GEOLOGICAL PROCESSES OF GOLD CONCENTRATION AND DEPLETION IN CALEDONIAN TERRAINS

by

JOSEPH ANDREW CRUMMY

A thesis submitted in conformity with the requirements for the degree of Doctor of Philosophy at the University of Glasgow

DECLARATION

I declare that this thesis is my own composition except where otherwise stated or acknowledged, and that no part of this thesis has been submitted for a degree at any other university.

J.A.Crummy

CONTENTS

LIST OF FIGURES PAGE

LIST OF PLATES PAGE

LIST OF TABLES | PAGE

ABSTRACT

Extensive exploration for gold in Scotland, undertaken as part of this research, has succeeded in locating several significant and previously unknown geological gold enrichments. Field and laboratory studies of these localities has identified several key metallogenic processes as responsible for the development of gold mineralisation in Scotland, knowledge of which will be useful to further exploration. These processes have been operative at deep crustal, and medium to shallow crustal levels and in the surface environment. Deep crustal processes comprised the formation of deep crustal gold reservoirs by large scale tectonism involving subduction and orogenesis in a collisional tectonic setting. Tapping of these deep crustal gold reservoirs by uprising magmas of the Silurian to Lower Devonian Appinite and Newer Granite suites provided a means of transportation of gold to mid-crustal levels. Hydrothermalism associated with magma emplacement resulted in gold deposition in breccia-pipes and in zones of enhanced crustal permeability at middle to high crustal levels. Gold deposition occurred as a result of boiling, effervescence and cooling of hydrothermal fluids at these crustal levels. The plutonism and cogenetic volcanism (represented by the ORS lavas) formed very large, very low grade repositories for gold. Subsequent erosion resulted in the unroofing of the concentrated and the large, low grade gold accumulations, exposing them to the supergene environment. Oxidation of sulphides, and leaching and remobilisation of the gold occurred, and gold was reconcentrated close to the water-table on mineralised structures and in deeply weathered regolith materials. Deep weathering under the warm, humid climatic conditions prevalent during Tertiary times is considered the most likely agent of this supergene gold remobilisation. Subsequent reworking of gold enriched regolith materials by modern-day alluvial activity created the alluvial gold concentrations seen today in several parts of Scotland. Scotland therefore shows potential for the development of both bedrock and alluvial gold deposits. None of the deposits discovered thus far has been proven to be commercially viable, but the potential for economic deposits exists in times of enhanced gold prices.

ACKNOWLEDGEMENTS

The work carried out for this thesis would not have been possible without the help of several groups of people and individuals. Navan Resources plc. are to be thanked for the provision of sponsorship for the four years duration of the project, and the advice and encouragement received from Kerr Anderson, Colin Andrew and Dave Munt is gratefully acknowledged. Supervision, advice and encouragement throughout from Allan Hall was invaluable, and other members of the academic staff whose brains I picked during the research including Mike Russell, Donald Ramsay, Brian Bell and Stuart Haszeldine are to be thanked. Technical help from Dougie Turner, Murdo McLeod, John Gilleece, Peter Ainsworth, Alan Jones, Suzanne Forbes, Jim Gallagher, George Gordon, Erchie Monaghan and Kenny Roberts was a great help. Douglas MacLean was particularly helpful in subverting my incompetence with a camera. Tony Fallick, Adrian Boyce, Terry Donnely and their technical staff at SURRC are thanked for their help with the sulphur isotopic work. Postgraduate students from the department to be thanked for frequent beneficial discussions of the work include Gian Rizzi, Mark Osborne, Calum Macaulay, Colin Ford, and Robbie Stewart. Chris McKeown is thanked for his secretarial and proof-reading skills in the latter part of thesis production. Constant encouragement throughout the work from Mike Gallagher of the British Geological Survey was also much appreciated. Access to land for exploration and research purposes was appreciated, and the landowners of the various prospects studied are to be thanked. Hospitality and tolerance from the farmers, keepers and residents, particularly John and Jim Patterson (Borland Glen), Sandy Anderson (Cushnie), Jim Scott (Morven) and Ian Hepburn (Dalnessie) was appreciated. The mechanics at Mickey Oates Motorcycles in Glasgow are thanked for frequent hints on how to get another field-trip out of my much abused means of field transportation.

Last, but not least, I would like to thank my parents for their prolonged moral and financial support through the 4.5 years spent on this work.

It was the above network of people that were responsible for the successful completion of the thesis, and they are all heartily thanked by the author.

INTRODUCTION

Gold has for long enjoyed the perceived financial status of being a safe haven for investment in times of international crises which have the potential to threaten other forms of investment. When the Soviet Union invaded Afghanistan in 1979/80 the western world perceived this as a potential strategic threat to the Middle Eastern oilfields, and economic turmoil ensued. As a reaction, recourse was made by governments and institutions alike to safer investments, including gold, the price of which rapidly climbed to over $800/oz. This price rise made gold a much more marketable commodity, and the mineral exploration community quickly paid attention to this. Vigorous exploration programmes were initiated world-wide, both in past or present gold producing regions and in underexplored terrains. Scotland was considered one of the latter and became the focus of attention of several junior exploration companies. Navan Resources plc. had recently been founded through flotation on the Dublin stock exchange, and subsequently made a decision to explore for gold in Scotland and Eire. As part of this exploration effort the company decided to fund research in the Department of Applied Geology, University of Strathclyde, into the geological controls of gold mineralization in Scotland. This PhD represents the contribution made through this research to their exploration effort.

Although Scotland represented an underexplored terrain with respect to gold, occurrences of the metal both in bedrock and in alluvial settings were known over a wide area. Metallogenic ideas had developed over the years to explain these gold occurrences but these had not been followed through in exploration terms due to the previous low gold prices. It was originally expected that the study of several of these occurrences and areas thought likely to contain other such occurrences would enable an understanding of the local and perhaps regional geological controls on the gold mineralising processes. In addition, the follow-through of the existing metallogenic ideas in an exploration context was intended to locate new gold occurrences which could be characterised , and the metallogenic model thus refined. The formulation of new metallogenic ideas and their follow-through in a similar manner was to provide a further dimension to the project. The PhD. was, then, proposed to include the study of known gold occurrences and the follow-through of of existing and new metallogenic ideas as exploration models. The existing and the newly discovered occurrences were to provide material for scientific study. The knowledge and understanding gained could then be applied to new prospects in Scotland to aid further exploration. However it rapidly became apparent that the existing occurrences and the bulk of the intended prospects were not available for study and as such the research as originally proposed was unworkable. The sudden interest in gold exploration in Scotland, involving anything up to 15 companies at any one time, resulted in a rush for exploration licenses, which logically included many of the known gold occurrences and the surrounding areas. Commercial exploration for gold in Scotland requires both a Crown Licence and an access agreement with the relevant landowner, and therefore exploration by one company in an area precludes access for such by a second party. Without the material represented by these known occurrences and intended prospects the original research strategy was unworkable and was therefore abandoned.

Adaption to this problem of lack of material basically involved finding new material, from scratch, to be studied in a similar way. This necessarily involved extensive and locally intensive exploration for new gold occurrences. Each chapter therefore includes a section on how this was undertaken and how the mineralization was eventually located. Gold being an extremely enigmatic metal takes time and effort to find, and the bulk of this effort is, in all cases, ultimately unsuccessful. Thus the exploration was a very time-consuming part of this work. Only that effort which proved successful is included here; an unsuccessful piece of exploration produces no material which can be studied scientifically in the way intended here and therefore has no place in the thesis.

Location of a new gold occurrence provided the necessary material to be studied. How it was studied was decided on a site-specific basis, and was constrained by the nature of the mineralization and the amount of exposure available. The former included considerations of the style of the mineralization, the nature of the host rock, any alteration present, the type of gangue minerals present and whether usable fluid inclusions were present in the gangue. The amount of exposure was a variable factor and largely depended on the degree of commercial interest shown in the prospect by Navan Resources plc. Natural exposure was always extremely poor but could be improved by trenching or pitting should the prospect merit it. Thus an extremely remote area with thick overburden deposits such as the Dalnessie prospect which posed overwhelming logistical problems for follow-up exploration and was not perceived as having serious commercial potential remained poorly exposed and only a limited amount of work could be carried out on material from the prospect. A prospect which showed adequate commercial potential and relative logistic simplicity such as at Cushnie or Borland Glen was subjected to extensive trenching or pitting which substantially improved exposure and provided much new material for subsequent study. The work eventually carried out for this thesis therefore reflects the number of occurrences found and the amount of follow-up exploration carried out by Navan Resources plc. on these prospects. The work contained in this thesis was carried out prior to, during and after any follow-up exploration done by the company. All the prospects described, except for Borland Glen were located by Navan Resources plc, with the vast bulk of the reconnaissance fieldwork carried out by the author. In the case of Borland Glen, the prospect was taken over by the company after the British Geological Survey had discovered rich alluvial gold localities in the central Ochil Hills and had tried in vain to locate a bedrock source for this gold, as described in Chapter 9.

The work described in this thesis can be placed within the broader contexts of the history of mineral exploration in Scotland and the development of metallogenic ideas relating to Scotland by consulting a few key pieces of literature. For a concise summary of the exploration work carried out before and during the author's work on this thesis, Gallagher (1992) and Coleman (1990) should be consulted. The general types of mineral deposit to be found in Scotland are described by Gallagher (1992) in the Grampian Highlands Regional Guide, and a more detailed inventory can be gleaned from Pattrick and Polya (1993), chapters 1,2 and 3. Metallogenic ideas relating specifically to the Scottish metallogenic sub-province are described in Russell (1985). The effort that went into the compilation of the above reviews is acknowledged by the author, as is the quality of these reviews. Duplication of this effort will be avoided here since the author does not believe that any improvement to this literature base can be made by reviewing these reviews. Rather, the author's effort will be streamlined towards the ends of describing the search for and characteristics of new mineral localities and the specific metallogenic processes relevant to them, as opposed to describing exploration programmes, mineral localities and metallogenic ideas that have already been adequately and concisely described.

Thesis Structure

The work carried out for this thesis was undertaken as material became available for study, i.e. as localities of interest were found in the field and, where appropriate, further exposed as part of Navan Resources' follow-up exploration. The type and amount of academic work carried out on the various prospects was dictated by the availability of material and was necessarily done in a scientifically illogical order. Only late on in the research was the common denominator between the various prospects (see thesis title) elucidated. The thesis itself was structured around this common denominator and does not reflect chronological order.

