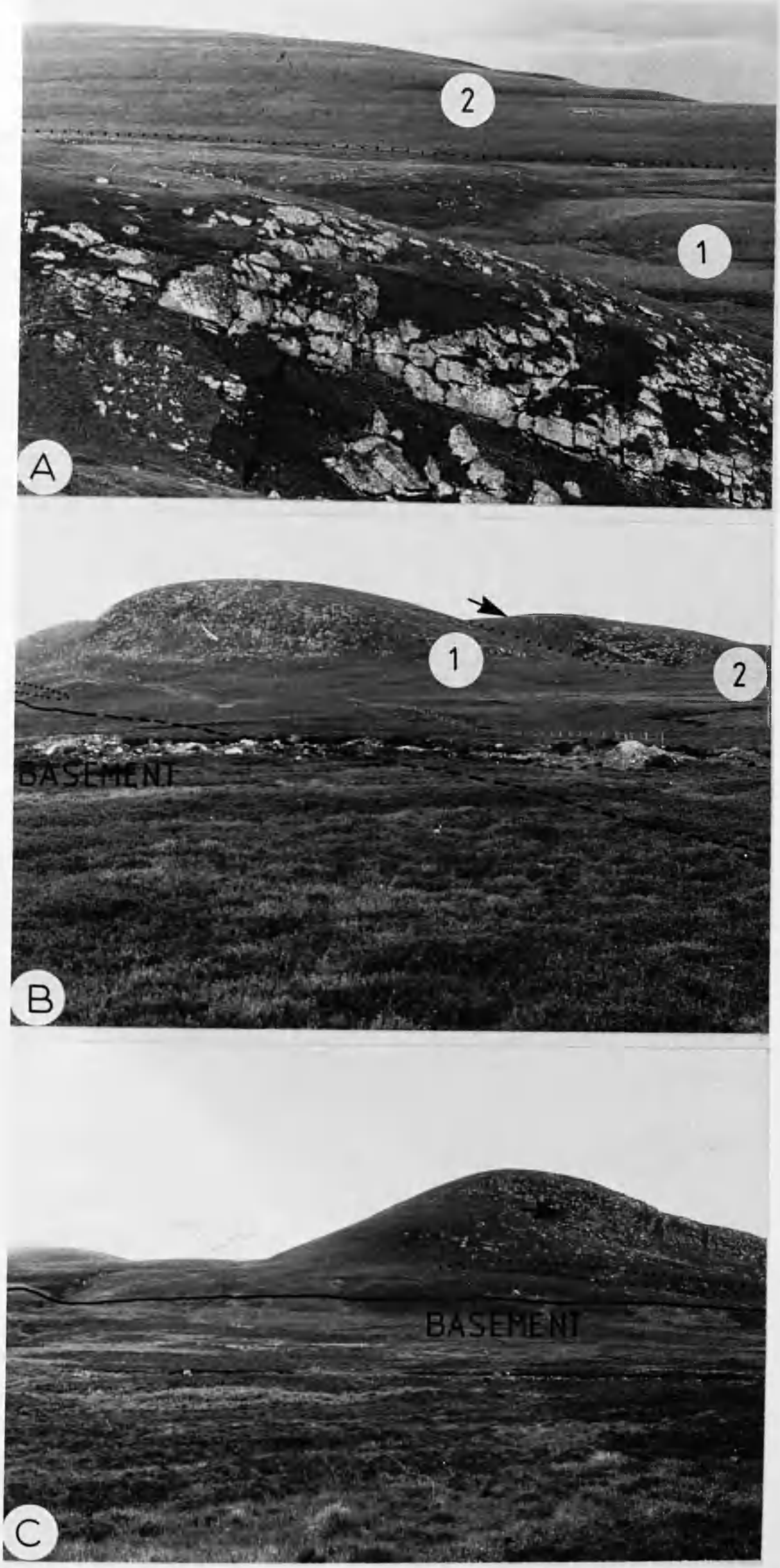
The conglomerates of the Beinn Smeorail Formation pass gradually into sandstones of the Col-bheinn Formation. The transition is exposed at Leadoch Rock (Fig. 7.5.1.). Nowhere else the passage is directly traceable.

Plate 7.4.1. A: In the foreground at Cnoc Cragaidh the structureless fanglomerates of the Oldtown - Killin Rock unit (**1**) are underlaid by sandstones and conglomerates interpreted as deposits of abundant fan segment (marked with arrows). The same segment horizon is also marked in Phot. **B**. In the background, near horizontal sandstones of the Col-bheinn Formation form the topmost, central part of the Golspie basin (**2**). Their gradational base is marked with dotted line;

B: View at Cnoc Cragaidh from the SW. (**1**) Cnoc Cragaidh Conglomerate; (**2**) Oldtown - Killin Rock Conglomerate. The arrow points to the horizon of the abandoned fan segment deposits from phot. **A.** The continuous to dashed line marks the contact with the basement;

C: View of the Cnoc Cragaidh from the SWW. (**1**) the lenticular, cross-stratified sandstone horizon underlies the main body of the Cnoc Cragaidh Conglomerate (dotted line) (see also Phot. **B** left and Fig. 7.4.1.). The arrow points to the horizon of rapid introduction of the coarser and richer in clasts conglomerates of Facies B1 (see also Fig. 7.4.1. & 7.4.2.B). A few meters thick conglomerate present below the cross-stratified sandstone and resting directly on the basement may belong to the Beinn Lunndaidh Formation.

Plate 7.4.1.



7.4.5. Sedimentary characteristics of the Beinn Smeorail Formation

7.4.5.1. Main sedimentary facies

The majority of the conglomerates making up the Beinn Smeorail Formation(BSF) resemble those of the Beinn Lunndaidh Formation (Facies B, C & C1) and some of them are clearly identical. But there are two new facies within the BSF which are varieties of Facies B and C: **Facies B1**: Heterogeneous, structureless conglomerates and pebbly sandstones (Cnoc Cragaidh variety of Facies B) and **Facies C2**: Assemblage of homogeneous, massive to planar-stratified and cross-stratified conglomerates and cross-stratified sandstones(Creag a' Bhodaich variety of Facies C).

7.4.5.1.1. Facies B1: Texturally heterogeneous, structureless conglomerates and pebbly sandstones (Cnoc Cragaidh variety of Facies B)

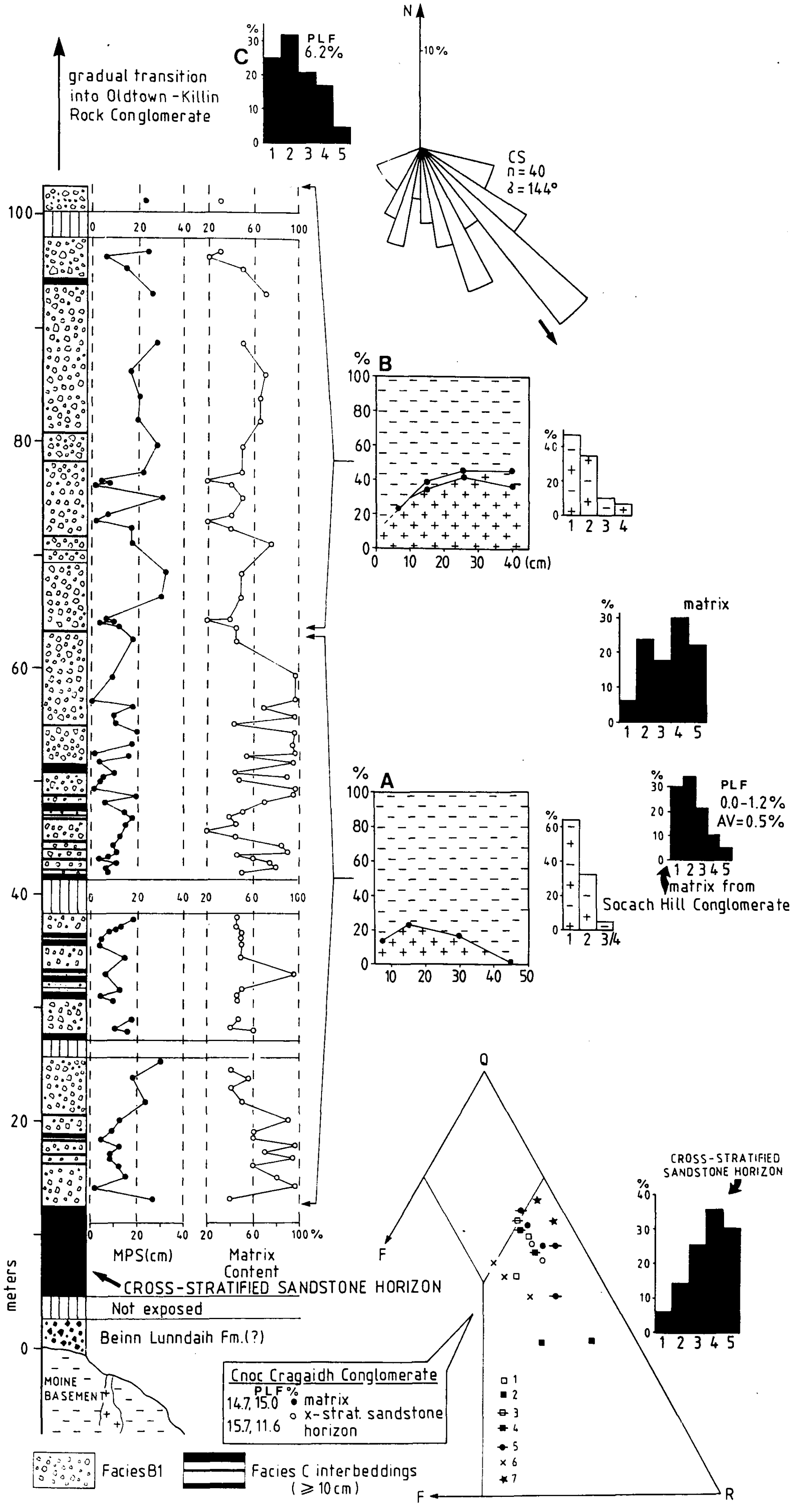
Description

Facies B1 is essentially present at only one locality, constituting the majority of the around 100 m thick and 450 wide Cnoc Cragaidh conglomeratic body (Fig. 7.4.1.). It occurs also as a minor component of the Socach Hill Conglomerate (Fig. 7.4.8. Log A) and Creag an Amalaidh Conglomerate (BLF, Fig. 7.1.23.).

The deposits of Facies B1 are structureless and range texturally from fine-grained sandstones with chaotically scattered clasts (down to 2%) to clast-supported conglomerates with clasts constituting up to 80%. Sporadic homogeneous, massive sandstones have also been found. The vast majority of the deposits in question, however, appear as generally poorly sorted, matrix-supported conglomerates and pebbly sandstones with matrix content varying between 40 - 70%. The particularly matrix-rich conglomerates and pebbly sandstones dominate the lower, approximately 45 m thick part of the Cnoc Cragaidh Conglomerate (Fig. 7.4.1. & 7.4.2.), and their average matrix content is around 65%. The remaining, upper part of the sequence consists mostly of the matrix- to clast-supported conglomerates with the matrix ranging from 20 - 70%, averaging 45%. Throughout the

Figure 7.4.1. Summary diagram, showing textural characteristics of the Cnoc Cragaidh Conglomerate versus clast composition and roundness of the gravel clasts and the associated sand fraction. For explanation of the symbols in the clast composition diagrams **A** & **B** see Fig. 7.1.20a.. Note a dramatic introduction of the coarser gravel fraction in the middle part of the sequence, combined with a decrease in amount of matrix.

Three-components diagram at the bottom illustrates petrographic composition of the sandstones associated with the Cnoc Cragaidh Conglomerate and the sandstones appearing in other units of the Beinn Smeorail Formation. <u>Oldtown - Killin Rock Conglomerate:</u> **1** - ss. interbeddings at Killin Rock, **2** - matrix from Facies B at Oldtown, **(7)** ss. from the lowest part of the unit at Cnoc Cragaidh; <u>Socach Hill Conglomerate:</u> **3** - ss. interbedding, **4** - matrix from Facies B1; <u>Creag a' Bhodaich Conglomerate:</u> **5** - matrix from Facies B-dominated topmost part of the unit, **6** - ss. horizons 1-3 (see also Fig. 7.4.4.). The filled histograms show roundness estimations for sandstones (matrix and beds). **C**: roundness of the grains from the cross-strat. ss. horizon (**7**). Note a decrease in proportion of rounded grains in the sandstone material associated with the upward transition of the Cnoc Cragaidh Conglomerate into Oldtown - Killin Rock Conglomerate. The palaeotransport rose-diagram applies to the Cnoc Cragaidh Conglomerate including the underlying, cross-stratified sandstone horizon (**CS**). Roundness scale after Powers (1953): **1** - angular, **2** - subangular, **3** - surounded, **4** - rounded, **5** - well rounded. **PLF%**: content of the low-grade metamorphic pelitic lithic fragments. (Locality: Cnoc Cragaidh, BSF)



gradual transition into Oldtown - Killin Rock Conglomerate
C
PLF 6.2%
N
10%
CS
n = 40
δ = 144°
B
A
matrix
PLF
0.0-1.2%
AV=0.5%
matrix from Socach Hill Conglomerate
MPS(cm)
Matrix Content
CROSS-STRATIFIED SANDSTONE HORIZON
Not exposed
Beinn Lunndaih Fm.(?)
MOINE BASEMENT
meters
Cnoc Cragaidh Conglomerate
PLF%
14.7, 15.0 • matrix
15.7, 11.6 ○ x-strat. sandstone horizon
Facies B1
Facies C interbeddings (≥ 10 cm)
Q
F
R
CROSS-STRATIFIED SANDSTONE HORIZON

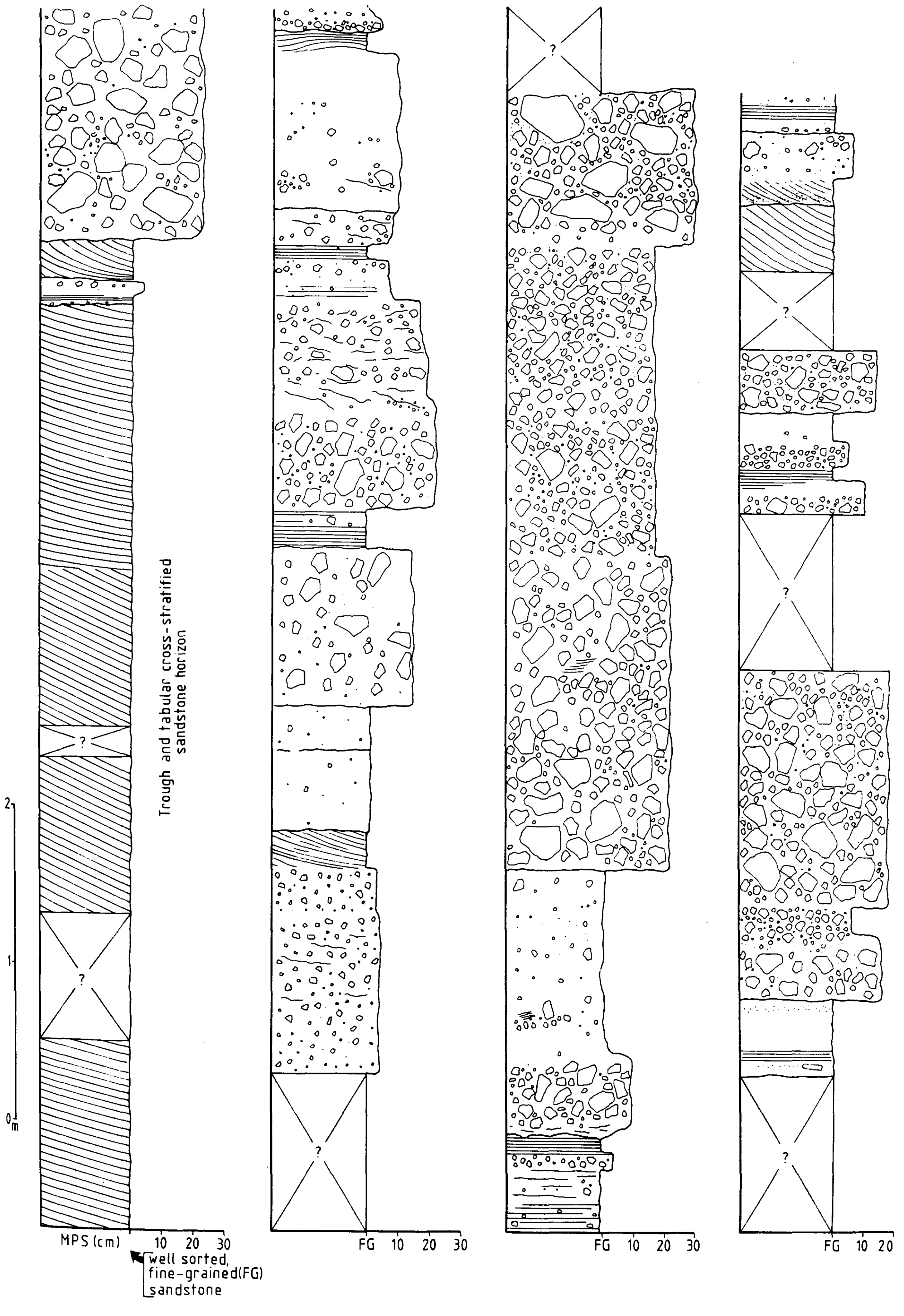
entire 100 thick section of the Cnoc Cragaidh Conglomerate the matrix remains the same, well sorted, fine-grained sandstone with negligible amount of finer-grained fraction (Plate 7.4.2.A&B). Unlike the gravel fraction a significant population of the grains in the matrix displays good roundness (Fig. 7.4.1. & Plate 7.4.2. A,B&D). Matrix in the pebbly sandstones and conglomerates of Facies B1 from the Socach Hill Conglomerate differs significantly from the Cnoc Cragaidh deposits because of the lower proportion of the well rounded grains and because of the considerably higher clay content (Fig. 7.4.1. & Plate 7.4.7.) (see also chapter 7.4.5.2.). The matrix of Facies B1 in the Creag an Amalaidh Conglomerate is also well sorted and contains a significant proportion of subrounded to very well rounded clasts (Fig. 7.1.20a. & Plate 7.1.11.B)

The maximum particle size (MPS) in the lower, matrix-rich portion of the Cnoc Cragaidh Conglomerate ranges from 1 - 30 cm, averaging 11 cm. The upper, richer in clasts part is coarser and its MPS varies between 4 - 33 cm, averaging 16 cm. The largest boulder found in the deposits of Facies B1 is 63 cm in size. The size of the largest particle in a bed (LPS) in the lower part of the sequence ranges from 6 - 63 cm, averaging 20 cm. The upper, clast-rich part has the LPS varying between 9 - 55 cm and averaging 29 cm. Introduction of the coarser and more conglomeratic deposits of Facies B1 in the middle part of the Cnoc Cragaidh Conglomerate appears to be very rapid (Fig. 7.4.2.B & Plate 7.4.1.C).

The gravel fraction is poorly sorted and the clasts are predominantly angular to subangular Moine siliceous granulites (see also chapter 7.4.5.2. and Fig. 7.4.1.).

Normally, the matrix material appears in a remoulded, homogenised state though there are common, irregular sandy chunks (Plate 7.4.3.C,), some of which show an early grain lamination (Fig. 7.4.2., 7.4.3.B & Plate 7.4.7.B). The lamination had evidently formed prior to the incorporation of the sandy material into the gravels of Facies B1. It is important to note that even in a situation of the remoulded character of the matrix, the sandy material typically appears to have not been thoroughly admixed with the gravelly detritus and clearly manifests in the deposits its original textural as well as petrographic identity (Plate 7.4.5.D). The non-uniform distribution of the matrix in the deposits of Facies B1 gives rise to the characteristic effect of textural heterogeneity (Plate 7.4.5.)

Figure 7.4.2a. Graphic log through the main part of the Cnoc Cragaidh Conglomerate dominated by the matrix-supported conglomerates and pebbly sandstones of Facies B1, interbedded locally with the stratified deposits of Facies C. For explanations of symbols see Fig. 7.4.2.C. The large scale cross-stratified sandstones underlie the main body of the pebbly sandstones and conglomerates of Facies B1 (see also Plate 7.4.1.C). (Locality: Cnoc Cragaidh, BSF)



Trough and tabular cross-stratified sandstone horizon
?
2
1
0m
MPS (cm)
10 20 30
well sorted, fine-grained(FG) sandstone
FG 10 20 30
FG 10 20 30
FG 10 20

Figure 7.4.2b. Continuation from Fig. 7.4.2a. The arrow points to the horizon of rapid appearance of the coarser and richer in clasts conglomerates of Facies B1 (see also Fig. 7.4.1. & Plate 7.4.1.C). Note the disrupted, originally stratified, sandstone bed directly below (chaotic system of parting features cuts the stratification). (Locality: Cnoc Cragaidh, BSF)

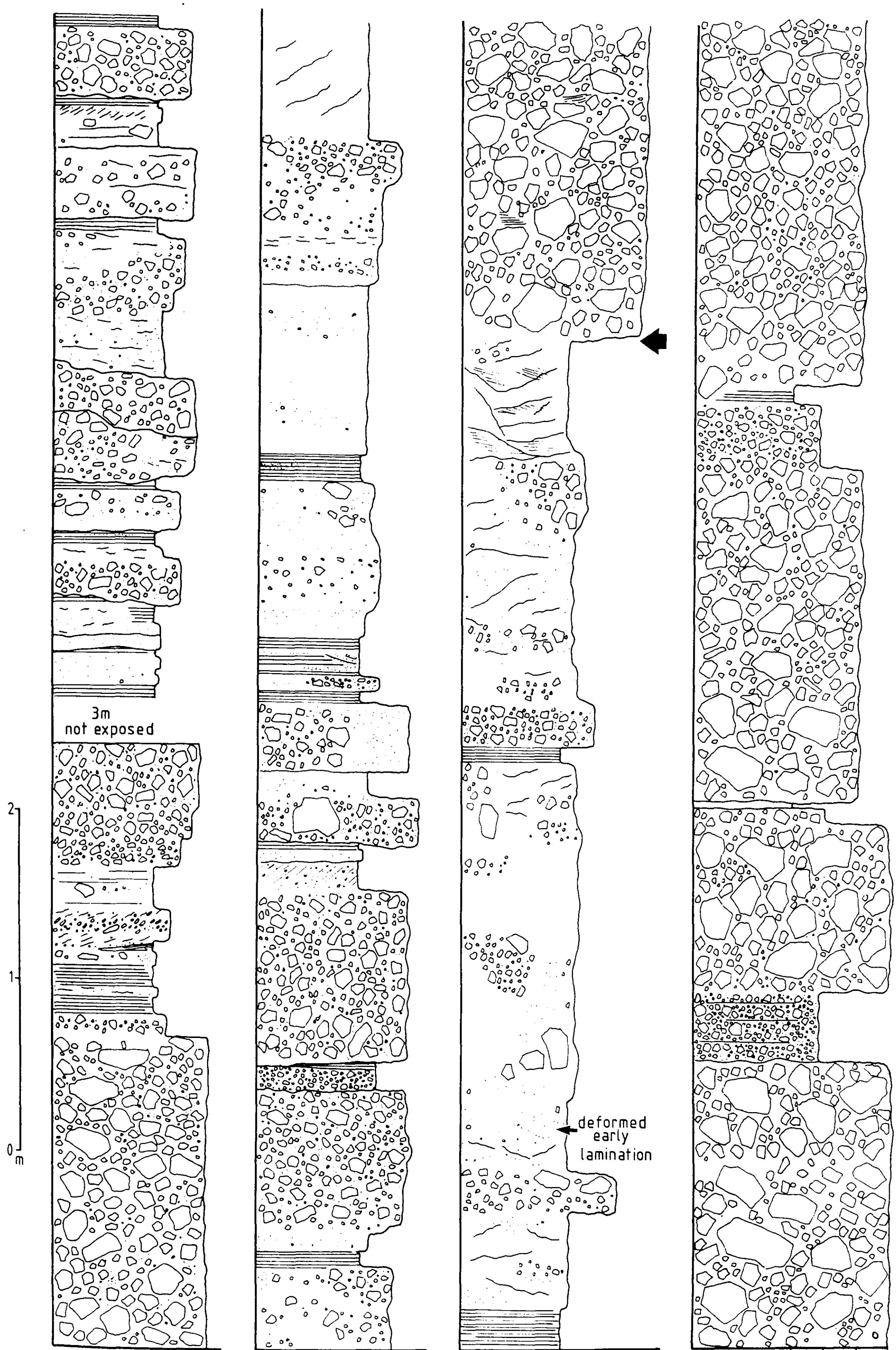
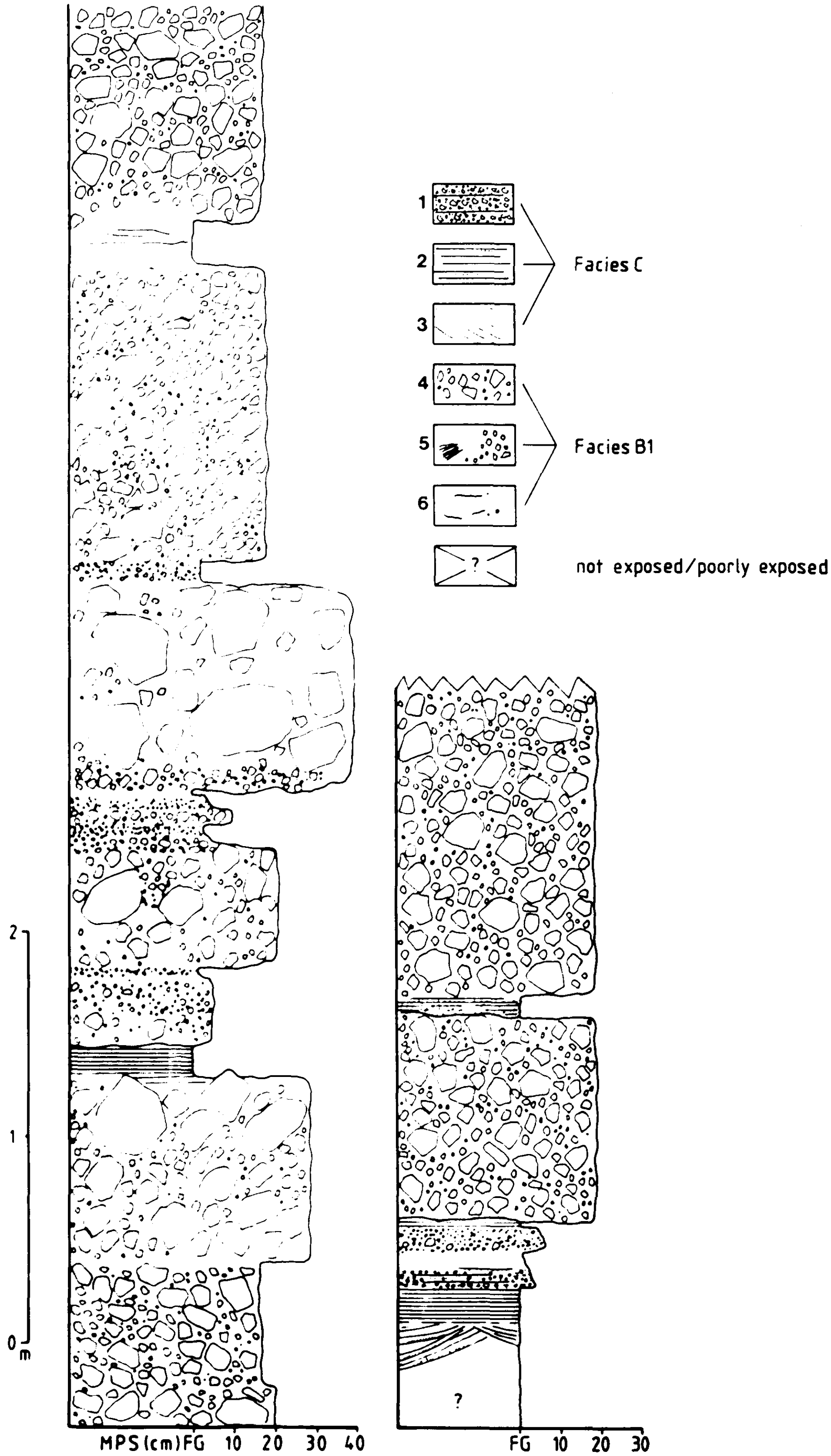

3m
not exposed
2
1
0
m
deformed
early
lamination
MPS (cm) FG 10 20
FG 10 20
FG 10 20 30
FG 10 20 30

Figure 7.4.2c. Continuation from the Fig. 7.4.2b. **Key: (1-3)** planar- to cross-stratified conglomerates and sandstones of Facies C; **(4-5)** structureless, texturally heterogeneous conglomerates and pebbly sandstones of Facies B1 with occasional, unremoulded sandy chunks with primary lamination **(5)**; (6) arcuate to planar parting features. (Locality: Cnoc Cragaidh, BSF)


1
2
3
Facies C
4
5
6
Facies B1
?
not exposed/poorly exposed
2
1
0
m
MPS (cm) FG 10 20 30 40
?
FG 10 20 30

The deposits of Facies B1 occur probably as amalgamated units and recognition of possible individual beds is possible only in places where planar-stratified or cross-stratified sandstone or conglomeratic interbeddings of Facies C intervene (Plate 7.4.3.C & 7.4.4.A,B) (see further in the text). In such cases the basal contacts of Facies B1 with the subjacent, stratified beds seem to vary from non-erosional to erosional, though the nature of the contacts is often difficult to establish with confidence. The latter deposits, however, are rare and this plus the fact that the lower, matrix-rich part of the Cnoc Cragaidh Conglomerate is only fragmentarily exposed, preclude appreciation of the overall geometry of the individual beds. The upper, particularly clast-enriched part is far better exposed (Plate 7.4.1.C, Fig. 7.4.2b. & 2c.), but the beds normally appear amalgamated and hence again the determination of their thickness, shape and lateral extend is not possible. The minimum thickness of the recognized beds is 10 cm and the maximum perhaps exceeds 2 m.

Difficulties with identification of the single beds arise from the conspicuous textural heterogeneity of the deposits, resulting from highly non-uniform dispersion of the particles in the matrix. The conglomerates often appear in irregular to lenticular patches surrounded by the clast-poor, massive pebbly sandstone (Fig. 7.4.2.& 7.4.3b.; Plate 7.4.5.C) or sandstone and it is difficult to determine whether these conglomeratic clusters represent either integral portions of the surrounding host deposits and both were deposited simultaneously or formed from separate depositional events (see the interpretation of the facies further in the text). The latter approach is often justified, considering the strongly lenticular shape of some of the conglomeratic clusters and the identified tongue-shape termini of some of them (Plate 7.4.6.B & Fig. 7.4.3b.). Some of the irregular conglomeratic clusters are matrix-free and show an open framework (see also Facies B, Fig. 7.1.4.B).

Taking into account the textural heterogeneity of the deposits of Facies B1, any form of vertical variability in the clast size (maximum particle size - MPS) seem to be inadequate criterion for discriminating individual beds. No particular form of grading has been recorded neither from the pebbly sandstone nor from the conglomerates.

The nature of the outcrop at Cnoc Cragaidh has not made practicable to take systematic

Plate 7.4.2. A, B & D: Microphotographs of the sandstone matrix from Facies B1. Note good sorting, negligible clay content and numerous well rounded grains. **D**: Note a large Moine clast on the left (PPL);

C: Microphotograph of the sandstone from the cross-stratified horizon, which underlies the Cnoc Cragaidh Conglomerate. Note evident textural affinities with the sandstone matrix (compare with phot. **A**; see also Fig. 7.4.1. for details). (Locality: Cnoc Cragaidh, BSF)

Plate 7.4.2.

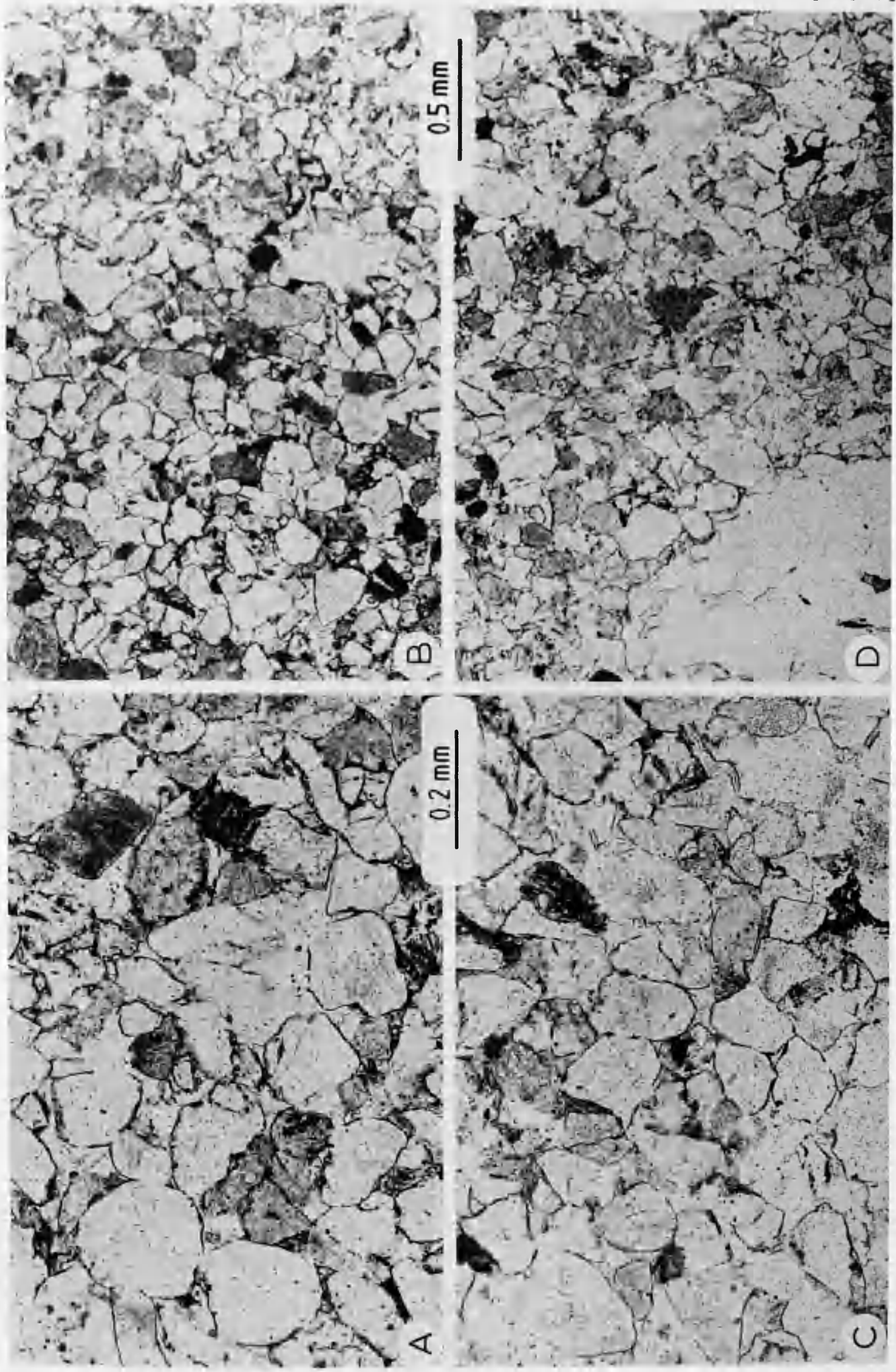


Plate 7.4.3. A: Debris flow deposits of Facies B1 underlaid by planar- and cross-stratified sandstones of Facies C. Ruler is 25 cm long;

B: (**1**) planar-stratified sandstones of Facies C covered by crudely stratified to massive pebbly sandstones (**2**); the latter deposits might have formed from a hyperconcentrated flow; (**3**) matrix-supported conglomerate of the cohesive debris flow(Facies B1);

C: Debris flow deposits of Facies B1. Note outsize boulders and patches of unremoulded sandy material (arrowed); (**1**) sandstone intraclast with preserved early lamination. Ruler is 25 cm long;

D: Fragment of poorly exposed, large scale cross-stratified sandstone horizon, which underlies the Cnoc Cragaidh Conglomerate. Ruler is 25 cm long. (Locality: **A-D** - Cnoc Cragaidh, BSF)

Plate 7.4.3.