The prospects studied individually exhibited geological processes of gold concentration and depletion operative at different crustal levels, from the mantle/deep crustal gold reservoirs tapped by uprising magmas to surface weathering processes. The work is described in the thesis on a prospect by prospect basis, ordered by the depth of crustal processes involved in the formation of gold enrichments on the prospect. Thus Chapters 1 and 2 deal with the tapping of mantle and deep crustal gold reservoirs by uprising appinitic magmas, emplacement of magmas into the middle crust and consequent gold concentration in associated breccia pipes. It involves a combination of a site-specific study and a regional study of the appinite suite of Scotland and Eire, and represents the deepest crustal level studied in the thesis. Mesothermal processes and their structural control are examined in Chapters 5 and 4 respectively which concentrate on the Socach gold deposit, and shallow level epithermal mineralization is studied on the Dalnessie prospect in Chapter 8. The remobilisation of gold from hydrothermal mineralization by surface weathering processes and its effects on the economics of a deposit are described in Chapter 6, again using material from the Socach deposit. The ultimate fate of gold remobilised and reconcentrated by supergene processes and its reworking by glacial and alluvial action are considered in Chapter 9 which deals with the Borland Glen prospect. A crustal cross-section of gold concentrating and depleting geological processes is, then, put together using information from four individual prospects, and this synthesis is presented in Chapter 7. As an aside, though directly relevant, the Sron Garbh Mo/W deposit is described in Appendix 1; it was located during routine exploration for Navan Resources plc. and serves to illustrate the diversity of metal enrichments to be found in Scotland. In so doing it emphasises the possible wider application of the ideas developed in the thesis to Scottish metallogenesis as a whole.

Equipment Used

Field transportation was nearly exclusively by MZ ETZ 125 Luxus motorbike, of 125cc engine capacity and 12bhp. Occasional use was made of a short wheel-base Landrover and a long wheel-base Isuzu Trooper, both of which proved to be inferior vehicles for the job.

Fluid inclusion work was carried out on a Linkam TH600 stage using a Leitz Dialux 20EB microscope with effective magnification up to 1500X. Cooling was achieved using a jet of zero-grade nitrogen passed in copper piping through liquid nitrogen, with the flow-rate controlled by a home-made pipe and valve system. The equipment was calibrated using the following standards; Chlorobenzene, Napthalamine, Sulphur and Tempil 149, 198, 253, and 302. Wafers were prepared by grinding the rock fragment to translucency followed by progressively finer lapping with calcined aluminium oxide down to 12 um then hand or machine polishing with 6 um and 3 um diamond paste until the desired optical clarity was achieved. Wafer thickness was consistently <0.5mm.

Thin section, polished thin section and polished block petrography and photomicrography was carried out on a Zeiss Axioplan microscope on sections prepared in the standard way by technical staff in the Department of Geology and Applied Geology, University of Glasgow.

Scanning electron microscope work was carried out on a Cambridge Instruments Stereoscan 200 electron microscope fitted with an energy dispersive analyser (EDAX) unit.

Self-potential geophysical equipment comprised an ITT Instruments MX20 voltmeter with an input impedance of 20 M over the voltage range 0-2volts and an accuracy of +/- 0.5%, two 100m single core cables and two home-made porous clay pots with copper rod filled with saturated copper sulphate solution.

VLF geophysical work was carried out using a Geonics EM16 instrument and the Rugby transmitting station.

Sulphur isotopic work was carried out at SURRC by the method of Robinson and Kusakabe (1975) and using, for final analysis, an Isospec 44 mass-spectrometer.

CHAPTER 1

FORMATION AND TAPPING OF DEEP CRUSTAL GOLD RESERVOIRS; GOLD AND THE CALEDONIAN APPINITE SUITE

Introduction; The Caledonian Appinite Suite As A Gold Exploration Target

Appinites are a suite of basic igneous rocks believed to be the plutonic equivalents of certain types of lamprophyre (Bowes and McArthur 1976). They are of world-wide occurrence within orogenic belts, and their type examples are intruded into the Caledonides of Scotland and Ireland. They characteristically occur in clusters close to or within large plutons of the Newer Granites suite with which they are thought to be genetically related. Their field relations, geochemistry and genesis are described in detail by Bowes and Wright (1967) and Hamidullah and Bowes (1987).

The close connection with lamprophyres provides the initial link with gold metallogenesis. Gold assays of lamprophyric rocks from Scotland carried out by Rock et al.(1987) returned grades of up to 523 ppb. They implied from this that lamprophyres have the propensity to carry gold. Subsequently, Rock and Groves (1988), and others (eg. Wyman and Kerrich 1989), have pointed to the spatial and temporal relationship between lamprophyres and gold deposits world-wide and implied a genetic link between the two on the basis of this. Rock and Groves (1988) consider that gold enrichments in lamprophyre compared with other igneous rocks may reflect two factors; 1) they tap deep regions of the Earth where gold may be enriched, and 2) they carry relatively high concentrations of CO_2, H_2O, F, K, Rb, and Ba, and moderate concentrations of S, and in so doing they mirror fluids known to deposit gold in veins.

The emplacement mechanism of lamprophyre can be regarded as a simple dyke intrusion process, hence the ubiquitous dyke like nature of lamprophyric bodies. Thus the magma rises largely uninhibited through the crust. Whilst this is an effective way of carrying gold to higher crustal levels, a mechanism for deposition and concentration of this gold is not present as part of the lamprophyre emplacement process, and this provides a possible explanation of the low gold grades reported by Rock et al (1987). The appinite emplacement process differs from that of lamprophyres in that uprise through the crust is accompanied by one or more explosive brecciation events (Bowes and McArthur 1976). The brecciation is thought to result from trapping of the volatile rich magma beneath a competent lithology, build up of volatile pressure beneath the trap and its subsequent sudden breaching. The process is responsible for the formation of the explosion breccia pipes adjacent to igneous stocks, a common characteristic of appinites.

The explosive brecciation event causes a sudden drop in volatile pressure (Hamidullah and Bowes 1987). This, it is suggested here, will cause boiling and devolatisation of the hydrothermal fluids associated with the magma. Boiling and/or devolatisation of CO_2 H_2S or SO_2 is known to be an effective agent of metal (including gold) precipitation from hydrothermal fluids (Seward, in Foster (1990)). Any such gold being carried by the volatiles will be dumped in the breccia-pipes, and on these grounds they constitute a gold exploration target. Thus the appinite suite are related to postulated carriers of gold (lamprophyres), and their emplacement process involves an effective gold

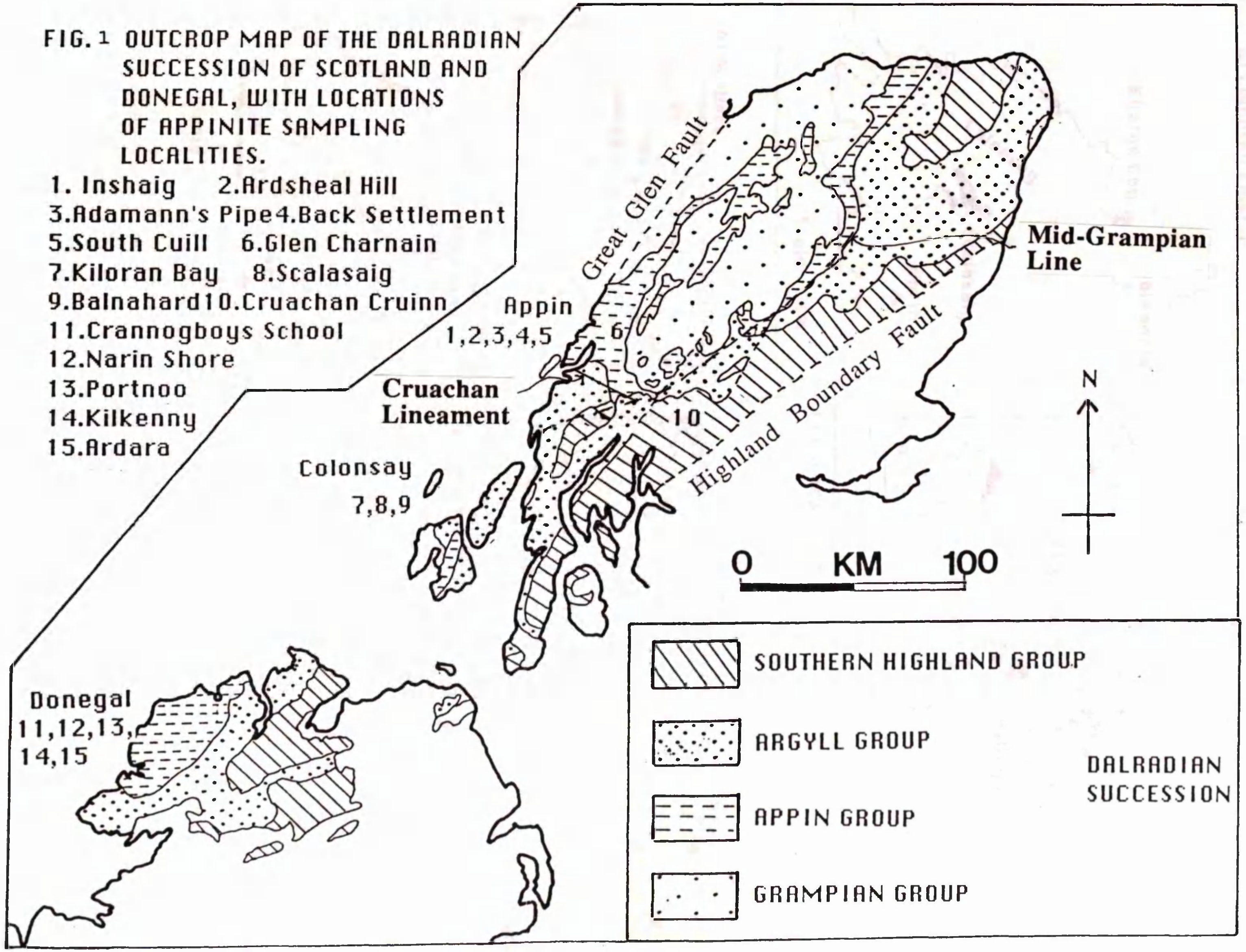
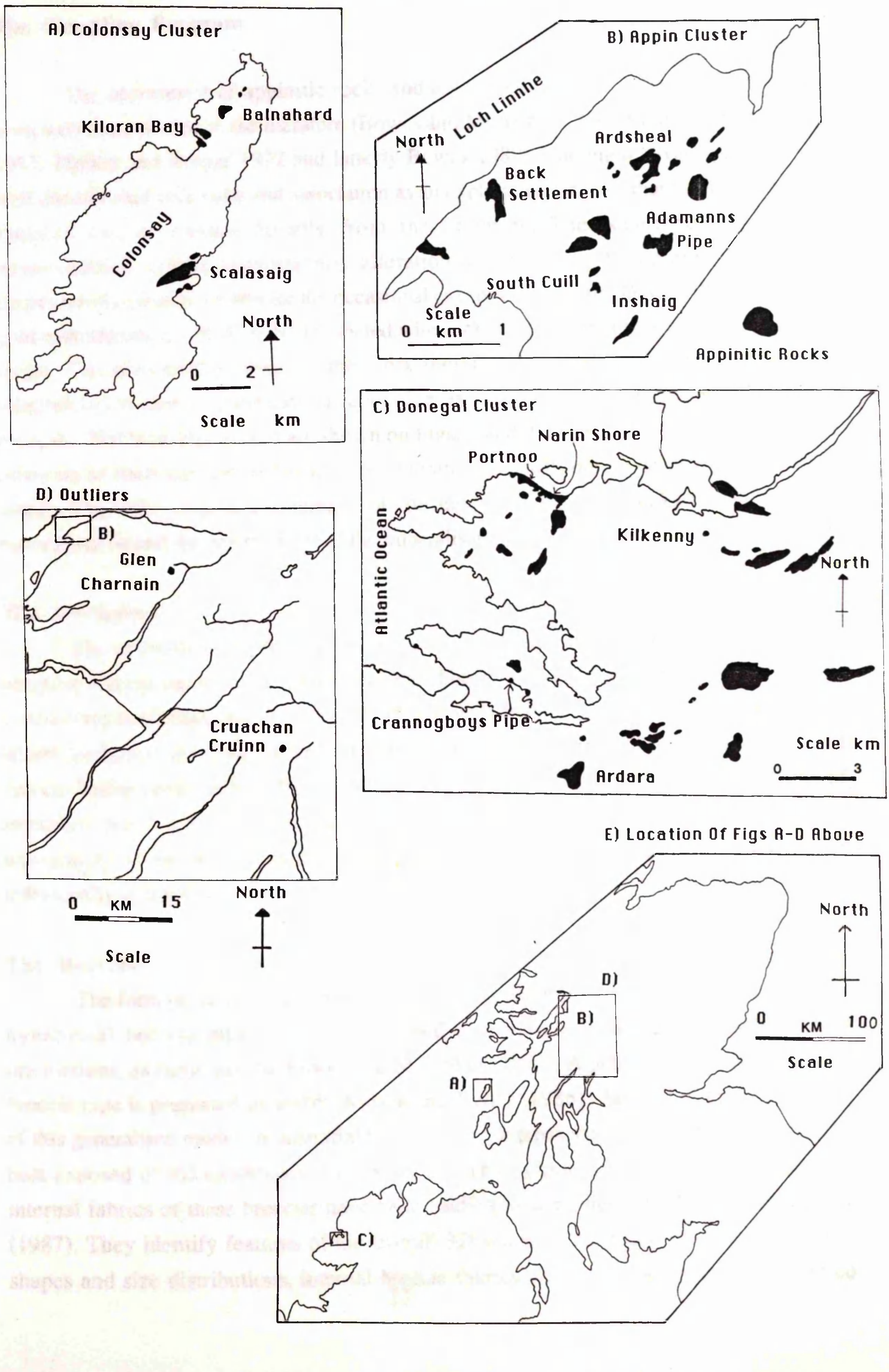


FIG. 1 OUTCROP MAP OF THE DALRADIAN SUCCESSION OF SCOTLAND AND DONEGAL, WITH LOCATIONS OF APPINITE SAMPLING LOCALITIES.

1. Inshaig 2.Ardsheal Hill
3.Adamann's Pipe 4.Back Settlement
5.South Cuill 6.Glen Charnain
7.Kiloran Bay 8.Scalasaig
9.Balnahard 10.Cruachan Cruinn
11.Crannogboys School
12.Narin Shore
13.Portnoo
14.Kilkenny
15.Ardara

Fig 2 ;Localities Of Appinitic Rocks Sampled For Sulphur Isotope Analysis.



precipitation mechanism. A program of sampling of the breccia pipes, looking in particular for any sulphide mineralization they host, was therefore initiated. This encompassed the well known appinite clusters of Colonsay, Appin and Donegal, and several outliers in Scotland.

The Sampling Program

The occurrence of appinitic rocks and associated breccias in the Caledonides has been well documented in the literature (Bowes and McArthur 1976, Hamidullah and Bowes 1987, Pitcher and Berger 1972 and latterly Bowes 1989). The main advantage in using a well documented rock suite and association as an exploration target is that the localities to be sampled can be chosen directly from the literature. The occurrence of sulphide mineralisation and/or hydrothermal alteration associated with appinites is not well documented however, except for the occasional exception (Rice and Davies 1979) Since any gold enrichments are likely to be associated with such features they represent a more specific target. The prospecting phase of the work therefore involved the search for sulphide mineralisation and/or hydrothermal alteration associated with appinites or their related breccias. The localities visited are shown on Figs. 1 and 2. Details of the geology and field relations of each site can be found in the literature and will not be described here in any detail. The following is a summary of the nature of the host rocks to the sulphide mineralisation and the general style of the mineralisation and alteration.

The Intrusions

The appinitic rocks themselves occur as small stock-like bodies with a rounded to irregular outcrop pattern up to 1km in diameter.The mineralogy and chemistry of these rocks is described in Hamidullah and Bowes (1987). Breccia bodies are developed on the upper or lateral margins of the stocks and occur as bodies up to 100m across. The igneous stocks and breccia bodies occur both as distinct entities and as hybrids, the latter involving invasion of intraclast porosity by the magma. Variations in the level of exposure and the local topography result in the igneous stock and associated breccia being exposed either individually or together.

The Breccias

The form of the breccia bodies sampled is consistent with the idea that they represent hypabyssal breccia pipes currently exposed at a variety of structural positions and orientations, as suggested by Bowes and McArthur (1976). A generalised model of such a breccia pipe is presented by Baker, Kirwin and Taylor (1986) . Several of the key features of this generalised model are identifiable in the breccia pipes sampled during this study. The best exposed of the localities visited is the cluster of pipes at Cruachan Cruinn, and the internal fabrics of these breccias have been studied in some detail by Platten and Money (1987). They identify features of the overall 3D shape of the pipes, clast compositions, shapes and size distributions, internal breccia fabrics and alteration styles which can be interpreted as the products of continuous gas fluidisation processes within an evolving hypabyssal breccia pipe. They do however regard the role of explosive brecciation in the evolution of the pipes as relatively minor. Bowes and McArthur (1976) describe the internal structure and overall form of breccia bodies in the Appin district and conclude that explosive brecciation was the main mechanism of breccia formation there. Pitcher and Berger's work on the Donegal appinites (Pitcher and Berger 1972) suggests the same for those examples. Inadequate time was available during this research for the detailed study of breccia textures and this dispute remains unresolved. The debate as to whether explosive brecciation played a part in the formation of the breccia pipes is however relevant to the prospectivity of the appinite suite, since this part of the process is suggested by the author to be critical to the concentration of gold in the breccia pipes, so the debate should be addressed.

Platten and Money (1987) argue against the occurrence of the explosive brecciation and suggest instead that the breccias were formed by a gas fluidisation process. Such a process occurring in breccias as open as those seen at Cruachan Cruinn would probably still involve devolatisation/boiling of the fluids as they moved into the relatively unconfined space within the breccia, so the gold precipitation part of the exploration model remains intact. They also state that the hydrothermalism at Cruachan Cruinn was post breccia formation, post breccia invasion by the igneous phase, and roughly syn-hornfelsing of the country-rocks. Thus, according to Platten and Money, the timing implied by the author's original exploration model is wrong. The hydrothermal activity which precipitated quartz, pyrite and gold in the breccia-pipes was roughly synchronous with the emplacement of the nearby igneous stocks and is probably the result of degassing of the volatile-rich magma into the most permeable lithology, the breccias. The overall process is envisaged as one of an advancing magma degassing into a breccia body which formed previously, so the connection between the hydrothermalism and igneous emplacement is maintained, albeit with the timing slightly modified. Thus, whether or not explosive brecciation actually occurred, the appinite emplacement process involves a boiling/devolatising event conducive to gold precipitation. On these grounds appinites remain prospective for gold regardless of the final outcome of the debate over explosive brecciation.

Mineralisation

Sulphide mineralisation is characteristically hosted by both the appinite and the associated breccias. In the igneous stocks pyrite and occasional chalcopyrite are found disseminated through the rock mass in very fine to fine grained form, and make up from 0 to 0.05vol% of the rock. Rare alteration zones, most notably carbonated zones in basic materials carry up to 3 vol% pyrite in narrow anastomosing fissures which on the outcrop scale constitute up to 5vol% of the rock. The breccia bodies host fine to coarse pyrite disseminated through the quartz matrix, and can constitute up to 0.5vol% of this material. Pyritic schist and quartzite clasts are a common occurrence within these breccias but the origin of this pyrite is ambiguous and not necessarily a product of hydrothermalism. Where magma is seen to have invaded the breccias, finely disseminated pyrite is hosted by the appinite in a similar manner to the mineralisation within the main stock. Appinites hosted by carbonate lithologies show pyritisation of these hosts in the wallrock to the breccias and igneous stocks and in locally derived clasts within the breccia pipes. All these styles of mineralisation were sampled, with an emphasis on the characteristically more richly mineralised breccia bodies.

Hydrothermal alteration of breccia clasts, wallrocks and igneous bodies is characteristically slight, usually amounting to only a thin zone of propyllitic alteration of metasedimentary and more acidic igneous lithologies. Basic igneous lithologies occasionally display thin (<30cm thick) anastomosing zones of intense carbonation hosting disseminated pyrite as described above. The alteration styles, its extent and intensity are unremarkable in prospecting terms, but a more detailed description can be found in Lowry et al (1993) and Platten and Money (1987).

Samples of sulphide mineralisation were sent to OMAC Laboratories for gold analysis using atomic absorption spectrophotometry. The bulk of the samples returned gold grades of below the analytical detection limit of 20ppb, and could not be described as anomalous. One batch of samples, from the Cruachan Cruinn breccias, showed gold grades consistently above this detection limit, with the maximum grade being 751ppb and several other samples returning grades of above 250ppb. Whilst these are not rich samples in any sort of economic sense they do represent significant enrichment above the average crustal abundance of gold (0-5ppb), and as such imply the operation, albeit not spectacularly efficiently, of ore forming processes.

The anomalous gold concentrations found in the Cruachan Cruinn breccia pipes justified further study of this locality. Details of the field relations and internal fabrics of the breccias can be found in Platten and Money.(1987). The intuitive notion that the explosive brecciation event, or the process of gas streaming through pre-existing open permeable breccias caused a drop in volatile pressure which encouraged effervescence of hydrothermal fluids and hence gold precipitation was targeted for study. The study of fluid inclusions in gangue or ore minerals from deposits world-wide has been shown to yield information pertaining to the precipitation of the mineral of economic interest. A fluid inclusion study of the quartz gangue within the Cruachan Cruinn breccias was therefore initiated. One particular pipe (no. C1 in Platten and Money 1987) was chosen for this study to save time, and should in any case be representative of the pipe cluster as a whole given the textural similarities and geographical proximity of the several breccia pipes.

The nature of the appinite suite as volatile-rich magmas necessitates their consideration as hybrid igneous/hydrothermal systems. In the present study it is the hydrothermal part of this system, as specifically relates to the gold precipitation part of the proposed metallogenic model, which is targetted. Chapter 2 deals with the igneous processes that relate to this model as well as the hydrothermal processes, but the two parts of this system are emphasised here as being largely inseperable. The presence of gold in the volatiles responsible for brecciation and mineralisation implies its presence in the hybrid igneous/hydrothermal system and necessitates the study of both parts of this system.