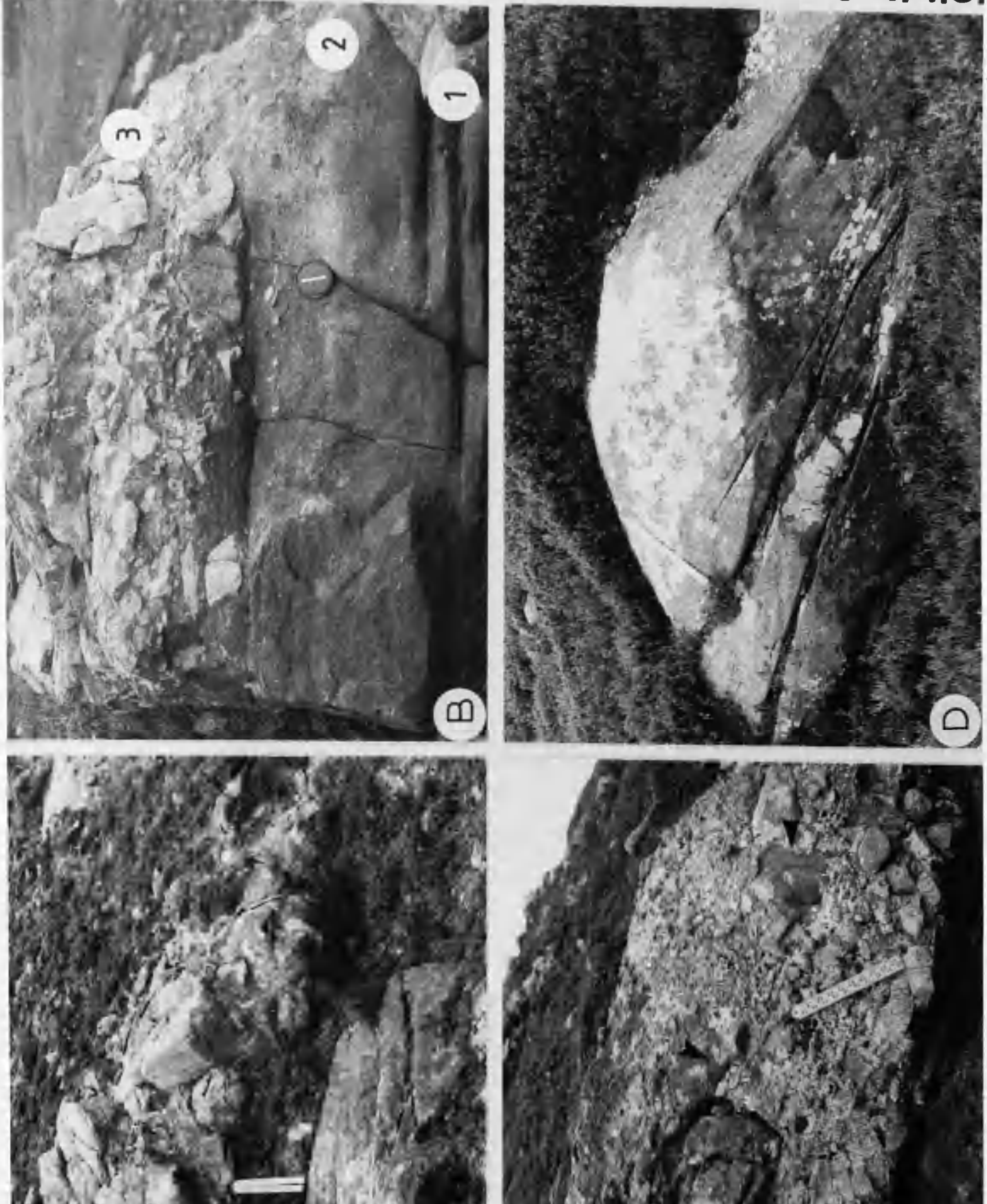
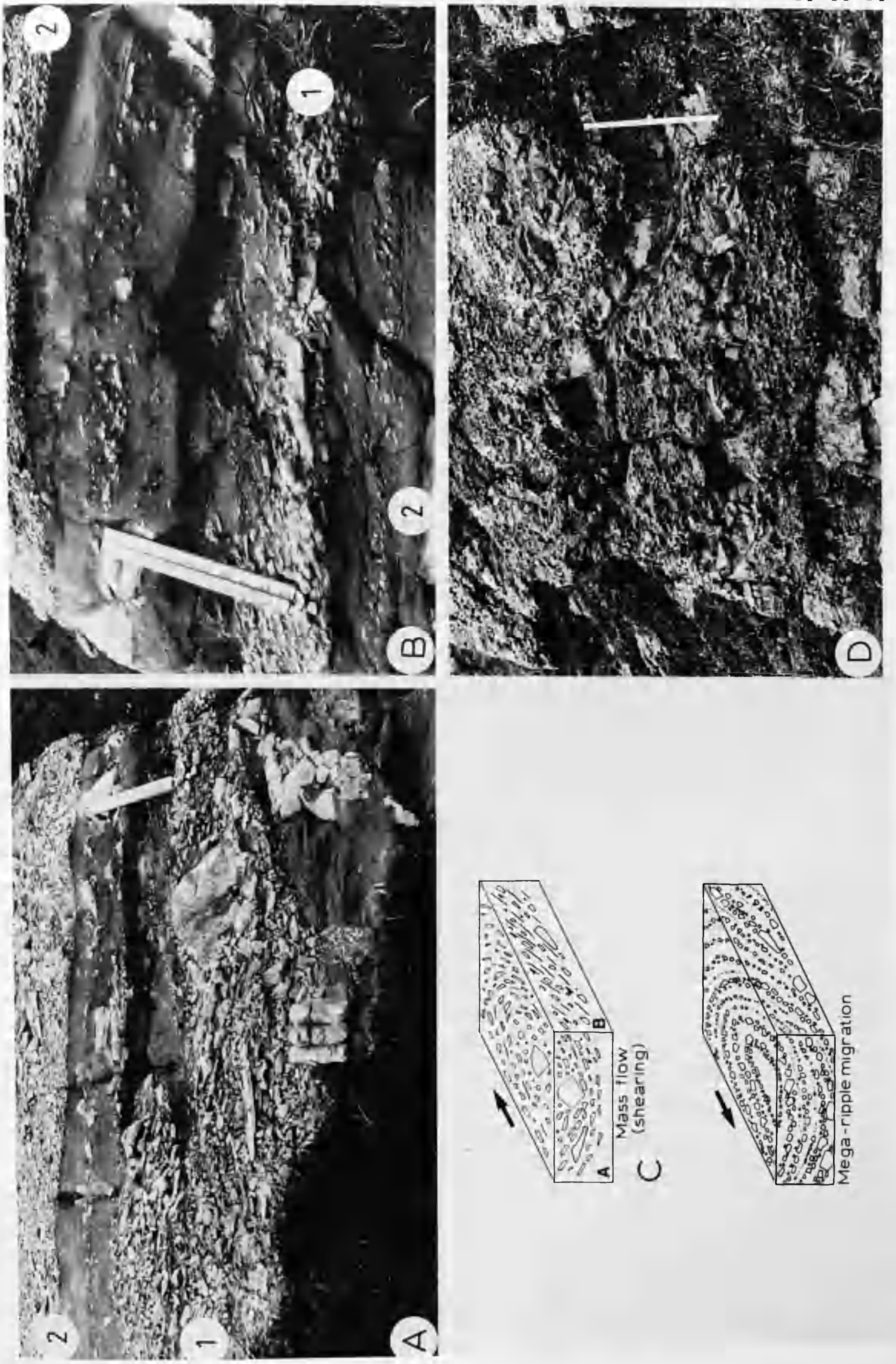


Plate 7.4.4. Photographs **A & B** show perpendicular to each other faces of the same outcrop. **1** - mass flow deposits of Facies B1; **2** - winnowing stage deposits of Facies C. The arrows points to the same erosional surface. Facies B1 shows up-stream dipping clast orientation, associated locally with discontinuous parting features (see also diagram **C**). Ruler is 25 cm long. The structure is interpreted as a "push-fabric" which developed during the mass flow movement rather than as a mega-ripple cross-stratification (**C**). Note that there is no evidence for grain segregation. Outsize clasts and unremoulded sandy chunk with preserved early lamination are present in the deposits of Facies B1. The upper, crudely stratified beds of Facies C (**2**) might have deposited from hyperconcentrated sediment flows - transitional between cohesive debris flows of Facies B1 and winnowing stage water flows. (Locality: Cnoc Cragaidh, BSF);

D: Sandstone bed of Facies C plastically deformed along a syndepositional fault. Ruler is 50 cm long. (Locality: Cnoc Cragaidh, BSF)

Plate 7.4.4.



measurements of clast orientation, that could be treated as meaningful, representative data. Visually the fabric has generally been found to be chaotic. In two sites, however, visually strong, preferential clast orientation has been recorded and this feature has been typically associated with arcuate to planar, discontinuous parting planes, developed in the surrounding sandstone matrix (Fig. 7.4.2.B & Plate 7.4.4.A,B). The latter features do not have grain size segregation and therefore are not regarded as bedding. In both instances the clasts as well as the adjacent parting features are inclined in the direction opposite to the mean palaeotransport vector, inferred from the cross-strata of the intervening deposits of Facies C (Fig. 7.4.1.). Only in one site two sections of the structure are available and both reveal that the clasts are oriented concordantly to the trough-shaped parting features (Plate 7.4.4.C). In most cases, however, the discontinuous parting planes are undulating and subparallel to the bedding and the larger clasts appear to follow their trend (Plate 7.4.5.A&B). In a number of places the parting features have been found in a totally disorganised arrangement, cutting occasionally the deformed true lamination (Fig. 7.4.2.D & 7.4.3b.).

The tongue-like bed shown in Plate 7.4.6. displays an interesting, "caterpillar structure", pronounced by a characteristic clast arrangement. The fabric appears "swirled" at the front of the "caterpillar bed".

As has already been mentioned above, the planar-stratified to cross-stratified sandstones and minor conglomerates occur locally within the deposits of Facies B1 as discontinuous beds and are regarded as equivalent of **Facies C** (see chapter 7.1.5.1.4.) in particular its sandy variety, common at Beinn Lunndaidh(BLF, Fig. 7.1.1e.). The stratified interbedddings normally cap erosionally or non-erosionally the structureless pebbly sandstone and conglomeratic deposits (Fig. 7.4.3a. & 3b.) The most laterally extensive(over 4 m) sandstone bed of Facies C at Cnoc Cragaidh (in the section oblique to the inferred mean, local palaeotransport direction) has been found infilling a broad, 35 cm deep depression on the surface of a conglomeratic bed of Facies B1 (Fig. 7.4.3a.).

In the lower, matrix-rich part of the Cnoc Cragaidh Conglomerate, a number of conglomerate and pebbly sandstone beds show crude, planar-stratification, defined by discontinuous pebble stringers (Plate 7.4.4.A&B). These sediments have been found in

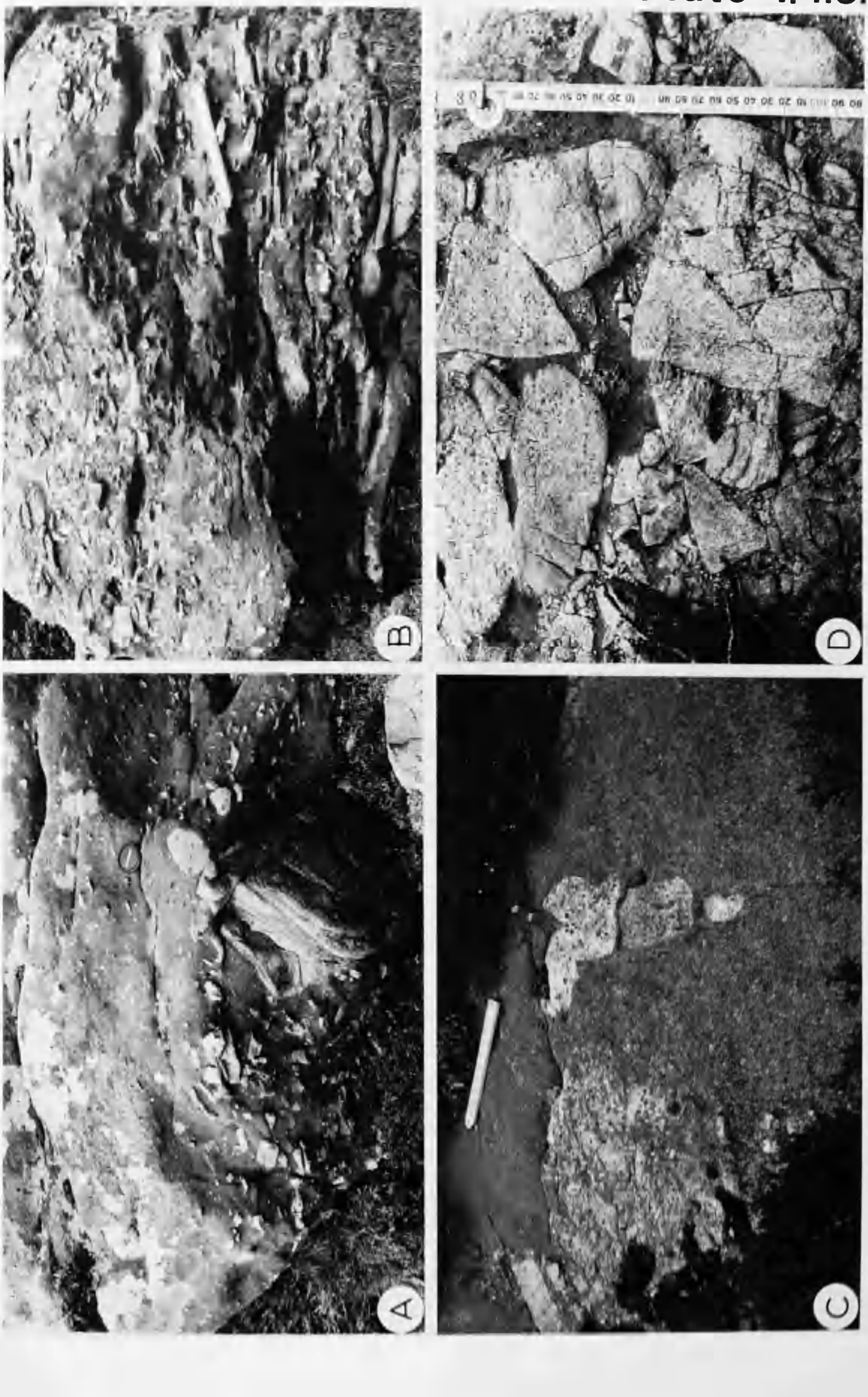
Plate 7.4.5. Photographs **A-D** demonstrate nature of the textural heterogeneity of the pebbly sandstones and the conglomerates of Facies B1 - non-uniform dispersion of particles.

A & **B**: Note subparallel with the bedding, discontinuous parting planes. Lense cap and ruler are 5 and 25 cm in size respectively;

C: Conglomeratic clusters enclosed in massive sandstone. Ruler is 25 cm long;

D: Fine-grained, well sorted sandstone matrix still displays locally its original textural identity. In the center Moine clast, which suffered brittle deformation prior to the incorporation into the sediment. Some of the fractures in the clasts opened due to compaction. Scale is in centimeters. (Locality: **A-D** Cnoc Cragaidh, BSF)

Plate 7.4.5.



places passing rapidly and gradationally into well planar-stratified sandstones.

In one site at Cnoc Cragaidh, close to the base of the upper, coarser part of the sequence, a discontinuous sandstone interbedding appears to have been plastically deformed ("boudinaged") along a normal, syndepositional fault (Plate 7.4.4.D).

The Cnoc Cragaidh Conglomerate is underlaid by a sandstone, which is a few meters thick (Plate 7.4.1.B,C & Fig. 7.4.2.A). Exact lateral extent of the latter unit is unknown, but it appears to be discontinuous, being exclusively subjacent to the Cnoc Cragaidh conglomeratic body, whose outcrop is around 450 m wide (in the section parallel to the local inferred mean palaeotransport to 144^o). In terms of texture and petrographic composition the sandstones are identical to the matrix in the conglomerates and pebbly sandstones, that rest directly above (see chapter 7.4.5.2.). Structurally, however, they differ and are large scale trough- to tabular cross-stratified (Plate 7.4.3.D & Fig. 7.4.2.A). The individual sets are over 1 m thick but poor exposure prevents detail recognition of the lateral geometry of the sets and the cosets. The cross-stratified sandstones interbed in the uppermost part of the horizon with the structureless deposits of Facies B1 but the actual appearance of the main body of the conglomerates and pebbly sandstones is abrupt (Fig. 7.4.2.A & Plate 7.4.3.A).

Interpretation

The structureless, fine-grained sandstone matrix-supported conglomerates and pebbly sandstones of Facies B1 are interpreted as a product of ***en mass*****, debris flow** deposition of sand and gravel.

Considering the good sorting of the sandstone matrix and its negligible clay content (Cnoc Cragaidh Conglomerate) it is very difficult to envisage a mass flow origin in which dissipation rate of excess pore water pressure could have been effectively reduced. On the other hand such conditions are critical to facilitating mobility of debris flows and to contributing to clast support through mechanism of buoyancy (Hampton, 1972; Pierson, 1981). The preservation of the sandy chunks with intact early lamination as well as patchy distribution of the sandy matrix - the features which give in fact rise to the distinctive textural heterogeneity of Facies B1 - suggest that the sandy material did have strength,

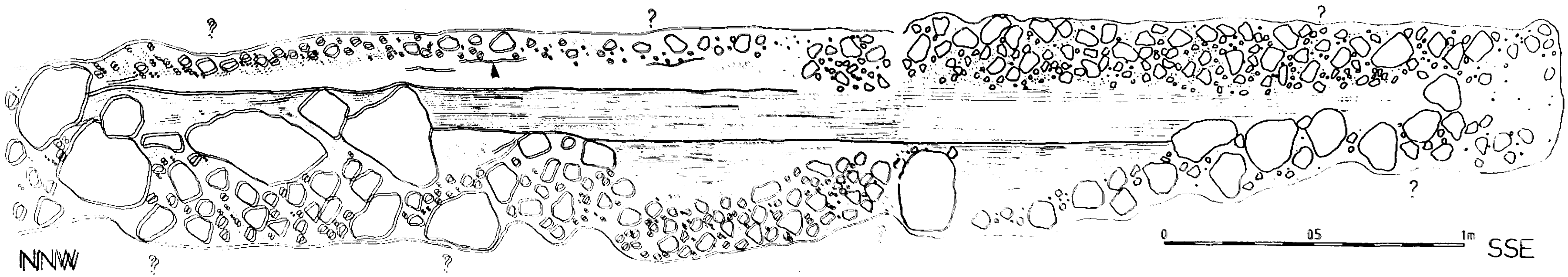


Figure 7.4.3a. Planar-stratified, fine-grained sandstones of Facies C filling a broad depression on the surface of the debris flow deposits of Facies B1. In the bed above the arrow points to one of the parting features, which possibly reflect shears associated with the laminar, mass flow movement. Note the textural heterogeneity of Facies B1. (Locality: Cnoc Cragaidh, BSF)

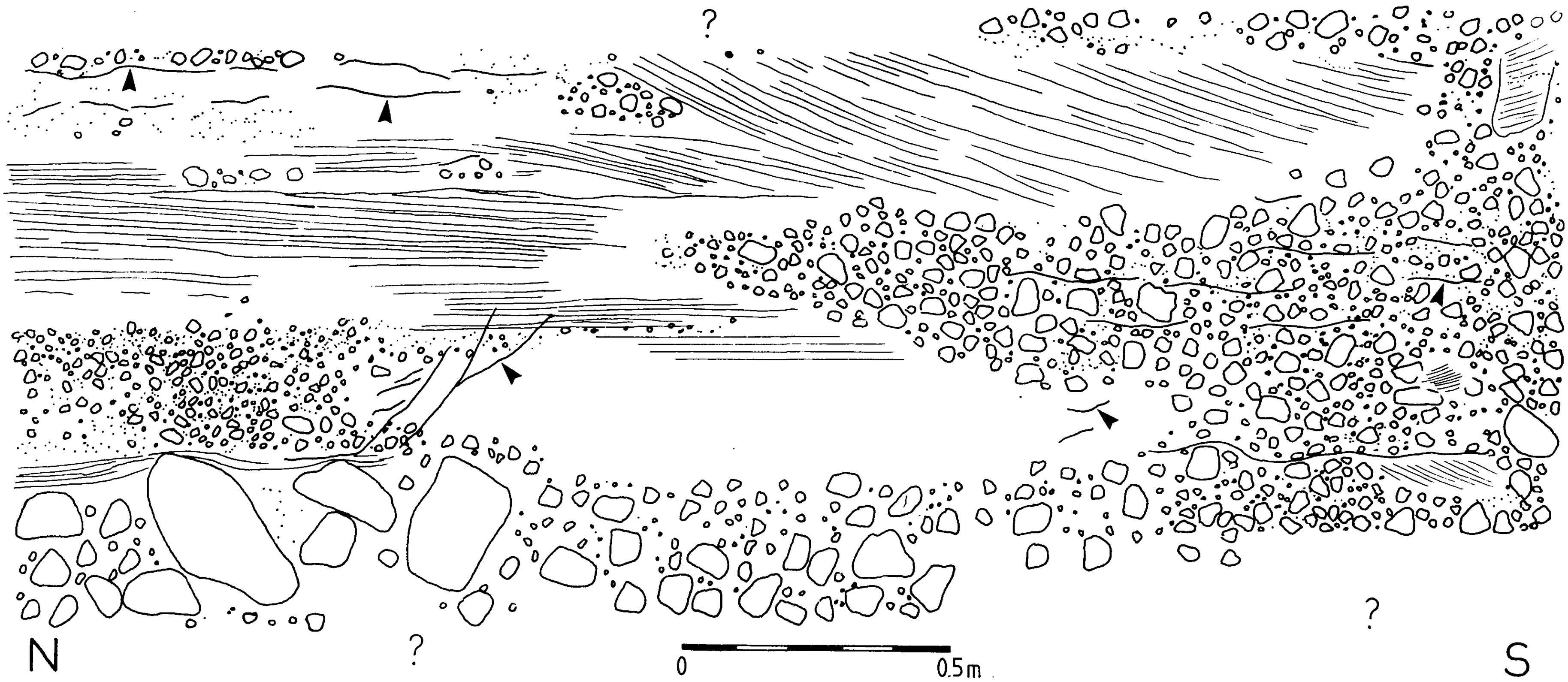


Figure 7.4.3b. Sketch depicts characteristic features of the conglomerates and pebbly sandstones of Facies B1: abruptly terminated "beds" (some of them distinctly tongue-shaped), textural heterogeneity - non-uniform dispersion of particles, presence of unremoulded sandy chunks with preserved early lamination and parting (shearing ?) features (arrowed). The debris flow deposits of Facies B1 are accompanied by the winnowing stage stratified deposits of Facies C. (Locality: Cnoc Cragaidh, BSF)

regardless of frictional resistance, and that the depositing debris flows were cohesive (Lowe, 1979; Nemec & Steel, 1984).

It is suggested that the source of the cohesion might have been early cement(-s) (e.g. grain-to-clay structural intergrowth (Dapples, 1979; DeVore, 1956), iron oxides, carbonates *etc.*), present in the sandy sediments during mobilisation, transport and mixing with the gravelly detritus. There is no direct independent evidence of petrographic or textural nature to support the proposed thesis. In view of the lack of appreciable amount of clay in the sandstone matrix, the fact that many blocks of the sandy material did not disintegrate and disperse immediately after the mobilisation and during the debris flow transport, and that the matrix did not admix thoroughly with the coarser material are regarded as indirect textural premiss for the active role of cohesion factor, derived from chemical bonds of cement phase (Ingels, 1962; Mitchell, 1976). The abundant in the sandstone matrix authigenic quartz might have replaced possible earlier forms of cement. The early iron oxide/clay cement was probably much more abundant in the equivalent sediments present in the Socach Hill and Creag an Amalaidh conglomerates (Plate 7.4.7. & 7.1.11B), but this dissimilarity does not appear to be followed by differences regarding the remaining textural and structural features of the latter debris flow deposits.

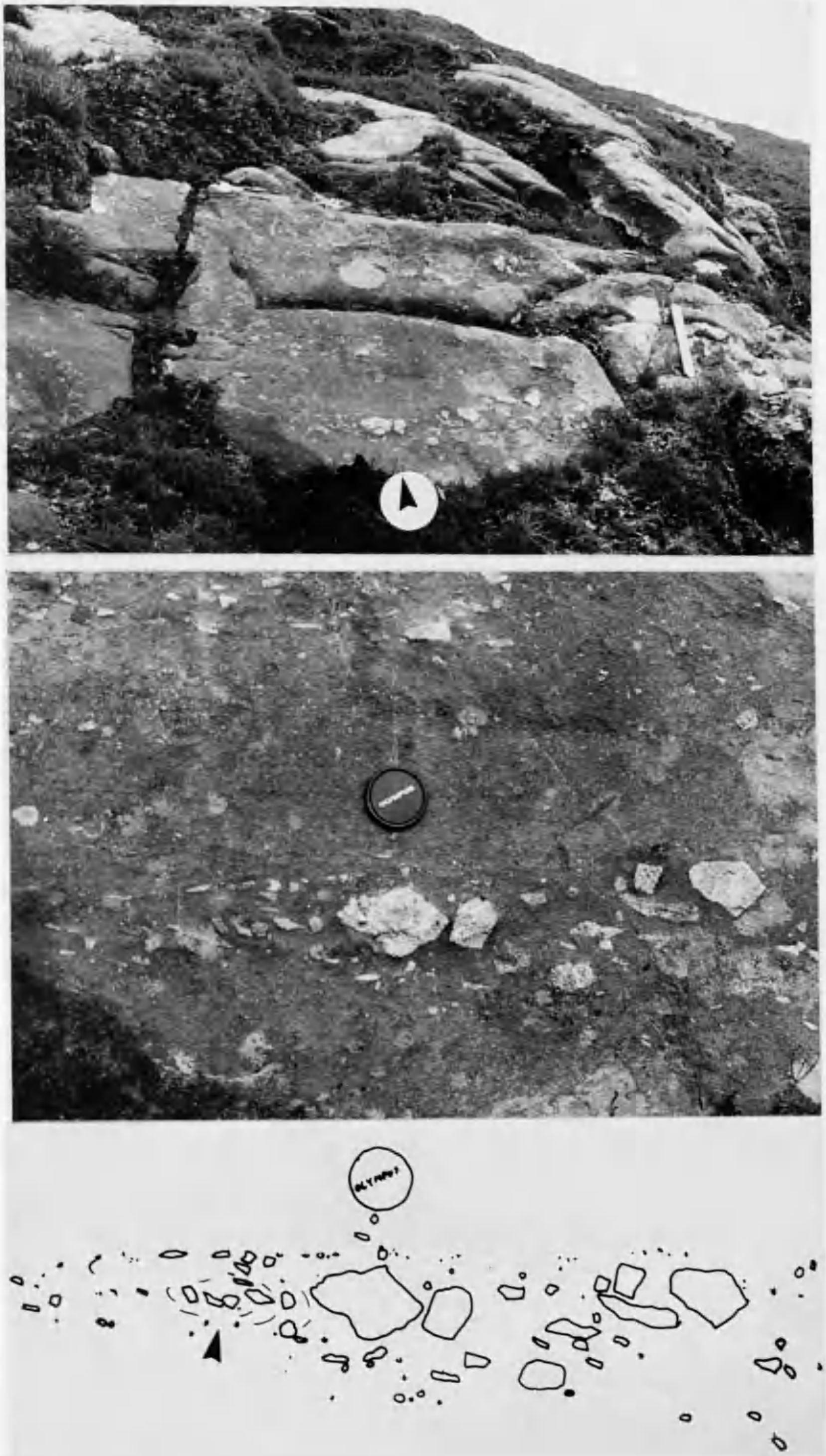
The textural heterogeneity may also indicate a relatively short lived mass flow transport, so that the sandy and the gravelly components did not admix thoroughly. This textural signature of the conglomerates and pebbly sandstones of Facies B1 together with the absence of grading do also suggest high density and viscosity of sand-rich debris flows, inhibiting turbulence and hence vigorous mixing and settling of the larger clasts.

The discussed deposits are thought to have moved essentially in a laminar fashion, and the subhorizontal discontinuous parting planes may perhaps represent shearing planes. The tongue-like and caterpillar-like termini of some of the beds of Facies B1 (Plate 7.4.6. & Fig.7.4.3b.) independently indicate the laminar flow regime (see also Bromley & Ekdale, 1987, fig. 3). The "trough-shape features" and associated up-current clast orientation (Plate 7.4.4.C) are seen as a form of "push-fabric" (Rust, 1981; Lawson, 1982; Wells & Harvey, 1987; see also Plate. 7.2.4.) developed in the compressional sectors of the tongue-shape debris flows with the elongate clasts oriented parallel to the arcuate(trough-shape) or

Plate 7.4.6. A: Structureless sandstones and pebbly sandstones of Facies B1. The arrow points to the "caterpillar structure" - the tongue-like terminus of the mass flow bed. Ruler is 25 cm long. (Locality: Cnoc Cragaidh, BSF);

B: Close up of the "caterpillar structure". Lense cap is 5 cm wide. The arrow on the attached drawing below indicates the "swirled" area.

Plate 7.4.6.



tabular, discontinuous shear/thrusting features. The above interpretation, however, should be treated as highly speculative for it is based only on one, and rather small 3-D exposure (Plate 7.4.4.A&B).

The structureless sandstones, pebbly sandstones and matrix- to clast supported conglomerates of Facies B1 display no accessory features which might indicate the corresponding, significantly diverse modes of the debris flow emplacement. Consequently, it appears that the clast concentration and the clast size (MPS) have had little impact upon the mechanism of the debris flow transport and deposition.

The stratified sandstones and conglomerates of Facies C represent processes of sheet wash and rill wash winnowing and reworking of the previously deposited debris flow deposits (see also chapter 7.1.5.1.4.). The thickest, winnowed deposits were preserved in the broad depressions on the irregular surface of the debris flow bodies (Fig. 7.4.3.A).

The crudely planar-stratified conglomerates and pebbly sandstones, laterally transitional in places into the stratified deposits of Facies C may represent product of deposition from hyperconcentrated, density-modified flows, transitional between the cohesive debris flows and the low-density, winnowing stage water flows (Beverage & Culbetson, 1964; Nemec & Muszynski, 1982).

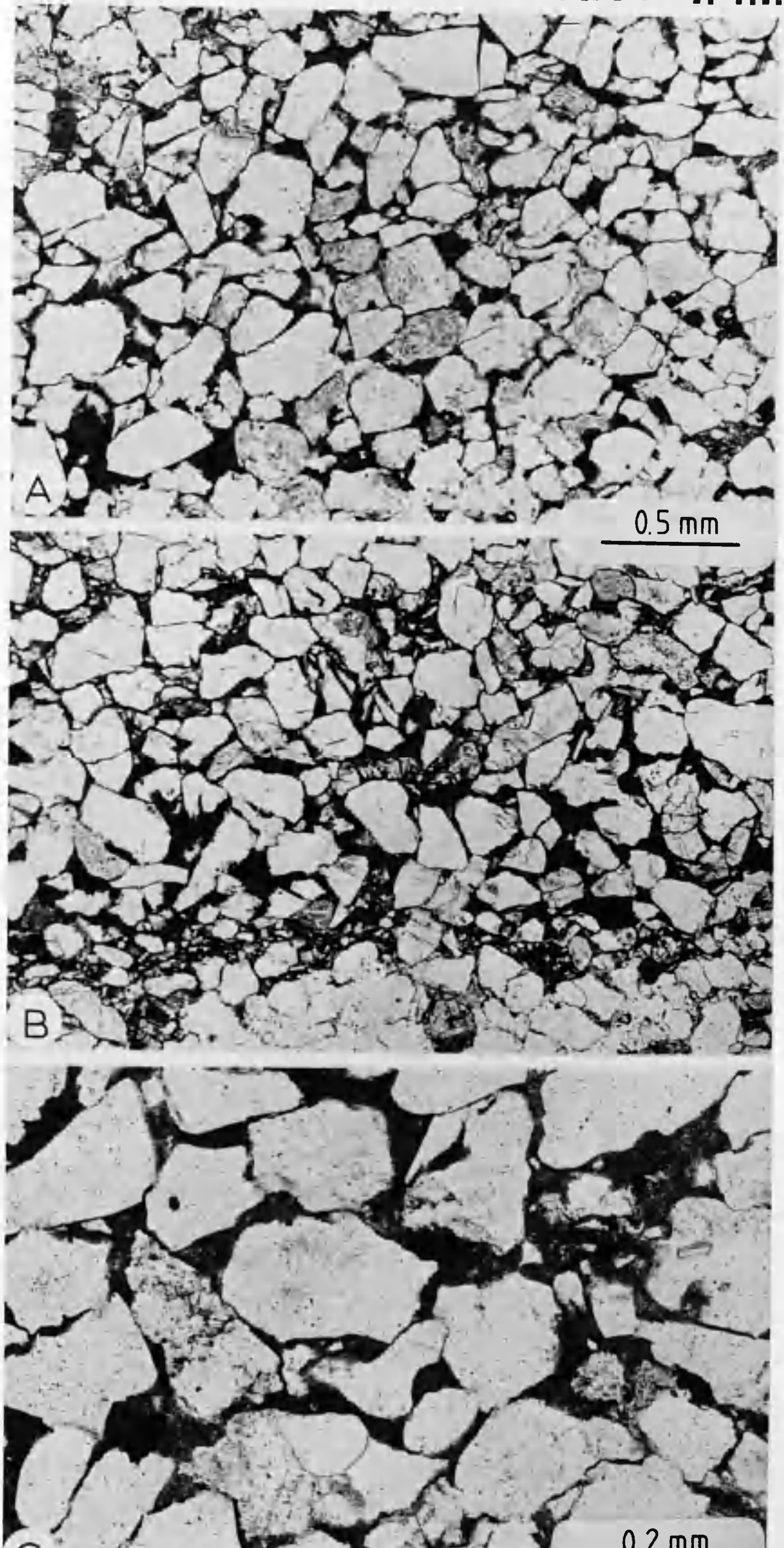
The trough and tabular cross-stratified sandstones, underlying the Cnoc Cragaidh Conglomerate may represent aeolian sediments, considering their perfect sorting, the fine grain size, the considerable proportion of well rounded grains and the significant proportion of the exotic lithic fragments(PLF) (see chapter 7.4.5.2.). These deposits are seen as a remnant of the source of the sandy matrix present in the overlying deposits of Facies B1 (for details see chapter 7.4.5.5.).

Plate 7.4.7. Photomicrographs **A-C** show textural details of sandstone matrix of Facies B1 from Socach Hill Conglomerate. Note very good sorting of the sand fraction. Abundant iron oxide-stained clay material (mainly chlorite 16-28%) is present in the pore spaces but absent between some of the grain contacts (C) (PPL);

B: Photomicrograph of unremoulded lamination present locally in the matrix (PPL).

(Locality: **A-C**: Killin Rock [NC 869 055], BSF)

Plate 7.4.7.



7.4.5.1.2. Facies C2: Assemblage of homogeneous, massive to planar-stratified and cross-stratified conglomerates and cross-stratified sandstones (Creag a' Bhodaich variety of Facies C)

Description

The conglomerates of Facies C2 dominate the main, middle part of the Creag a' Bhodaich Conglomerate where they are about 60 m thick (Fig. 7.4.4.) and are exposed at Creag a' Bhodaich. They are generally poorly to moderately sorted, sandy and predominantly clast-supported. Their maximum clast size(MPS) varies from 2 - 17 cm, averaging around 11 cm. The largest boulder recorded was 30 cm in size.

The sandy matrix ranges from well sorted, very fine-grained to poorly sorted and very coarse-grained with scattered granules. Individual beds are texturally homogeneous and variabilities in grain size, sorting and amount of sandy matrix are associated with stratification. The majority of the conglomerates of Facies C2 are well to crudely planar-stratified, low-angle cross-stratified and structureless (Fig. 7.4.5a. & 7.4.5b.; Plate 7.4.8. & 7.4.9.) and there appears to be vertical as well as lateral gradation between the four structural varieties. The stratification is often accentuated by a few centimeters thick, discontinuous, well sorted, open framework horizons and common 1 - 30 cm thick, very fine- to very coarse-grained, planar- to cross-stratified lenticular sandstone interbeddings.

Around 10% of the total section of Facies C2 is represented by structureless beds which in terms of their characteristics closely correspond to the deposits of Facies B. They appear to be most abundant in the lower part of the section (Fig. 7.4.5a.) and their maximum particle size averages 15 cm with the largest clast 37 cm in diameter.

The better sorted, less sandy horizons within the planar-stratified beds of Facies C2 display well developed clast imbrication, and its orientation is essentially consistent with the palaeodispersal pattern derived from dip azimuth of the cross-strata (Fig. 7.4.4.).