Fluid Inclusion Geothermometry/Geobarometry Of Cruachan Cruinn Breccia Pipes

Petrography of Inclusion Population

Petrographic analysis of hydrothermal quartz revealed two distinct types of quartz which host equally distinct inclusion populations as illustrated on Plate 1. The two quartz types differ in strain state. Unstrained to very slightly strained, anhedral quartz hosts regular shaped inclusions arranged in a random scatter through the crystals. More highly strained quartz is distributed through the rock mass in discontinuous linear zones. Strain state is slight to medium, giving rise to undulose extinction, and the strain continues through unstrained quartz as thin, healed fractures sub-parallel to the more pervasively strained zones. Strained quartz hosts inclusions similar to those in the unstrained material but showing variable degrees of strain-induced stretching and decrepitation effects, which produce more irregular shapes, frequent empty inclusions and a more clustered overall distribution. This gives the strained quartz a dirtier appearance at low magnification. The overall make-up of the hydrothermal quartz, then, is of unstrained to very slightly strained, clean quartz cut by zones of more highly strained, dusty looking quartz. Inclusion fills in both varieties are of the H_2O/CO_2 /NaCl type, with a noticeable variation in the CO_2 content within individual crystals in both cases.The quartz, and the inclusions it hosts, are considered to be of a single generation, with later non-pervasive strain affecting only parts of the rock mass to produce the two distinct types observed.

This petrographic distinction between the fluid inclusion populations gradually became apparent as the thermometric study progressed. Thus the bulk of the data is not rigourously petrographically constrained, but the importance of this constraint to the interpretation of the data is recognised. In this retrospective context, bimodal data distributions can reasonably be expected to reflect the properties of the two inclusion populations. It is known from petrographically constrained T_h data that inclusions in strained quartz show lower temperatures than those in unstrained hydrothermal quartz. Other bimodal distributions can reasonably be interpretted similarly, whilst uni-modal distributions will reflect the similarity between inclusion fills in inclusions hosted by strained and unstrained quartz.

Geothermometry

A) Data

Geothermometric and geobarometric measurements were made on primary inclusions from both varieties of hydrothermal quartz. The results are tabulated in Appendix 5 and are illustrated graphically on Figs 3 A-D, with summary statistics included where appropriate.

Initial Melting Temperatures; a wide data-spread is apparent, ranging between -39 °C and -13 °C, with a mean of -24.1 °C. Two sub-populations are crudely discernible, centred around -28 °C and -18 °C respectively.

PLATE 1; PHOTOMICROGRAPHS OF HYDROTHERMAL AND STRAINED QUARTZ TEXTURES FROM CRUACHAN CRUINN BRECCIA PIPE.

A,B; Typical hydrothermal quartz textures; subhedral to euhedral quartz crossed by a zone of non-pervasive strain. Note dusty appearance of strained zone in Plane Polarised Light (Plate A) and the development of fanned extinction patterns seen in the same field of view under Crossed Polars (Plate B). Note also the simple extinction pattern shown by unstrained quartz and its cleaner appearance in Plane Polarised Light. Strain zones are irregularly distributed and randomly orientated, and are transitional with unstrained quartz. Compare with Plates 15b,c and Fig. 35 (this volume) where radial extinction patterns are developed in a regular fashion close to quartz crystal tips, as a result of recrystalisation of cryptocrystallinne silica.The present feature is demonstrably the result of non-pervasive straining of hydrothermal quartz rather than recrystallisation of cryptocrystalline quartz.

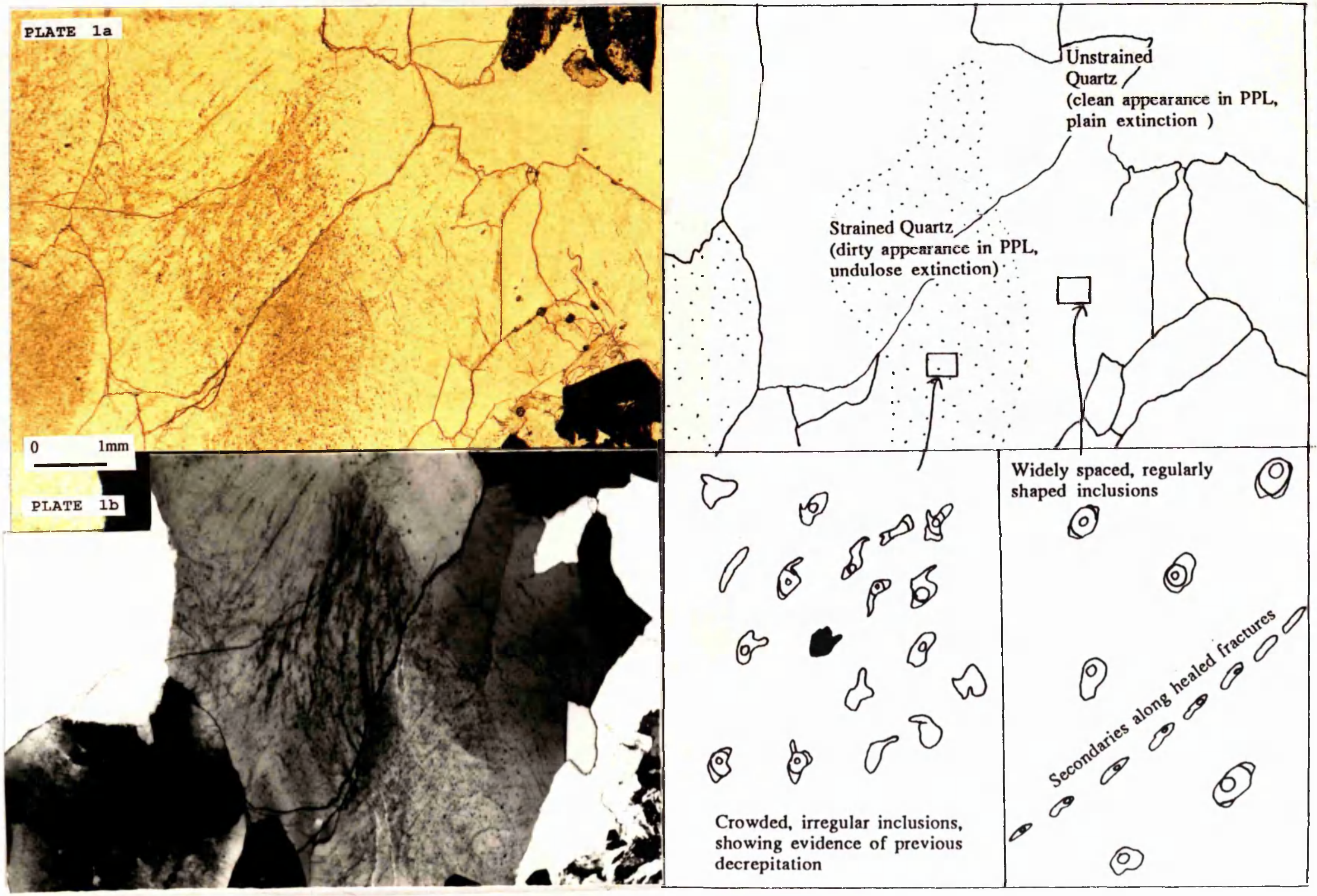
PLATE 2; FLUID INCLUSIONS IN HYDROTHERMAL QUARTZ FROM CRUACHAN CRUINN BRECCIA PIPE

A) Primary H_2O+CO_2 +NaCl inclusion cluster in unstrained hydrothermal quartz.

B) Inclusion morphologies in strained hydrothermal quartz; notice the pronounced, angular apophyses and re-entrants indicative of bursting and resealing of the inclusions during their lifetime.

C) Trails of secondary inclusions in healed fractures cutting unstrained hydrothermal quartz which hosts primary inclusions, one of which can be seen near the top, left of centre of the picture.

Plate 1; SCHEMATIC REPRESENTATION



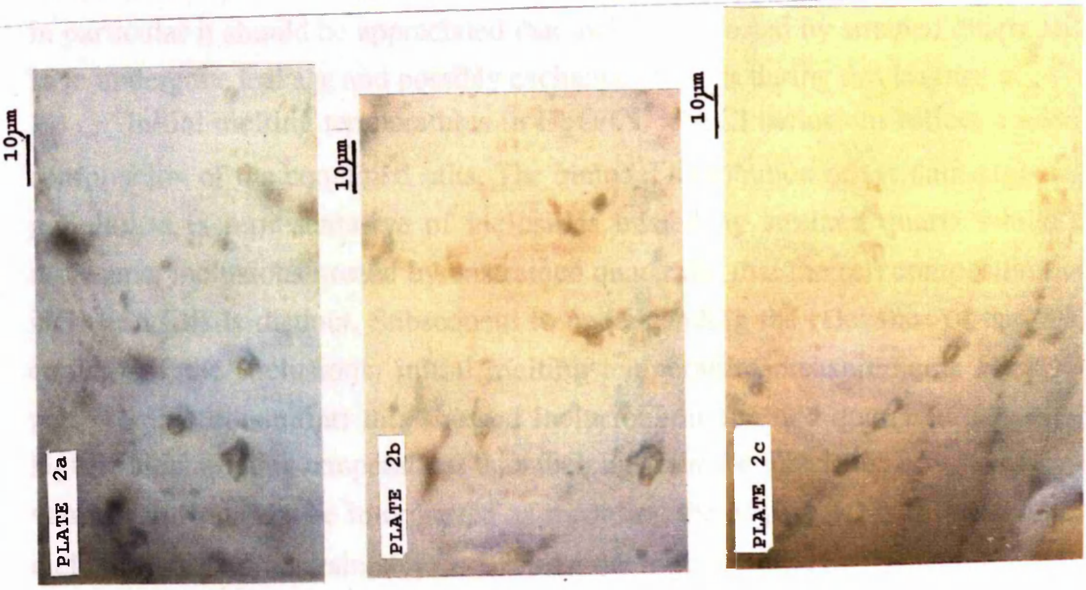


PLATE 2a
10µm
PLATE 2b
10µm
PLATE 2c
10µm

Initial Melting Temperatures; a wide data-spread is apparent, ranging between -39 °C and -13 °C, with a mean of -24.1 °C. Two sub-populations are crudely discernible, centred around -28 °C and -18 °C respectively.

Final Melting Temperatures; a single population is apparent with a mean of -9.7 °C and the bulk of the data ranging between -16 °C and -4 °C, with no significant skew.

Total Homogenisation Temperatures; data show two distinct populations, corresponding to the two varieties of hydrothermal quartz. Both show ranges of around 60 °C, with a mean of 218°C and a range between 170 and 240°C for strained quartz and a mean of 296°C and a range between 265 and 320 °C for unstrained quartz, with slight positive skews to both these populations.