Massive to planar-stratified conglomerate beds are sheet-like in geometry and have thickness ranging between 8 - 200 cm, though they normally appear amalgamated and composed of many stacked sheets (Plate 7.4.9.A). The composite nature of the beds is

Figure 7.4.4. Summary log through the middle part of the Creag a' Bhodaich Conglomerate, showing facies distribution versus clast composition, clast roundness and palaeodispersal. (**1-4**) sandstone horizons, interpreted as deposits of aeolian origin, though possibly reworked by stream flows (see also Plate 7.4.8.B). **CS** - data of cross strata orientation from Fans 1 and 2; **FL** - strike of a flute mark; **CH** - strike of a channel; **imb** - data of clast imbrication (inferred palaeoflow). No direct palaeotransport indicators are available from the topmost, Facies B -dominated, part of the Creag a' Bhodaich Conglomerate(Fan 3). (Locality: Creag a' Bhodaich, BSF)

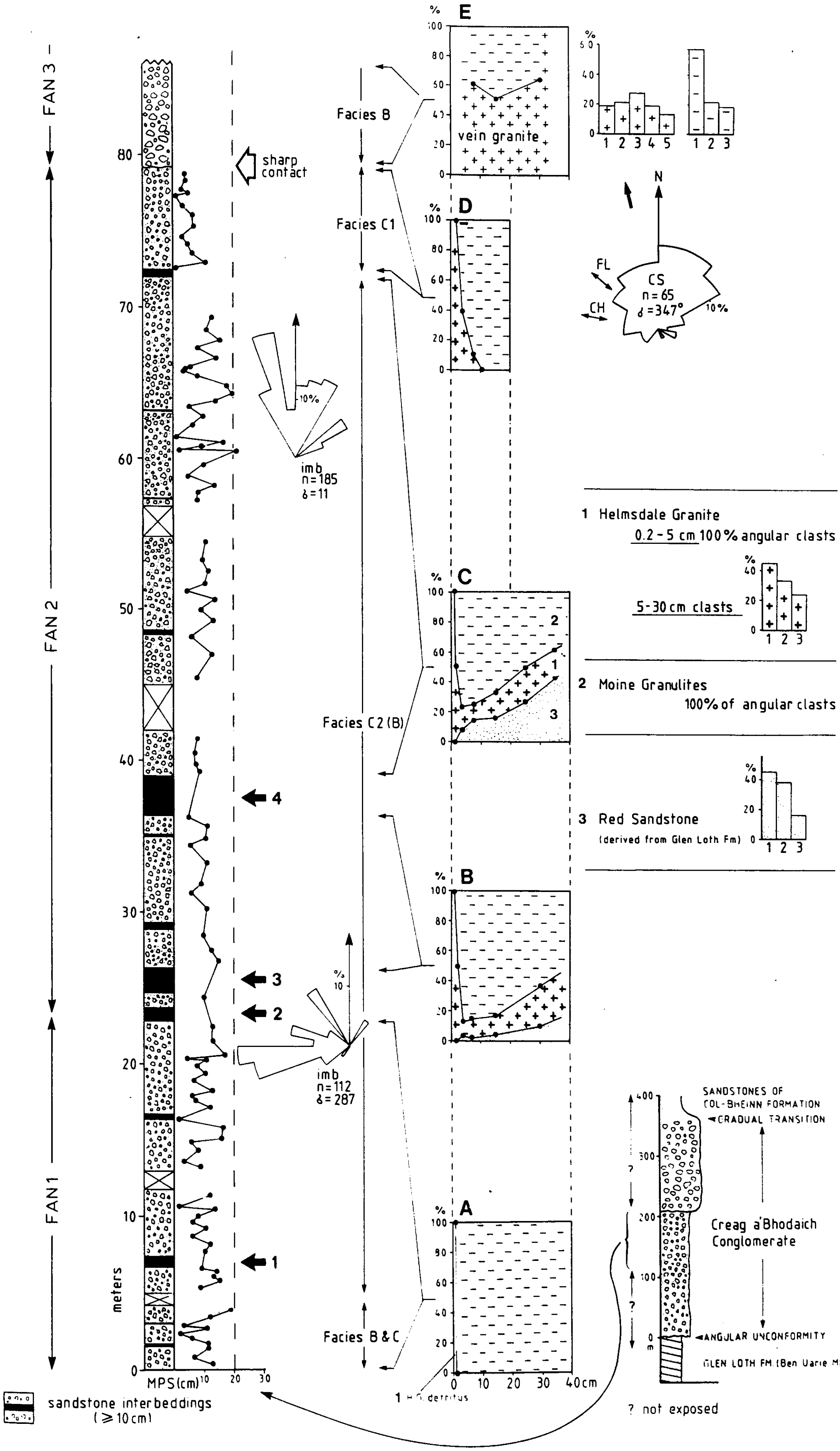

FAN 3
FAN 2
FAN1
meters
MPS(cm)
sharp contact
sandstone interbeddings (≥10 cm)
imb n=185 ϑ=11
imb n=112 ϑ=287
Facies B
Facies C1
Facies C2 (B)
Facies B & C
vein granite
CS n=65 ϑ=347°
FL
CH
N
1 Helmsdale Granite
0.2-5 cm 100% angular clasts
5-30 cm clasts
2 Moine Granulites
100% of angular clasts
3 Red Sandstone
(derived from Glen Loth Fm)
SANDSTONES OF COL-BHEINN FORMATION
GRADUAL TRANSITION
Creag a'Bhodaich Conglomerate
ANGULAR UNCONFORMITY
GLEN LOTH FM (Ben Uarie Mb)
? not exposed
1 H.G. detritus

Figure 7.4.5a. Exemplary graphic log from the Fan 1 (see Fig. 7.4.4) composed of the debris flow and the sheetflood deposits of Facies B and C (left) and from the lower portion of Fan 2 composed of the stream flow and the sheetflood deposits of Facies C2 (right). The structureless beds may represent deposits of hyperconcentrated sediment flows (transitional to debris flows of Facies B). **2 & 3** - the sandstone horizons of possible aeolian origin, though probably partly reworked by stream flows. Note that foresets orientation in the sandstone horizons is generally consistent with the overall northward palaeodispersal pattern, inferred from the section of the Creag a' Bhodaich Conglomerate (see Fig. 7.4.4.). (Locality: Craeg a' Bhodaich, BSF)

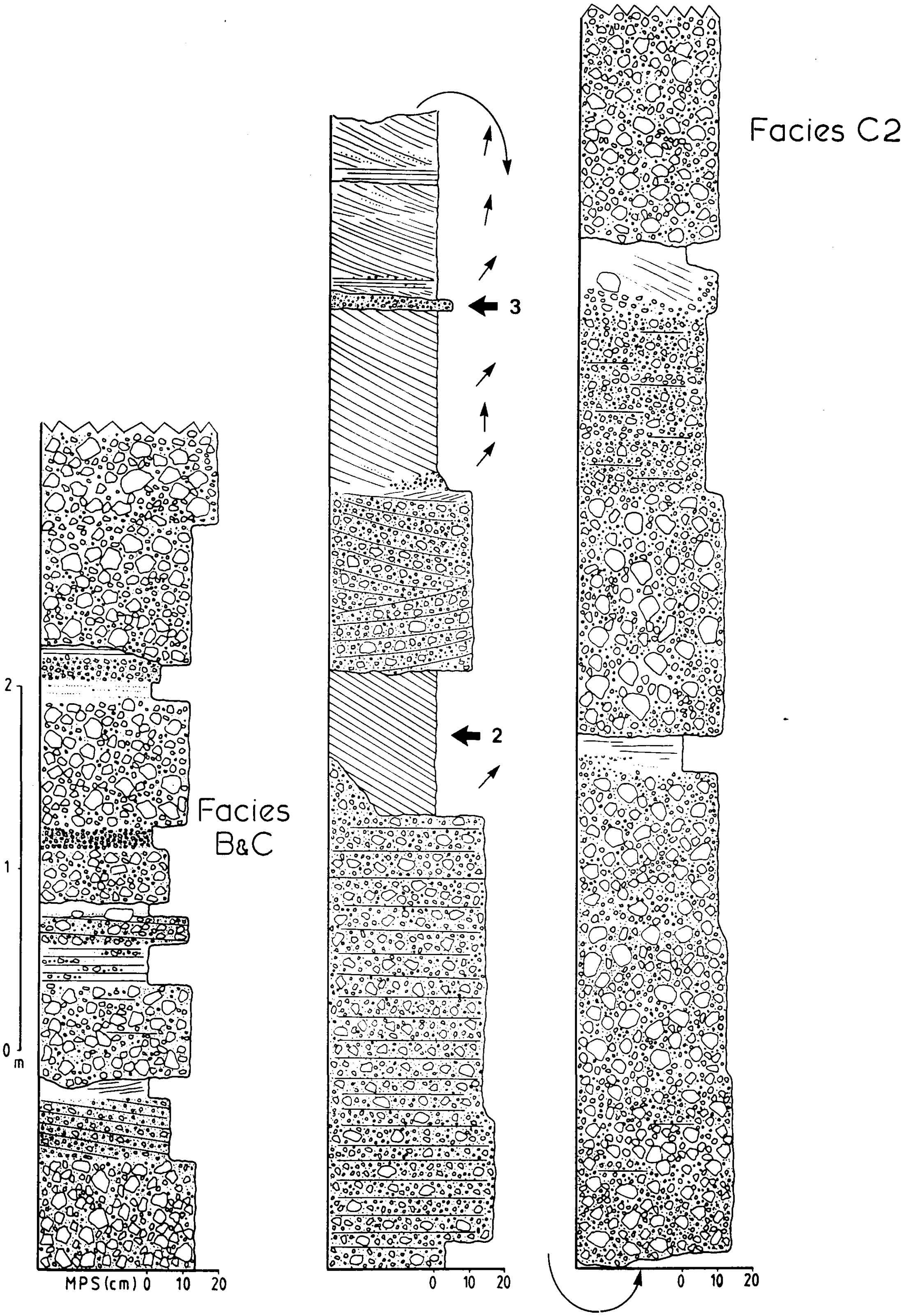
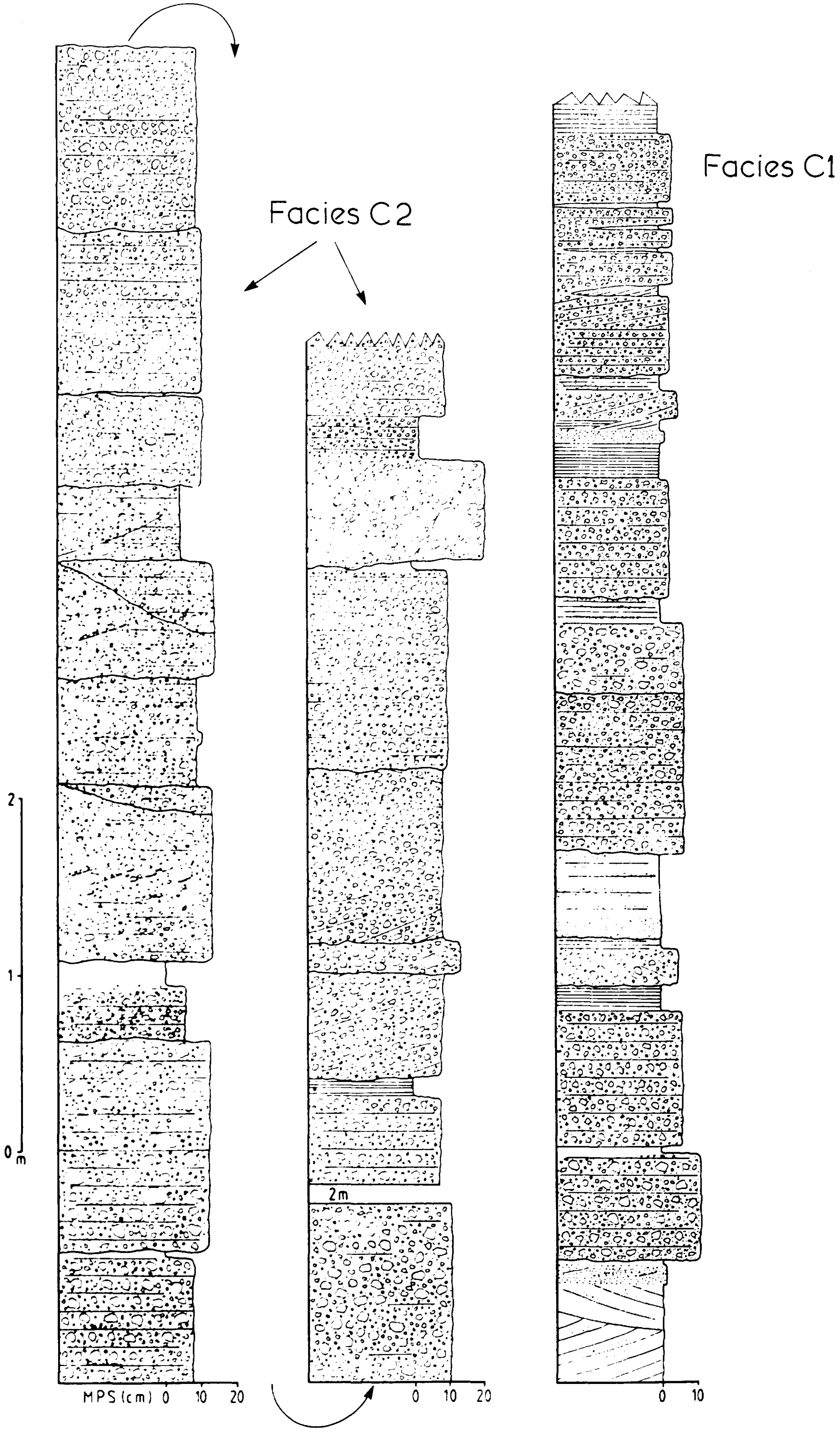

Facies C2
3
2
Facies B&C
2
1
0
m
MPS (cm) 0 10 20
0 10 20
0 10 20

Figure 7.4.5b. Graphic logs from the upper part of the stream flow/sheetflood-dominated (Facies C2) part of Fan 2 (left) and from the finest-grained portion of the Fan 2 represented by the sheetflood conglomerates of Facies C1 (right). (Locality: Creag a' Bhodaich, BSF)


Facies C2
Facies C1
2
1
0 m
2m
MPS (cm) 0 10 20
0 10 20
0 10

typically revealed by the presence of sandstone lenses. The basal contacts of the beds are usually irregular to flat and are either erosional or non-erosional. Detail recognition of the lateral geometry of the beds has not been possible for the limited extent of the exposures.

The trough and tabular cross-stratified conglomerates constitute only about 5% of the total package of the deposits of Facies C2. Texturally they do not differ from the dominant, structureless, planar-stratified and low angle cross-stratified deposits, though they do not contain the sandstone lenses.

No particular form of grading has been recorded from the conglomerates of Facies C2, except for occasional dramatic, upward transitions into sandstone interbeddings,

The gravel fraction is dominated by angular and subangular fragments of the Helmsdale granite and Moine siliceous granulites (Fig. 7.4.4.A,B,C). There is also present a significant proportion of rounded red sandstone clasts, most likely derived from the underlying deposits of the Glen Loth Formation(Ben Uarie Member) (see also chapter 7.4.5.2. for details).

Four horizons of well sorted, fine- to medium-grained sandstones occur within the conglomeratic deposits of Facies C2. They are large scale trough and tabular cross-stratified. The horizons 1 and 2 (Fig. 7.4.4. & 7.4.5a.) are perfectly sorted, fine-grained and contain no coarser-grained laminae. The horizon 3 (see also Plate. 7.4.8.B) is erosionally intervened in the middle by the conglomeratic interbedding but the sandstone is mainly fine-grained with minor coarse-grained to granule interlaminations and scattered at the base of one foreset pebbles up to 1 cm in size (Fig. 7.4.5a.). The horizon 4 is predominantly medium-grained with minor granules and pebbles up to 1 cm, concentrated at the base of the foresets.

Thickness of the sandstone foresets in all four horizons ranges from 18-80 cm. Inclination of the laminae is normally less then 30^{o} and their orientation is in accord with the general orientation of the other surrounding sandstone and conglomerate cross-strata (compare Fig. 7.4.5a. with 7.4.4). The sandstones contain a significant proportion of rounded grains (Plate 7.4.10.D), and this feature in conjunction with the other, presented above textural/structural characteristics, differs them from the surrounding coarser-grained, poorly sorted deposits.

Plate 7.4.8. **A:** Planar- to low angle cross-stratified conglomerates of Facies C2. Ruler is 50 cm long;
B: Large scale, trough cross-stratified sandstone horizon 3 (see Fig. 7.4.5.A) of possible aeolian provenance but having formed through reworking by stream flows. The arrow points to the middle conglomeratic interbedding. Ruler is 50 cm long;
C: Planar-stratified conglomerates of Facies C1, composed exclusively of arkosic detritus. The largest clasts are individual orthoclase feldspar phenocrysts derived from the porphyritic portion of the Helmsdale granite. (see Phot. **D** for close up). Lense cap is 5 cm wide. (Locality: **A-D** - Creag a' Bhodaich, BSF)

Plate 7.4.8.

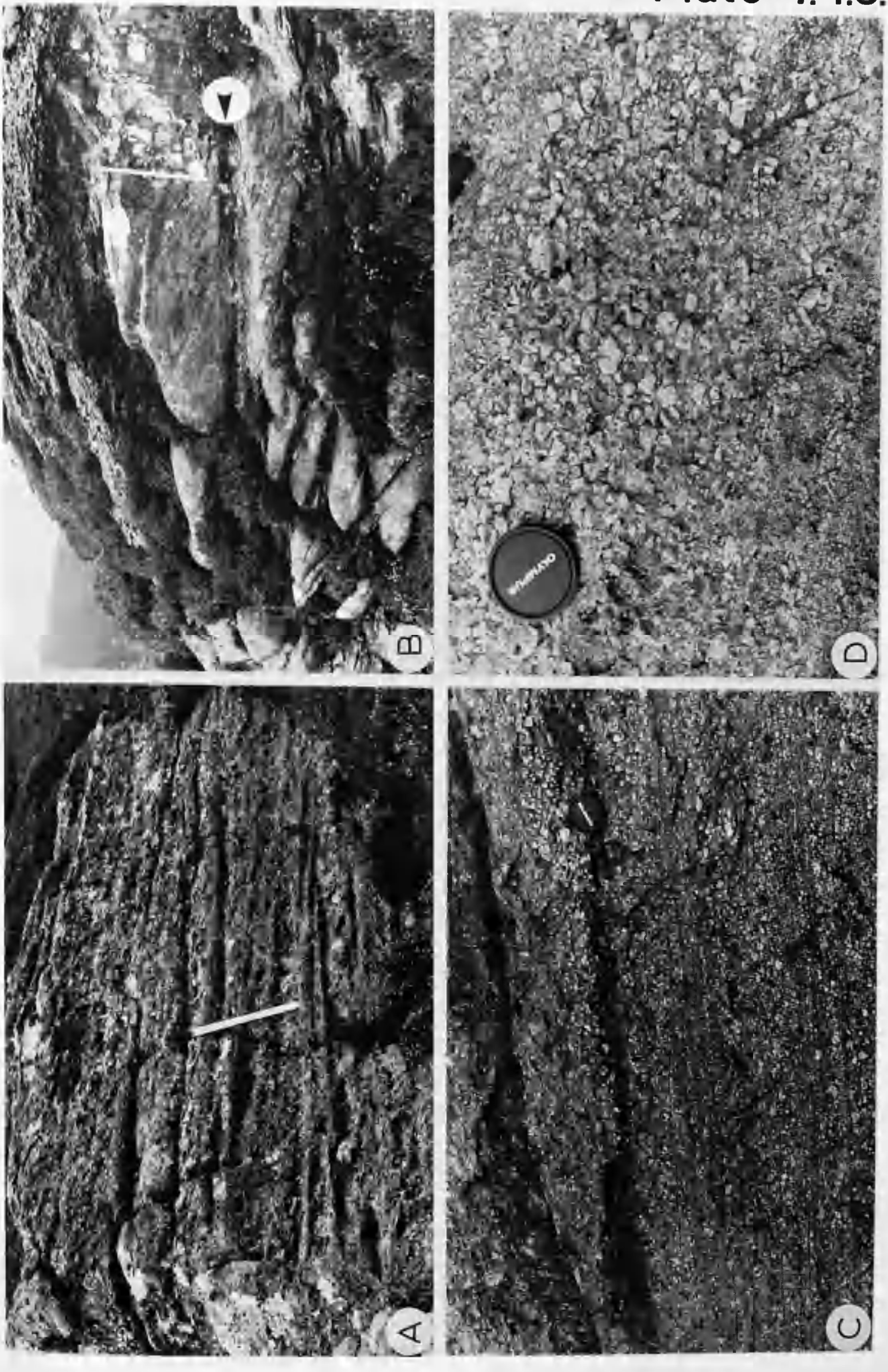
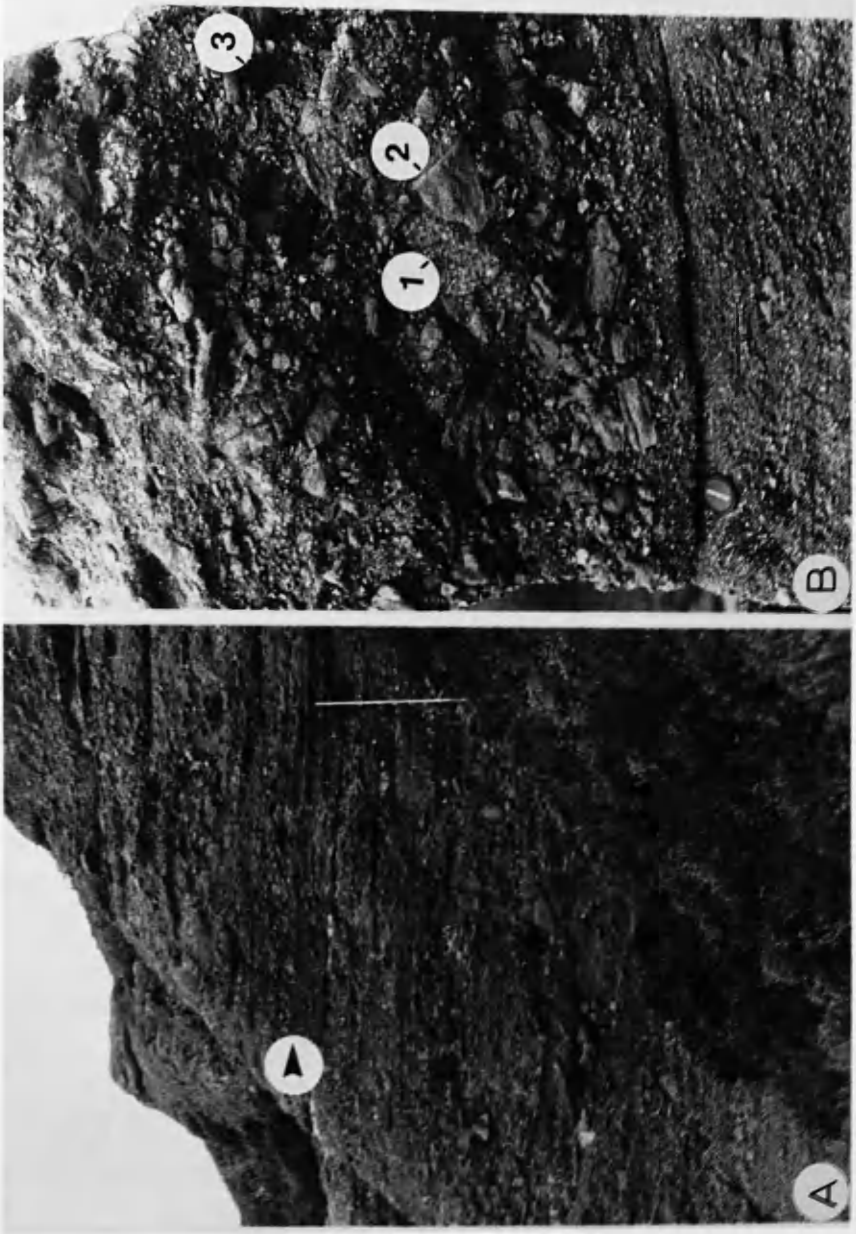


Plate 7.4.9. A & B: Deposits of Facies C2.

A: Planar- to low angle cross-stratified conglomerates. The arrow points to the finer-grained conglomeratic bed, composed predominantly of Helmsdale granite derived detritus. Ruler is 1 m long;

B: The upper, structureless bed consists mainly of Moine granulite **(2)** and red sandstone **(3)** clasts. Helmsdale granite cobbles **(1)** are also present but the arkosic detritus is most abundant in the finest gravel fractions (see the planar-stratified bed below) with scattered Moine clasts being largest but subordinate (see Fig. 7.4.4.). (Locality: **A-B** - Creag a' Bhodaich, BSF)

Plate 7.4.9.



The conglomerates of Facies C2 pass gradually into almost exclusively planar-stratified conglomerates and subordinate sandstones of Facies C1 (Fig. 7.4.4.).

Interpretation

The conglomerates of Facies C2 most likely represent product of deposition from unchannaelised **sheetfloods** (crude to well planar-stratified and low angle cross-stratified beds) and from confined(channaelised) or re-confined **stream flows**(tabular and trough cross-stratified conglomerates) (McKee *et al.*, 1967; Tunbridge, 1981; Blair, 1987 a,b). The structureless to crudely stratified, texturally homogeneous beds might have been deposited from density-modified sheetfloods (or hyperconcentrated flows (Beverage & Culbetson, 1964; Lord & Kehew, 1987), the flows transitional between cohesive debris flows(Facies B) and low-density sheetfloods(Facies C) (Wasson, 1979; Nemec & Muszynski, 1982; Pierson & Scott, 1985; Smith, 1986; Wells & Harvey, 1987) (for detail discussion of this aspect see chapter 7.1.5.1.4.). The sheetflood deposits of Facies C2 correspond to the bed-types A, C and E of Facies C (Fig. 7.1.12.). Alternatively, the well and crudely planar-stratified to low angle cross-stratified conglomerates may represent parts of bars (longitudinal bars?) (Eynon & Walker, 1974; Hein & Walker, 1977; Bluck, 1976, 1986; Rust, 1978; Steel & Thompson, 1983; Nemec *et al.*, 1984).

The four sandstone horizons (Fig. 7.4.4.1-4) differ texturally from the generally poorly sorted, coarser-grained, much thinner and less continuous sandstone interbeddings, accompanying the conglomerates of Facies C2. It is likely that the sandstones are of aeolian origin, though most of them appear to have become reworked by the water currents and partially admixed with the coarser detritus. It seems quite improbable for the stream flows to accumulate, directly on the surface of the poorly sorted sandy gravels, the perfectly sorted, fine-grained, homogeneous sandy beds (horizons 1 & 2, Fig.7.4.4. & 7.4.5a.) as a residue product of winnowing of the gravelly sediments. High foreset dip angle of cross-stratification in the horizon 2 (30 - 32^{o}) may additionally indicate avalanching of dry sand (Reading, 1986; Tucker, 1981). There are no other independent evidence, like for example presence of translatant ripple lamination (Reading, 1986), that could support the proposed aeolian provenance of the sandstone horizons. Degree of their exposure is too limited for drawing possible constructive conclusions from size and geometry of the foresets.

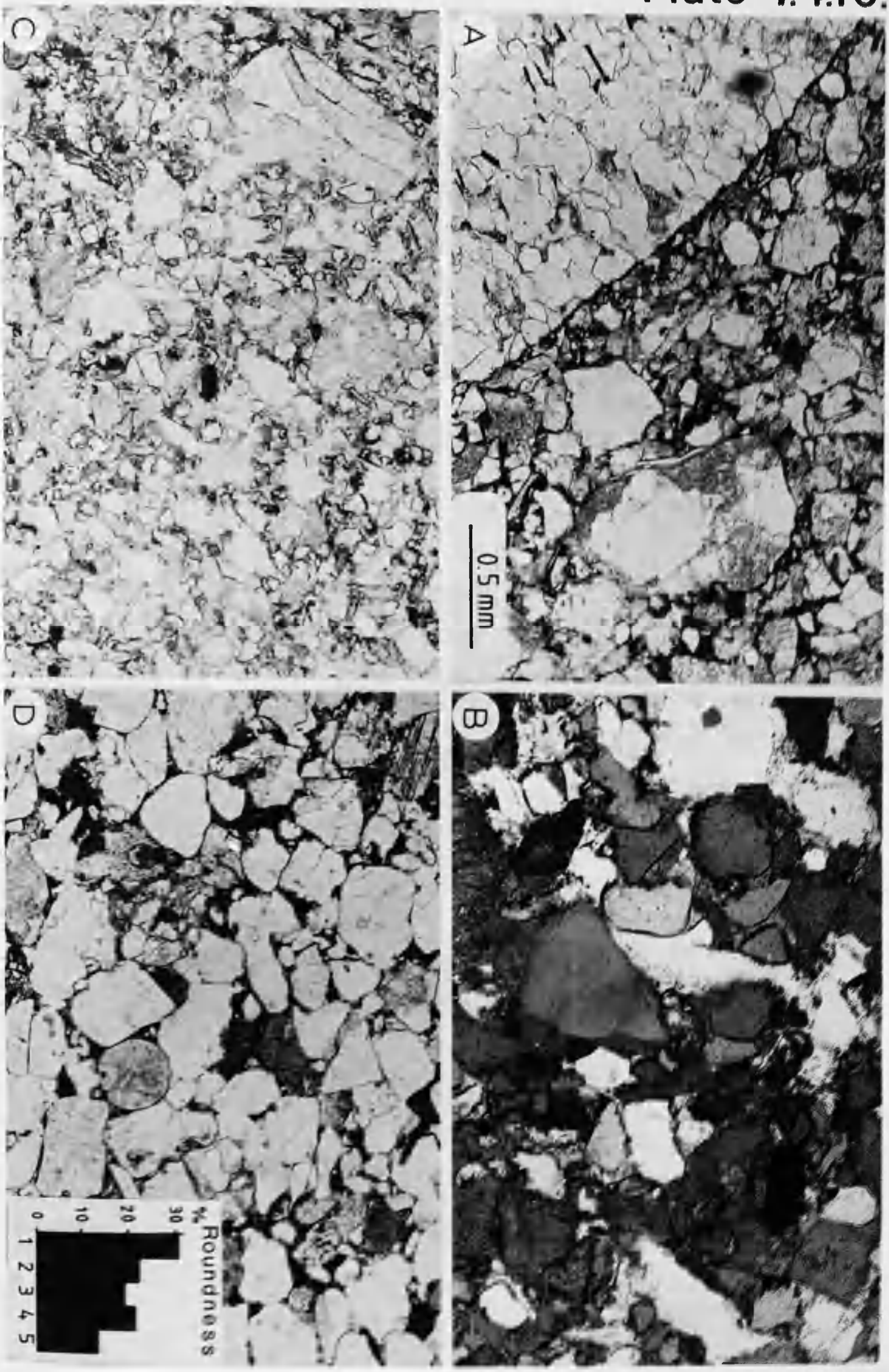
Plate 7.4.10. A: Photomicrograph of extremely poorly sorted sandstone matrix from Facies B consisting of angular grains. The conglomerate, however, contains a proportion of rounded gravel-grade clasts (see also Fig. 7.4.6.B) (PPL). (Locality: Oldtown, BSF);

B: Photomicrograph shows abundant quartz overgrowths cement, present in the sandstone matrix of Facies B (XPL). (Locality: the same as above);

C: Another example of extremely poorly sorted matrix from Facies B (PPL). (Locality: Creag a' Bhodaich, BSF);

D: Photomicrograph of sandstone from the horizon 2 (see Fig. 7.4.4. & 7.4.5.A) (XPL). The well sorted, fine-grained sandstone contains a significant proportion of rounded and well rounded grains(see attached histogram). Roundness scale after Powers (1953) (for explanation see Fig. 7.4.1.). (Locality: Creag a' Bhodaich, BSF)

Plate 7.4.10.



7.4.5.2. Petrographic composition and clast roundness in the Beinn Smeorail Formation

In terms of clast composition and textural characteristics the conglomerates of the Beinn Smeorail Formation (BSF) strongly resemble the deposits of the Beinn Lunndaidh Formation, for again there is an apparent striking correspondence between the composition of the gravel fraction and in most cases of the sand fraction, and the lithology of the Moine Series-dominated basement, that outcrops in the vicinity of the basin and most likely constitutes the main portion of its substrate (see also chapter 7.1.5.2.).

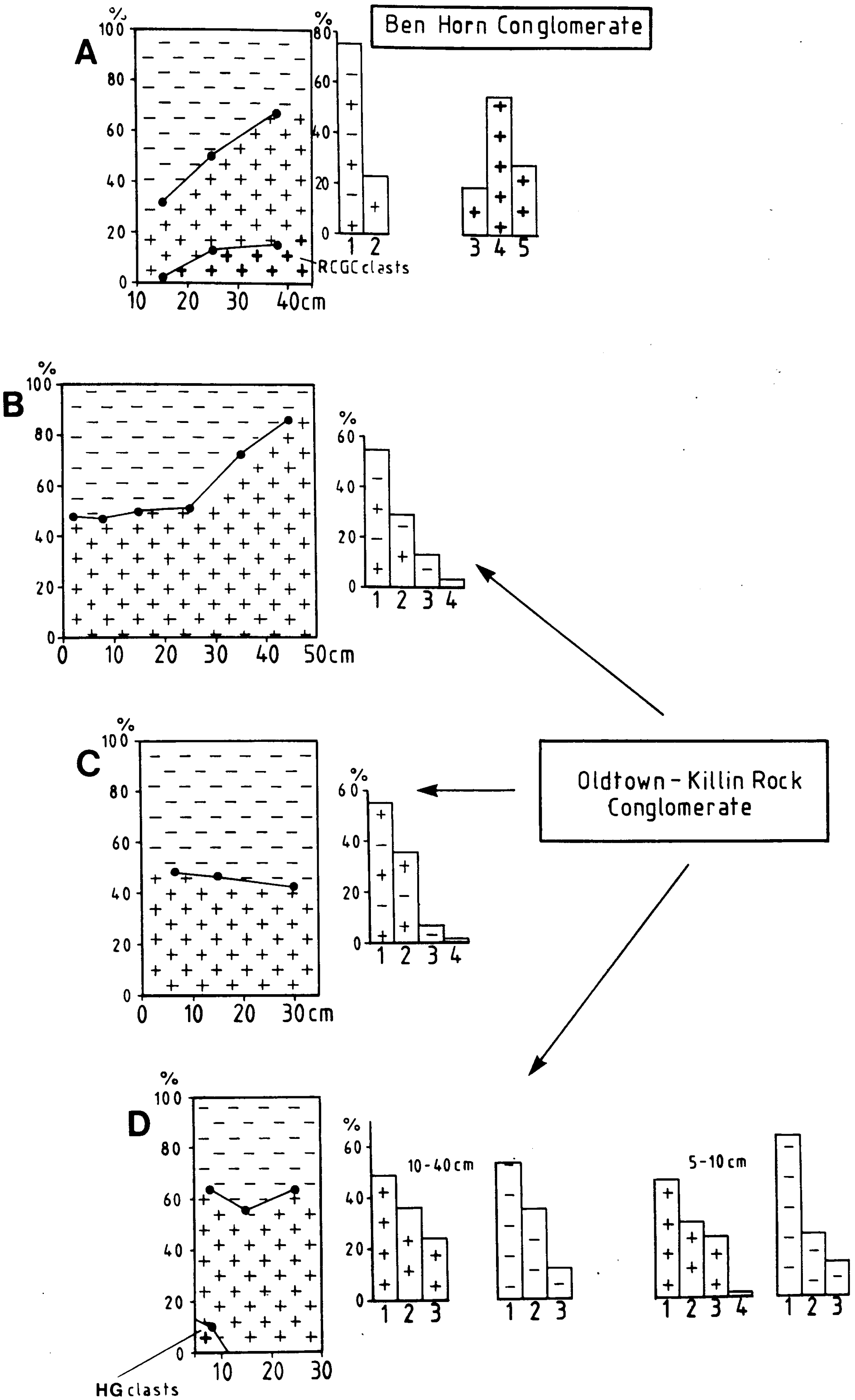
Ben Horn Conglomerate

This most SW located unit of the BSF is the only one which contains clasts derived from the Rogart Central Granodiorite Complex (RCGC). The granodiorite clasts have analogous frequency distribution to the Mound Rock Conglomerate (see chapter 7.1.5.2.; Fig. 7.1.20a. & 20b.) and their proportion increases with increasing size of the particles considered (Fig. 7.4.6.A). The RCGC clats are also typically subrounded to well rounded. It is worth mentioning that the presence of the RCGC clasts in the Ben Horn Conglomerate is consistent with its NE palaeodispersal pattern, determined from the clast imbrication (Fig. 7.4.12.). Over 80% of the clasts in the Ben Horn Conglomerate are represented by Moine siliceous granulites and granite of the Rogart Migmatite Complex, including vein granite, pegmatite and aplite. These clasts are angular to subangular (Fig. 7.4.6.A). Coarse-grained, poorly sorted matrix in the Ben Horn Conglomerate has not been examined under microscope. However, in the field it appeared to be, in terms of composition, closely related to the gravel material.

Oldtown - Killin Rock Conglomerate

The prominent, central body of the BSF contains no debris derived from the Rogart Central Granodiorite Complex. At the western margin of the basin (Oldtown, Carrol Rock and Gilbert's Hill) the conglomerates consist in approximately equal proportions of clasts of Moine metasediments and vein granite (Fig. 7.4.6.B & C). Siliceous granulite clasts

Figure 7.4.6. Clast composition diagrams and clast roundness histograms from Ben Horn and Oldtown - Killin Rock conglomeratic units. Localities: **A** - Ben Horn; **B** - Oldtown; **C** - Gilbert's Hill; **D** - Killin Rock. **RCGC** - clasts derived from Rogart Central Granodiorite Complex; **HG** - detritus derived from Helmsdale granite. Roundness scale in the histograms after Powers (1953) **1** - angular, **2** - subangular, **3** - subrounded, **4** - rounded, **5** - well rounded. For explanation of other symbols see Fig. 7.1.20a.


Ben Horn Conglomerate
A
B
C
D
RCGC clasts
HG clasts
Oldtown - Killin Rock Conglomerate
10-40 cm
5-10 cm
40cm
50cm
30cm

with granite veins are common but have not been included in the diagrams. At Cnoc Cragaidh the clast composition is very similar. The Moine and the granite clasts show much the same degree of roundness and are mainly angular to subangular, though there is a subordinate (up to 20%) component of subrounded and rounded clasts (Fig. 7.4.6.B,C; Plate 7.4.10.A). At Oldtown in the coarsest part of the conglomeratic unit (Fig. 7.4.7) the granite boulders typically dominate the largest fractions.