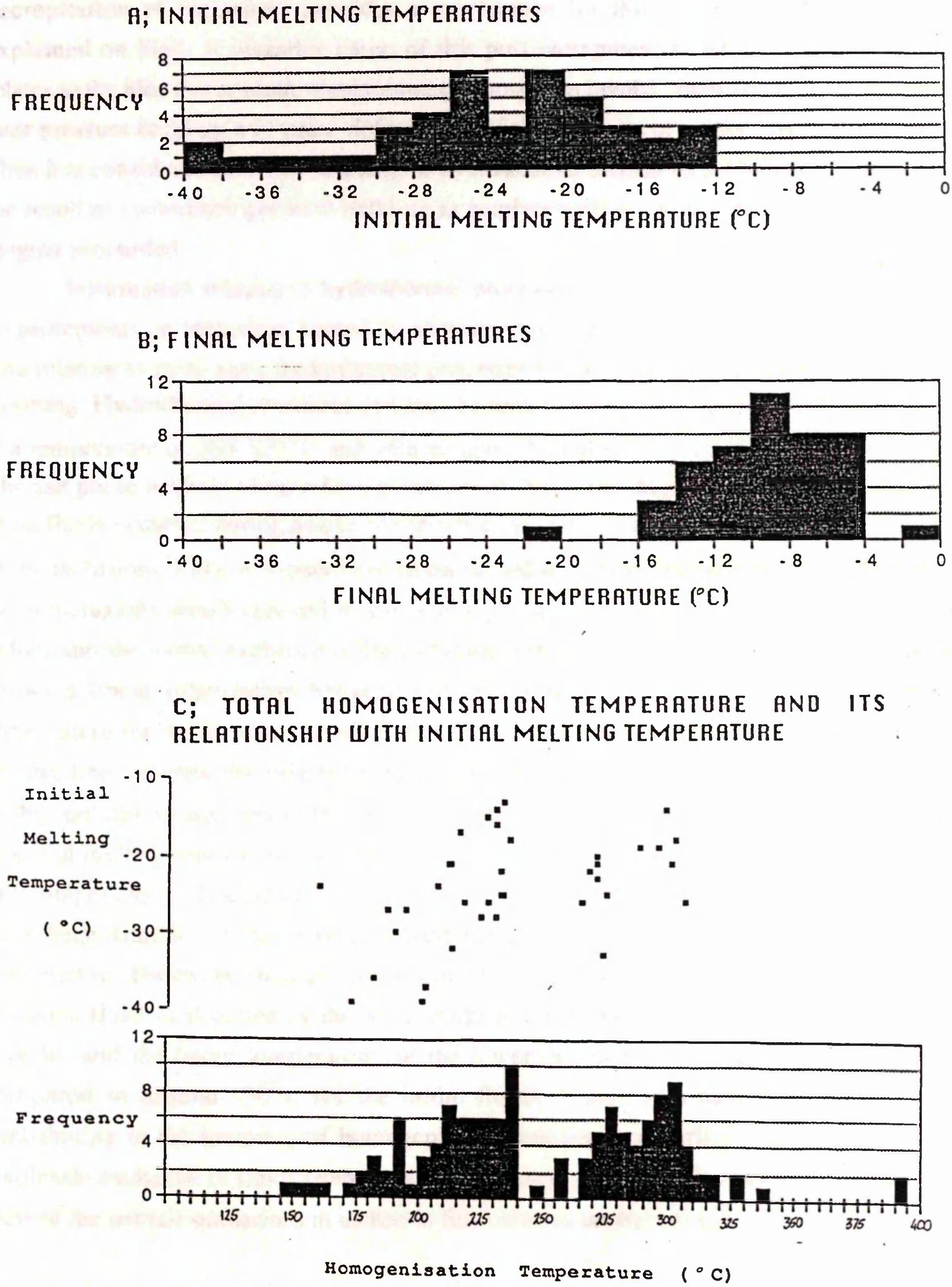
B)Interpretation

Interpretation of this thermometric data needs to be undertaken within the context of the observed variation in the strain state of the quartz and the morphology of the inclusions. In particular it should be appreciated that inclusions hosted by strained quartz are likely to have undergone leakage and possibly exchange of fluids during this leakage.

Initial melting temperatures in $H_2O/CO_2/NaCl$ inclusions reflect a wide range in composition of the contained salts. The bimodal distribution of the data suggests that one population is representative of inclusions hosted by strained quartz whilst the other represents inclusions hosted by unstrained quartz, ie. that the salt composition of the two inclusion fills is distinct. Subsequent to understanding the relevance of the petrographic context of the inclusions, initial melting temperature measurements were made with petrographic constraint; this showed inclusions in strained quartz to possess generally higher initial melting temperatures than their unstrained equivalents. Lower temperature T_{im} values can therefore be interpretted as recording the $MgCl_2$ + NaCl salt compositions of inclusion fills in unstrained quartz, whilst the higher values on Fig.3a represent the more NaCl/KCl dominated salt compositions of inclusion fills in strained quartz. Within the context of the idea of fluid exchange during straining of inclusions, this is interpretable as the exchange of an $MgCl_2$/NaCl dominated inclusion fill with an NaCl/KCl dominated exotic one.

Final melting temperature reflects the effective salinity of the inclusion fluid. The narrow overall range in values thus implies a narrow and similar range in salinities of both the original inclusion fluid and the exotic fluid. Thus final melting temperature has not been reset during stretching of inclusions and the exotic fluid with which the inclusion fluids mixed on bursting had a similar salinity. However, salinities derived from final melting temperature measurements on CO_2 bearing inclusions can only be interpretted as upper bound values on account of the exaggerating effect imparted by the presence of CO_2. This upper bound value can be taken here as 20wt% NaCl. More reliable salinity estimations derived from clathrate melting temperatures are discussed later.

FIGS 3 A-D; THERMOMETRIC CHARACTERISTICS OF INCLUSION FLUIDS IN HYDROTHERMAL QUARTZ, CRUACHAN CRUINN BRECCIA PIPES.



The wide spread in homogenisation temperature data and the two distinct sub-populations within this spread are a consequence of a single inclusion population which has been affected by non-pervasive strain. The lower temperature sub-population is derived from inclusions hosted by strained quartz whilst the higher temperature population is derived from inclusions hosted by unstrained quartz. Thus, the effect of this strain has been to lower the homogenisation temperature of the inclusions. The evidence for stretching, leakage and decrepitation of inclusions provides a mechanism for this change, as illustrated and explained on Fig4. A plausible cause of this post-entrapment straining of the inclusions relates to the idea that appinite emplacement is thought to involve multiple brecciation events; later pressure build up will cause deformation of the products of earlier brecciation events. Thus it is considered here that straining of hydrothermal inclusions at Cruachan Cruinn was the result of subsequent pressure build-up as emplacement of the next pulse of volatile-rich magma proceeded.

Information relating to hydrothermal processes will be derived from thermometric measurements on inclusions hosted by unstrained quartz, whilst strained quartz will yield data relating to these same hydrothermal processes but with the effects overprinted by later straining. Hydrothermal processes can thus be seen to have involved H_2O/CO_2 /salt fluids at a temperature of 265-320 °C and with an upper bound salinity of 20 equiv. wt% NaCl. The salt phase is likely to have been a mixture of NaCl and $MgCl_2$ salts. Effervescence of these fluids occurred during quartz precipitation, as evidenced by the variable CO_2 content of the inclusions. Later non-pervasive strain caused stretching, leakage and decrepitation of these inclusions which resulted in the resetting of homogenisation temperatures to lower values and the partial exchange of fluids between the inclusion and an exotic fluid. Fig.3c shows a linear relationship between homogenisation temperature and initial melting temperature for the strained inclusion population; this is interpreted here as representing a mixing line between the original inclusion fluids and the exotic fluids with which they exchanged during straining of the inclusions. This also adequately explains the wide spread in initial melting temperature data shown, through the mixing of two fluids with different salt compositions. The effective salinities of the inclusion fluid and the exotic fluid would have been similar, so this mixing would not produce a wide spread in final melting temperature. The exotic fluid contained a greater proportion of KCl salts than the original inclusion fluid, as depicted by the wider range in initial melting temperatures of this fluid (Fig.3c) and the lower temperatures at the lower extreme of this range (around -40^0C compared to around -30^0C for the initial fluid). It may also have been cooler, thus contributing to the lowering of homogenisation temperature during straining. However, wholesale exchange of fluids from the entire inclusion population is considered unlikely in view of the overall similarities in inclusion fills between unstrained and strained quartz.

Geobarometry

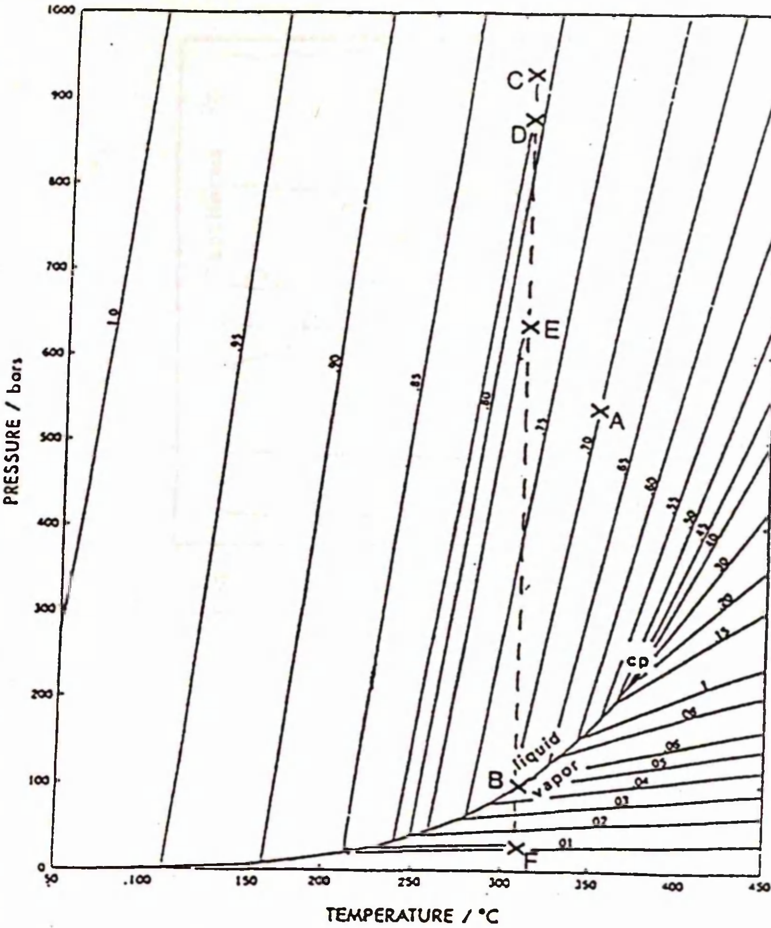
Variable CO_2 /H_2O ratios of inclusion fills in a single inclusion population can be taken as evidence for inhomogeneity of the fluid, caused by effervescence of CO_2 during quartz precipitation. They also provide a useful geobarometer, as described by Roedder

(1984) .CO_2 contents were derived by visual estimation for this study (for an assessment of the accuracy and reliability of such estimates see Chapter 5 where a pilot study was carried out in connection with another fluid inclusion study using a broadly similar inclusion population). Vol.% CO_2 data for Cruachan Cruinn inclusions are tabulated in Appendix 5. When CO_2/H_2O ratios and total homogenisation temperatures are plotted against one-another on the P-X plot shown on Fig.5b deductions can be made about the ambient pressure during hydrothermal quartz precipitation. The exercise was not carried out for inclusions hosted by strained quartz, since considerable resetting of this recorded ambient pressure is to be expected during any straining event (geobarometric measurements were made with petrographic constraint on host quartz type). The results are shown graphically on Fig.3e and define a data-field corresponding to an ambient pressure of 400-900bars. Geobarometric work by Hamidullah and Bowes (1987) using mineral assemblages in appinitic magmas themselves (in Appin) records gradual build-up of pressure to around 5kb prior to brecciation, with a sudden pressure drop to an less than 1kb on explosive brecciation. The two studies are therefore consistent. Brecciation does not result in the development of permeability connecting with the earth's surface; it is a vertically localised event. The pressure recorded is therefore liable to be a lithostatic one, and will correspond to a crustal depth of 1.85-3.3km. Thus, pressure build-up results in explosive brecciation and sudden pressure drop to a lithostatic value, at a crustal depth of 1.85-3.3km.

It should be pointed out however that Fig. 5 depicts the situation for the H_2O/CO_2 system. The addition of NaCl to this system causes substantial expansion of the CO_2 /H_2O immiscibility field (Bowers and Helgeson 1983), resulting in any pressure estimates derived by this method over the temperatures relevant here being underestimates. The additional uncertainty over the true salinity of the fluids at Cruachan Cruinn (upper bound 20 equiv.wt.% NaCl but including contributions from CO_2 as well as from salts) constitutes a further potential source of error in these pressure estimates. A better idea of the true salinity of the fluids can be obtained from measurement of clathrate melting temperatures. This was only appreciated late on in the fluid inclusion study, and ten token measurements were therefore made on inclusions in unstrained quartz in order to better constrain the effects of true salinity on geobarometric results. Clathrate melting temperatures were consistently between 7.5 and 9 C, which translates into salinities of between 2 and 6equiv.wt.% NaCl. Given these salinities and the homogenisation temperatures of inclusions in unstrained quartz of between 260 and 320 C, some under-estimation of the geobarometric results will result.Thus, pressure estimates and the derived palaeodepths at Cruachan Cruinn are poorly constrained; however, the consistency of these results with the barometric work carried out by Hamidullah and Bowes (1987) using silicate mineral pairs and the geochemistry of individual silicate phases in the appinitic magmas (see Fig 5A) implies that the geobarometric data from Cruachan Cruinn are not entirely unreasonable, so the two data-sets can be utilised to give an approximate crustal depth of brecciation and hydrothermalism associated with appinite emplacement.

Applying the pressure estimate of Hamidullah and Bowes (1987) to the Cruachan Cruinn thermometric data allows a pressure correction to be applied to homogenisation

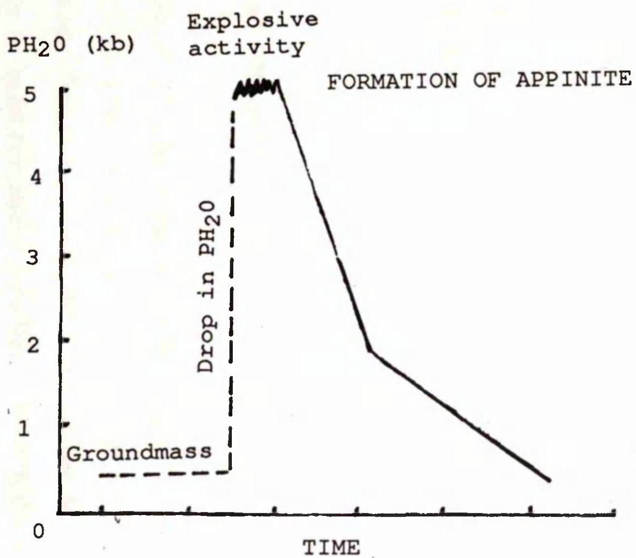
FIG. 4 ; GRAPHICAL ILLUSTRATION OF THE EVOLUTION OF FLUID INCLUSIONS DURING NON-PERVASIVE STRAIN, CRUACHAN CRUINN BRECCIA PIPE (for explanation see text)



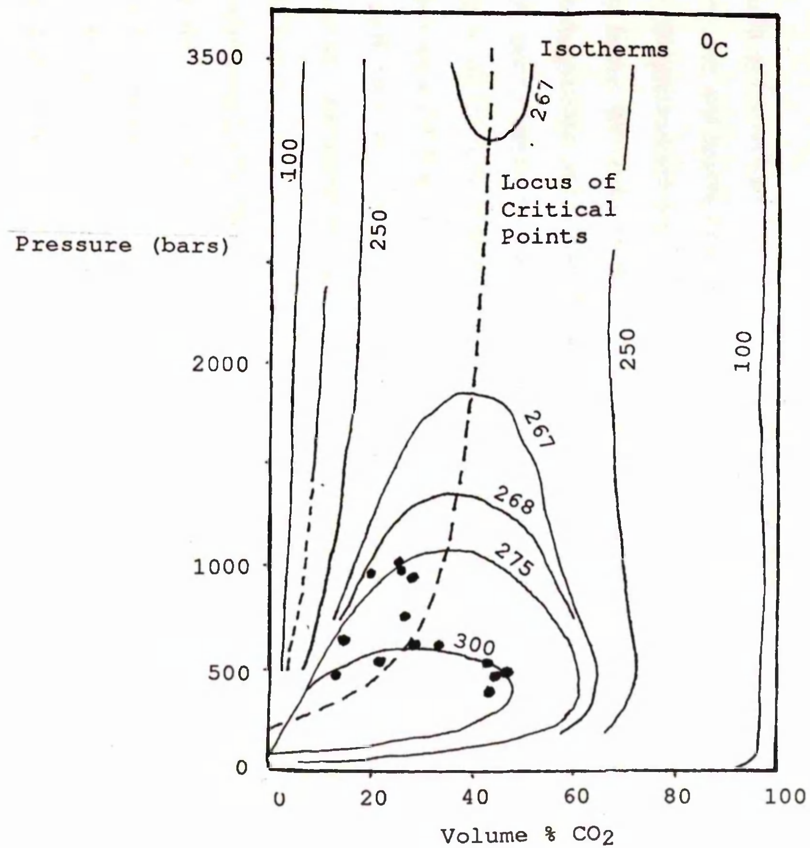
EXPLANATION; an inclusion is trapped at a pressure and temperature represented by point A. Cooling after trapping follows an isochoric path to B, where the inclusion fluid exsolves into the two phase state. The explanation focuses on point B as a reference point as this represents a measured homogenisation temperature. During straining of an inclusion at stage B, the dominant physical change will be a rise in pressure, represented by the vertical line between B and C. At a certain point, C say, the inclusion either bursts or stretches, and the density of the inclusion fluid decreases, causing the inclusion to follow a pathof decreasing pressure and density along CD. The inclusion reseals or re-equilibrates at its new density and pressure at point D, which is at a similar temperature to B, its state prior to straining. The length of the path CD will be variable; where it reaches E an inclusion of higher density than B will result; where it reaches F an inclusion of much lower density than B will result. These correspond to the filled and empty inclusions seen in the strained quartz. Both E and F, and all intermediate points, lie on different isochores to B, and thus show homogenisation temperatures lower than those in unstrained quartz., as a result of the effect of this strain on the form of the inclusions and the nature of the inclusion fluids.

FIG.5b; GEOBAROMETRY OF THE CALEDONIAN APPINITE SUITE

A) USING MINERAL ASSEMBLAGES IN MAGMATIC PHASE (AFTER HAMIDULLAH AND BOWES 1987)
BACK SETTLEMENT PIPE IN ARGYLLSHIRE, SCOTLAND TAKEN AS EXAMPLE



B) USING CO_2 BEARING FLUID INCLUSIONS IN CRUACHAN CRUINN BRECCIA PIPE (METHOD AFTER ROEDDER 1984)



temperatures of inclusions hosted by unstrained quartz (Potter 1987). This yields trapping temperatures of between 300 and 380°C for the hydrothermal fluids which precipitated this quartz.

The Origin Of The Fluids

The nature of the fluids at Cruachan Cruinn as revealed by fluid inclusion work has already been described; here we are interested in what these fluids represent. The close association of the breccias with igneous stocks and the occurrence of hydrothermal quartz as an interstitial phase within these breccias immediately suggests that the fluids which precipitated this quartz were magmatic, at least in the sense that they were derived from the adjacent magma. Whether all components of that fluid were of purely magmatic origin is a matter that is addressed later in the sulphur isotopic study. In the meantime the term 'magmatic fluid' will be used as a field term. On straining and leakage of inclusions this magmatic fluid exchanged with an exotic (ie. from outwith the inclusions themselves) one. The exotic fluid is difficult to characterise specifically, since it is nowhere uniquely preserved as inclusion fills; the nature of the fluid is discernible only on the basis of its effects on mixing with the initial inclusion fluid. The temperature of the exchanging fluid is thus indeterminate; its salinity is constrainable as similar to that of the initial fluid (<3.5wt.%NaCl) on the grounds that no spread in T_{fm} data is apparent on fluid exchange, and its salt composition is interpreted to be more KCl and less $MgCl_2$ dominated than the initial fluid on the grounds that a rise in initial melting temperature is apparent on fluid exchange.

The salinity recorded for this exotic fluid is higher than that usually interpreted as meteoric (<3.5equiv.wt% NaCl). The lack of any convincing evidence of a source of marine water since breccia formation, and the post-metamorphic timing of appinite emplacement (Rodgers 1992) preclude both marine and metamorphic fluids as likely sources of this later fluid. In the absence of these options, the fluid resident in the metamorphic pile during appinite emplacement must have constituted this exchanging fluid. Thus brecciation and mineralisation were the products of magmatic fluids, and later non-pervasive strain allowed exchange of this fluid with an ambient crustal fluid resident in the metamorphic pile at the time of appinite emplacement.

Gold Transportation And Deposition

The chemical means of gold transportation in hydrothermal fluids at Cruachan Cruinn and the mechanism for gold precipitation can be further constrained using the knowledge gained about these fluids from the fluid inclusion work. Most of the work carried out on gold solubility in hydrothermal fluids has considered the role of chloride and reduced sulphur complexing, as both are present in adequate concentrations in hydrothermal ore fluids and both form complexes with gold (Foster 1991). These are therefore considered the most likely contenders for the complexing agents responsible for gold solubility in hydrothermal fluids at Cruachan Cruinn. Comparison of data compiled by Seward (in Foster 1991) on equilibrium constants relating to the formation of $Au(HS)_2^-$ and $AuCl_2^-$ complexes shows that at the hydrothermal fluid temperatures derived from fluid inclusion work at Cruachan Cruinn, the sulphur complex is markedly more stable and therefore gold will be more soluble as a sulphur complex than as a chloride complex. Sulphur compounds are therefore considered the most likely gold complexing agent.It should be pointed out however that this analysis does not consider the pH of the fluids, which is known to affect the stability of both complexes but which is unconstrained by the fluid inclusion work on samples from Cruachan Cruinn.