Matrix in the Facies B-dominated conglomerates at Oldtown, Carrol Rock and Gilbert's Hill is extremely poorly sorted, very coarse-grained lithic arenite/wacke (Fig. 7.4.1. & 7.4.10.A). Proportion of the interstitial, iron oxide-stained clay material (illite/mica and chlorite, Fig. App.2.J). ranges from 13.5 - 24%. Texture of the clay matter, present in the deposits of Facies B is discussed in chapter 7.1.5.1.2.. Petrographically the grains in the matrix closely match the composition of the gravel grade and the lithic fragments are represented by a mixture of granulite and granite components in a range of 44 - 54%. No fragments of low-grade pelitic metasediments (PLF) have been found. The grains in the matrix are mostly angular and are cemented by authigenic quartz in proportion 15.7 - 33%, whose formation seems to postdate the crystalization of chlorite (Plate 7.4.10.B). No other forms of cement have been recorded.

At Killin Rock (at the eastern part of the basin) the clast composition is similar, though the conglomerates contain also a minor proportion of the distinctive granitic detritus, derived from the porphyritic portion of the Helmsdale granite (Fig. 7.4.6.D). It typically concentrates in the finest gravel mode as angular individual particles. A minor component of rounded clasts of the porphyritic Helmsdale granite up to 30 cm in size is also present. The tendency of the Helmsdale granitic detritus, to dominate the finest gravel fractions is opposite to the frequency distribution of the RCGC and RMC clasts (see Creag a' Bhodaich Conglomerate further in this chapter).

Although at Killin Rock the boundary between the Socach Hill Conglomerate, composed entirely of Moine clasts (see further in this chapter) and the Oldtown - Killin Rock Conglomerate is sharp (Fig. 7.4.8. & 7.4.11.), in locality Killin Rock [NC 874 060] (Log D, Fig. 7.4.8.) the latter conglomeratic body comprises in its lower portion individual beds, composed entirely of Moine detritus. Note also that the proportion of the vein granite clasts generally increases up the succession (compare Fig. 7.4.8. & 7.4.9.). At Killin Rock two red sandstone pebbles have been found in the conglomerate.

At Killin Rock the Oldtown-Killin Rock conglomeratic unit, characterised by the lower MPS, contains numerous sandstone interbeddings (Fig. 7.4.9. & 7.4.11.). These parallel- to cross- stratified sandstones are coarse- to very coarse-grained, poorly sorted lithic arenites and mineralogically appear to be more mature then the matrix in the conglomerates at Oldtown, Carrol Rock and Gilbert's Hill (Fig. 7.4.1.). These rock fragments correspond in terms of composition to the gravel fraction. The grains are mainly angular and subangular. Subrounded to rounded clasts constitute up to 24%. Mixture of iron-oxide stained clay (mainly chlorite), appearing typically as uneven coatings on the detrital grains and quartz cement range from 13 - 9% and 6 - 11% respectively. The authigenic quartz seems to postdate the formation of chlorite.

Socach Hill Conglomerate

This relatively fine-grained conglomeratic unit, around 11 m thick, underlying the Oldtown - Killin Rock Conglomerate at the eastern margin of the basin rests directly on the Moine basement (Fig. 7.4.8. & 7.4.11.). The Socach Hill Conglomerate is entirely composed of the angular siliceous granulite clasts. At one locality at Killin Rock [NC 869 055] the lowest, 1.5 m thick portion of the conglomerate totally consists of unsorted clasts of two-mica schist, which in fact constitutes the subjacent schist-sliver, embodied by the dominant siliceous granulites. The absence of the vein granite detritus in this conglomeratic unit mimics the lithology of the basement outcropping to the NE, which is entirely represented by the Moine metasediments.

Matrix in the Socach Hill Conglomerate is represented by well to very well sorted lithic wacke with clay matter (hematite-stained chlorite, illite/mica) constituting 16 - 27.8% of the whole rock. The clay seals the pore spaces and normally separates the detrital grains (Plate 7.4.7.). A minor proportion of the grains display good roundness (Fig. 7.4.1.). The lithic fragments are represented by assemblage of granitoid and high-grade metamorphic clasts. The low-grade, pelitic, lithic fragments are present in negligible proportions (0.0 - 1.2%, averaging 0.5%).

Cnoc Cragaidh Conglomerate

The gravel fraction in the Cnoc Cragaidh Conglomerate is primarily represented by angular and subangular Moine siliceous granulite clasts (Fig. 7.4.1.A). Subrounded and rounded particles make up less than 20%. Vein granite is also present and its proportion gradually increases upwards. The decreasing frequency of the granitic clasts among the coarser gravelly fractions in the lower portion of the Cnoc Cragaidh Conglomerate might be a result of limited thickness of the granite veins, which yielded the detritus. The clasts of Moine granulites with veins of granite are common and have been separately included in the diagram (Fig. 7.4.1.B) depicting clast composition in the upper, coarser part of the conglomeratic unit. Here the granite constituent displays the characteristic tendency of concentrating in the population of the largest clasts. Negligible number of clasts of vein quartz and deformed granulite, which suffered brittle deformation have been recorded (Plate 7.4.5.D).

The clast composition of the gravel fraction in the Cnoc Cragaidh Conglomerate closely corresponds to the characteristics of the Oldtown - Killin Rock Conglomerate and in both cases it mirrors the lithology of the Caledonian basement, outcropping to the W. In both cases the clast composition is consistent with the inferred S and SE palaeodispersal patterns (Fig. 7.4.1., 7.4.10., 7.4.11. & 7.4.12.).

Matrix in the conglomerates and pebbly sandstones of the Cnoc Cragaidh Conglomerate displays distinctive mineralogical features that differ the latter deposits from the other conglomeratic units of the Beinn Smeorail Formation. Unique textural characteristics of the matrix, discussed in chapter. 7.4.5.1.1. will be only briefly signaled below.

The matrix material is represented by well sorted, fine-grained lithic arenite with lithic fragments constituting 28 - 34% (Fig. 7.4.1.). It is compositionally and texturally identical to the sandstone horizon, which underlies the Cnoc Cragaidh Conglomerate (Fig. 7.4.1. & Plate 7.4.2.). It is noteworthy the matrices in the Socach Hill Conglomerate (SE margin of the basin) and in the Creag an Amalaidh Conglomerate (BLF) show similar textural characteristics (Plate 7.4.7. & 7.1.11.B). Hematite/clay matter occurs as thin coatings on the grains. The coatings have been found to be either continuous or discontinuous along the contacts between the grains. The main form of cement is authigenic quartz, appearing mainly as overgrowths and constitute 13 - 15% of the rock (Plate 7.4.12. & 7.4.13.). As opposed to the gravel detritus a significant proportion of the sand-size grains display good roundness and this feature of textural maturity characterises a variety of detrital grains from phyllites to feldspar and monocrystalline quartz, though the schistose clasts show slightly better roundness.

The low-grade, pelitic, lithic fragments (PLF) constitute 11.6 - 15.7% (av. 14.3%) of the total point counted population of the detrital grains (Fig. 7.4.1.). Clasts designated to this category range from phyllites or schists to quarzites and cherts (Plates 7.4.12. & 7.4.13.). They are represented by intergrown in various proportions mixtures of very fine micas (muscovite and chlorite), chert, microquartz and locally megaquartz. Phyllites and schists manifest strong, locally folded, schistosity (Plate 7.4.12.C & 7.4.13.B,C). Chert particles have often been found containing minor, scattered fine mica crystals with or without detectable alignment. Megaquartz is very rare and when occurs it typically appears in gradational relationship with the microquartz. In a number of clasts the megaquartz crystals have been found "floating" in the mica background (Plate 7.4.12.D), with schistosity occasionally wrapping around them (possible early detrital grains). Plate 7.4.13.D shows at high magnification a chert grain with enclosed clast (probably feldspar).

Significant proportions of an analogous spectrum of low-grade pelites, chert and quartzite clasts have been recorded from the Ben Tarvie - Creag an Amalaidh Conglomerate(Beinn Lunndaidh Fm.) (Fig. 7.1.20a.), from the Beinn Dhorain Member(Glen Loth Fm.) (Golspie basin) (Fig. 7.2.21.), and from Ousdale Mudstones (Badbea basin). Lesser content of the PLF grains characterises Ben Uarie Member (Glen Loth Fm.) (Fig. 7.2.21.).

Provenance of the low-grade pelitic, lithic fragments has not been established. There are no known low-grade terrains in the vicinity of the Golspie basin and the Badbea basin which could be considered as a possible source of the clasts. On the other hand, taking into account the recycled origin of the sediments in question (see chapter 7.1.5.4., 7.2.6.3. & 7.4.5.5. for details) an *ultimate source* (Ehlers & Blatt, 1982) should be accounted for.

Plate 7.4.12. **A - C**: Photomicrographs of the low-grade metamorphic, pelitic lithic fragments (PLF).

A: Well rounded grain of phyllite in the center; fine muscovite enclosed in cryptocrystalline quartz. Note abundant quartz overgrowths(**Q**) (XPL);

B & D: Rounded to angular phyllite clasts. Monocrystalline quartz locally accompanies the fine mica (XPL);

C: Rounded phyllite grain (XPL). (Locality: **A, B & D** - Cnoc Cragaidh Conglomerate, BSF; **C** - Culmaily, Beinn a' Bhragaidh Member, GLF)

Plate 7.4.12.

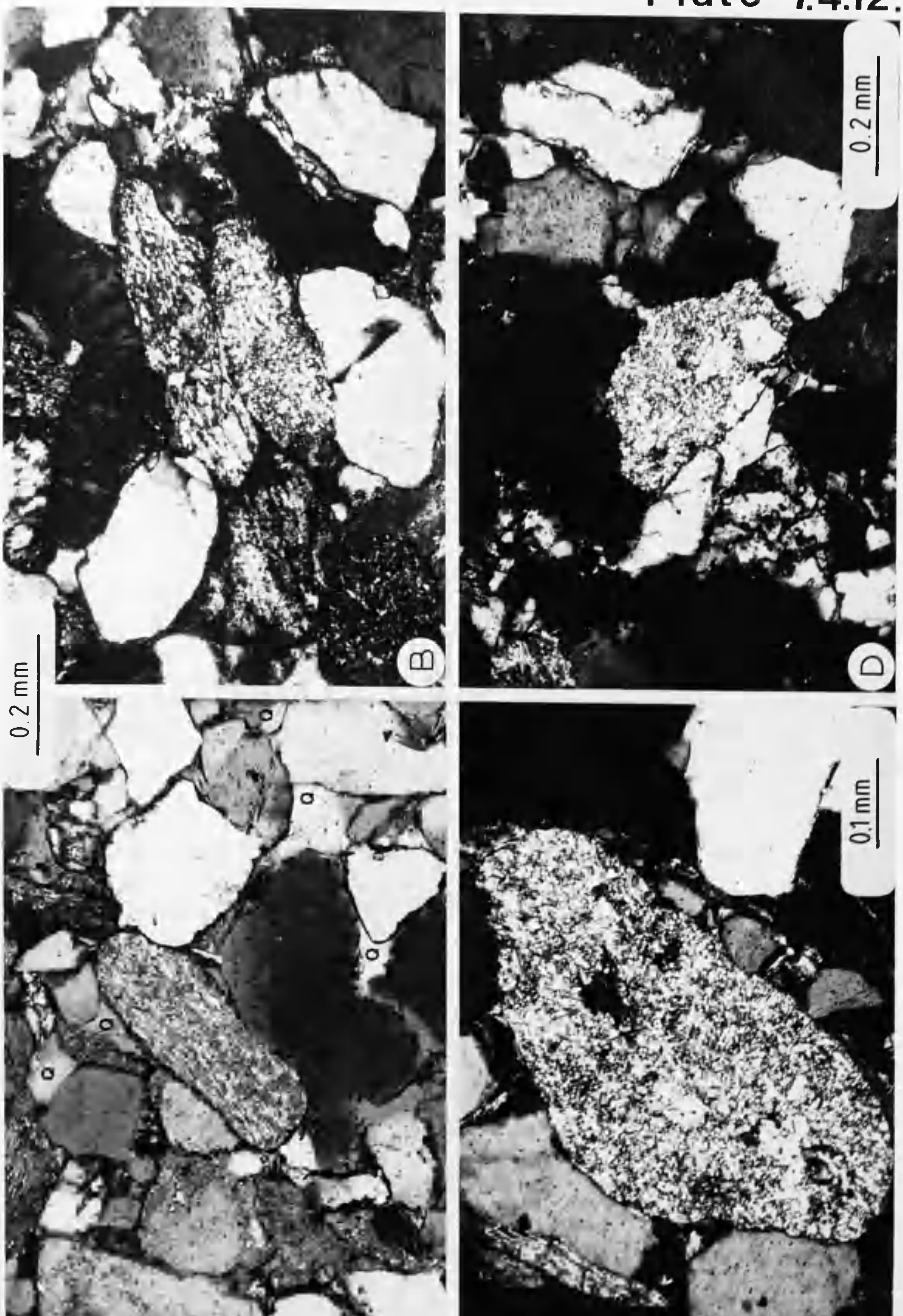


Plate 7.4.13. Low-grade metamorphic, pelitic lithic fragments (PLF).

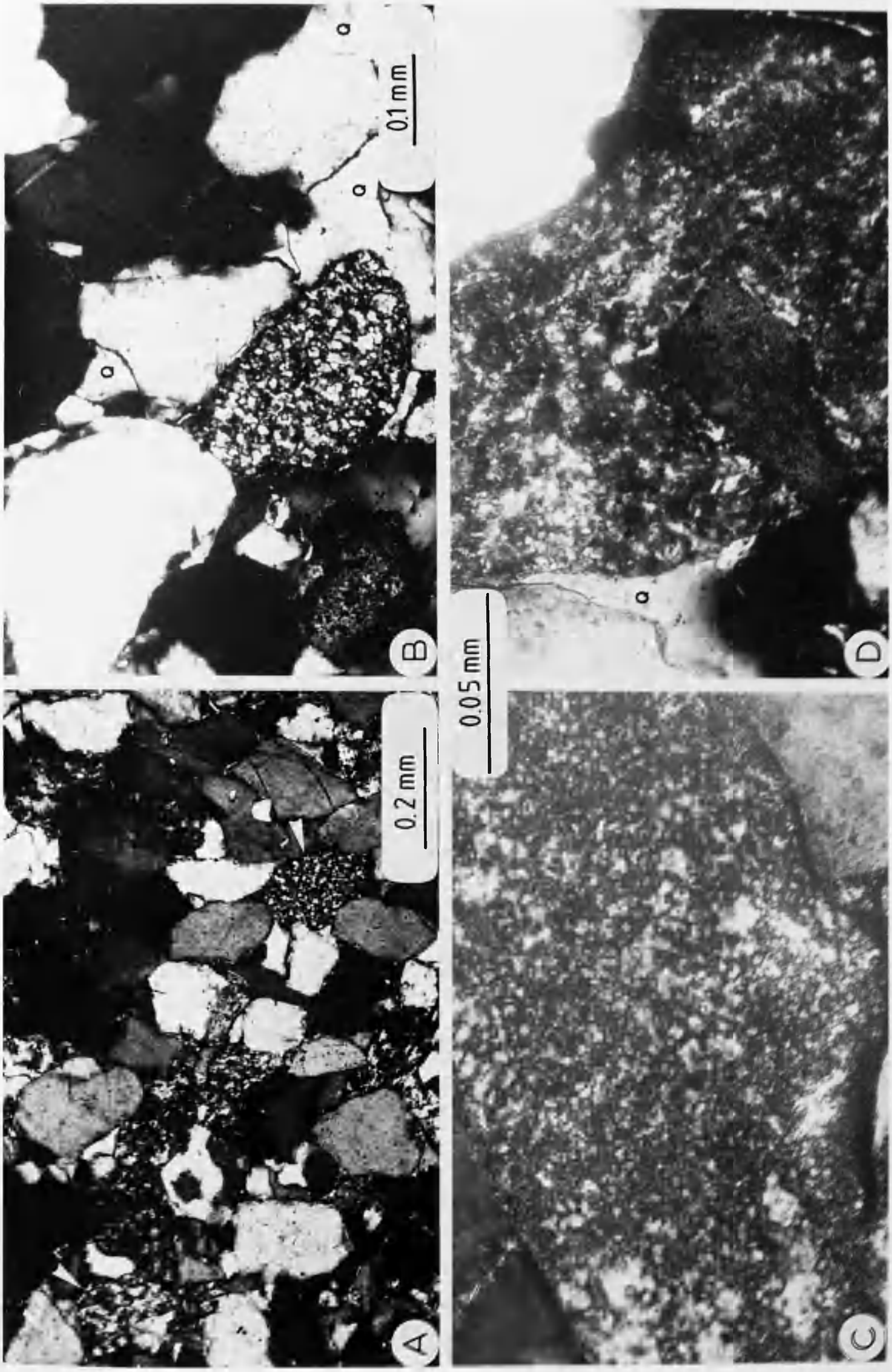
A & B: Well rounded quartzite grains (arrowed in **A**). Note a considerable amount of authigenic quartz (**Q**) (XPL);

C: Chert clast (XPL);

D: Clast of chert, enclosing detrital feldspar grain (?). **Q** - quartz overgrowth.

(Locality: **A-D** - Cnoc Cragaidh, BSF)

Plate 7.4.13.



The Beinn Dhorain Member and the Ousdale Mudstones, with the average PLF content 11.4% and 9.5% respectively (Fig. 7.2.21.), display generally similar as the Cnoc Cragaidh Conglomerate southward palaeodispersal pattern (Fig. 7.4.1.). The Ben Tarvie - Creag an Amalaidh Conglomerate and Ben Uarie Member, both containing less of the PLF clasts, were dispersed to the E and N respectively.

In the light of the multi-cycle depositional history of the sediments in question the mentioned above palaeotransport data appear to have little relevance to the elucidating of the problem of provenance of the PLF component, for they clearly apply only to the very final, and as has been argued earlier in the chapters 7.1.5.4., 7.2.6.3. & 7.4.5.1.1., to the relatively short distance, *en mass* transport of the discussed sediments into the basin and resedimentation within the basin.

Small size of the low-grade pelitic rock fragments (predominant fine-grained sand grade and smaller) precludes meaningful, detail petrographic or chemical studies of the clasts. It is tempting, however, to mention here that the fragments of phyllite, schist, quartzite and chert, recognized in the Golspie basin and the Badbea basin, display striking similarities with the cryptic low-grade metasediments, present in abundance in the Lower Old Red Sandstone Crowton Group and "Grewacke Conglomerate" of the Midland Valley (Bluck, 1978; Haughton, 1986).

The remaining lithic constituents of the matrix have been derived from granitoid and other metamorphic, high-grade (Moine ?) terrains. There are present trace amounts of considerably altered to iron oxide volcanic clasts of approximately intermediate composition.

Among the monocrystalline grains, quartz and K-feldspar (with common microcline) are prominent. Plagioclase and muscovite are negligible. It is important to mention here that the deposits of Beinn Dhorain Member, Ben Uarie Member (Glen Loth Formation, Golspie basin) and of Ousdale Mudstones (Badbea basin), characterised by presence of PLF clasts contain ubiquitous, though statistically negligible, detrital chlorite.

The matrix as well as the underlying sandstone horizon associated with Cnoc Cragaidh Conglomerate appear both in terms of texture and petrographic composition neither related to the gravel fraction in the conglomerate nor to any of the adjacent rocks, that is to the subjacent siliceous granulites and vein granite of the Caledonian basement with a thin cover of possible conglomerates of the Beinn Lunndaidh Formation and to the overlying or laterally adjacent Oldtown - Killin Rock Conglomerate.

Creag a' Bhodaich Conglomerate

The thickest, around 360 m thick, conglomeratic unit of the Beinn Smeorail Formation, occupying the NE part of the Golspie basin, displays new, distinguishing compositional characteristics, though only its middle portion is sufficiently exposed to observation.

The Moine siliceous granulite clasts again are present and appear to be the common, ubiquitous component of all the conglomeratic units of the Beinn Smeorail Formation. The Moine, predominantly angular debris generally dominates the Creag a' Bhodaich Conglomerate but its proportion gradually diminishes in the upper part of the section (Fig. 7.4.4.). The lowermost, over 20 m thick, part of the section consists almost entirely of Moine clasts. The arkosic, Helmsdale granite-derived detritus, typically dominates the finest gravel fractions. The lowest part of the section contains also negligible proportion of red sandstone clasts (see further in the text). The proportion of the two latter constituents dramatically increases in the middle part of the section and reaches up to 50% (Fig. 7.4.4.B,C). Here, the Helmsdale granite debris (mostly individual orthoclase feldspars) dominates the finer gravel grades, though it also occurs in a more less constant proportions among the coarser particles (see also Plate 7.4.9.A,B). Unlike the arkosic detritus the red sandstone clasts appear to be gradually more abundant in the coarser fractions (Fig. 7.4.4. & Plate 7.4.9.B). The latter sedimentary component is represented by calcareous to non-calcareous, well sorted, with regard to the sand grade, very fine- to fine-grained lithic arenites and wacke (Fig. 7.2.21.) with predominantly angular grains and argillaceous matrix ranging from 13 - 20%. The sandstone clasts often show parallel-lamination and ripple cross-lamination. A few pebbly mudstone pebbles with the distinctive Helmsdale granite clasts have also been found. The sandstone clasts contain low-grade pelitic, lithic fragments(phyllite, chert) in proportion ranging from 5.5 - 10%. The red sandstone clasts perfectly match, texturally as well as compositionally, the underlying sediments of the Ben

Uarie Member and the Beinn Dhorain Member (Glen Loth Formation) and the latter rocks are thought to have been the source for the sandstone detritus in the Creag a' Bhodaich Conglomerate.

The sandstone clasts quickly disappear in the upper part of the section of Creag a' Bhodaich Conglomerate (Fig. 7.4.4.). This compositional change corresponds to the decrease in the maximum particle size (MPS) and to the transition into deposits of Facies C1. This finest-grained portion of the section consists mainly of the arkosic detritus, derived exclusively from the porphyritic portion of the Helmsdale granite (Plate 7.4.8.C & D). The Moine clasts appear only in the subordinate coarser interbeddings.

The latter part of the Creag a' Bhodaich Conglomerate closely resembles the Ousdale Arkose Conglomerate of the Beinn Lunndaidh Formation which forms the basal unit of the sedimentary succession in the NE part of the Golspie basin as well as in the Badbea basin (chapter 7.1.5.2.).

Four sandstone horizons (Fig 7.4.4.1-4), of possible aeolian origin (for details see chapter 7.4.5.1.2.), stand out in the studied section as texturally distinct. As opposed to the Facies C2-related sandstone interbeddings, these rocks are well to very well sorted and contain a significant component of subrounded to well rounded grains (Plate.7.4.10.D). Compositionally the sandstones are lithic arenites with dominant fragments of granitoid rocks (Fig. 7.4.1.). High-grade and low-grade metamorphic lithic fragments are also present as well as sporadic particles of sandstones and mudstones.

The described above main part of the examined section of the Creag a' Bhodaich Conglomerate contains <u>no vein granite clasts</u>, the onse which are so ubiquitous in the other conglomeratic units of the Beinn Smeorail Formation (with exception of the Socach Hill Conglomerate). This compositional signature together with the presence of the Helmsdale granite and the red sandstone components, appear to be fully consistent with the NW - N palaeodispersal pattern inferred from the cross-strata orientation in the conglomerates and from the clast imbrication (Fig. 7.4.4.), and clearly match the source terrains present upstream during the sedimentation of the Creag a' Bhodaich Conglomerate (see next chapter for further discussion).

The topmost portion of the studied part of the Creag a' Bhodaich Conglomerate is characterised by a rapid appearance of massive, coarse conglomerates of Facies B. Unfortunately, the main part of these deposits, forming Carn Garbh is not accessible to detail observation. The conglomerates consist in the majority of vein granite clasts (Fig. 7.4.4.E). Siliceous granulite particles with veins of pink granite have also been found. While the granite clasts range from angular to well rounded, the granulite detritus is predominantly angular and subangular. Matrix, constituting 40 - 60% of the rock is extremely poorly sorted lithic arenite (Fig. 7.4.1.) with iron oxide/clay material appearing in proportions 7.7 - 3.0% (Plate 7.4.10.C). With regard to the petrographic composition the matrix sandstone closely corresponds to the gravel fraction and is characterised by presence of granitic and high-grade metamorphic rock fragments. The sandstone contains very abundant quartz cement, ranging in proportion from 41.6 - 44.8% and its formation seems to have involved total dissolution of some of the quartz grains in the matrix.

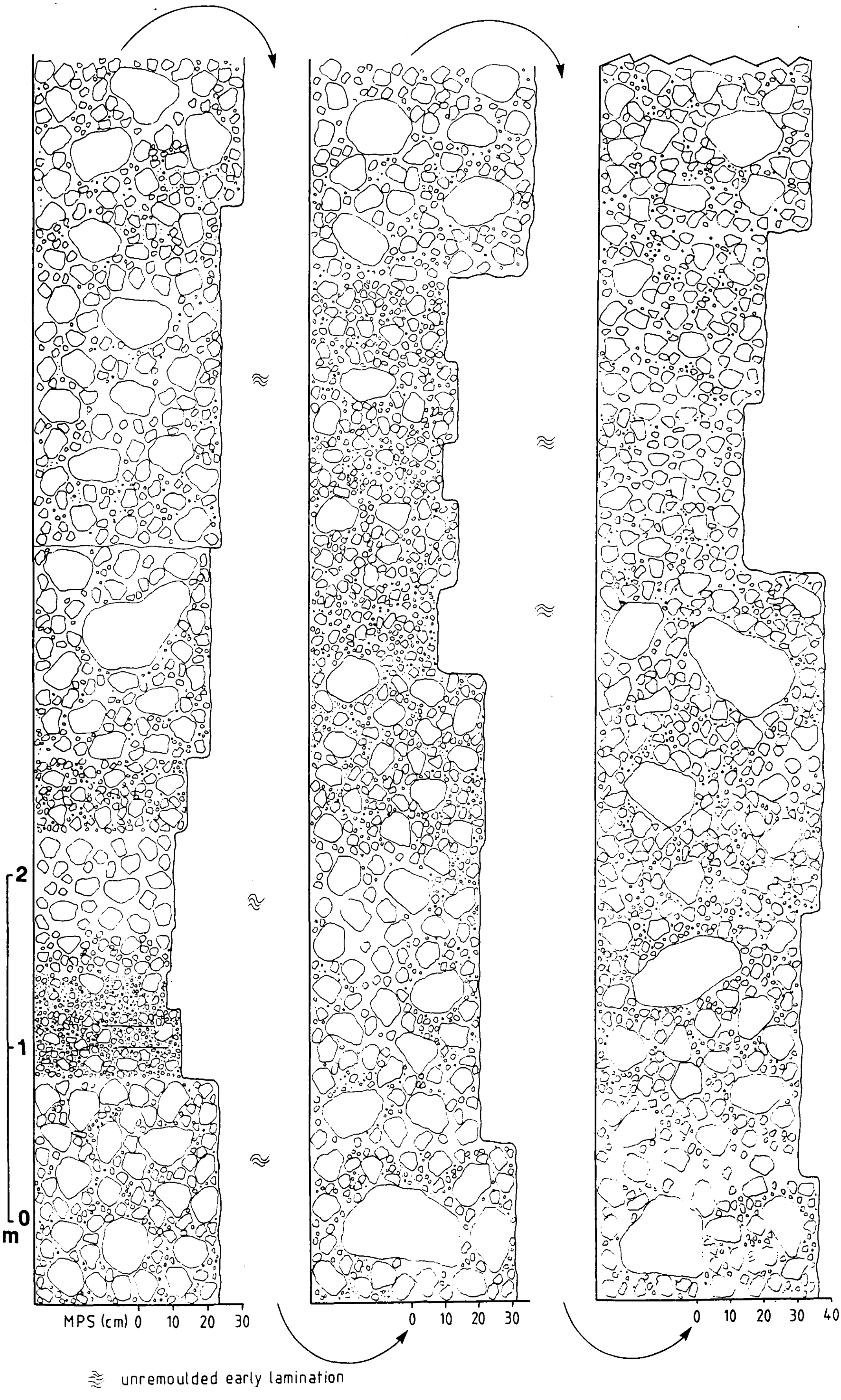
Clast composition of the Morven, Smean and Maiden Pap Conglomerate and the Badbea Braccia, located in the Braemore basin and Badbea basin respectively, appears to reflect lithology of the neighbouring basement (Read *et al.,* 1925; Crampton *et al.*, 1914) but these deposits have not been studied in detail by the present author.

7.4.5.3. Vertical and lateral facies variability versus clast composition and palaeodisperasal in the Beinn Smeorail Formation

The Ben Horn Conglomerate is fragmentarily exposed only at the summit of Ben Horn. It appears to comprise deposits analogous to Facies B and C (with predominance of the latter and conglomerates of somewhat "intermediate" features). Unfortunately the inaccessible face of the exposure has precluded measuring of the section and verification of the facies characteristics and its vertical variability.

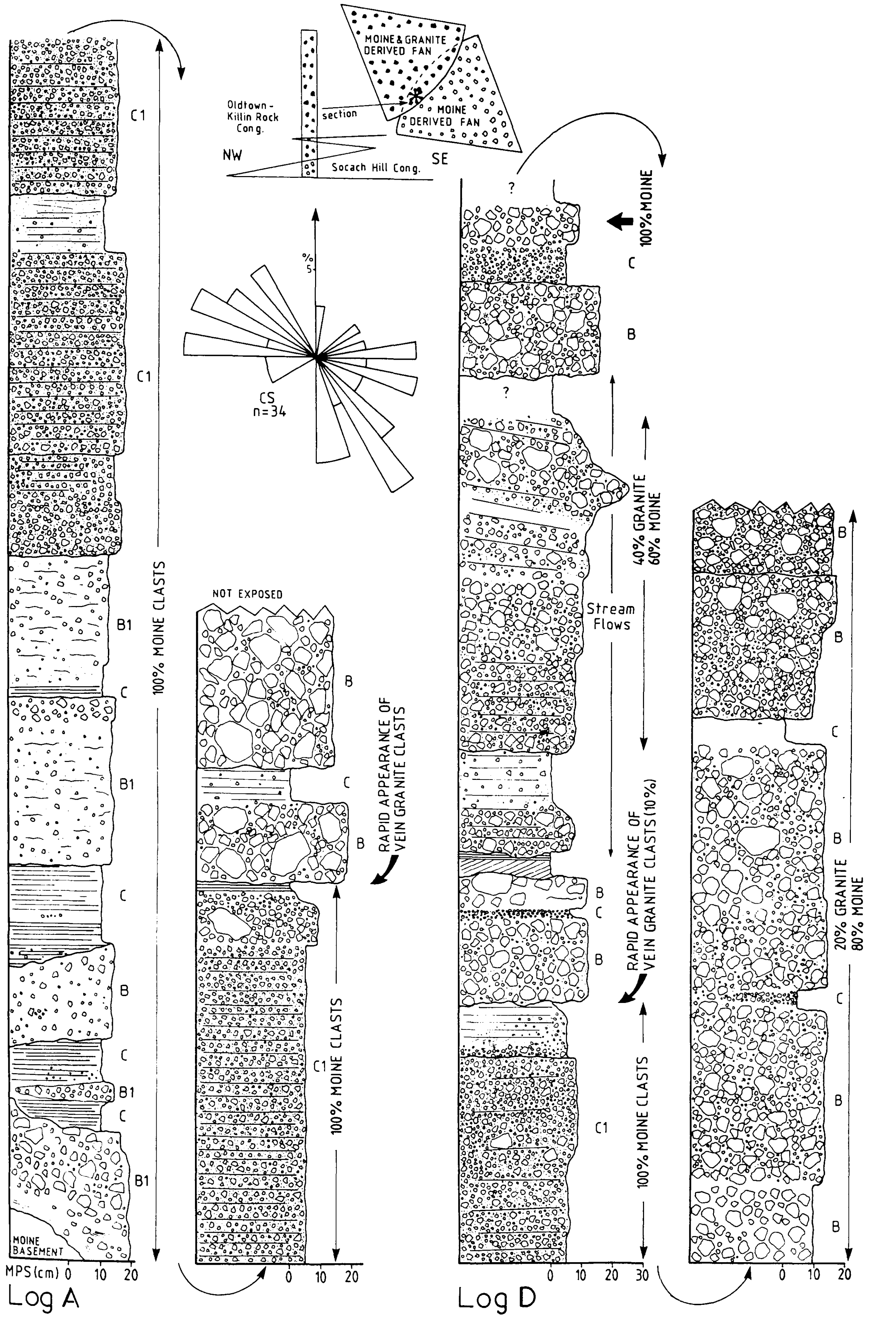
The Oldtown - Killin Rock central conglomeratic unit thinns out to the SE from 200 m at the NW margin of the Golspie basin (Oldtown, Carrol Rock) to around 30 m at the SE margin (SE of Duchary Rock). The 100 m thick conglomerate, exposed at Cnoc Cragaidh, above the Cnoc Cragaidh Conglomerate, possibly represents the NE

Figure 7.4.7. Graphic log through the debris flow, Facies B-dominated, coarsest (proximal) portion of the Oldtown - Killin Rock Conglomerate. Bed boundaries within the deposits of Facies B are normally unrecognizable. (Locality: Oldtown, BSF)



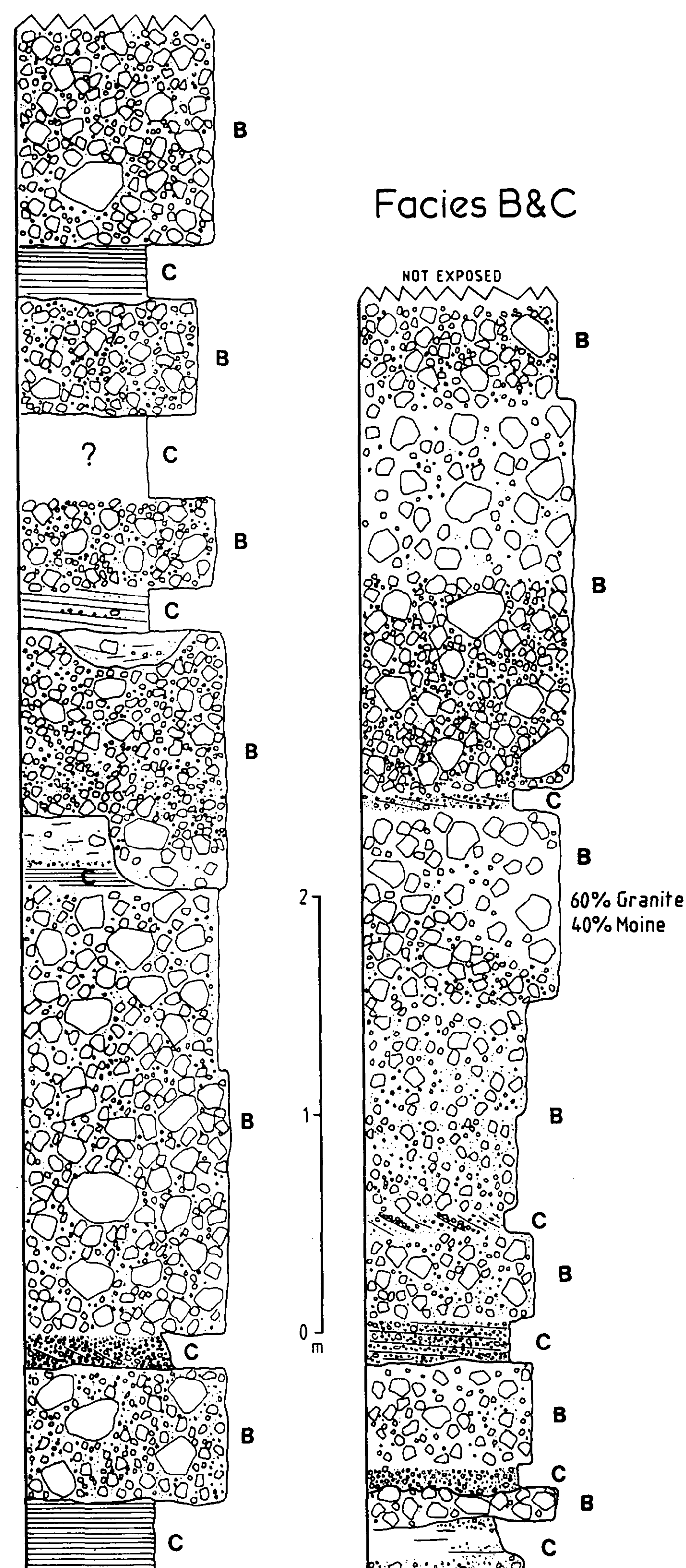
2
1
0
m
MPS (cm) 0 10 20 30
0 10 20 30
0 10 20 30 40
unremoulded early lamination

Figure 7.4.8. Log A through the Socach Hill Conglomerate, which is composed entirely of Moine granulite clasts, and through the lowest portion of the Oldtown - Killin Rock Conglomerate made up of vein granite and Moine material. The sharp boundary between the two units is manifested by a rapid appearance of vein granite detritus(arrowed), derived from the NW (see also Fig. 7.4.11.). (Locality: Killin Rock [NC 877 060]);
Log D shows the topmost portion of the Socach Hill unit and the lower part of the Oldtown - Killin Rock Conglomerate. Note the single bed composed entirely of Moine granulite clasts at the top of the first column, enveloped within the deposits made up of "mixed" (granite & Moine granulite) detritus. (Locality: Killin Rock [NC 874 060]). The variability in clast composition suggests interfingering of two independent alluvial fans(or fan systems) accumulating off the opposite basin margins. This hypothesis is supported by the palaeotransport and other data derived from the Oldtown - Killin Rock Conglomerate and from the Socach Hill Conglomerate (see Fig. 7.4.11.). The schematic diagram above shows that the "Moine only beds" within the Oldtown - Killin Rock Conglomerate may represent distal members of the Socach Hill fan dispersing in the opposite direction than the Oldtown - Killin Rock fan.



MOINE & GRANITE DERIVED FAN
MOINE DERIVED FAN
Oldtown - Killin Rock Cong.
section
NW
SE
Socach Hill Cong.
%
5
CS
n=34
C1
B1
C
B
100% MOINE CLASTS
MOINE BASEMENT
MPS (cm) 0 10 20
2
1
0
m
Log A
NOT EXPOSED
RAPID APPEARANCE OF VEIN GRANITE CLASTS
?
100% MOINE
40% GRANITE 60% MOINE
Stream Flows
RAPID APPEARANCE OF VEIN GRANITE CLASTS (10%)
20% GRANITE 80% MOINE
0 10 20 30
Log D

Figure 7.4.9. Graphic log from the upper portion of the Oldtown - Killin Rock Conglomerate composed of Facies B and C. Note numerous sandstone beds and occasional scours. This portion of the conglomeratic unit exposed at Killin Rock represents alluvial fan deposits which are more distal, in relation to the fanglomerates at Oldtown, Carrol Rock and Gilbert's Hill (compare with Fig. 7.4.7.; see also Fig. 7.4.11.). (Locality: Killin Rock [NC 866 057])


Facies B&C
NOT EXPOSED
B
C
B
C
?
B
C
B
C
B
C
B
C
60% Granite
40% Moine
B
C
B
C
B
C
B
C
2
1
0
m
0 10 20
MPS (cm) 0 10 20

Log C

continuation of the Oldtown - Killin Rock unit. The SE wedging out of the Oldtown Rock - Killin Rock Conglomerate in the area of Loch Brora (Fig. 7.4.11.) is accompanied by a decrease in the maximum particle size (MPS) 1cm/km and by a appearance of the deposits Facies C deposits, including sandstone beds (Fig. 7.4.8., 7.4.9. & 7.4.11.). These trends are consistent with the palaeodispersal pattern inferred from the cross-strata orientation at Rinacoul Rock and Killin Rock (Fig. 7.4.11.).

The bimodal palaeodispersal pattern from Killin Rock displays also the NW component, which generally concurs with the palaeotransport direction inferred for the underlying Socach Hill Conglomerate on the basis of orientation of scarce cross-strata, 100% Moine clasts composition and restricted position of this thin conglomeratic body to the NE margin of the basin and is probable wedging out to the N and NW (Fig. 7.4.11.).

It is worth mentioning that at Killin Rock the Oldtown - Killin Rock Conglomerate contains in its lowest part single beds which are made up entirely of Moine clasts (Fig. 7.4.8.Log D). These isolated beds appear to be identical to the deposits of the subjacent Socach Hill unit. At Killin Rock the "vein granite & Moine" beds contain also a minor proportion of Helmsdale granite clasts and some sporadic particles of red sandstone. At the latter locality the general granite content increases upwards (compare Fig. 7.4.8. & 7.4.9.).

At Cnoc Cragaidh the Oldtown - Killin Rock unit comprises in its lowermost part a lenticular horizon which is composed mainly of stream flow sandstones and minor conglomerates. Thickness of theses deposits is around 15 m and lateral extend 240 m in the section at 65^{o} to the determined local, mean palaeocurrent direction (Fig.7.4.10. & Plate 7.4.1.A, B).

The examined sections from the Oldtown - Killin Rock Fan (Fig. 7.4.11.) reveal no consistent trends with regard to vertical variability in the maximum particle size (MPS). This is except for the topmost transition of the conglomerates into the sandstones of the Col-bheinn Formation (Fig. 7.4.11.).

The Socach Hill Conglomerate shows no significant vertical variations in terms of facies characteristics, clast composition and palaeodisparsal (Fig. 7.4.8.). No data are available about the lateral trends owing to the limited exposure.

The Cnoc Cragaidh Conglomerate, composed mainly of Facies B1, shows in its

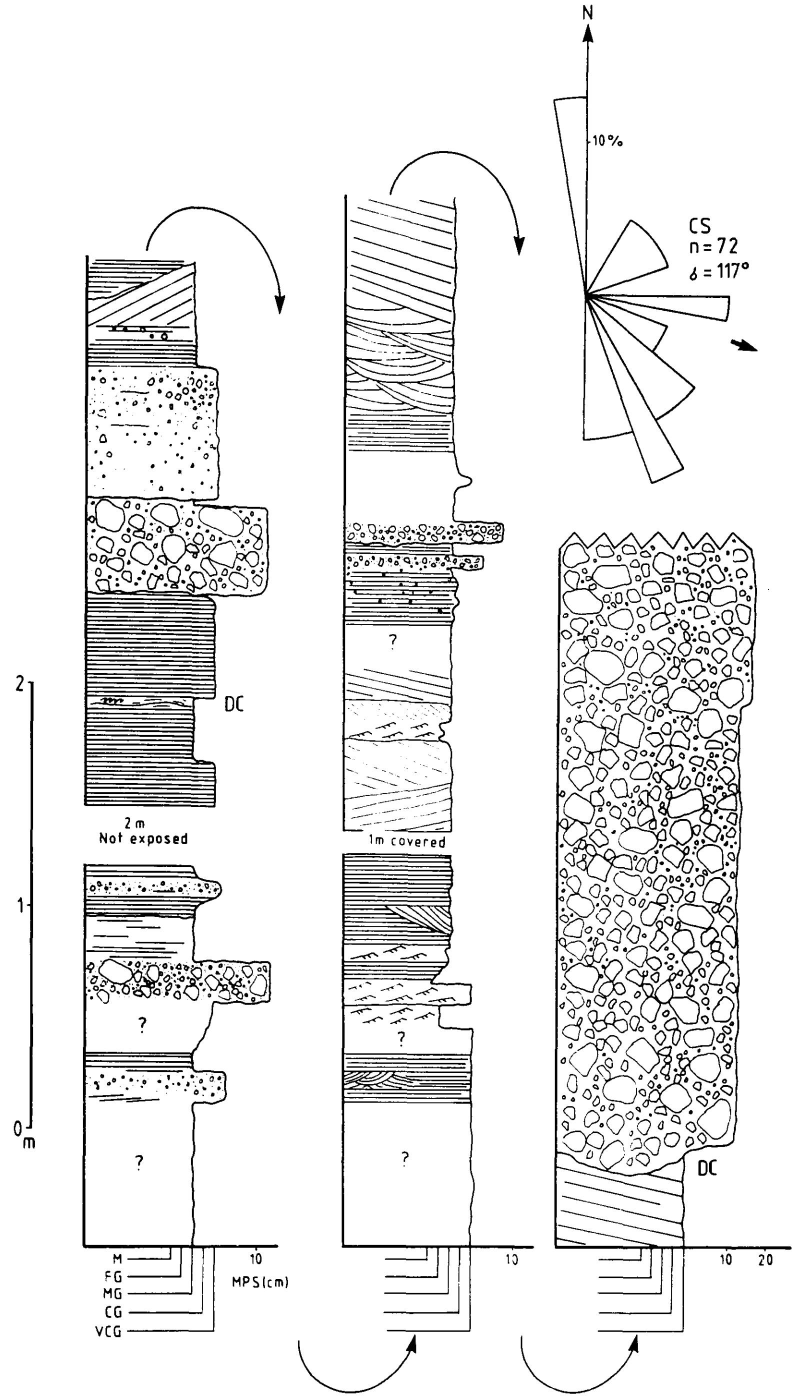
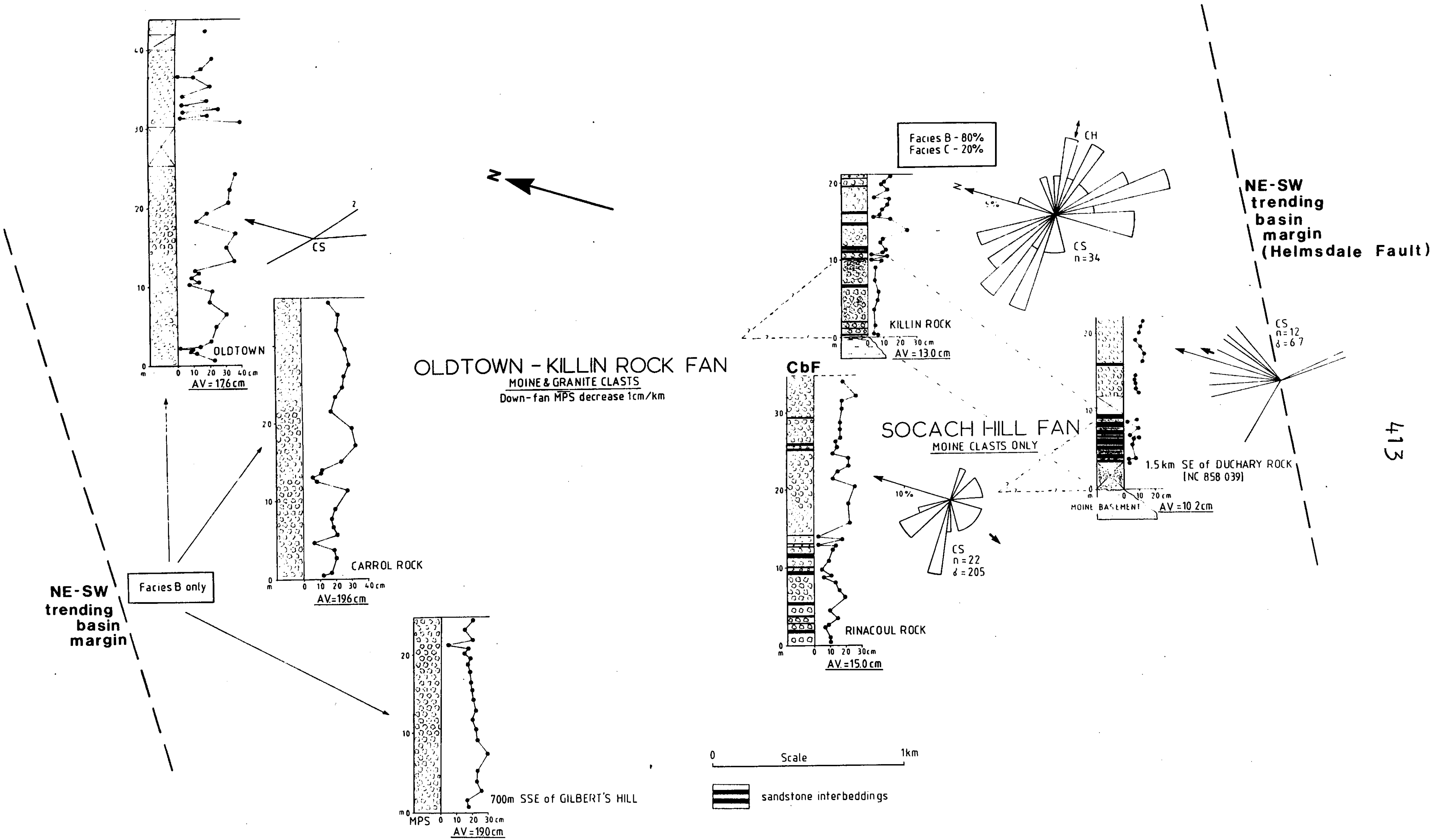


Figure 7.4.10. Planar-stratified, cross-stratified and current ripple cross-laminated sandstones, with occasional desiccation cracks (**DC**), and minor conglomerates make up the lenticular body in the lowest part of the Oldtown - Killin Rock Conglomerate exposed at Cnoc Cragaidh (see also Plate 7.4.1. A,B). These deposits probably represent a product of sedimentation in ephemeral streams and sheetfloods, occasionally invading abandoned fan segment. The rapid appearance of the Facies B deposits (arrowed) indicates an avulsive initiation of active fan segment. Palaeocurrent data from the sandstones closely correspond to the palaeodispersal pattern, derived from the underlying Cnoc Cragaidh Conglomerate(see Fig. 7.4.1.). **CS** - cross strata orientation.

Figure 7.4.11. Schematic logs from the Oldtown - Killin Rock Conglomerate (Fan) from the area of Loch Brora (see Fig. 3.3.). The alluvial fan body fines and wedges out to the S. This trend is consistent with the palaeocurrent data as well as with the down-fan increase in proportion of the water-laid deposits of Facies C, including sandstone beds . At Rinacoul Rock the conglomerates pass gradationally into the sandstones of the Col-bheinn Formation (see also Fig. 7.5.1a. & 7.5.1b.). The Socach Hill Conglomerate (Fan), which is compositionally distinctly different, probably wedges out to the N and NW of the the SE margin of the Golspie basin. Estimated total thicknesses of the considered fanglomeratic units is 200 m at Oldtown, 70 m at Killin Rock, and 30 m SE of Duchary Rock. **CS** - cross strata orientation; **AV** - average MPS in locality.



NE-SW trending basin margin (Helmsdale Fault)
NE-SW trending basin margin
OLDTOWN - KILLIN ROCK FAN
MOINE & GRANITE CLASTS
Down-fan MPS decrease 1cm/km
SOCACH HILL FAN
MOINE CLASTS ONLY
OLDTOWN
AV = 17.6 cm
CARROL ROCK
AV = 19.6 cm
700m SSE of GILBERT'S HILL
AV = 19.0 cm
MPS
KILLIN ROCK
AV = 13.0 cm
RINACOUL ROCK
AV = 15.0 cm
CbF
1.5 km SE of DUCHARY ROCK
[NC 858 039]
MOINE BASEMENT
AV = 10.2 cm
Facies B - 80%
Facies C - 20%
Facies B only
CS
n = 34
CH
CS
n = 12
δ = 67
CS
n = 22
δ = 205
10%
5%
N
Scale
0
1km
sandstone interbeddings

upper part a rapid introduction of the coarser detritus and decrease in amount of sandy matrix (Fig. 7.4.1.; see also chapter 7.4.5.1.1.). The latter conglomeratic unit is in a gradational contact with, what is believed to be, a north-eastward continuation of the Oldtown - Killin Rock Conglomerate. The transition is manifested by an upward disappearance of well sorted, fine-grained sandy matrix, containing the distinctive component of low-grade mrtamorphic, pelitic, lithic fragments (PLF) (Fig. 7.4.1.C). The sandstones from the stream flow-dominated horizon, from the base of the Oldtown - Killin Rock Conglomerate, display textural and petrographic features, which are somewhat common for both, the Cnoc Cragaidh and the Oldtown - Killin Rock units. The both conglomeratic bodies appear to have been derived from similar NW direction (Fig. 7.4.1. & 7.4.10.).

No data are available on lateral variability of facies distribution, composition and palaeodispersal in the Cnoc Cragaidh Conglomerate.

The vertical facies variations and changes of clast composition within the Creag a' Bhodaich Conglomerate versus palaeodispersal pattern have been discussed in the previous chapter and will be briefly summarised below (refer also to Fig. 7.4.4):

1) The lowest part of the section (Fan 1), composed of Facies B and C overlaps with the portion of the section which is dominated by the Moine granulite clasts;

2) The deposits of Facies C2 form the main part of of the observed section and display diverse clast-composition (Fan 2). The lower part of the sequence is composed mainly of the Moine granulite debris. However, the majority of the Facies C2 conglomerates contain also abundant Helmsdale granite detritus and red sandstone clasts (the latter material has most likely been derived from the underlying Glen Loth Formation);

3) The sequence of Facies C2 comprises four sandstone horizons (1-4) which are texturally distinctly different from the host deposits and are probably of exotic, aeolian provenance;

4) The conglomerates of Facies C2 pass upwards into finer-grained deposits of Facies C1 which are almost exclusively composed of Helmsdale granite derived detritus.

The summarised above main part of the observed section of the Creag a' Bhodaich Conglomerate yields generally northward palaeodispersal pattern, which entirely concurs with the clast provenance.

The topmost part of the discussed section covers the lowest portion of th Facies B-dominated portion of the Creag a' Bhodaich Conglomerate. These coarse conglomerates appear rapidly in the section and contain distinctly different suite of clasts. They lack Helmesdale granite and red sandstone detritus. Instead there are abundant vein granite clasts, accompanied by the Moine debris. No palaeotransport indicators are available from the latter deposits but the clast composition, very similar to the one which characterises the Oldtown - Killin Rock Conglomerate, suggests derivation from the NW, that is from the opposite direction than the underlying conglomerates.

No information are available with regard to lateral variability within the Creag a' Bhodaich Conglomerate.

7.4.5.4. Sedimentary environment of the Beinn Smeorail Formation

Ben Horn Conglomerate

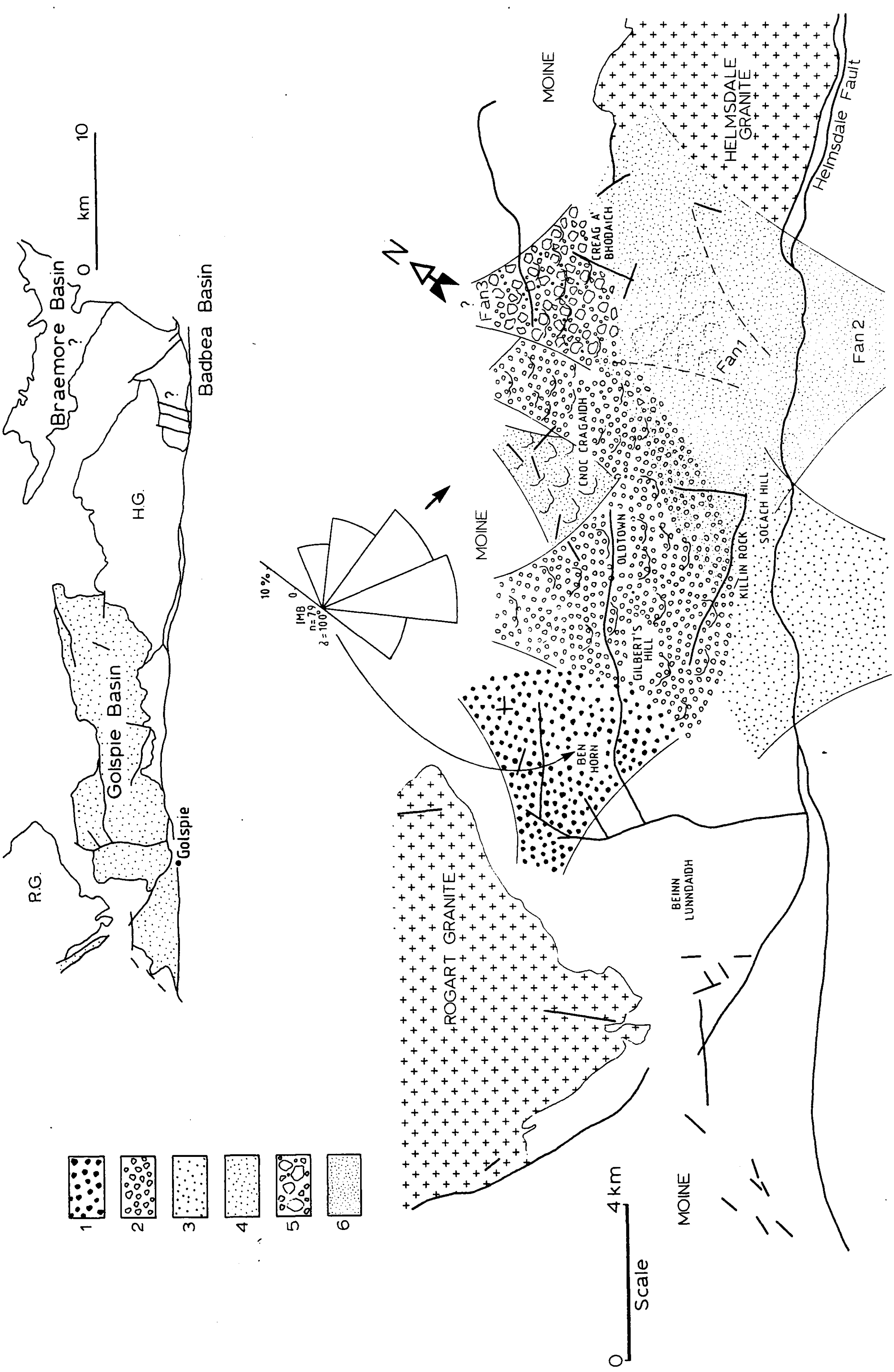
Although no detail data are available with regard to the sedimentary characteristics of the Ben Horn Conglomerate, it represents probably a small remnant of an alluvial fan (or a fan system) which built out in the approximately NE direction through accumulation of sheetflood and debris flow gravels (Fig. 7.4.12.). The observed deposits closely resemble Facies B and C. It appears that the extend of the dispersal of the clasts derived from the Rogart Central Granodiorite Complex is larger than during the sedimentation of the Beinn Lunndaidh Formation.

Oldtown - Killin Rock Conglomerate

The features of the Oldtown - Killin Rock Conglomerate discussed in the chapters 7.4.5.2. and 7.4.5.3. clearly indicate that it represents an alluvial fan body which prograded in the S-SE direction. The diagnostic characteristics are: (1) abundance of debris flow deposits (Facies B), (2) fan-like palaeodispersal pattern implying the palaeotransport from the possible fault-controlled, western margin of the basin and (3) the corresponding decrease in thickness of the fan body and in grain size (down-current increase in the proportion of stratified, water-laid sandstone and conglomerate beds of Facies C) (see chapter 7.1.5.3. for cited references).

The Oldtown - Killin Rock Fan displays very similar characteristics as the Ben Tarvie, Creag an Amalaidh and Mound Rock fans of the BLF (chapter 7.1.5.3.). Its growth proceeded mainly through accumulation of gravelly debris flows of Facies B whose deposits dominate the most proximal, fanhead sector (Oldtown(Fig. 7.4.7.), Carrol Rock, Gilbert's Hill (see also Fig. 7.4.11.)). In the more distal parts (Killin Rock, Rinacoul Rock) the deposition by currents of planar-stratified and cross-stratified gravels and sands produced beds of Facies C, analogous to the once recognized from the fanglomerates of the Beinn Lunndaidh Formation and from the lowest portion of of the Creag a' Bhodaich Conglomerate (Fan 1; see further in the text). The stream flow-generated large scale cross-bedded deposits are negligible in the Oldtown - Killin Rock fan.

Figure 7.4.12. Envisaged palaeogeography during development of the Beinn Smeorail Formation. For the other supporting palaeotransport data see Fig. 7.4.1. & 7.4.10. **?** - tentative alluvial fan palaeodispersal based on the fact that the clast composition mimics the lithology of the local basement. Key: **1** - Ben Horn Conglomerate; **2** - Oldtown - Killin Rock Conglomerate; **3** - Socach Hill Conglomerate; **4** - Cnoc Cragaidh Conglomerate; **5** - Fan 3 of Creag a' Bhodaich Conglomerate; **6** - Fans 1 & 2 of Creag a' Bhodaich Conglomerate. **imb** - imbrication data for the Ben Horn Conglomerate (inferred palaeoflow)


Braemore Basin
Golspie Basin
Badbea Basin
H.G.
R.G.
Golspie
0 km 10
MOINE
HELMSDALE GRANITE
Helmsdale Fault
CREAG A' BHODAICH
Fan3
Fan1
Fan 2
CNOC CRAGAIDH
OLDTOWN
KILLIN ROCK
SOCACH HILL
GILBERT'S HILL
BEN HORN
BEINN LUNNDAIDH
ROGART GRANITE
IMB
n=79
10 %
0
Scale
0
4 km
1
2
3
4
5
6

The lenticular stream flow sandstone/conglomerate horizon, appearing in the lowest part of the Oldtown - Killin Rock Conglomerate at Cnoc Cragaidh (Fig. 7.4.10.), represents probably and abundant fan segment, occupied by ephemeral low-energy sandy sedimentation and sporadically invaded by gravelly debris flows and sheetfloods. The rapid appearance of the Facies B conglomerates marks probably an avulsive initiation of the debris flow-dominated gravelly fan sedimentation (Heward, 1978).

Socach Hill Conglomerate

The Oldtown - Killin Rock fan probably overstepped during its S-SE progradation the axis of the NE-SW trending ridge of Moine - hypothetically viewed as the eastern margin of the Golspie basin during the sedimentation of the Beinn Lunndaidh Formation - and simultaneously onlapped the NW dispersed Socach Hill Conglomerate (Fig. 7.4.11. & 7.4.12.). The latter fanglomerate formed in result of debris flow and sheetflood deposition (Facies B1, C and C1) and is composed exclusively of relatively fine-grained, Moine granulite, gravelly detritus. This, only a few meters thick conglomeratic body represents probably a distal portion of a larger alluvial fan derived from the SE. The bimodal palaeocurrent distribution, recognized from the lowest portion of the Oldtown - Killin Rock Conglomerate at Killin Rock (Fig. 7.4.8) and the presence of the monomict beds composed exclusively of the Moine clasts and enveloped by the the polymict ("Moine & Granite") conglomerates suggest a temporary interfingering of two alluvial fans (or fan systems) which built out basinward from the opposite directions and dispersed distinctly different types of detritus. The small proportion of the Helmsdale granite and sporadic red sandstone clasts present in the Oldtown - Killin Rock Conglomerate at Killin Rock indicate a subordinate influx of the granitic detritus from the NE, corresponding probably to the development of the Fan 2 (Creag a' Bhodaich Conglomerate; see further in the text and Fig. 7.4.12.).

Cnoc Cragaidh Conglomerate

The around 100 m thick Cnoc Cragaidh Conglomerate composed mainly of Facies B1 and characterised by the unique features of the matrix (see chapter 7.4.5.1.1.), is represented as an individual alluvial fan body which built out through accumulation of cohesive debris flows, intervened by minor, sheet-wash reworking of the debris flow deposits and deposition of stratified sandy and gravelly beds of Facies C. The rapid increase in the proportion and size of the gravelly fraction in the middle part of the Cnoc Cragaidh unit (Fig. 7.4.1. & 7.4.2.), may reflect a tectonically, uplift-induced influx of the larger volumes of the coarser debris (Steel, 1976; Steel & Gloppen, 1980). The syndepositionally deformed deposits of Facies C (Plate 7.4.4.D) may suggest that fan deposits suffered an *en mass* remobilisation due to instability of the depositional slope (see also chapter 7.1.5.3.).

Creag a' Bhodaich Conglomerate

The examined section of the Creag a' Bhodaich Conglomerate is composed of debris flow, sheetflood and stream flow deposits (Facies B, C, C1 and C2 respectively) and hence it is interpreted as a product of accumulation of predominantly gravelly sediments in alluvial fan environment. The recognized vertical variability of clast composition as well as some of the rapid facies changes are interpreted in terms of stacking of three individual alluvial fan bodies, derived from distinctly different source terrains (Fig. 7.4.12.).

The lowest, over 20 m thick, part of the section is represented by the debris flow and the sheetflood fanglomerates of Facies B, C and C2, composed almost exclusively of Moine granulite detritus - Fan 1(Fig. 7.4.4.).

The gradual but relatively rapid upward increase in proportion and size of the Helmsdale granite detritus and the introduction of the red sandstone clasts (the latter most likely derived from the Glen Loth Formation) indicate an appearance of a new dispersal system - Fan 2, which might have coalesced with the Moine-derived Fan 1. Because of the lack of sufficient palaeocurrent data it is impossible to evaluate this notion and to determine whether the Fan 2 represents an entirely individual, new dispersal system draining the exposed deposits of the Glen Loth Formation, Helmsdale granite and the Moine rocks or for example two interdigitated fans - one draining the granite and the adjacent sediments of the Glen Loth Formation, the other one derived mainly from the Moine basement.

The available palaeoflow data indicate a general northward dispersal for both Fans 1 and 2, possibly initiated by the reactivated uplift along the Helmsdale fault. The recognized at Killin Rock in the Oldtown - Killin Rock Conglomerate minor proportion of the Helmsdale granite detritus and the sporadic red sandstone clasts would indicate the southward component of the latter dispersal system and marginal interfingering with the Oldtown-Killin Rock fan (Fig. 7.4.12.).

The Fan 2 developed mainly through deposition of gravels and minor sands from sheetfloods and stream flows of Facies C2. It comprises also in the lower part the sandstone beds of probable aeolian origin. The sequence is fining-upwards in the topmost part and this trend is accompanied by the transition into the sheetflood deposits of Facies C1, composed predominantly of Helmsdale granite detritus. The fining-upwards reflects probably a phase of recession of the alluvial fan sedimentation, associated either with backwearing of the source terrain or with a lateral shift of the depocentre, both resulting in reduction in competence of the depositing flows.

The topmost, over 100 m thick part of the section of the Creag a' Bhodaich Conglomerate consists entirely of the debris flow deposits of Facies B - Fan 3 (Fig. 7.4.4.). The latter fanglomerates have composition which is markedly different from the underlying deposits for they contain a substantial proportion of the vein granite clasts (which are absent below) and on the other hand they lack the Helmsdale granite and red sandstone clasts,which are abundant in the Fans 1 and 2.

No palaeoflow indicators are available from the Fan 3, although the clast composition - very similar to the one recognized in the Oldtown - Killin Rock and Cnoc Cragaidh units - justifies a speculation that the debris flow-dominated alluvial fan(-s) of the topmost part of the Creag a' Bhodaich Conglomerate might have been derived the west. (Fig. 7.4.12.).

The conglomerates of Fans 1 and 2 are finer-grained than the most of the other, previously described fanglomerates in the Golspie basin and contain the smallest proportion of the debris flow deposits. Hence, while these are seen as deposits of relatively distal sectors of the fans dispersing from the south, the overlying, debris flow-dominated Fan 3 represents the most proximal fanhead setting.

Alluvial fan geometry

Following the points made in the discussion in chapter 7.1.5.3. regarding alluvial fan geometry of the Beinn Lunndaidh Formation (BLF) it is thought that the debris flow-dominated alluvial fans of the Beinn Smeorail Formation (BSF), also fringing the western basin margin (Oldtown - Killin Rock, Cnoc Cragaidh fan, Fan 3 of the Creag a' Bhodaich Conglomerate) might have had steeper slopes than the the sheetflood- and stream flow-dominated Fan 2 of Creag a' Bhodaich Conglomerate and Socach Hill Conglomerate, dispersing from the S and SE. Consequently the former fans would have had a smaller radius (Bull, 1964; Hooke, 1968; Steel, 1976; Steel *et al.*, 1977; Gloppen & Steel, 1981). There are, however, no reliable independent data which could support these speculations. It also appears impossible to link the diversity in the sedimentary style of the fans of the BSF to a particular form of tectonic control. The Helmsdale fault as well as the faults along the western margin of the Golspie basin are high-angle to vertical. As it argued in the next chapter, similarily as in the case of the Beinn Lunndaidh Formation, aspects of textural evolution of of the BSF and their provenance highlight an alternative controlling factor.

7.4.5.5. Textural evolution and provenance of the Beinn Smeorail Formation

Similarily as in the case of the Beinn Lunndaidh Formation the textural evolution of the Beinn Smeorail Formation can be described in terms of two main models.

7.4.5.5.1. Debris flow, resedimented conglomerates - second cycle

The second-cycle scenario involves *en mass* resedimentation of the pre-existing, semi-lithified gravels and sands, which is manifested in the textural heterogeneity of Facies B and B1. The details of the proposed concept of textural evolution of the debris flow Facies B are fully applicable to the Oldtown - Killin Rock fan, Fan 1 and 3 of the Creag a' Bhodaich Conglomerate. They are discussed in the chapter 7.1.5.4. (see also Fig. 7.1.26.) and will not be repeated here. The main points of the concept are summarised below:

(1) The deposits of Facies B originated through resedimentation of pre-existing piles of gravels, considerably enriched in sandy fraction; the latter occurring either as separate beds or/and as matrix in the gravels. It is believed that these source sediments(possible earlier fan or fluvial depossits) had achieved some degree of lithification priŏr to the resedimentation associated with introduction of clays, iron-oxides and possibly caliche related carbonates.

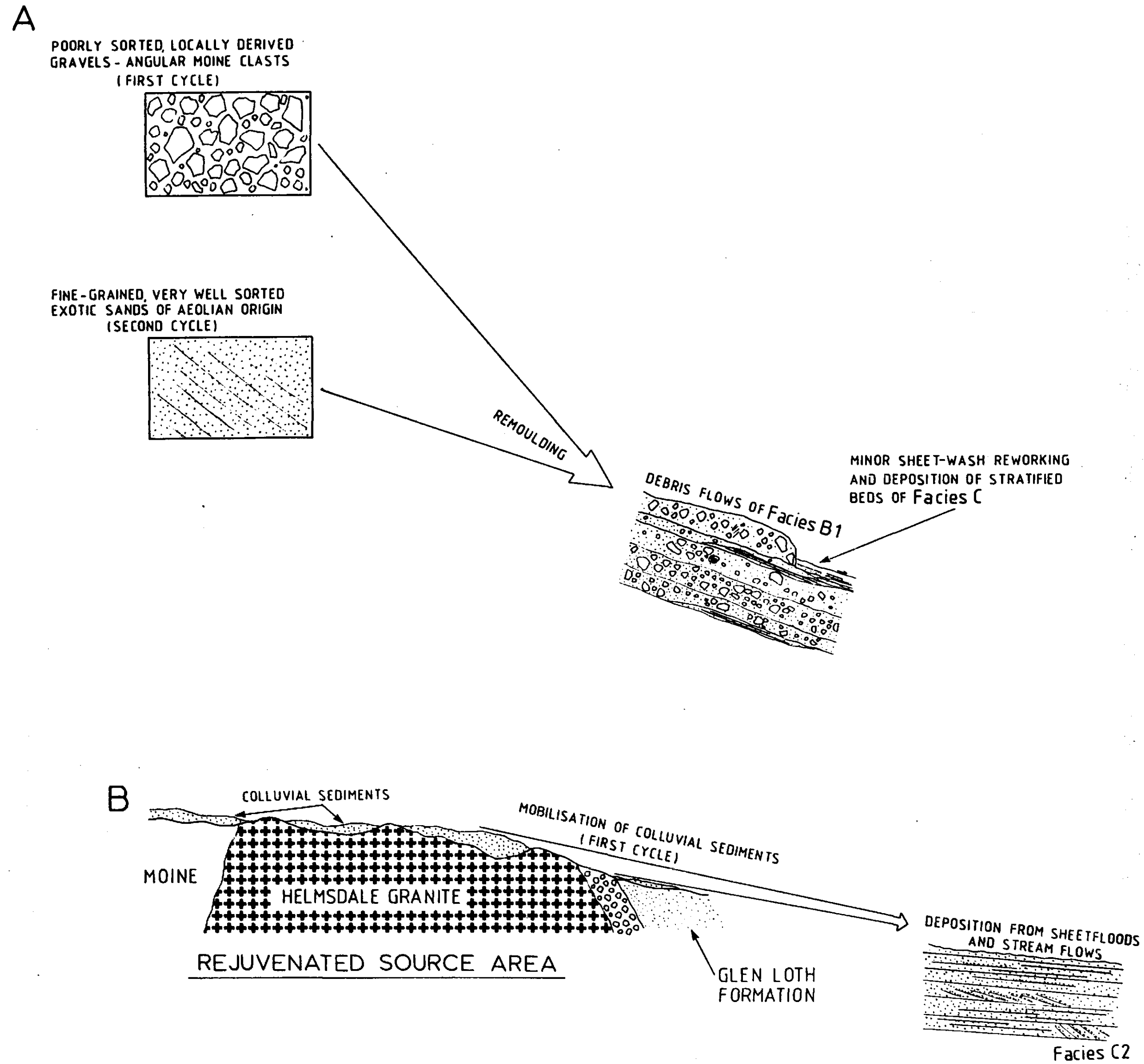
(2) The common bimodal textures and significant proportion of subrounded to well rounded Moine clasts also suggest that the early gravelly sediments undergone some size segregation and textural modification prior to the resedimentation.

(3) The abundance of angular clasts indicates a possible incorporation of the first-cycle colluvial sediments, derived from the weathered and penecontemporaneously denudated basement.

The development of the Facies B1-dominated Cnoc Cragaidh Conglomerate and Socach Hill Conglomerate demands a separate consideration for it appears to represent an extremely vivid case of resedimentation and mixing of two groups of sediments, which are entirely unrelated, in terms of texture and provenance.

In the texturally heterogeneous pebbly sandstones and matrix- to clast-supported

Figure 7.4.13. Diagrams depict main aspects of textural evolution of the debris flow deposits of Facies B1(Cnoc Cragaidh Conglomerate) (**A**) and the stream flow/sheetflood deposits of Facies C2 (Creag a' Bhodaich Conglomerate, Fan 2)(**B**). (compare with Fig. 7.1.26.)