The chemical behaviour of gold sulphur and gold chloride complexes on boiling and/or phase separation of hydrothermal fluids has been been considered by Seward (in Foster 1991). He considers adiabatic closed-system boiling in the Rotokawa geothermal field in New Zealand. This situation is analogous to that at Cruachan Cruinn insofar as no temperature change is apparent on effervescence and the whole process is considered to operate within the confines of a breccia-pipe which is not open to the atmosphere, so is in effect a closed system. Phase separation is shown to result in a dramatic loss of solubility of both gold-sulphur and gold-chloride complexes. At Cruachan Cruinn gold deposition would have occurred on reduction of gold-sulphur complex solubility which closely followed the effervescence of carbon-dioxide bearing hydrothermal fluids caused by explosive brecciation.

With the assumption that it was in fact sulphur complexing which facilitated hydrothermal gold transport, the origin of this sulphur becomes critical to understanding the processes of gold transportation through the crust. For gold to be assimilated into hydrothermal fluids as sulphur complexes, adequate sulphur must be previously available for complexing. A sulphur bearing fluid traversing a gold reservoir and assimilating gold as gold-sulphur complexes en route is envisaged. Alternatively, assimilation of country-rocks as xenoliths within an uprising magma will incorporate the contained gold and sulphur. In both cases the process will involve contamination of original original magmatic or hydrothermal sulphur with crustal sulphur. The final composition of this sulphur will thus record the original magmatic/hydrothermal composition plus any crustal contamination effects. The gold reservoir tapped by the uprising magma and/or hydrothermal fluid will be somewhere within the emplacement path of the magma/fluid. The final sulphur composition may then provide clues to the nature of this gold reservoir. The isotopic composition of sulphur has been shown by Lowry (1992) and Laour (1991) to distinguish crustal provinces through which the Newer Granites have been emplaced. A similar treatment of the appinite suite may reveal similar information and in so doing help to elucidate the nature of the gold reservoirs tapped during emplacement. A sulphur isotopic study of the Caledonian appinite suite was therefore initiated.

Appinites can be described as 'volatile-rich magmas' and as such they constitute a hybrid magmatic/hydrothermal metallogenic system, and it is this hybrid system which is considered responsible for gold transportation through the crust. Whether gold and sulphur are transported in the magmatic or the volatile phase is not actually known. However it is considered that the two components of this hybrid system will become more distinct as emplacement proceeds; uprise through the crust will involve a progressive lowering of overburden pressure which will encourage the separation of a volatile phase from the magma. At deeper crustal levels, then, magmatic processes will be predominant in the assimilation of gold and sulphur from crustal rocks, whilst at higher crustal levels hydrothermal processes will gain in importance. The overall effect for the hybrid system as a whole, as concerns its final sulphur composition and gold content, will be the same. Within this system, the enhanced gold grades recorded from the breccias but not from the magmas suggests that at higher crustal levels gold partitions into the hydrothermal part of the system. Sulphur remains in both the hydrothermal and the magmatic phase, as evidenced by the presence of sulphides within both breccias and the igneous rocks. No wholesale alteration of the igneous phase is observed, so the sulphides hosted by the igneous phase are considered to be a primary constituent of the appinite rather than a product of hydrothermal flushing of the rock. Some isotopic fractionation of sulphur between the hydrothermal and magmatic parts of the system may occur. In order to investigate this, the sulphur isotope study was not confined to the breccia materials but incorporated the associated magmas as well.

CHAPTER 2

SULPHUR ISOTOPIC VARIATION WITHIN THE CALEDONIAN APPINITE SUITE OF SCOTLAND AND IRELAND; A RECONNAISSANCE STUDY

Introduction

Given that sulphur is considered, for solubility reasons (see Chapter 1), to be the most likely complexing agent responsible for hydrothermal gold transport at Cruachan Cruinn, the source of this sulphur is important metallogenetically and may provide indirect clues as to the source of the gold. Given also the field evidence for the consistent nature of sulphide mineralization associated with the appinites, which suggests a consistent mode of formation at the local scale , the fact that only one such locality is gold mineralized points to a difference between the mineralizing systems that is not discernible at the local scale. The difference is more likely to be a product of the entire emplacement process, including initial generation of the magma, traversing and tapping of deep and mid-crustal rocks, crustal ponding and explosive brecciation. The best way to study processes is to consider the suite as a whole and how variations in these individual factors affect the end product. To this end a regional sulphur isotopic reconnaissance of the Caledonian appinite suite was initiated using sulphide samples collected during the prospecting phase of the work. Regional coverage of these samples was good, and included the best known clusters of appinitic rocks, ie. the Appin, Colonsay, Arrochar and Donegal clusters. Good lithological control was achieved by sampling from both the breccia pipes and the associated igneous stocks, allowing the study of internal process control of sulphur isotopic values between different associations of sulphides hosted by appinitic rocks.

The samples used for this study are listed on Table 1 and their localities shown on Figs 1 and 2. For localities from which more than one sample was analysed, the suffix ig on Table 1 refers to pyrite hosted by the igneous phase whereas all others were sampled from breccia-pipes. Sulphide concentrates were obtained by crushing the rocks to one inch chip size and drilling by hand, and their purity was checked by XRD analysis. Sulphur isotope analyses were performed at SURRC using the method of Robinson and Kusakabe (1975) and an Isospec 44 mass spectrometer for final analysis. The results are shown on Table 1 and are illustrated graphically on Fig 5 after being subdivided according to the the specific host to the sulphide sampled, ie. igneous or breccia phase. Statistical analyses of the results are presented on Table 1B.

The data set for both the igneous and breccia hosted sulphides shows one main data cluster, occupying the ranges -1.0 to 6.1‰ (mean 4.4‰) and 0.8 to 9.2‰ (mean 5.4‰) and respectively.The positions of these clusters deviate from the expected sulphur isotopic value for basic igneous rocks as shown on Fig.5, though only by 3-5‰ . Laoar (1990) and Lowry (1992) reported $\partial^{34}S$ values for the Newer Granites which deviated from mantle signatures, and interpreted this as being due to contamination by crustal sulphur from the rocks through which the granites were intruded. By analogy, the data forming the main clusters here are interpretted as due to crustal contamination of an original mantle signature. In addition to these main data clusters a few anomalous points and one anomalous cluster are recognisable. Igneous hosted pyrite from Cruachan Cruinn shows an unusually light $\partial^{34}S$ signature, implying that this crustal contamination is not apparent. Anomalously light signatures are also shown by a cluster of data for the breccia hosted sulphides comprised of analyses from Cruachan Cruinn breccia-pipes and the South Cuill breccia pipe in Appin. A further one-point anomaly exists for the Ardara breccia in Donegal which shows a substantially heavier signature than the main data-set. It is the cause of the contamination and the generation of the anomalous values which is the target of this study.

THE NATURE OF THE SULPHUR ISOTOPE PROBLEM

The overall conclusion that can be reached from the sulphur isotope characteristics of appinites just described is that the original mantle signatures have been altered to slightly more crustal values. A similar conclusion was reached by Laouar (1990) for the related Newer Granites and was interpreted as the result of contamination of mantle sulphur by crustal sulphur during emplacement. A marked provinciality was noted by Lowry (1992), the main control on which was the nature of the crust being intruded, and a similar provinciality is noted by Halliday for Sm-Nd and U-Pb isotopic systematics. The data for the appinites presented here is nowhere near as comprehensive as that gathered by these previous authors and is in particular limited to appinites currently exposed within the Dalradian metamorphic pile. The interpretation is therefore necessarily limited to a comparison with the conclusions reached from these previous studies. It is the source of this contamination which is the subject of this investigation, and also the variation in the degree of contamination; it is to be hoped that an explanation can be found for the anomalous (within this data base at least) sulphur isotopic characteristics of the cluster of appinites at Cruachan Cruinn which interestingly enough are also anomalously gold bearing. It is therefore necessary to evaluate the nature and isotopic characteristics of the sulphur sources within the crust believed to be responsible for contamination.

CRUSTAL SULPHUR SOURCES

In assessing the sulphur budget of the rocks traversed by the appinites during emplacement the major components that must be considered are;

1) Mantle rocks-the original source of the magma

2) Deep crustal material beneath the Dalradian metamorphic pile.

3) The Dalradian metamorphic pile, including all mineralised and unmineralised lithologies.

with the necessary prerequisite that they were present on the emplacement path of the appinite prior to their intrusion date of 419-431Ma (Rodgers 1991).

The relative juxtaposition of these various rocks is also of crucial importance to whether they will be available for assimilation by an uprising magma. In the case of deep crustal rocks this will depend on large scale tectonic processes and the evidence will come

TABLE 1 : SULPHUR ISOTOPIC DATA FOR APPINITES FROM SCOTLAND AND IRELAND

LOCALITY	MINERAL	d34S	
Glen Charnain	pyrite	7.31	
Cruachan Cruinn 2	pyrite	o.755	
Cruachan Cruinn 4	pyrite	2.184	
Cruachan Cruinn 1	pyrite	1.588	
Cruachan Cruinn Ig	pyrite	-0.99	ARGYLLSHIRE, SCOTLAND
Kiloran Bay1	pyrite	8.19	
Balnahard ig	pyrite	6.001	
Kiloran Bay 7 ig	pyrite	5.849	
Scalasaig ig	pyrite	3.389	
Inshaig Ig	pyrite	6.12	
Ardsheal	pyrite	6.08	
Ardsheal Ig	pyrite	4.72	
Ardsheal Ig 2	pyrite	5.107	
Adamanns	pyrite	6.966	
Back Settlement	pyrite	9.004	
Back Settlement Ig	pyrite	5.081	
South Cuill	pyrite	2.356	
South Cuill Ig	pyrite	5.873	
Back Settlement Ig	pyrite	4.931	
Crannogboys	pyrite	9.208	
Narin Shore	pyrite	5.17	DONEGAL, IRELAND
Portnoo	pyrite	7.77	
Kilkenny ig	pyrite	4.397	
Ardara	pyrite	18.44	

Ig refers to the igneous phase, all others are from breccia pipes

TABLE 1B; SUMMARY STATISTICS OF SULPHUR ISOTOPIC SIGNATURES OF APPINITIC ROCKS AND THEIR ASSOCIATED BRECCIAS FROM SCOTLAND AND IRELAND.

	n	mean	std.dev.	range
IGNEOUS PHASE	11	4.58	2.02	-1.0 to +6.1
BRECCIA BODIES	13	6.55	4.61	0.75 to 18.4

largely from analyses of deep seismic profiles and other geophysical techniques (Hall 1985), which provide indirect information on rocks not exposed at the surface. For Dalradian rocks, the availability for assimilation will be determined by their presence or absence within the emplacement path of the appinite. This will be a function of the current stratigraphic position of the exposed appinite, the large scale structure of the metamorphic pile and the post-metamorphic erosion level. The emplacement path of the appinites is here considered from the deepest up.