A
POORLY SORTED, LOCALLY DERIVED GRAVELS - ANGULAR MOINE CLASTS (FIRST CYCLE)
FINE-GRAINED, VERY WELL SORTED EXOTIC SANDS OF AEOLIAN ORIGIN (SECOND CYCLE)
REMOULDING
DEBRIS FLOWS OF Facies B1
MINOR SHEET-WASH REWORKING AND DEPOSITION OF STRATIFIED BEDS OF Facies C
B
COLLUVIAL SEDIMENTS
MOBILISATION OF COLLUVIAL SEDIMENTS (FIRST CYCLE)
MOINE
HELMSDALE GRANITE
REJUVENATED SOURCE AREA
GLEN LOTH FORMATION
DEPOSITION FROM SHEETFLOODS AND STREAM FLOWS
Facies C2

conglomerates of Facies B1 the fine-grained, well-sorted sandstone matrix contains a significant proportion of well rounded grains and an appreciable percentage of the exotic, low-grade metamorphic, pelitic lithic fragments(PLF) of unknown provenance (Fig. 7.4.1. Plate. 7.4.2., see also chapter 7.4.5.1.1. & 7.4.5.2.). The poorly sorted gravel fraction on the other hand is represented by the high-grade Moine siliceous granulite and vein granite clasts.

It is thought that the cross-stratified sandstone horizon, of probable aeolian origin, being texturally and compositionally identical as the matrix in the overlying conglomerates (Fig. 7.4.1. & 7.4.2a.) represents a remnant of the source of the sandy matrix, preserved below the alluvial fan body. No such possible source of the matrix have been found in case of the Socach Hill Conglomerate nor in case of the Creag an Amalaidh Conglomerate (BLF).

Insufficient exposure of the Cnoc Cragaidh Conglomerate makes impossible to outline a possible palaeogeographic setting and circumstances for the processes of mobilisation and remoulding of the exotic sands and Moine gravels, except for that the mixed in various proportions sediments were deposited as debris flows in the alluvial fan environment (Fig. 7.4.13.). The absence of large boulders in Facies B1, which are normally commonly found in the fanhead sectors of the debris flow-dominated alluvial fan bodies in the Golspie basin, may suggest that the gravel fraction had undergone some limited reworking and size segregation prior to the resedimentation and remoulding with the "exotic" sandy material. The mixing of these diverse groups of sediments represent another case of the <u>fan-building related textural inversion</u>.

It appears clear that the generation of the debris flow-dominated fans of the BSF must have been to great extend if not entirely conditioned by the supply of abundant, pre-existing, relatively easily mobilised sediments. Tectonic scarps bounding the basin might have merely acted as a physiographic framework for the processes of resedimenatation of a wide range of sediments into the basin and as has already been mentioned in the previous chapter it is not clear whether the tectonic factor had any impact upon the diversity of the alluvial fan sedimentation of the BSF.

7.4.5.5.2. Sheetflood and stream flow - first-cycle conglomerates

The sheetflood and stream flow conglomerates of the Fan 2 (Facies C2, C1), recognized in the Creag a' Bhodaich Conglomerate (Fig. 7.4.4.) are texturally homogeneous - polymodal, clast-supported, with little sandy matrix. The rare, possible debris flow beds, appearing among the Facies C2 deposits of Fan 2 (Fig. 7.4.5b.) show no textural heterogeneity, the signature which is so distinctive of the debris flow conglomerates of Facies B and B1. Consequently the conglomerates in question are interpreted as a product of first-cycle alluvial fan sedimentation in response to the rejuvenation of the source terrain - Helmsdale porphyritic granite, possibly also incluiding the Moine rocks, with adjacent lithified deposits of the Glen Loth Formation and the Beinn Lunndaidh Formation ?(Ousdale Arkose Conglomerate) (Fig. 7.4.13.). Alternatively, assuming the scenario of the Fan 2 having formed in result of interfingering of the fans derived from the distinctly different drainage areas, the granulite debris might have been brought through by an independednt dispersal system draining the Moine basement. The latter fan is possibly represented by the Moine clasts-dominated Fan 1.

The abundant in the Fan 1 deposits of Facies B suggest that a substantial proportion of the Moine detritus might represent a second-cycle resedimented material.

It is thought that in the circumstances of the first-cycle sedimentation, similarily as in the case of the Ousdale Arkose Conglomerate (see chapters 7.1.5.3.), the limited volumes of the source debris(colluvium) with insignificant proportion of the finer-grained fractions(sand and smaller) could not facilitate mass flow sedimentation, and hence are regarded as key factors promoting the sheetflood/stream flow style of the alluvial fan sedimentation.

Significance of the tectonic factor, with regard to the aspect of such an "subtle" variability in the depositional processes on the alluvial fans in the Golspie basin remains unknown.

7.5. Col-bheinn Formation (CbF)

7.5.1. Introduction

The Col-bheinn Formation consists mostly of sandstones and forms the topmost part of the upper, Middle Old Red Sandstone group of the infill of the Golspie basin (Fig. 6.2.). This lithostratigraphic unit is termed *"Flaggy Sandstones of Col-bheinn and Meal Coire Aghaisgeig"* in Read *et al.* (1925). The formation is regarded as a lithostratigraphic equivalent of the Berriedale Sandstone Formation and Berriedale Flagstone Formation (Read *et at.*, 1925; Mykura, 1983) (Fig. 6.1.), which are present in the Badbea basin and the Braemore basin (Fig. 7.2.22.). The two latter units appear under names *"The Berriedale Sandstones and Flagstones"* in Crampton *et al.* (1914).

Mykura (1983a) designated the deposits in question as a formal lithostratigraphic unit "Col-bheinn Formation" after name of the summit in the central part of the Golspie basin (Fig. 3.3.).

7.5.2. Distribution and thickness

The near horizontal sandstones of the Col-bheinn Formation occupy the central part of the Golspie basin, comformably overlying the conglomerates of the Beinn Smeorail Formation. The sandstones form mountain masses of Col-bheinn (Plate 7.4.1.A) and Meall Coire Aghaisgeig (Read *et al.*, 1925). In the SW the formation is in the NW-SE trending fault contact with the conglomerates of the Beinn Lunndaidh Formation. It also appears to be faulted over a short distance against the sandstones of the Glen Loth Formation(Beinn a' Bhragaidh Member)

Thickness of the Col-bheinn Formation is around 260 m but its top is not seen and the deposits probably were originally much thicker.

Abundant blocks of Caithness flagstones are present in the Upper Jurassic (Kimmeridge) "Boulder Beds" exposed on the shore east of Helmsdale fault as far south as Lothbeg Point (Fig. 3.3.) (Bailey & Wair, 1932; Crowell, 1961; Neves & Selley, 1975; Selley, 1976; Lam & Porter, 1977; Friend & Williams, 1978; Hurst, 1981; Pickering, 1983). It suggests that in the northern part of the Golspie basin the higher part of the upper, Middle Old Red Sandstone group originally consisted of Caithness Flags (Mykura, 1983a).

7.5.3. Lower boundary

The sandstones of the Col-bheinn Formation are in a rapidly gradational contact with the underlying conglomerates of the Beinn Smeorail Formation. The transition is well exposed at Leadoch Rock and at Duchary Rock (Fig. 7.4.11., 7.5.1.; 7.5.2.; see also chapter 7.5.4.4.1.).

The deposits of the Berriedale Flagstone Formation and Berriedale Sandstone Formation are also in a transitional relationship with the underlying conglomerates of Badbea Breccia and Morven, Smean and Maiden Pap Conglomerate (Fig. 7.2.22.). Total thickness of the latter sandstones is 450 m.

7.5.4. Sedimentary characteristics of the Col-bheinn Formation

Introduction

The deposits of the Col-bheinn Formation are generally very poorly exposed and only outcrops south of Loch Brora (sections from Leadoch Rock and Duchary Rock) give some insight into the facies characteristics of the lowest part of the formation. Fragmentary, small exposures, scattered on the SW and NE slopes of Meal Coire Aghaisgeig and Cagar Feosaig and on the SW slope of Col-bheinn yield some palaeotransport data(cross-strata orientations), and offer a very crude picture of facies present in the upper portion of the Col-bheinn Formation. No distinctly new facies have been recognized among the deposits in question.

7.5.4.1. Leadoch Rock and Duchary Rock sections

Description

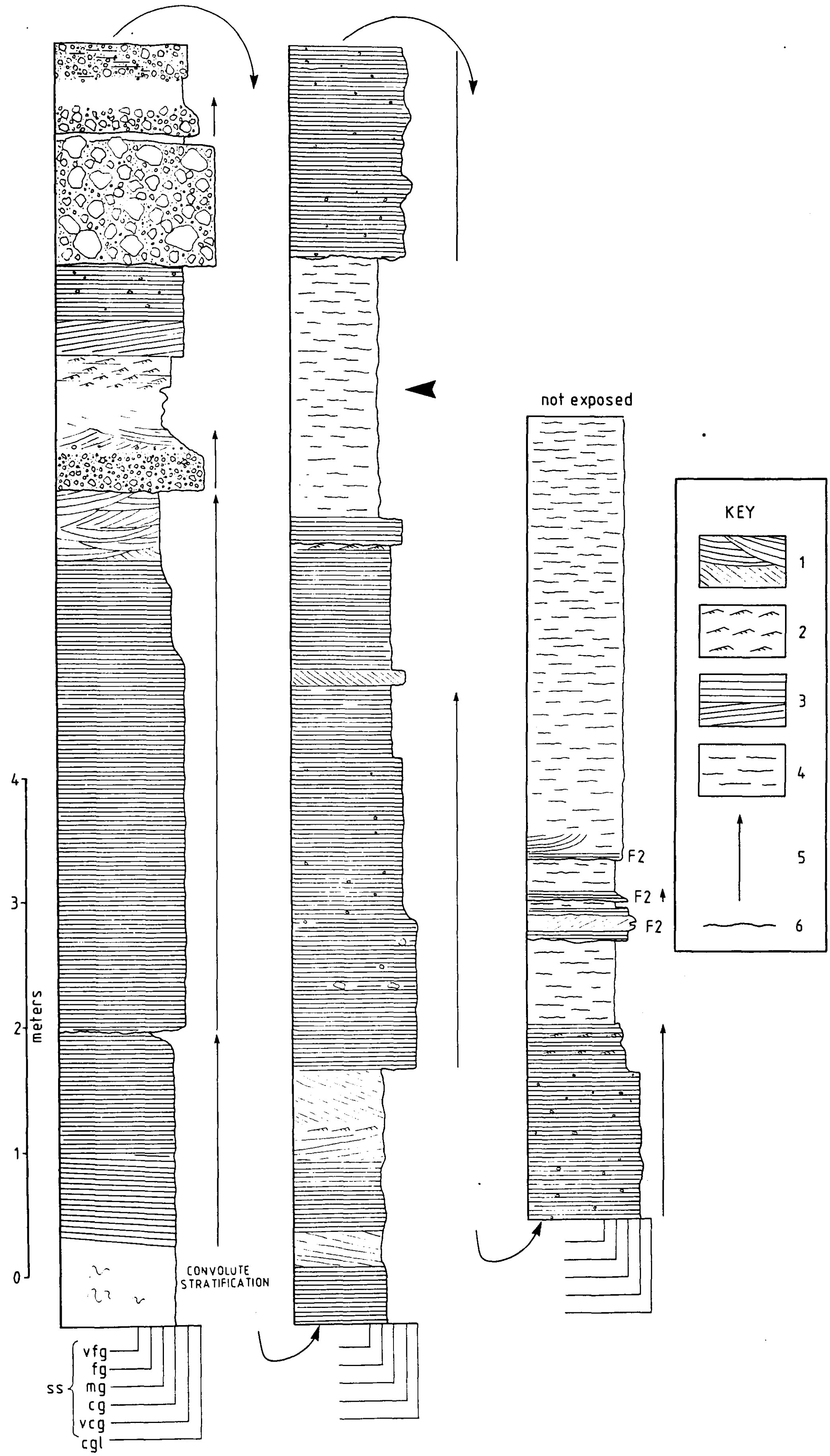
The lowest 30 m the Col-bheinn Formation is exposed at Leadoch Rock and at Duchary Rock (Fig. 7.5.1. & 7.5.2; Plate 7.5.1.). It is in the majority represented by planar-stratified(occasionally seen parting lineation) and low angle cross-stratified sandstones. They are predominantly coarse- and very coarse-grained, poorly sorted, commonly with scattered angular granite and granulite pebbles. The sandstones contain negligible amount of clay fraction. Trough cross-stratified beds are rare.

The planar-stratified deposits are organised into generally well defined, sheet-like, flat erosionally-based beds. Their lateral extend exceeds probably 100 m. The recognized individual beds range in thickness from 0.0 - 3 m and often display fining-upwards(or normal grading). The planar-stratified, sheet-like beds closely resemble the sandstones described in the assemblage of Facies G2(chapter 7.2.6.1.15. & Plate 7.2.21.B).

The accompanying conglomerates appear as structureless and crudely planar- to cross-stratified, poorly sorted beds. They are rare in spite of vicinity of the contact with the Oldtown - Killin Rock Conglomerate(BSF).

Cross-strata orientation data from this part of Col-bheinn Formation indicate

Figure 7.5.1. Graphic log of the section from Leadoch Rock. The arrow points to the Facies F1 "marker bed", present also at Duchary Rock (350 m SSE of Leadoch Rock (see also Fig. 7.5.2.)). Lower part of the section is dominated by planar-stratified sheetflood deposits, which formed at the toe of the Oldtown - Killin Rock Fan (see also Plate 7.5.1.). **KEY**: (**1**) cross-stratification; (**2**) current ripple cross-lamination; (**3**) planar-stratification and low angle cross-stratification; (**4**) structureless/shear-layered muddy sandstones of Facies F1. (**5**) fining-upwards (or normal grading). The fine- to coarse-grained, stratified deposits associated with Facies F1 are regarded as Facies F2 (marked).


not exposed
KEY
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2
3
4
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6
F2
F2
F2
4
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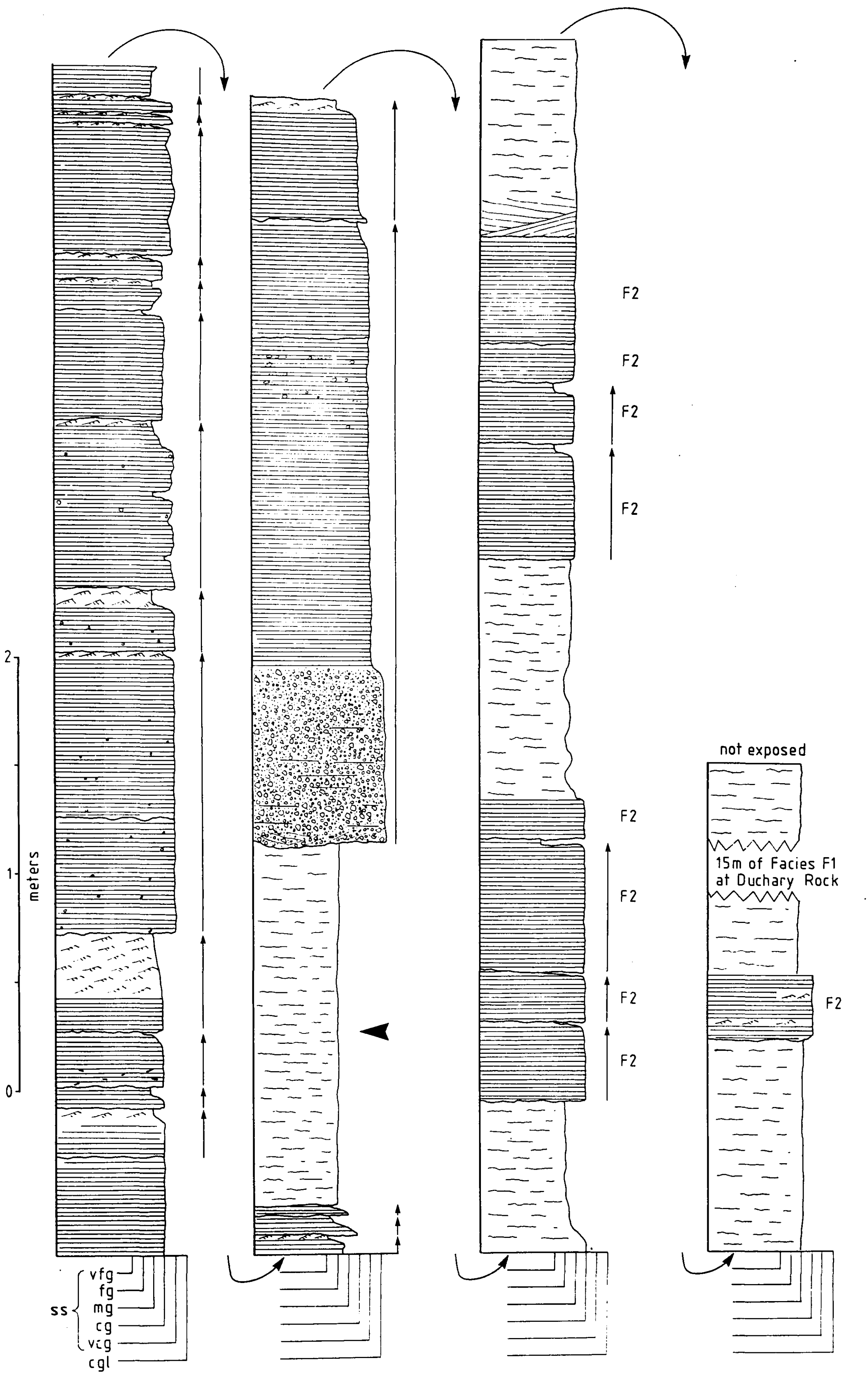
0
meters
CONVOLUTE STRATIFICATION
ss
vfg
fg
mg
cg
vcg
cgl

Figure 7.5.2. Graphic log of the section from Duchary Rock - lateral equivalent of the section from Leadoch Rock (Fig. 7.5.1.). The arrow points to the Facies F1 marker bed. For explanation see Fig. 7.5.1. (see also Plate 7.5.1.).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F2
not exposed
15m of Facies F1
at Duchary Rock
F2

palaeotransport to the SW, which is generally consistent with the palaeodispersal of the subjacent Oldtown - Killin Rock Fan (Fig. 7.4.11.).

In the upper portion of the discussed sections(Leadoch Rock & Duchary Rock) the planar-stratified, coarse-grained sandstones are rapidly replaced by texturally heterogeneous, structureless to shear-layered sandstones of Facies F1 (see chapter 7.2.4.1.7.). They are fine- to medium-grained, well sorted with regard to the sand fraction and contain an appreciable amount of clay matrix (17 - 20%).

The deposits of Facies F1 deposits are intervened in places by fine- to coarse-grained, planar- stratified and cross-stratified sandstone beds of Facies F2.

The deposits of both facies occur as laterally extensive, parallel-sided sheets (Fig. 7.2.20.). In approximately middle part of the studied sections one isolated bed of Facies F1 appears sandwiched in between the planar-stratified pebbly sandstones and coarse-grained sandstones (Fig. 7.5.1. & 7.5. 2.). It is continuous for at least 400 m. A few meters above, Facies F1 is clearly dominant and appears in units 0.1 - 5 m(minimum) thick, which most likely represent amalgamated beds (see also chapter 7.2.4.1.7.). In the area of Leadoch Rock and Duchary Rock the Facies F1-dominated portion of the Col-bheinn Formation has approximate thickness of 45 m.

7.5.4.2. Upper part of the Col-Bheinn Formation

Description

The remaining, major portion of the Col-bheinn Formation is very poorly exposed on the SW and the NE slopes of Meal Coire Aghaisgeig and Cagar Feosaig and also on the SW slopes of Col-bheinn (Plate 7.4.1.A). The sandstones are mainly medium- to very coarse-grained with occasional conglomeratic interbeddings, and appear to be predominantly trough cross-stratified. Planar-stratified and ripple cross-laminated sandstones have also been found. In a few sites the sandstones have been recorded to be arranged in fining-upward units with scour- or trough-like bases and a few centimeters thick conglomeratic lag deposits at the very bottom. The trough cross-strata orientations from three localities yield a consistent NE-NNE palaeodispersal (Fig. 7.5.3.). While the

Plate 7.5.1. Photograph of the NE face of Duchary Rock. The arrows point to the marker bed of Facies F1 (see Fig. 7.5.2.). Sheetflood deposits appear well defined above and below the marker horizon. Massive, sandy debris flow deposits of Facies F1 dominate the topmost part of the section.

Plate 7.5.1.

majority of the infills of the Golspie basin are brown-red in colour, the sandstones of the topmost part of the Col-bheinn Formation, exposed at Col-bheinn are cream-white (absence of iron-oxide pigment). North-east of Meall Coire Aghaisgeig Read *at al.* (1925) report a "thin bed of greenish shale with *Ptilophyton*?" (see geological map 1: 63 360, sheet 103). The latter deposits have not been found by the present author.

7.5.4.3. Petrographic features of the sandstones of the Col-bheinn Formation

The sandstones of the Col-bheinn Formation range from lithic to sublithic arenites (Fig. 7.5.3.). The rocks are mostly medium- to very coarse-grained and poorly sorted. The grains are predominantly angular and subangular, though there locally appears a noticeable fraction of subrounded to well rounded clasts (Fig. 7.5.3.). Feldspar grains seem to show slightly better roundness.

The rock fragments are represented by granite, granulite and two-mica schist. The low-grade pelitic lithic clasts(phyllite, chert, quarzite - PLF) are either absent or appear in trace proportions. Micritic and sparry calcite, mudstone and sandstone clasts (intraclasts?) have locally been recorded. Muscovite is present in proportions between 0.0 - 4.7% (av.1.7%). Biotite, typically considerably altered to iron-oxide and clay, and detrital chlorite appear in trace amounts.

K-feldspar grains (mostly orthoclase and subordinate microcline) 17.5 - 3.7%(av.11.3%) of the detrital grains. Plagioclase(albite - oligoclase) appear in proportions ranging from 0.0 - 3.1%(av.1.2%). The K-feldspars are represented by a mixture of fresh and weathered grains. Quartz occurs mainly as a monocrystalline variety. Polycrystalline grains appear in trace fraction.

Magnetite and garnet are most common among trace constituents. Apatite, rutile, zircon, spinel have also been recorded.

It is important to note that there appear to be no significant petrographic differences between the deposits of Facies F1 and F2 the surrounding sandstones of the Col-bheinn Formation (Fig. 7.5.3.).

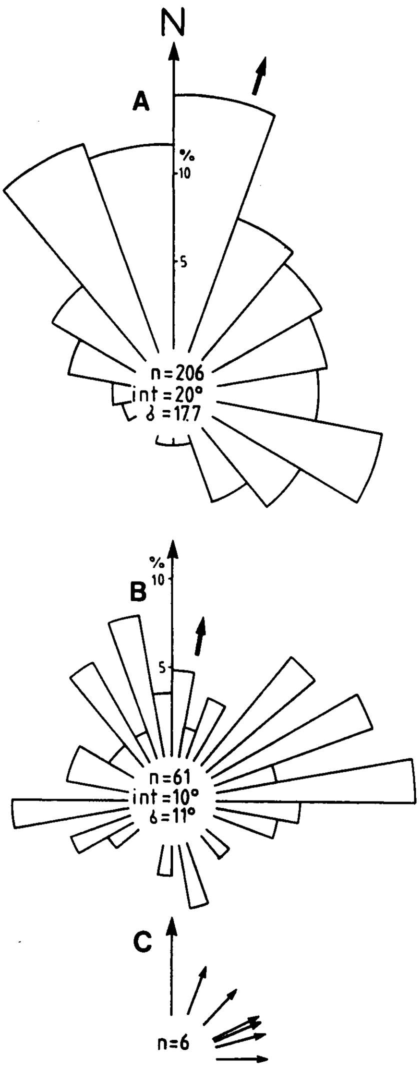
Figure 7.5.3. Rose-diagrams show data of cross-strata orientation from the Col-bheinn Formation.

A: SE slope of Cagar Feosaig [NH 879 075];

B: SE slope of Col-bheinn (An Dubh-Iochan);

C: SW slope of Col-bheinn [NH 880 099].

Three-components diagram on the right summarises petrographic composition of the sandstones of the Col-bheinn Formation. Localities: **1** - SE slope of Cagar Feosaig; **2** - [NH 880 099]; **3** - SW slope of Col-bheinn (An Doubh-Iochan); **4** - Duchary Rock (Facies F1 & F2); **5** - NE slope of Cagar Feosaig (upper, "stream flow" part of the formation). The petrographic classification of sandstones is after Pettijohn *et al.* (1973). The histograms below display results of roundness estimations for the point-counted sandstone samples (the encircled numbers correspond to the numbers in the composition diagram above). Roundness scale after Powers (1953): **1** - angular, **2** - subangular, **3** - subrounded, **4** - rounded, **5** - well rounded.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int=20°
δ=17.7
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n=61
int=10°
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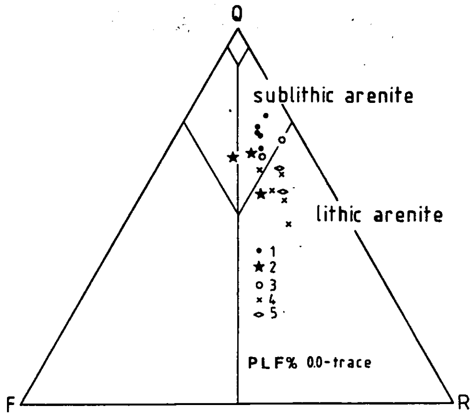
n=6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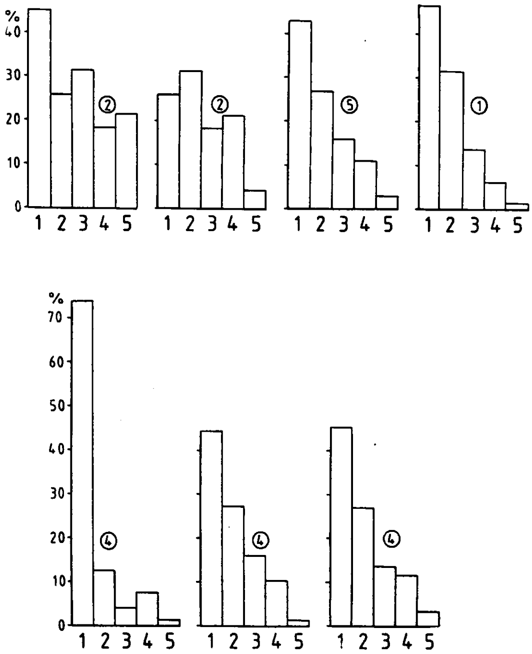
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0
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④

The subordinate conglomeratic interbeddings contain angular and subangular clasts of Moine silliceous granulite, vein granite, aplite and vein quartz.

Similarly as in the case of the remaining underlying deposits of the Golspie basin, in the sandstones of the Col-bheinn Formation authigenic quartz(overgrowths) is a prominent form of cement. It constitutes 2.8 - 27.5%(av.14.4%). K-feldspar overgrowths are ubiquitous throughout the formation, though appear most abundant (up to 2.8%) in the topmost (cream-white in colour) portion of the sequence, exposed at Col-bheinn. The latter part of the formation is also characterised by presence of authigenic muscovite and chlorite. The former often appears also as spherulitic or variolitic aggregates.

Sparry calcite cement has been found only locally (in 5 samples out of 17) in range of 5.3 - 10.3%(av.7.3%). It post-dates the formation of the quartz cement and feldspar overgrowths, typically replacing both, the detrital host grains and the overgrowths. Proportion of the interstitial iron-stained clay, occurring mainly as uneven coatings on the grains, varies between 1.5 - 20.5% (av. 8.8%). The clay material is most abundant in the deposits of Facies F1 (16.8 - 20.5%).

7.5.4.4 Sedimentary environment of the Col-bheinn Formation

7.5.4.4.1 Leadoch Rock and Duchary Rock sections

The sheet-like, parallel-sided beds of planar-stratified sandstones and pebbly sandstones, which dominate the lowest, 30 m of the Col-bheinn Formation (Leadoch Rock and Duchary Rock) are interpreted as a product of deposition from unconfined, high-energy(upper flow regime) **sheetfloods** (Bull, 1977; Nemec & Muszynski, 1982; Blair, 1987a,b; see also chapter 7.2.6.1.15. for a possible analog).

It appears very likely that these non-channaelised flows operated at the toe of the Oldtown-Killin Rock alluvial fan(or fan system), which was dispersing from the north. Consequently the sheetfloods would represent a distal depositional response to the debris flow activity, which dominated the main, more proximal sectors of the fan (Fig. 7.4.11.) (Blair, 1987a; Nemec & Muszynski, 1982; Wasson, 1977). Rare, massive to crudely stratified conglomerate beds, accompanying the sheetflood deposits (Fig. 7.5.1.), are indentical to the fanglomerates outcroping below, and probably represent catastrophic incursions of the sandy fan toe sector by coarse gravelly debris flows and hyperconcentrated gravelly flows, which might have been distally transitional to the sandy sheetfloods.

Rapid, upward transition from fanglomerates into sheetflood sandstones reflect either sudden cease of the alluvial fan outbuilding or/and dramatic abandonment fan lobe (Steel, 1976; Steel *et al.*, 1977; Heward, 1978).

The discussed lowest, 30 m thick portion of the Col-bheinn Formation represents the distal, sheetflood-dominted sector of the alluvial fan with insignificant tendencies towards development of rill flows (confined or post-sheetflood, re-confined flows). This is indicated by the absence of scours and larger channels as well as by the scarcity of the cross-stratification (Fig. 7.5.1. & 7.5.2.). With regard to the latter aspect the discussed deposits differ from the assemblage of Facies G2, which does contain channel-fill complexes, incised into the sheetflood beds (Plate 7.2.21.B).

The interpreted herein sheetfloods must have been been relatively ephemeral events of rapidly declining competence and flow regime. They deposited widely ranging in thickness planar-stratified beds with only locally preserved current ripple cross-laminated, finer-grained cappings. The latter subordinate deposits are a record of wanning flow stage(lower flow regime) accumulation.

In the light of the interpretation, presented in chapter 7.2.6.1.9., the structureless to shear-layered, muddy sandstones of Facies F1, appearing rapidly above the alluvial fan-related sheetflood deposits (Fig. 7.5.1. & 7.5.2.), represent product of deposition from **sandy debris flows**. The mass flows are thought to have been been characterised by active cohesive strength and by essentially laminar flow conditions. The associated, subordinate deposits of Facies F2 appear much less common than in case of the sequence of the Ben Uarie Member from Ben Uarie and Beinn Dhoràin (Fig. 7.2.16.). These planar-stratified and cross-stratified, sheet-like beds are seen as a result of deposition from unconfined to broadly confined **sheetfloods** (McKee *et al.*, 1967; Scott *et al.*, 1969; Williams, 1970; Tunbridge, 1981a,b), which operated between or concurrently with the sandy debris flows, reworking their deposits. According to the reasoning laid out in the chapter

7.2.6.1.10. Facies F1 & F2 formed in a subaerial environment.

However, fitting the outlined above interpretation of Facies F1 and F2 (the former in particular) into the overall palaeoenvironmental context, encounters serious difficulties. The dominant, sandy debris flow Facies F1 appears texturally as well as structurally unrelated to the adjacent coarser grained sandstones and pebbly sandstones. The fine- to medium-grained, muddy, though well sorted with regard to the sand fraction, sheets of Facies F1 contain no coarser detritus, even in the place where occur sandwiched between the coarser, often pebbly, poorly sorted, non-argillaceous sheetflood beds (Fig. 7.5.1. & 7.5.2.). This is except for sporadic scattered grains of maximum granule grade (Plate 7.2.19.B). Consequently it seems highly improbable for the sandy debris flows to have mobilised in the same source area as the sheetfloods, that is on the alluvial fan surface. Note that the formation of around 45 m thick package of mostly Facies F1 did require an abundant supply of previously segregated, semi-lithified, interbedded sands and muds, which once mobilised *en mass*, could generate the texturally heterogeneous sandy mass flows (e.g. Plate 7.2.17.).

In terms of structure the sandstones of Facies F2 do strongly resemble the underlying sheetflood deposits. Texturally, however, they appear somewhat different, being well sorted, with no coarser detritus(in spite of their upper flow regime characteristics). They also occur in close association with the units of Facies F1. Consequently, taking into account the textural features of Facies F2 and its position in the studied sections, it might be genetically related to the sandy debris flow deposits of Facies F1, being to some extent a product of their reworking (see also chapter 7.2.6.1.10.).

For the Moine siliceous granulites and the associated granite veins make up the basement on both sides of the Golspie basin (though in different proportions), the presence of similar rock fragments in the sandstones of Facies F1 and F2 does not serve as sensitive enough indicator of their provenance. Unfortunately, no meaningful palaeotransport indicators are available form these deposits, which could help to elucidate the problem of their origin. Consequently, the palaeoenvironmental context of Facies F1 and F2 in the discussed section of the Col-bheinn Formation(Leadoch Rock and Duchary Rock) as well as their provenance remain unknown.

7.5.4.4.2. Upper part of the Col-bheinn Formation

Very poor exposure of the main, upper portion of the Col-bheinn Formation allows only to conclude that the predominantly cross-stratified sandstones and subordinate conglomerates, organised locally into fining-upward units, most likely represent **stream flow deposits**. The inferred, corresponding NE-NNE (Fig. 7.5.3.) palaeotransport accords with the general NE palaeodispersal during the Middle Old Red Sandstone fluvial sedimentation south of the Golspie basin (Tarbat Ness - Black Isle, Fig. 3.3.; Armstrong, 1977; Mykura, 1983a). The angular to subangular clasts of siliceous granulite and vein granite, present in the conglomeratic interbeddings, together with the analogous rock fragments present the sand fractions, point to the Moine-dominated basement rocks as the source terrain.

7.6. Development of the Golspie basin during the sedimentation of the Beinn Smeorail Formation and the Col-bheinn Formation - Summary

The sedimentation of the Beinn Smeorail Formations (BSF) was preceded by a phase of local folding and erosion of the lower group of the infill of the Golspie basin (Read *et al.*, 1925). The resulting angular unconformity is most pronounced along the basin margins (Carrol Rock, Oldtown, Allt Smeorail and Creag a' Chrionaich). The corresponding unconformities are also apparent in the Badbea basin and in the Braemore basin. According to Mykura (1983b) the penecontemporaneous Middle Old Red Sandstone faulting, folding and thrusting took place in the Inverness-shire (Foyers area). The thrusting and folding, affecting the Lower Old Red Sandstone deposits in the Mealfuarvonie area (Mykura & Owens, 1983) and at Struie (Armstrong, 1964, 1977) may correspond to the compressional/transpressional events in the Foyers area directed NW-SE (Mykura & Owens, 1983; Mykura, 1983a).

In terms of environment of sedimentation the development of the BSF resembles the general palaeogeographic scenario of the Beinn Lunndaidh Formation. While in response to the rejuvenation of the source terrains the debris flow-dominated alluvial fans formed along the western margin of the basin (Oldtown - Killin Rock Cong., Cnoc Cragaidh Cong., Fan 3 of the Creag a' Bhodaich Cong.) the sheetflood/stream flow Fan 2 of the Creag a' Bhodaich Conglomerate developed at the eastern margin.

There is no evidence for the postulated Middle Old Red Sandstone "large rivers" (Mykura, 1983a, fig. 8.13) flowing from the W and SW in the region of the Golspie basin.

Contrary to the period of the BLF sedimentation, during which the thickest conglomeratic deposits formed in the south (Mound Rock area), the depocenter of the BSF was located in the northern sector of the basin (Creag a' Bhodaich area) (Fig. 7.4.12.).

A new element in the development of the Golspie basin during the BSF sedimentation was the westward and south-westward component of the palaeodrainage, identified from the Socach Hill Conglomerate and from the Oldtown - Killin Rock Conglomerate at Killin Rock. The recognized also at Killin Rock minor proportion of the Helmsdale granite detritus and the sporadic red sandstone clasts suggest that a southward component of the dispersal system of the Fan 2 (Creag a' Bhodaich Cong.), interfingered distally with the S-SE propagating Oldtown - Killin Rock fan and with the N-NW dispersing Socach Hill fan.

The westward component of the palaeodispersal indicates that during the BSF sedimentation the Golspie basin was at least temporarily isolated from the east.

The debris flow-dominated alluvial fans (Oldtown - Killin Rock Cong., Cnoc Cragaidh Cong., and Fan 3, Creag a' Bhodaich Cong.), fringing the western margin of the basin, originated through *en mass* mobilisation of the previously accumulated in the drainage area vast volumes of gravels and sands of variable provenance. The source sediments had undergone a variety of reworking and clast segregation prior to the second-cycle mobilisation and the debris flow deposition. Some of the source sediments (i.e. the exotic matrices from the Cnoc Cragaidh and Socach Hill units) have an *ultimate*, enigmatic provenance unlike the accompanied, locally derived gravel fractions.

The first-cycle Helmsdale granite and Moine detritus together with the sandstone clasts derived from the eroded sediments of Glen Loth Formation, were deposited primarily from the sheetfloods and the stream flows building up the Fan 2 of the Creag a' Bhodaich Conglomerate.

The fining-upward passage of the BSF into the sandstones of the Col-bheinn Formation reflects a phase of widespread recession of the alluvial fan sedimentation. At Leadoch Rock and Duchary Rock (Fig. 7.5.1. & 7.5.2.) the only exposed transitional section is represented by the sandstone sheetflood deposits which formed at the toe of the retreating Oldtown - Killin Rock fan.

The palaeoenvironmental context of the around 45 m thick pile of the massive to shear-layered sandy debris flow deposits of Facies F1 and the associated sheetflood beds of Facies F2 remains unsolved. It is primarily for the lack of palaeocurrent data as well as for the absence of diagnostic petrographic signatures.

The upper part of the Col-bheinn Formation is extremely poorly exposed, but the small scattered exposures suggest that the sandstones and the subordinate conglomerates formed in a fluvial system, dispersing to the NE and draining mostly the Moine-dominated terrain.

8. Tectonic control of the development of the Orcadian basin

The Golspie basin represents an integral, small component of the prominent structure of the Orcadian basin and therefore the aspect of the tectonic control over its development has to be discussed in the context of the entire Orcadian basin.

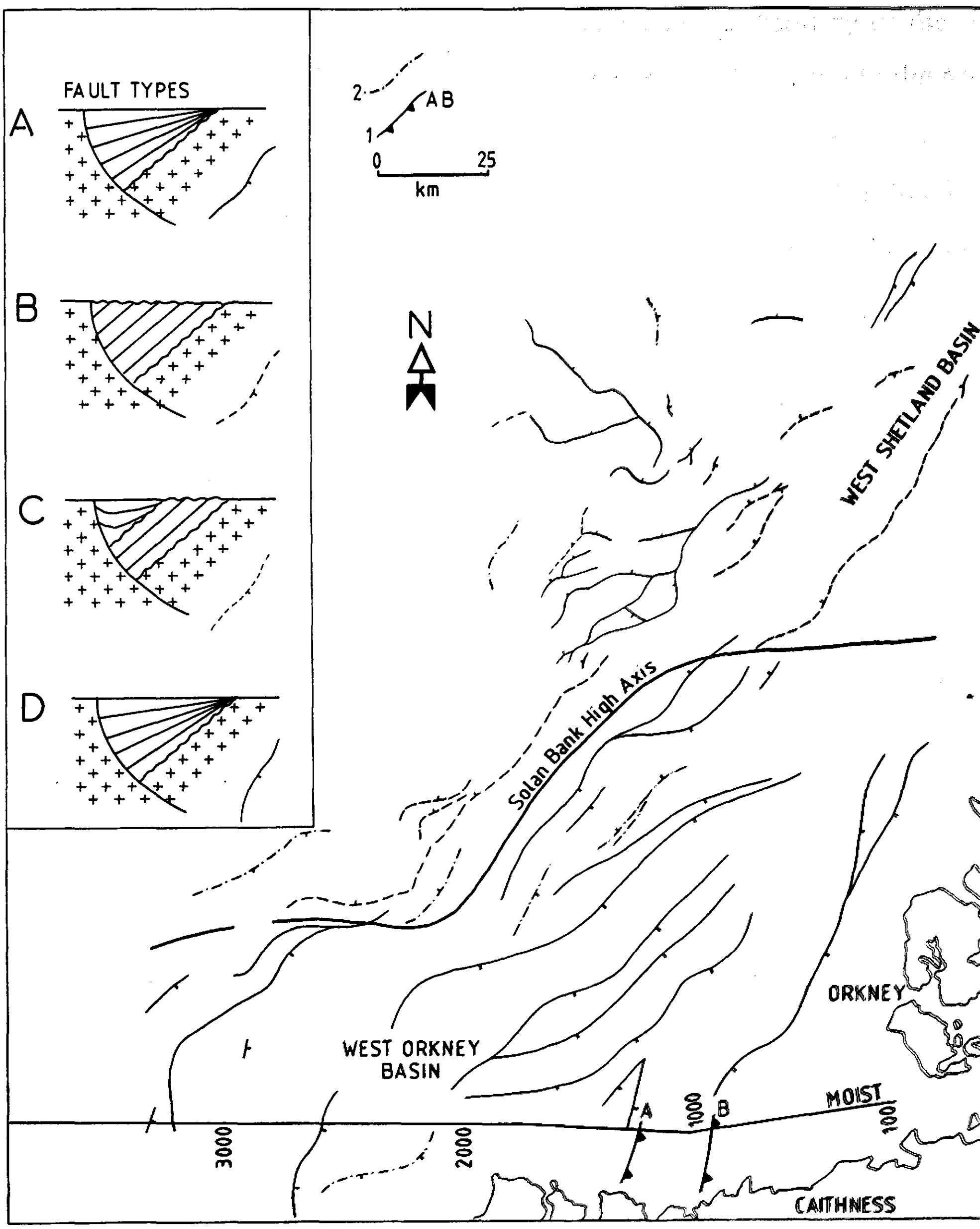
Anderton *et al.* (1979), Leeder (1982) and Mykura (1983a) regard the Old Red Sandstone infills of the Orcadian basin as an example of internal molasse (Allen *et al.*, 1967; Miall, 1978). Anderton *et al.*, 1979 see strong similarities between the Orcadian basin and the basins flanking the Alpine-Pyrenean orogens, the Siwalik Basin in the Himalayas and intra-Cordilleran molasse basins in the Chilean-Bolivian Andes.

For it is estimated that during the Caledonian orogeny in the Northern Highland 21.5 - 30 km of crust had been eroded prior to the initiation of the Orcadian basin, and because consequently the non-marine Old Red Sandstone facies were deposited on the Caledonian lower crust (Soper & Barber, 1982; Blundell, 1984; Blundell *et al.*, 1985; Watson, 1985) the Orcadian basin should be seen as a post- or late-orogenic rather than as a syn-orogenic (molasse) basin (Watson, 1985; see also Steel *et al.*, 1985).

At the end of Silurian penetrative ductile deformation gave way to inhomogeneous deformation and ultimately to block movements. The main fracture/fault systems of the Highlands were established during the late-orogenic period (Watson, 1984).

At present the regional tectonic regime, responsible for the formation of the Orcadian basin is viewed in two distinctly different ways. A direct association of the formation of the Orcadian basin with strike-slip movements of the Great Glen Fault has been indicated by Mykura & Phemister(1976), Smith & Watson(1983), Mykura(1983b), Mykura & Owens(1983), Leeder (1982), Watson (1984,1985) and Trewin (1985). McClay *et al.* (1986), on the other hand, draw an analogy between the the tectonic setting of all Old Red Sandstone basins in Scotland, Norway and Greenland and the mid-Tertiary evolution of the Basin and Range Province in the western United States. Extension is seen as a direct consequence of the collapse of the overthickened Caledonian crust (see also Beach, 1985, p.497). Astin (1985) considers that active extensional faulting controlled the sedimentation in the Middle Old Red Sandstone Eday Group (Orkney) and that the episode of Devonian

Figure 8.1. Map of the West Orkney basin showing fault types. Fault positions shown at top Basement level (after Kirton & Hitchen, 1987). **A** - Permo-Triassic wedges at "surface". Caledonian thrusts subsequently relaxed during the Permo-Triassic (or possibly earlier). Found to the SE of the Solan Bank Axis; **B** - Parallel bedded Permo-Triassic at "surface". Faulting initiated during or after Permo-Triassic. Permo-Triassic outside half-graben removed by erosion. Found to the NW of the Solan Bank High Axis; **C** - Parallel bedded Permo-Triassic in bottom of half-graben. Faulting initiated during or at the end of the Permo-Triassic with Permo-Triassic outside half-graben being removed by erosion. Further infill of half-graben by Mesozoic sediments. Only One example found; **D** - Middle Jurassic wedges on Basement. Growth faulting initiated in Middle Jurassic.**1** - possible positions of Moine Thrust (after Brewer & Smythe, 1984); **2** - age of the initial fault movement uncertain.


FAULT TYPES
A
B
C
D
2
1
AB
0
25
km
N
WEST SHETLAND BASIN
Solan Bank High Axis
WEST ORKNEY
BASIN
ORKNEY
MOIST
A
B
3000
2000
1000
100
CAITHNESS

extension gave rise to the present structure of the Orkneys. Enfield and Coward(1986,87) argue that the Old Red Sandstone basins of northern Scotland formed in result of either regional crustal extension or thinning due to relaxation of an originally thick Caledonian orogenic belt.

As far as the "extensional models" are concerned the recognition of the listric fault geometries, associated with the "Old Red Sandstone" basins is central to the McClay's *et al.*(1986) analogy with the Basin and Range and to the Astins's (1985) and Enfield and Coward's (1986,87) proposals. Conviction of McClay *et al.* (1986) and Enfield and Coward (1986,87) that the half-grabens bounded by easterly dipping listric faults in the West Orkney basin (Fig. 3.2. & 8.1.) (Brewer & Smythe, 1984; Enfield & Coward, 1987; Kirton & Hitchen, 1987; Cheadle *et al.*, 1987) contain Devonian sediments has not been substantiated so far. Unequivocal Devonian deposits of the Orcadian basin seen on the eastern end of MOIST profile are acoustically transparent and distinct from the "seismically layered" infills of the half-grabens seen further to the west (Brewer & Smythe, 1984). Consequently, the age of the listric faults observed in the seismic profiles remains uncertain. These may well be Permo-Triassic or Jurassic structures (Kirton & Hitchen, 1987) (Fig. 8.1.). North of the Solan Bank High axis the half-grabens are filled with Permo-Triassic and Middle Jurassic sediments (Kirton & Hitchen, 1987). Also the Minch basin to the west and Moray Firth basin to the east (Fig. 3.2.) contain thick Mesozoic infills (Binns *et al.*, 1974; Cheshire *et al.*, 1983).

It is worth mentioning that some of the half-graben sediments visible on the MOIST profile (Brewer & Smythe, 1984) and on sections of commercial data (Enfield & Coward, 1987) are parallel-bedded and sharply cut by the fault (Fig. 8.1.), what suggests that they were deposited prior to the Devonian(?) or later fault initiation (Kirton & Hitchen, 1987).

Onshore in the NE Scotland, no listric growth faults of proven Devonian have been recognized. The faults bounding the Old Red Sandstone basins in eastern Sutherland eastern Ross-shire(Black Isle) and Inverness-shire are typically high angle to vertical. The Devonian thrusting, folding and angular unconformities are well documented in the area (Mykura, 1983b; Mykura & Owens, 1983; Read & Phemister, 1925; Crampton & Carruthers, 1914; see also chapter 3). The high-angle to vertical faults, which bound the

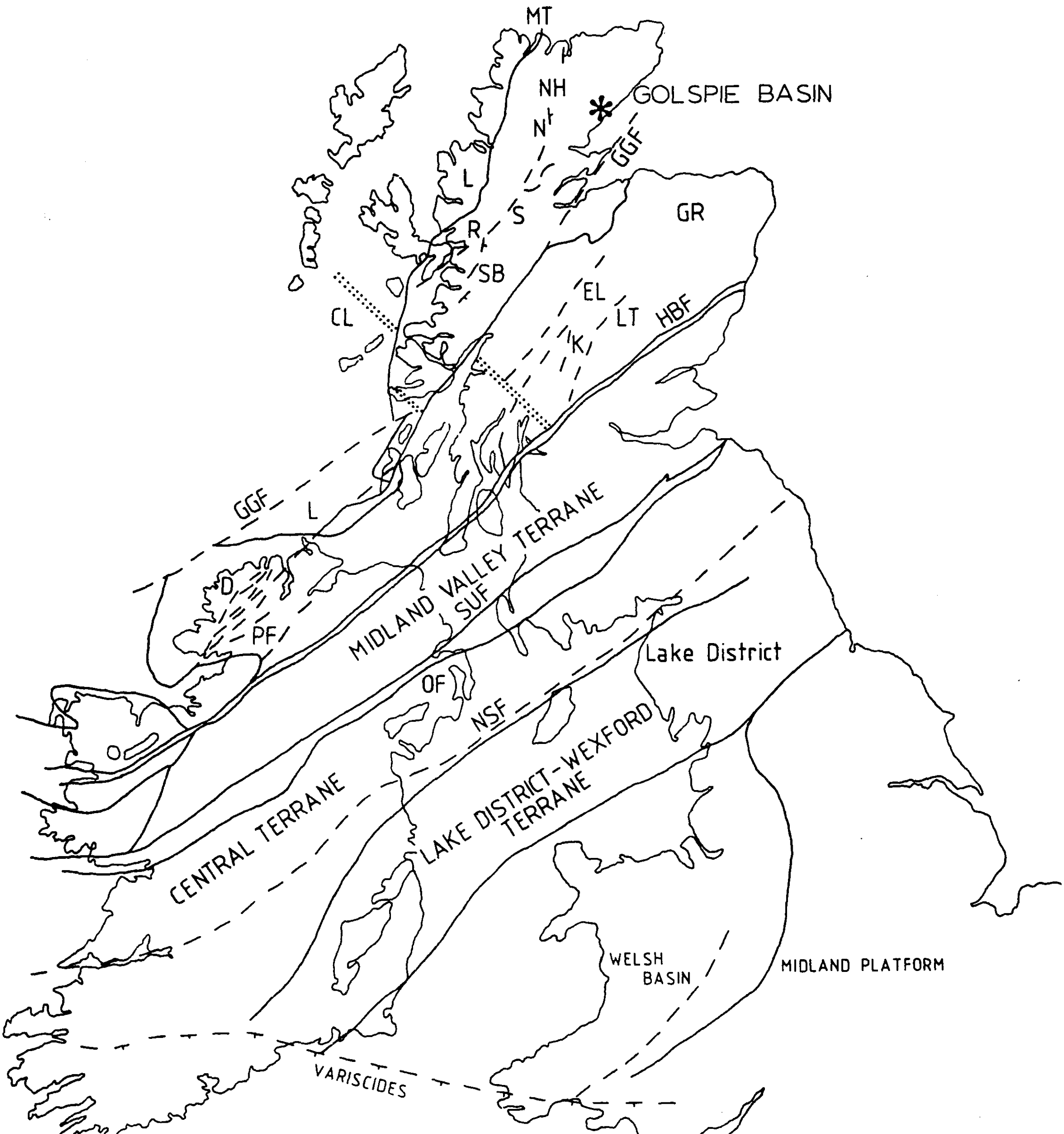


Figure 8.2. Generalized map of evidence for late Caledonian sinistral strike-slip movements in Scotland and Ireland discussed in the text. Selected terrane boundaries marked (after Hutton, 1987). **MT** - Moine Thrust; **NH** - Northern Highland Terrane; **N** - Naver Slide; **L**- Lewisian; **GGF** - Great Glen Fault; **R** - Ratagain Granite; **S** - Strathconnan Fault; **CL** - Cruachan Lineament(double dotted line); **SB** - Sgurr Beag Slide; **EL** - Ericht-Laidon Fault; **LT** - Loch Tay Fault; **K** - Killin Fault; **PT** - Pettigo Fault; **D** - Donegal Shear Zone; **HBF** - Highland Boundary Fault; **SUF** - Suthern Uplands Fault; **OF** - Orlock Bridge Fault; **NSF** - Navan-Silvermiles Fault.

Golspie basin approximate a rhomb pattern (Fig. 3.3.). These structures suggest that a compressive or transpressive stress component was associated with the major NE-SW trending faults. Moreover, there are numerous independent lines of evidence for wide-spread sinistral deformation throughout Britain and Ireland during the late Silurian and early Devonian. These include (see also Fig. 8.2.):

(1) NE-SW trending faults in the Grampian Highalands(Ericht-Laidon Fault, Killin Fault, Loch Tay Fault, Pettigo Fault) as well as faults of the Scottish segment of the Great Glen Fault, which appear to be first-order Riedel shears associated with the Highland Boundary Fault (Smith, 1961; Johnston & Frost, 1977; Soper & Hutton, 1984; Hutton,1987);

(2) late Silurian - early Devonian sinistral strike-slip associated with the Kingledores Fault(Orlock Bridge Fault in Ireland) (Anderson & Oliver, 1986);

(3) sinistral transpressive cleavage pattern in the Lower Palaeozoic rocks adjacent to the southern boundary of the Southern Uplands (Navan - Silvermines Fault) (Soper & Hutton, 1984; Hutton, 1984);

(4) early Devonian non-axial planar cleavage in the slate belts of the Lake District and Central Ireland (Sanderson *et al.*, 1980; Cameron, 1981; Soper & Hutton, 1984; Sanderson & Marchini, 1984; Murphy, 1985);

(5) cleavage transections associated with the development of sub-horizontal stretching lineations (suggestive of trunscurrent motion) and strictly axial planar cleavage invariably related to the occurrence of steep, down-dip stretching lineations (suggestive of across-strike shortening and thrusting) (Hutton, 1987);

6) the clockwise transection of F_1 folds by S_1 cleavage combined with sub-horizontal extension in the cleavage plane, local development of vein arrays deformed by sinistral shear and an abundance of sinistral wrench faults dated as a result of late Silurian - early Devonian sinistral transpression in the SW Irish continuation of Suthern Uplands (Anderson, 1987);

(7) early steep stretching lineation superseded by a sinistral shear during the development of the S_1 cleavage inferred from the incremental strain studies on pyrite pressure shadows and other works in the Balbriggan area of eastern Ireland (Murphy,

1985);

8) late Caledonian sinistral displacement of the Cruachan lineament along the Great Glen Fault system (Hall, 1986).

9) the emplacement of c. 400 Ma "newer" granites into dilational openings on sinistral shear zones (Hutton, 1982,87; Soper, 1986; Hutton & Dewey, 1986);

10) late Silurian/early Devonian sinistral transpressive deformation of granitoids c. 400 Ma in eastern Ireland (Murphy, 1987);

11) terrane accretion models for the assembly of the late Caledonian crust require major juxtaposition of far-travelled exotic terranes by strike-slip motion during the Silurian and early Devonian (Bluck, 1984,85; Soper & Hutton, 1984; Hutton & Dewey, 1986; Dewey & Shackelton, 1984; Hutton, 1987).

McClay *et al.*(1986) and Enfield and Coward(1987) attempt to support their model of the Old Red Sandstone regional extension by recent reinterpretations of the Devonian basins in western Norway as essentially extensional structures (Hossack, 1984; Norton, 1986; Seranne & Seguret, 1987).

According to Steel and Gloppen (1980) oblique-slip faulting is the main tectonic element of the basins development. Steel *et al.* (1985) discuss advantages and disadvantages of both approaches - models (see Appendix 1 & Fig. App.1.1.). They emphasize that the extensional fault movements, recognized along the eastern end of the basins remain to be dated. Recent palaeomagnetic studies in Kvamshesten basin suggest late Silurian/early Devonian magnetization which probably dates the time of thrust movements (Torsvik *et al.*, 1986). According to Sturt and Torsvik (1986) reactivation of the "Caledonian" and "Devonian" structures was widespread during the Mesozoic.

Steel *et al.* (1985) stress also that "if the low-angle faulting is shown to be syndepositionally important, it remains debatable whether these faults were primary driving mechanism in basin migration or secondary to the supposed oblique-slip faults". Indeed, the same problem applies to the extensional models of McClay *et al.*(1986), Astin (1985) and Enfield & Coward (1986,87) for the Devonian basins in northern Scotland. Even assuming that the half-grabens of the West Orkney basin (Fig. 8.1.) do contain Devonian sediments whose deposition was controlled by the growth listric faults this is not an

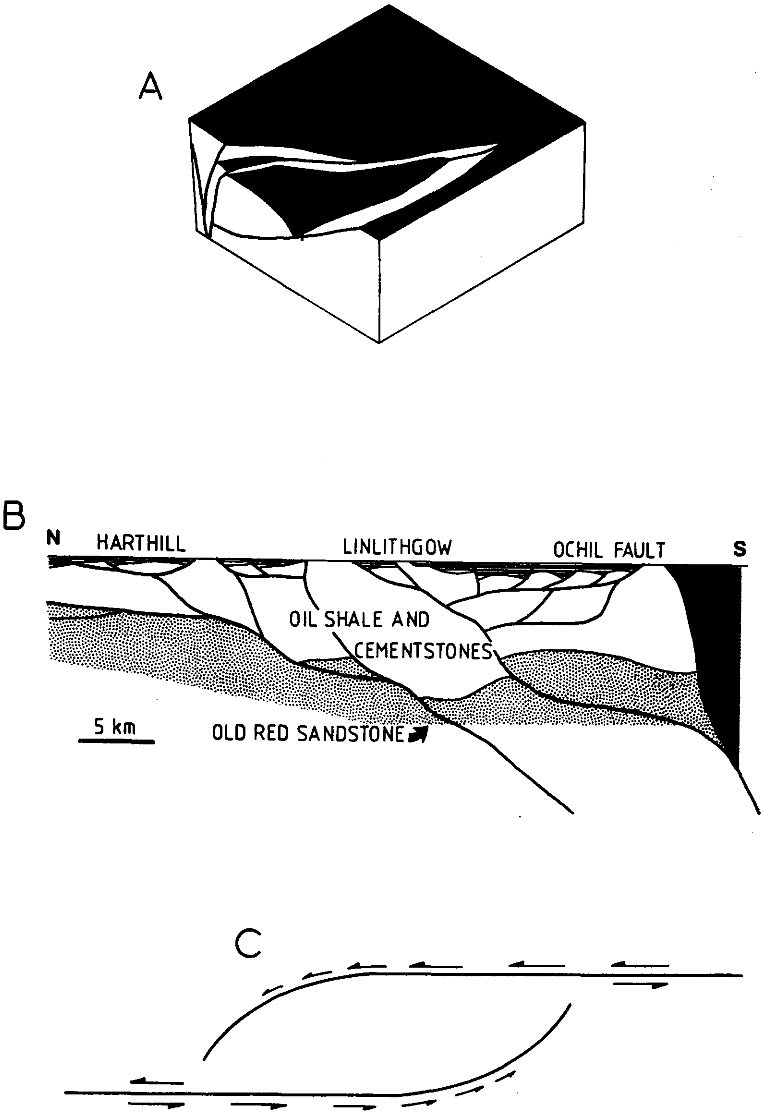


Figure 8.3. A: Isometric sketch of model of linked extensional leaf and strike- or oblique-slip fault system (after Gibbs (1987, fig.12)).

B: Simplified geological cross-section of the Central Coal Basin of the Midland Valley of Scotland showing intermediate and upper fault leaves developed as a "carapace" to the simpler basement strike-slip shears (after Gibbs (1987, fig. 15)).

C: Simplified pull-apart interpretation of the Vienna basin (after Royden (1985, fig. 12)). Displacement decreases along the faults within the basin, so that near the ends of the faults("releasing bends") there is little strike-slip component.

absolute argument for the Devonian regional crustal extension. There are sedimentary basins in which deep-rooted strike-slip faults pass at higher levels into fault-bounded "leaves" (Gibbs, 1987; Fig. 8.3.A). Such an "mixed-mode" combination of strike-slip and dip-slip arrays is necessary to allow crust to thin under a pull-apart basin. Examples of such basins are Midland Valley of Scotland (Fig. 8.3.B), Carboniferous province of England, Vale of Pickering (Gibbs, 1987), Gas Area of Southern North Sea (Gibbs, 1986) and Vienna basin (Royden, 1985). Deep seismic profiles do not normally directly image steeply dipping faults and these may well have been missed on the MOIST (Brewer & Smythe, 1984) and on the other profiles (Brewer & Smythe, 1984; Cheadle *et al.*, 1987; Enfield & Coward, 1986,87; Kirton & Hitchen, 1987).

The NE-SW trending Great Glen Fault system appears to be a good candidate for a structure which primarily controlled the initiation of the Orcadian basin, especially in the light of the presented above ample evidence for late Silurian/early Devonian sinistral strike-slip deformation in the region. The Main Donegal Granite (c. 400 Ma) was emplaced into a shear zone while the pluton crystallized. This zone lies in a major bifurcation of the Great Glen Fault system in the Irish sea, and it is thought to be a related feature (Hutton, 1987).

However, according to Parson (1979) studies of structures developed during both ductile and brittle deformations in Fort Augustus area indicate a post-Devonian SE-NW compressions with no strike-slip movement along the Great Glen Fault.

At present there are no direct evidence which could unequivocally indicate a particular sense and distance of the pre-Devonian/Devonian transcurrent movement along the Great Glen Fault. Several workers (Harris *et al.*, 1981; Roberts & Harris, 1983; Fettes *et al.*, 1985) have highlighted the stratigraphic and deformational contrasts across the Great Glen Fault, which would indicate considerable displacements. Smith and Watson (1983) argue for a maximum c.100 - 200 km sinistral movement, quoting the lithological and age similarities between the crustal blocks of Northern and Grampian Highlands and between the Old Red Sandstone facies on either side of the Great Glen Fault (but see also Storetvedt, 1986). Such an proposed displacement corresponds to the c.100 km sinistral strike-slip movement postulated by Kennedy (1946). Hall (1986) suggests a maximum 50 km, sinistral, late Caledonian movement along the Great Glen Fault, on account of the offset of the Cruachan lineament. The suggested by Hall (1986) contemporaneity of the movements along the Great Glen Fault and the Moine Thrust concurs with the sinistral offset of the Sgurr Beag Slide by the Strathconan Fault, which also deformed parts of the 425 Ma Ratagain granite before it crystallized (Halliday *et al.*, 1984; Hutton, 1987).

Storedvedt (1986), basing on palaeomagnetic data from the Ordovician and Devonian rocks of northern Scotland, suggests that major strike-slip motion along the Great Glen Fault was initiated in the late Middle Devonian. The displacement is inferred to have been sinistral of the order of 600 km. The second major movement is proposed to have taken place during Hercynian and was dextral of 200 - 300 km.

No lateral offsets have been recognized from the Golspie basin, but on the other hand such displacements are very difficult to document in lithologically monotonous terranes like for example vast Moine basement and associated conglomerates containing its clasts. Assuming that the shape of the outcrop of the Golspie basin, highlighted by the fault pattern, approximates a rhomboidal, sinistral pull-apart feature (?) (Fig. 3.3. & 8.3.) (Mann *et al.*, 1983), the two distinctly different granites(Rogart and Helmsdale) and associated conglomerates, which could eventually serve as offset markers, would be located at "releasing bends" (Fig. 8.3.C). These sectors of pull-apart structures are characterised by a minimum strike-slip displacement (Royden,1985). Such an small offset would hardly be detectable considering a relatively minor transcurrent displacement required for formation of the small structure as the Golspie basin (Mann *et al.*, 1983).

Many workers have emphasized presence of unconformities and considerable facies variations in rapidly subsiding pull-apart basins (Reading, 1980; Manspeizer, 1985; Christie-Blick & Biddle, 1985 and others). Although the Golspie basin, as well as the other marginal sectors of the Orcadian basin to the south display such characteristics, these are not diagnostic of strike-slip basins (Christie-Blick & Biddle, 1985). Dramatic facies changes are also expected in purely extensional settings (e.g. Leeder & Gawthrope, 1987).

As has been summarised in chapters 7.3. and 7.6. the distribution in the Golspie basin of the predominantly resedimented deposits as well a their textural/stuctural diversity appear to be to a great extent a resultant of variable sediment supply due to variable abundance in the drainage area of a wide range of unconsolidated sediments rather than a function of a direct tectonic control.

At present in the light of the presented above ample evidence of a structural nature for the late Caledonian strike-slip and lack of unequivocal data to support the model of Devonian extensional tectonics it is justified to regard strike-slip regime as a most logical structural framework for initiation of the Orcadian basin and other Old Red Sandstone basins in Scotland.

9. Conclusions

The Golspie basin is a NE-SW trending, marginal component of the post- or late-orogenic Old Red Sandstone Orcadian basin. Ample structural evidence indicate the Late Caledonian strike-slip regime to be a logical framework for initiation of the Old Red Sandstone sedimentation in the region. Deposits of the Golspie basin are represented by two main sequences of the Lower and Middle Old Red Sandstone age separated by an angular unconformity. Up to 400 m thick basal conglomerates of the Beinn Lunndaidh Formation (BLF), extensively developed along the western and the southern margin of the basin, represent deposits of alluvial fans whose sedimentation was dominated by debris flow deposition (Facies A, B and B1). The NE edge of the basin was fringed by sheetflood-dominated fans of Facies C1; the deposits have a maximum thickness 180 m.

Although the fault-controlled basin margins are thought to have provided a physiographic framework for the alluvial fan development, sediment supply appears to have been a significant factor controlling the distribution and the diversity in sedimentation styles. While the texturally homogeneous, Helmsdale granite-derived, sheetflood arkoses of Facies Cl represent a classical example of first-cycle sedimentation, the textural heterogeneity of the debris flow deposits of Facies B and B1 (i.e. presence in the same beds of chaotically distributed bimodal and polymodal textures, common bimodal-only beds, abundance of sandstone matrix (locally of distinctly different provenance than the gravel fraction - Facies B1), and presence of outsize semi-lithified rip-up clasts), strongly suggest that the debris flow-dominated alluvial fans were supplied by pre-existing, sand-enriched gravels, which had undergone a significant size segregation prior to resedimentation, remoulding with sand, and the deposition as debris flows. Although, clast composition of the BLF conglomerates mimics lithology of the adjacent Caledonian basement, the diverse degree of clast roundness further indicates the presence of resedimented (second-cycle) deposits as well as a possible first-cycle component.

The distinctive textural signatures of Facies B and B1 also indicate an essentially cohesive nature of the depositing debris flows. It is proposed that the cohesion factor in the flows might have been imparted not only by electrostatic/electromagnetic interactions between clay particles but also by chemical bonds of the early cements present in the source sediments, prior to the mobilisation and the resedimentation (grain-to-clay structural intergrowth, iron oxides, carbonates). A static grain-to-grain contact and buoyancy are seen as additional clast supporting mechanisms operating in the debris flows. Deposits transitional between the debris flow and the sheetflood conglomerates have been recognized as subordinate.

In the southern part of the Golspie basin, the development of gravelly alluvial fans was succeeded by sandy stream flow/sheetflood sedimentation (Facies G2) which resulted in the deposition of over 600 m thick Beinn a' Bhragaidh Member of the Glen Loth Formation (GLF). As a result of poor rock exposures it is impossible to infer any detailed palaeodispersal pathways and to correlate these deposits with the distinctly different sediments of the Beinn Dhorain Member and the Ben Uarie Member (BDM and BUM respectively), appearing above the BLF fanglomerates in the northern part of the basin.

In response to subsidence in the area of Glen Loth the sheetflood-dominated alluvial fans were brought into fan-delta-related interplay with a lacustrine environment, which was abundantly supplied with exotic, externally derived fine-grained sediments. This transgressive scenario is reflected in a rapid, fining-upward transition from the BLF into the BDM. The subaqueous setting of the resulted fan-delta was dominated by mudflow sedimentation, and *en mass* mixing of the fan-borne, first-cycle gravels with the second-cycle lacustrine sediments. The resulting Facies E1 and E2 are characterised by shear-layering reflecting dominant laminar flow conditions (layer-parallel extension and shearing) during the mass flow emplacement. The mudflows are interpreted as cohesive because of the high amount of clay and presence of carbonate matrix. The main part of the 450 m thick BDM consists in the majority of the subaqueous mudflow deposits of Facies E2 derived from the north.

An analogous fan-delta environment is represented by the lowest part of Ousdale Mudstones (Badbea basin), although here it was succeeded by stream flow and by lacustrine sedimentation represented (Facies G1). Similarily as in the Golspie basin the muds of Facies E1, E2 and E3 (as well as Facies G1) represent a second-cycle, exotic material containing distinctive low-grade metamorphic lithic fragments of an enigmatic provenance. The same southward palaeodispersal pattern, characterising the deposits of the BDM and Facies G1 of Ousdale Mudstones suggest a possible common source area of the exotic detritus.

In the continuously subsiding northern sector of the Golspie basin the mudflow sedimentation of the BDM was followed by a northward emplacement of cohesive sandy debris flows of Facies F1 and sheetfloods of Facies F2. These well sorted very fine- to fine-grained sandstones make up the 150 m thick Ben Uarie Member. Various palaeocurrent data consistently indicate that intrabasinal uplift in the central part of the basin may have been responsible for the mobilisation of the pre-existing, considerably reworked sands and formation of extensive sandy aprons.

Sedimentation of the Middle Old Red Sandstone Beinn Smeorail Formation (BSF) was preceded by a phase of local folding and erosion of the Lower Old Red Sandstone infills of the basin (BLF and GLF), possibly related to the strike-slip activity along the Great Glen Fault. The development of the BSF resembles the general palaeogeographic scenario of the BLF. While in response to the rejuvenation of the source areas the second-cycle, debris flow-domianted alluvial fans formed along the western margin of the basin (Facies B and B1); the first-cycle, locally derived sheetflood and stream flow fans developed at the eastern margin (Facies C1 and C2). However, contrary to the period of the BLF sedimentation, when the thickest fanglomerates formed in the south (Creag an Amalaidh - Ben Tarvie and Mound Rock fans), the depocenter of the BSF sedimentation was located in the northern sector of the basin (Creag a' Bhodaich Conglomerate). A new element in the development of the Golspie basin, associated with the BSF sedimentation was an additional westward and south-westward component of palaeodispersal (Fan 2 of Craeg a' Bhodaich Conglomerate and Socach Hill fan) indicating at least temporary isolation of the Golspie basin from the east.

No evidence have been found for the postulated *large scale rivers* (Mykura, 1983a), dispersing from the W and SW in the region of the Golspie basin.

The dramatic passage of the BSF into sandstones of the Col-bheinn Formation (CbF) reflects a phase of widespread recession of the alluvial fan sedimentation. At Leadoch Rock and at Duchary Rock the transition is represented by sandstone sheetflood and debris flow deposits which formed at the toe of the retreating Oldtown-Killin Rock fan, though the exact provenance of the latter mass flow deposits has not been established.

Upper part of the CbF represents probably fluvial system analogous to Facies G2 and dispersing to the NE.

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APPENDIX 1

Models of tectonic control of the Old Red Sandstone basins in western Norway

(after Steel *et al.*, 1985)

Three main models for basin generation have been proposed (Fig. App.1.1).. Model A involves hinge-faulting, model B oblique-slip faulting and model C listric normal faulting. Steel *et al.* (1985) discuss applicability of the models in explaining characteristics of the basins (for details see Steel *at al.*, 1985).

Model A proposed by Bryhni (1978) can be seen as a variant of a purely extensional "propagating rift" model. As the basin migrates headwards so does the sediment-supplying hinterland. The limitations of the model are: a) its probable inability to sustain continuous, abundant sediment supply which is strongly suggested by great thickness of the infills of the basins and abundant coarsening-upward sequences and b) lack of mechanism to cause the western end of the basinal area to migrate and tilt eastwards. An advantage of this of the model is that the source area is constantly renewed due to eastward migration.

In **model B** oblique-slip faulting is the main tectonic element with adjacent zones of both tension (basinal) and compressional (source area) (Steel & Gloppen, 1980). The main objection to this model has been the apparent lack of previously documented strike-slip faults in Western Norway. However, it has never been suggested that these are major strike-slip faults, rather subordinate splays from an orogen-parallel sinistral megashear through the North Atlantic at this time (Ziegler, 1978,1985).

The major advantage of the model B is that it has the potential to produce continously sustained relief (and thus a continuous sediment supply) and a continuously migrating depression/uplift "couplet". Other advantages of the model are the production of an asymmetric basin and the potential of the steep northern margin fault to produce scree/debris flow fans and slide masses.

Model C like A, relies on purely tensional tectonics and suffers from having a non-dynamic hinterland. Moreover, and in contrast to model A, model C retains the same source area during the entire period of basin infiling, i.e. the source area remains static

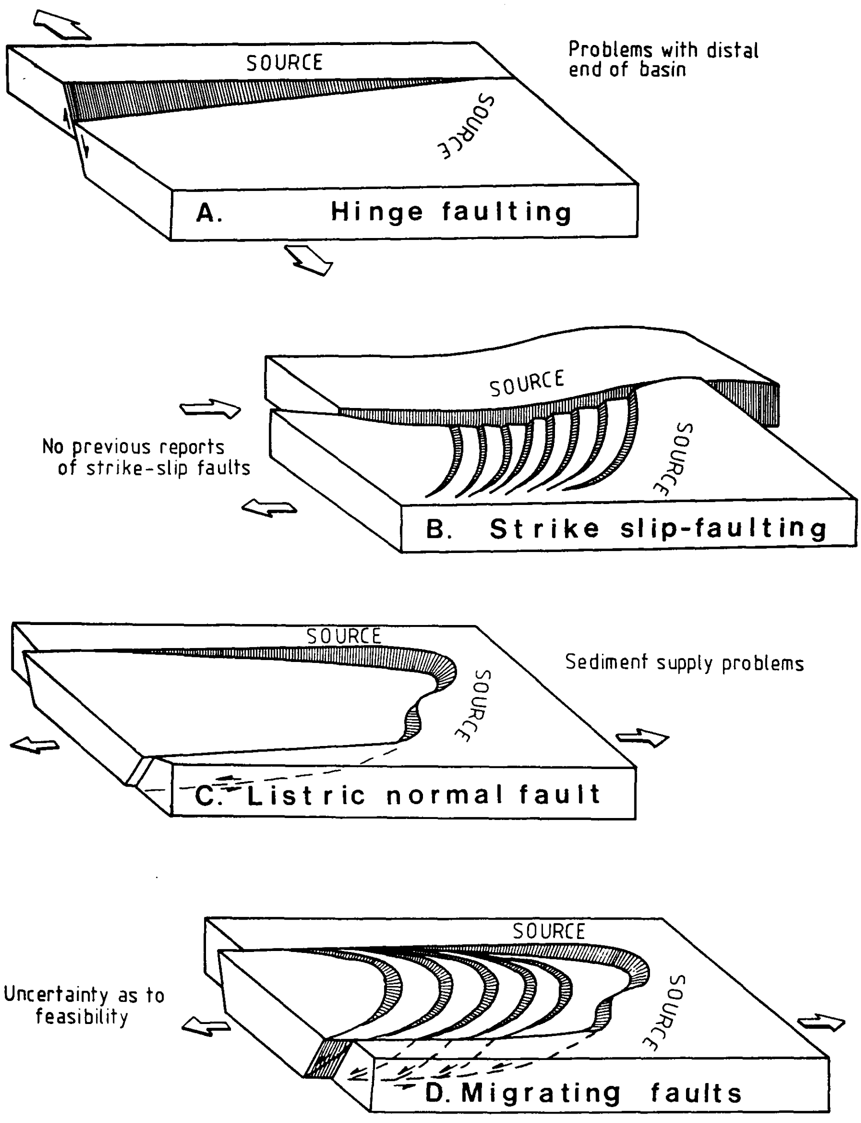


Figure App.1.1. Various syndepositional tectonic models for the Devonian basins of western Norway: **A**: from Bryhni (1964, 1978); **B**: from Steel (1976) and Steel & Gloppen (1980); **C**: from Hossack (1984). After Steel *et al.* (1985).

while the basinal area slides westwards. With continuous downwearing and backwearing of the same source terrain it is difficult to envisage an abundant and continuous sediment supply, as demanded by constraint. Another unfortunate aspect of model C concerns the westward sliding of the depocentre. Such wholescale sliding, particularly if successive semiconsolidated basinal segments should remain attached to each other and to the "locomotive" basement block (and this is uncertain along such a flat-lying fault), should have caused large-scale deformation. This is not evident. In favor of model C, however, is the recent evidence that several of the low-angle faults along the eastern ends of the basins show evidence of normal rather than thrust movement (Hossack, 1984; Norton, 1986; Seranne & Seguret, 1987). Another feature of late deformation, the E-W folding, may also be accounted for in model C, in terms of accommodation folds that tend to accompany extensional fault ramps (Hossack, 1984). A variant of the listric fault model, where the listric system propagates eastwards by tensional slip across successive listric faults should be noted. This type of model was mentioned by Bryhni (1982), and possibly also by Bjorlykke (1983), but neither of these authors have provided new data or attempted to test the notion.

Model D has a more dynamic source area than model C, and as such is probably better able to satisfy the sediment supply constraint. As in model B, there is a real eastward migration of the depocentre with time, rather than simply a westward slip-page, as in C. In addition (as in B) there is probably no necessary dislocation between the newly deposited sediment and its immediate subsurface, so no predicted major deformation in the sediment pile along the basin floor. A possible major disadvantage of model D is that it is an uncertain that such systems systematically migrate, rather than simply collapse simultaneously along their length.

APPENDIX 2

Results of X-ray diffraction (XRD) for the clay fraction separated from the matrix of Facies B, E1 and E2

EXPLANATIONS

AR - air dry sample

GL - gloculated sample (50-60°)

600° - heated sample

A - E: samles from matrix of Facies B

A - Meall Odhar (Meall Odhar - The Craggan Conglomerate, BLF);

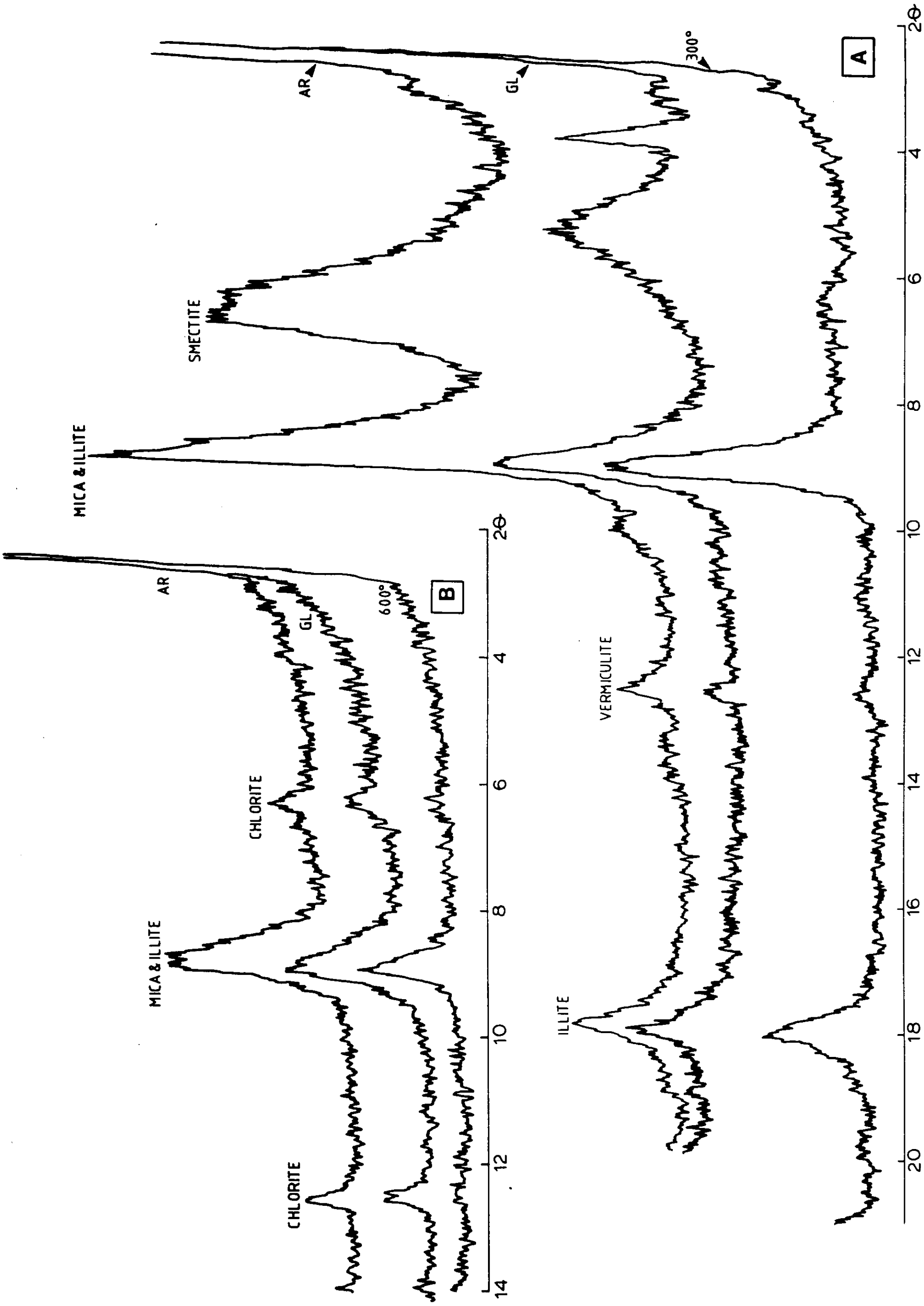
B & C - Mound Rock (Mound Rock Conglomerate, BLF);

D - Creag an Amalaidh (Mound Rock Conglomerate, BLF);

E - Ben Tarvie (Ben Tarvie Conglomerate, BLF);

F - I: samples from mudstone component of Facies E1 and E2; Beinn Dhorain (Beinn Dhorain Member, GLF);

J - Oldtown (Oldtown - Killin Rock Conglomerate, BSF).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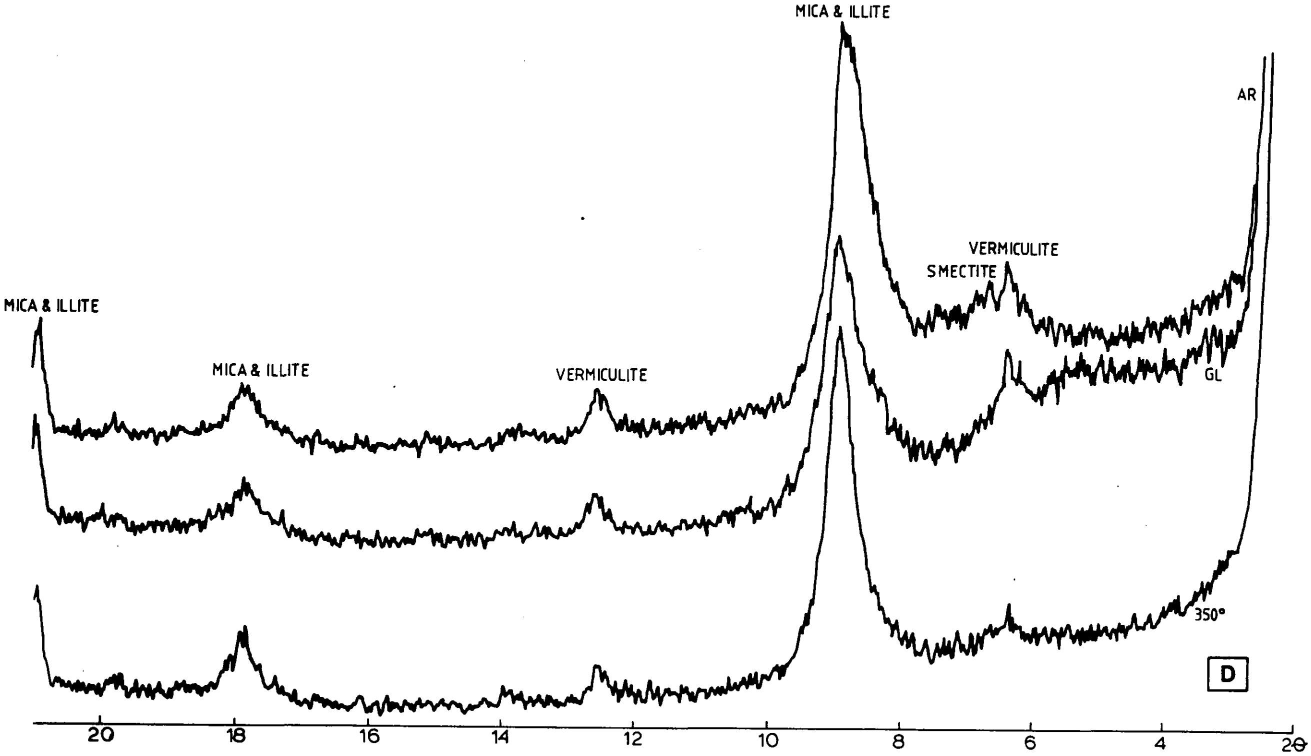
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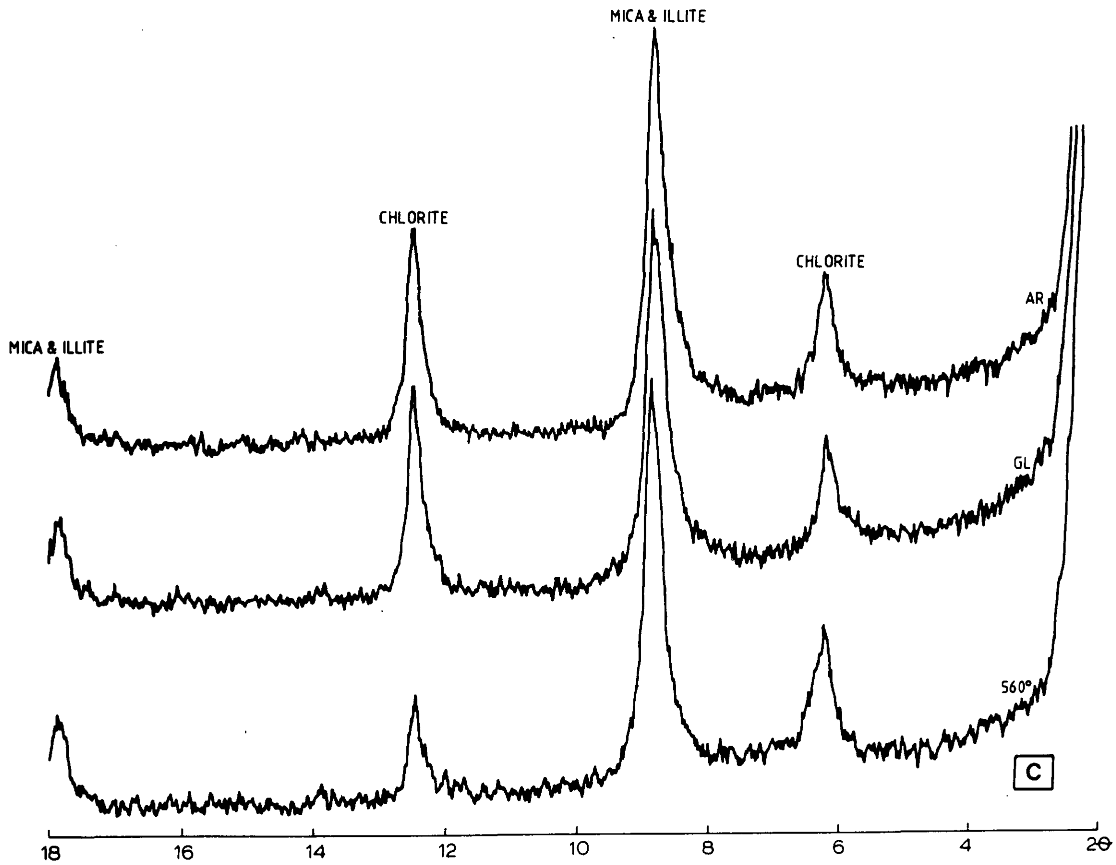
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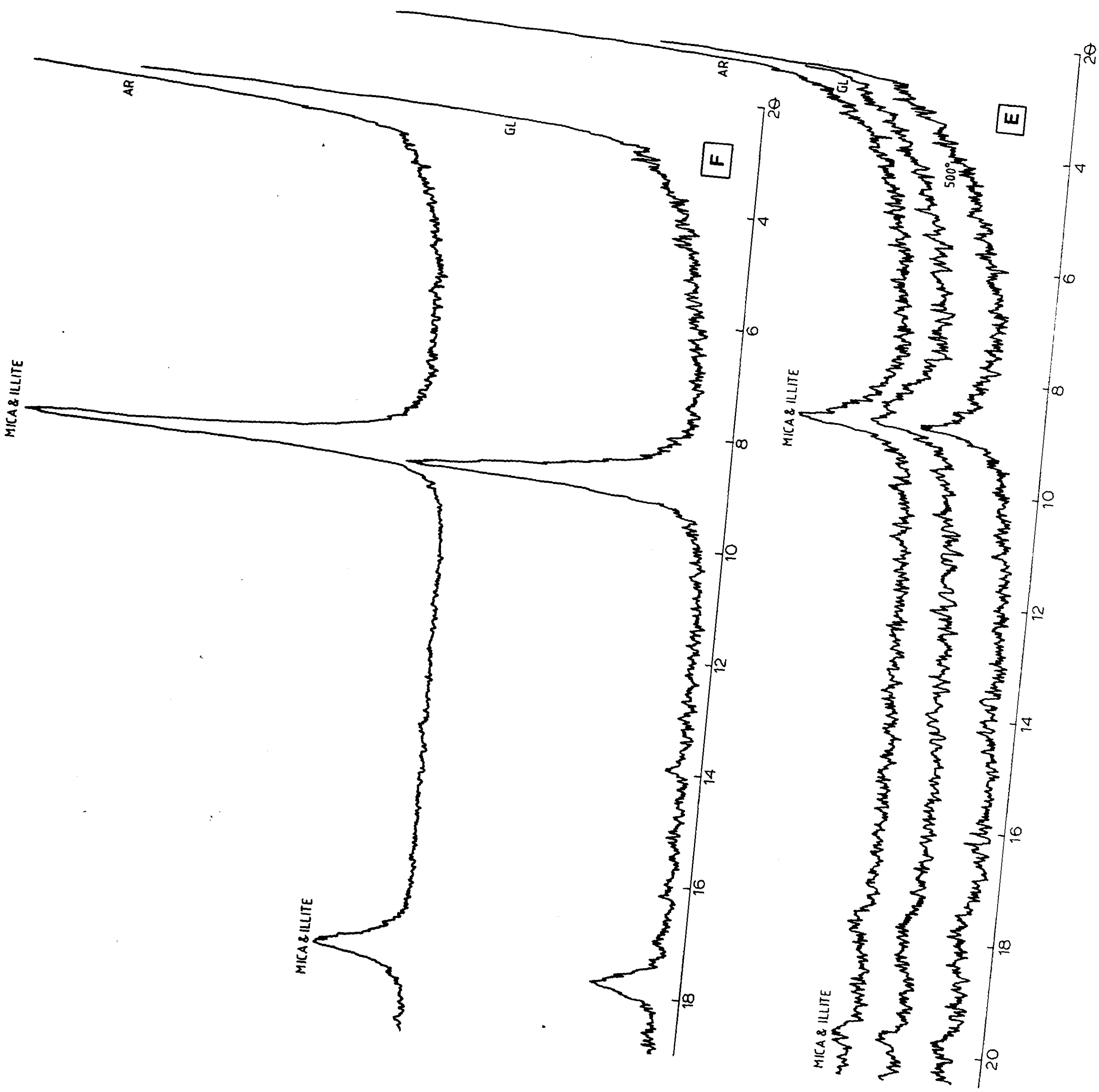
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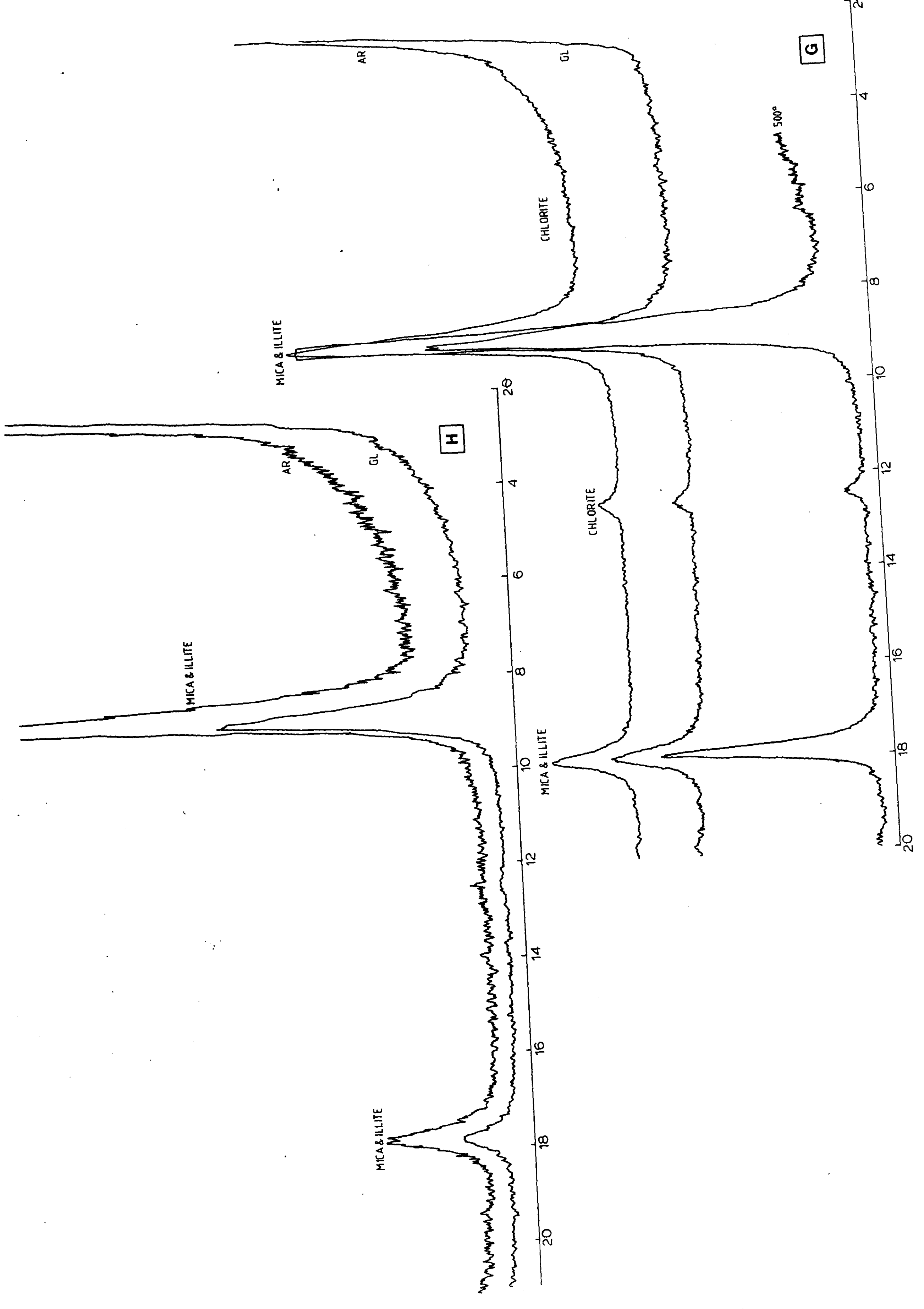
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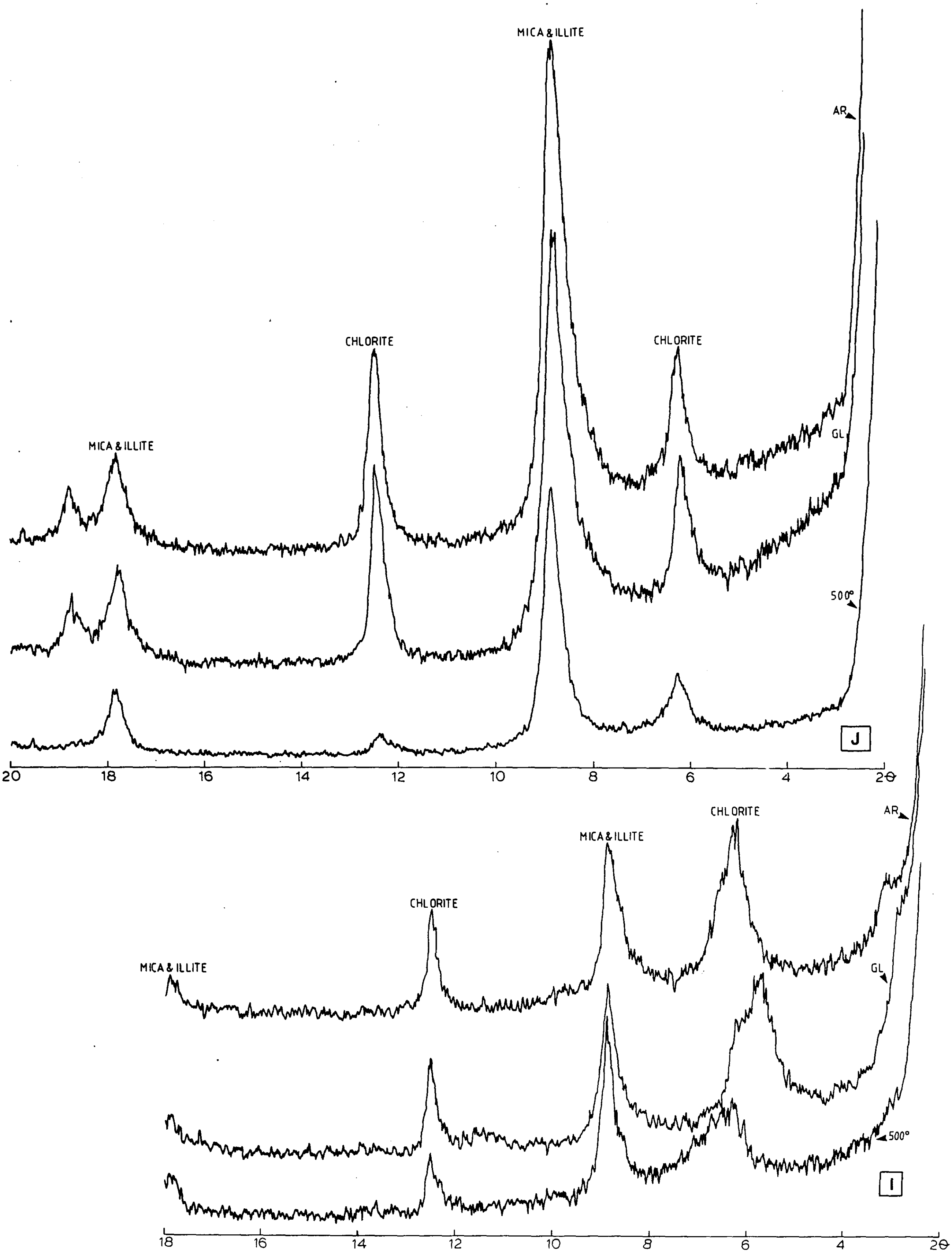
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APPENDIX 3

FACIES SUMMARY

Facies	Distinctive Features	Interpretation	Palaeoenvironmental Context
A	- massive breccias or breccio-conglomerates - chaotic fabric - clast-supported (filled framework) - outsize boulders (see p.34)	<u>mass flow deposition</u> of <u>texturally unmodified</u> gravels - scree and landslides	proximal sector of alluvial fan
B	- poorly sorted conglomerates - matrix- to clast-supported - bimodal to ploymodal - texturally heterogeneous - organized to disorganized fabric - gravelly and sandy intra-clasts - amalgamated, sheet-like beds - lack of grading - av. MPS = 19-17cm - outsize boulders (see p. 38)	<u>debris flows</u>, <u>occasionally</u> transitional to sheetfloods (see p.86) (redeposition of pre-existing, texturally modified gravels and sands)	alluvial fan
B1	- poorly sorted conglomerates and pebbly sandstones - texturally heterogeneous - mainly chaotic fabric - sandy intraclasts - amalgamated, sheet-like beds - lack of grading - av. MPS = 11-16 cm (see p. 344)	<u>debris flows</u> (see p. 364) (redeposition of pre-existing, texturally modified gravels and sands)	alluvial fan

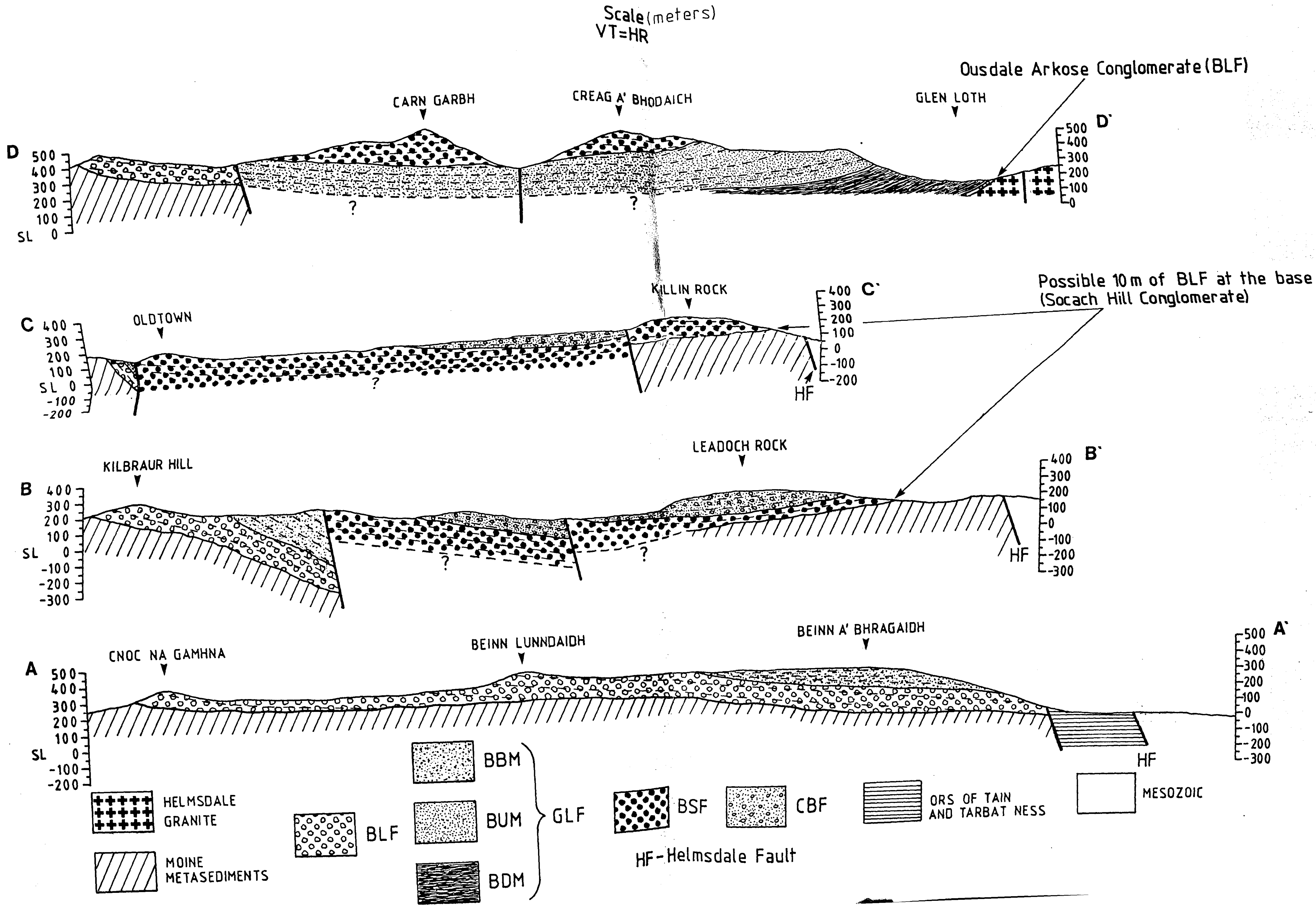
Facies	Distinctive Features	Interpretation	Paleaoenvironmental Context
C	- well to poorly sorted conglomerates - texturally homogeneous - parallel-stratified to low angle cross-stratified - common imbrication - well defined, sheet-like beds; av. thickness 16-19 cm - common normal grading - av. MPS = 5-4 cm (see p. 73)	<u>sheetfloods</u> - traction and/or turbulent suspension (see p. 103) (reworking of the previous gravels and sands)	alluvial fan
C1	- well to moderately sorted conglomerates - clast-supported - parallel-stratified - amalgamated, sheet-like beds - MPS dictated by size of the orthoclase crystals in the Helmsdale granite (0.5-3cm) (see p. 110)	<u>sheetfloods</u> (see o. 112) (deposition of first-cycle arkosic detritus)	alluvial fan or subaerial portion of fan-delta
C2	- moderately to poorly sorted conglomerates and sand-stones - clast-supported - texturally homogeneous - massive to planar-stratified and cross-stratified - av. MPS = 11cm (see p. 373)	<u>sheetfloods</u> and <u>stream flows</u> (p. 385)	alluvial fan

Facies	Distinctive Features	Interpretation	Palaeoenvironmental Context
E1 & E2	- conglomerates, muddy conglomerates, pebbly mudstones (av. MPS = 0.4-4.3 cm) and mudstones - massive to shear-layered - sedimentary boudinage - texturally heterogeneous - disorganized to organized fabric - amalgamated, sheet-like beds - lack of grading - cracks and brecciation (see p. 160 & 183)	mudflows - layer-parallel spreading (see p. 200 & 224) (redeposition of pre-existing, texturally modified gravels and muds) remobilization of the mudflow deposits	subaqueous portion of fan-delta
E3	- ripple cross-laminated and parallel-laminated mudstones - subordinate parallel-laminated limestone - well defined beds; av. thickness 3.3-11 cm (see p. 204)	current ripple migration fall-out from suspension carbonate precipitation (see p. 242)	subaqueous portion of fan-delta lacustrine environment
F1	- muddy sandstones & sandstones massive to shear-layered - sedimentary boudinage - texturally heterogeneous - amalgamated, sheet-like beds (see p. 245)	sandy debris flows - layer-parallel spreading (redeposition of pre-existing, texturally modified sands)(see p.266)	sandy apron
F2	- planar - stratified, cross-stratified and ripple cross-laminated sandstones - well defined sheet-like beds av. thickness = 37.7 cm-7.3 cm - common normal grading (see p. 259)	sheetfloods (reworking of previously deposited sands) (see p. 272)	sandy apron

Facies	Distinctive Features	Interpretation	Palaeoenvironmental Context
G1	- assemblage of large scale, trough cross-stratified sandstones and conglomerates and structureless, ripple cross-laminated and parallel-laminated mudstones - subordinate massive muddy conglomerates and pebbly mudstones - av. MPS = 0.5-2.3 cm (see p. 291)	stream flows sheetfloods flood plain crevasse splays in-channel mass flows related to collapse of banks (see p. 295)	alluvial plain
G2	- assemblage of planar-stratified and large scale trough/tabular cross-stratified sandstones and pebbly sandstones - sheet-like beds (planar-stratified deposits) - channels filled with cross-stratified deposits - subordinate massive to ripple-laminated sandstones and mudstones - clasts up to 15 cm (see p. 302)	stream flows sheetfloods (see p. 305)	alluvial plain

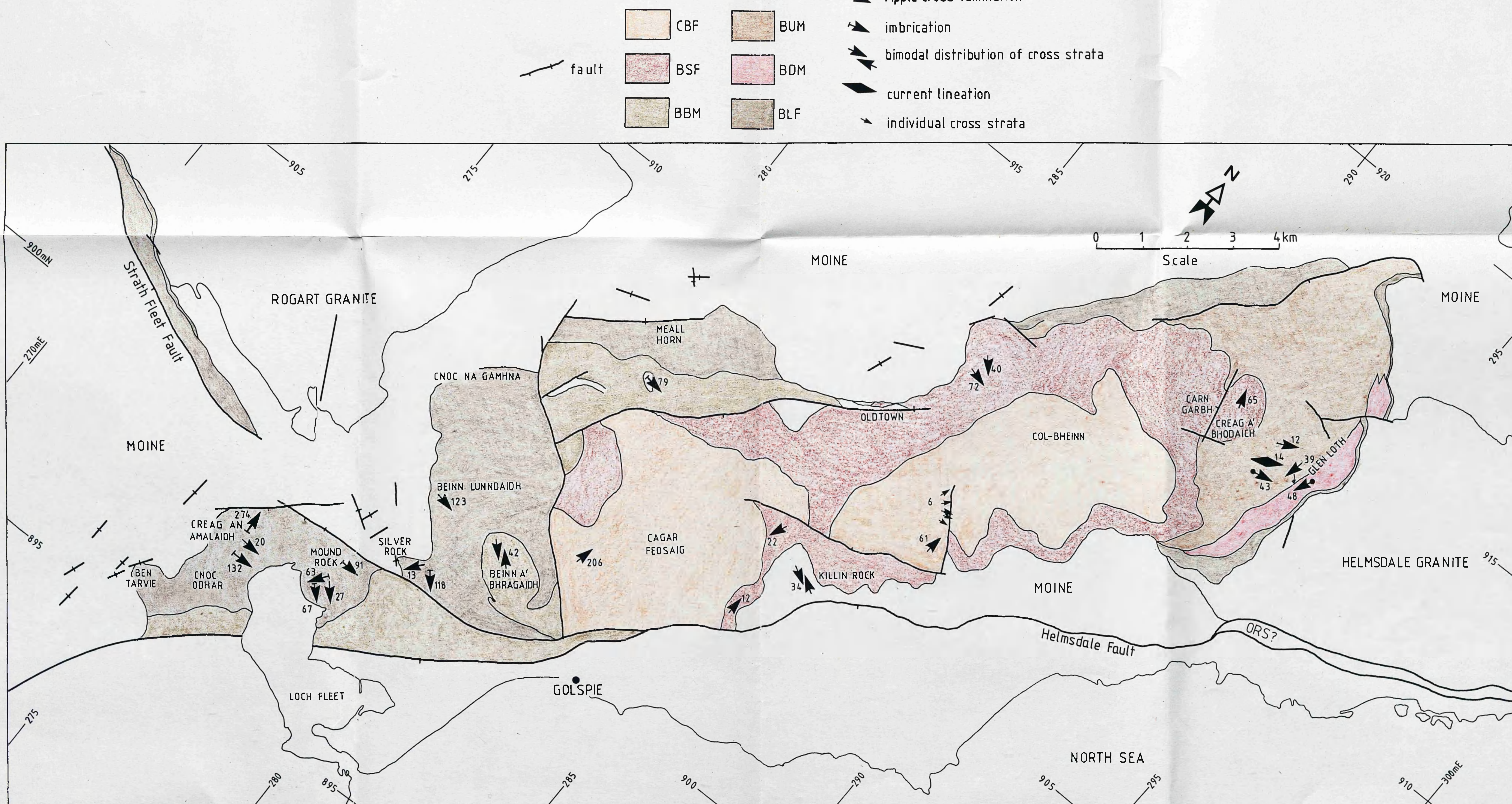
APPENDIX 5

HORIZONAL CROSS-SECTIONS THROUGH OUTCROP OF GOLSPIE BASIN



APPENDIX 6

MEAN PALAEOCURRENT VECTORS PLOTTED ON THE OUTCROP OF THE GOLSPIE BASIN



APPENDIX 4

GEOLOGICAL MAP OF OUTCROP OF GOLSPIE BASIN