Mantle Sulphur

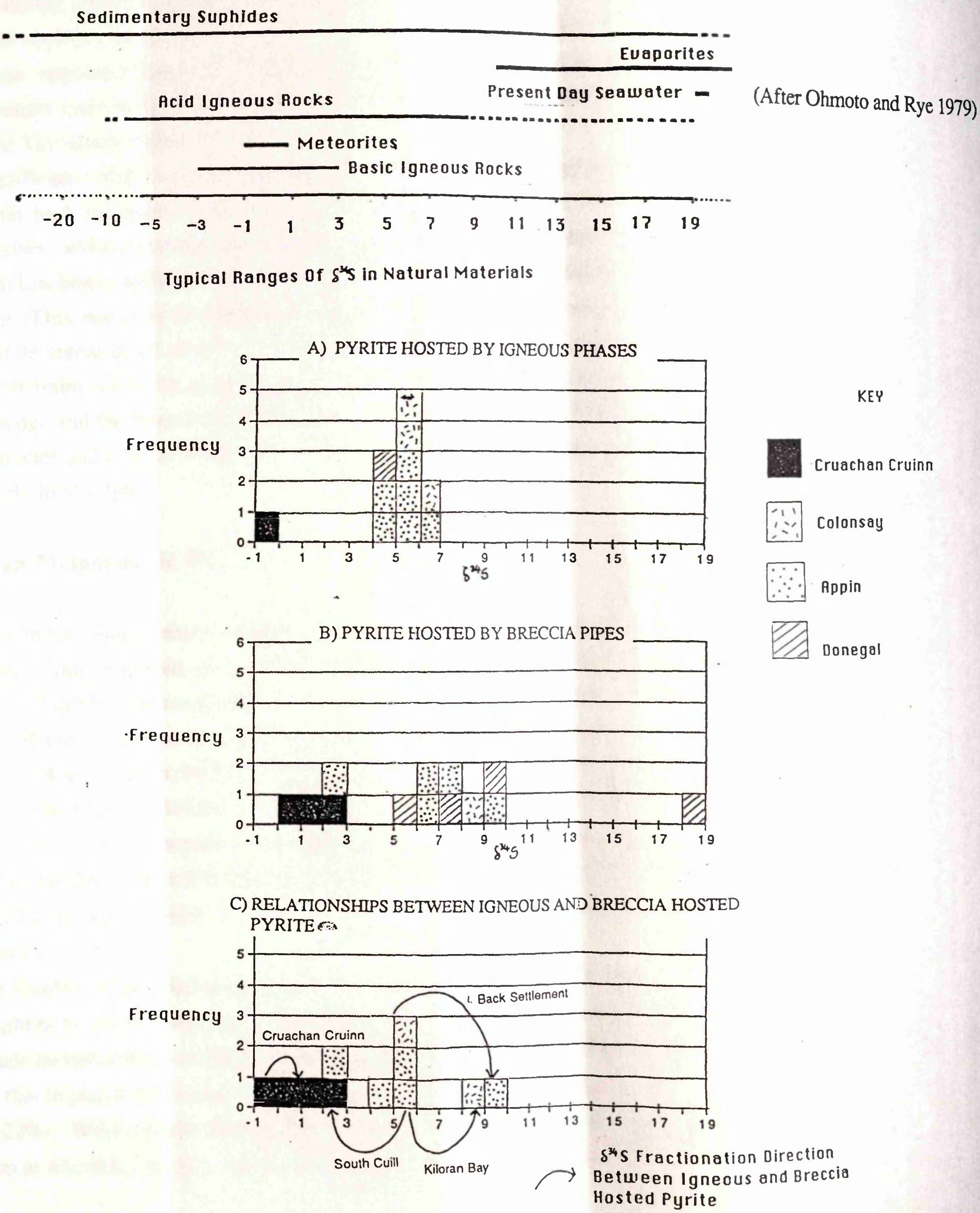
The sulphur isotopic composition of the mantle has been regarded as occupying the range 0+/-2. Some uncertainty remains however, and a degree of heterogeneity is now considered likely due to the incorporation of crustal sulphur during subduction. Chaussidon et al (1987) report $\partial^{34}S$ values from sulphide inclusions in diamonds from kimberlites of between +1 to +9.5‰. Appinites, being mantle-derived rocks are thus likely to have original sulphur isotopic signatures of 0+/-2 ‰ but with similar uncertainty. A north-south chemical zonation of the mantle underneath Scotland revealed by analyses of mantle xenoliths (Halliday 1985) is a further source of such heterogeneity, but its likely effects on sulphur isotopic systematics is not known.

Deep Crustal Sulphur

Constraint on the nature of the crust at depth beneath the Dalradian metamorphic pile is largely geophysical, with the evidence summarised by Hall (1985). The bulk of Scotland north of the Highland Boundary Fault is considered to be underlain by crust of Lewisian affinity, with a wedge of strongly seismically reflective material underneath the Southern Highlands (Fig 6). This wedge is thought to be of mafic composition, it thickens towards the south-east and has been explained as a slice of subducted oceanic crust related to the closure of the Iapetus Ocean. This layer and the crust as a whole are believed to be thinnest under the Islay Dalradian and thickest towards the Highland Border. Also significant is the recognition of the Cruachan Lineament and the suggestion that it separates basement rocks of different natures, with greater volumes of Caledonian Granite to the NE and a significantly greater proportion of basic volcanics and intrusives to the SW. Samples used in this study are from both sides of this lineament; Appin samples are to its NW, Colonsay samples to its SE, and Cruachan Cruinn lies directly above the proposed deep crustal lineament.

Hallidays' Mid Grampian Line may have significance to the Dalradian sulphur budget. It basically marks the Palaeozoic/Proterozoic boundary, and represents a time when rifting and lithospheric separation started, resulting in the deposition of the Upper Dalradian on the cumulates and plutonic root zones of the Tayvallich Volcanics (Russell 1985). Thus,

Fig. 5 SULPHUR ISOTOPIC DATA FOR CALEDONIAN APPINITES OF SCOTLAND AND IRELAND COMPARED WITH TYPICAL RANGES OF $\delta^{34}S$ IN NATURAL MATERIALS.



south of this line a greater proportion of igneous material will be present in the crust. This conclusion is roughly in line with the geophysical evidence presented by Hall (1985) which points to a greater proportion of igneous material in the deep crust to the SW of the Cruachan Lineament. In terms of the provinciality defined by Sm-Nd and U-Pb isotopic systematics (Halliday 1984) , Cruachan Cruinn appinites lie in the Southern Highland field while the Appin appinites lie in the Argyll field as defined by Halliday (1987). Thus the Cruachan Cruinn appinite cluster was the only one out of this sample set to be intruded through the younger crust to the SW of the Mid-Grampian Line and the underlying mafic root zones of the Tayvallich Volcanics.

The significance of the various deep crustal rocks to the overall sulphur content of the crust is that both the mafic rocks forming the deep crustal wedge and the basic volcanics/intrusives which constitute a substantial proportion of the lower crust to the south of the Cruachan Lineament and/or the Mid Grampian Line will form substantial reservoirs of mantle sulphur. This reservoir is therefore likely to be dominated by sulphur with a primordial mantle signature of close to 0‰. Its contribution to the total sulphur budget available for contamination of the uprising appinite will be a function of the local thickness of the mafic wedge and the proportion of basic material in the lower crust. Deep crust of a non-mafic character and a lower crust with less basic material will not form a reservoir of such distinctively light sulphur.

The Dalradian Metamorphic Pile

Most of the sulphur isotopic work carried out in the Dalradian to date has been on mineralised and unmineralised rocks of the Argyll Group, largely on account of the preponderance of sulphide mineralization, mainly of the stratabound variety, which has made this part of the succession of interest to economic geologists. Some work has been done outwith the Argyll Group; Hall (1987) reports analyses of sulphides from the Appin Group Ballachuilish Slates which are of particular relevance here since they form the host rocks to one of the clusters of appinites sampled for this study. Pyrite in these slates shows $\partial^{34}S$ of +15‰ (+/-2‰) which is thought to be inherited from precursor pyrrhotite of either evaporitic sulphate origin or, more likely (Hall, pers. comm.) bacteriogenic sedimentary pyrite

In the Easdale Slate (Hall et al 1987) pyrite porphyroblasts have $\partial^{34}S$ of +12 to +16‰ , thought to be the product of of retrogressive metamorphism of pyrrhotine formed during prograde metamorphism of diagenetic pyrite. Preservation of some of the diagenetic pyrite shows that in places the metamorphic effects are not apparent, and in such cases $\partial^{34}S$ pyrite was +22‰ .Willan and Coleman (1983), whilst studying the host rocks to baryte mineralization at Aberfeldy showed sulphides in unmineralised schists to have $\partial^{34}S$ of -5.7 to+16‰.

Mineralization Hosted By The Dalradian Metamorphic Pile

Another major sulphur source within the Dalradian is the contained stratabound sulphide and sulphate mineralizations within the metamorphic pile. Later cross-cutting and vein filling sulphide mineralization is sometimes related to intrusion of post-metamorphic granites and is younger than the emplacement date of the appinite suite; thus this sulphur is not available for assimilation by the appinites and does not figure in this analysis.

The main types of sulphur-bearing mineralization hosted by Dalradian rocks are the massive synsedimentary Ba/Pb/Zn type typified by the Foss baryte deposit, the smaller Pb/Zn showings found in Argyll Group rocks and the laterally extensive stratabound pyrite horizons of the Central Highlands. Willan and Coleman(1983) compile data from the Aberfeldy Ba/Pb/Zn deposits and other strata bound deposits. At Aberfeldy they show that the bulk of baryte sulphur has a heavy isotopic signature of +27 to +36‰ derived by mixing of a hydrothermal brine with Vendian seawater. Sulphide sulphur signatures from the deposit are also heavy ($\partial^{34}S$ = +18 to +28‰) and are considered to be hydrothermal in origin. Unmineralised schists, both here and elsewhere have contrastingly light sulphur signatures of -5.7-+16 which is believed to be of bacteriogenic origin. (Scott et al 1991 and Willan and Coleman 1983). Similarly, at the stratigraphically equivalent Beinn Heasgarnich locality, Scott et al show $\partial^{34}S$ sulphide of +13.4 to +18‰ and $\partial^{34}S$ baryte of +26 to +28‰ . They interpret the latter as indicating an original sulphur source in Dalradian seawater, with the isotopic signature later modified by exchange with a reduced H_2S bearing metamorphic fluid . Sulphide sulphur $\partial^{34}S$ values are interpreted as indicating a sulphur source in the underlying strata.

Other minor base-metal rich iron sulphide mineralizations in the Dalradian also have comparatively light $\partial^{34}S$ of -4.3-+0.4 (Willan and Coleman 1983) and are thought to be derived from the leaching of basic rocks at depth in the sedimentary pile. Scott et al (1991) analysed sulphides from unmineralised and mineralised lithologies within the Argyll Group. Unmineralised material from the volcanogenic Ben Lawers Schist, including the pyrite horizon showed $\partial^{34}S$ of -4 to +4‰ reflecting the igneous origin of these sulphides, though some analyses outwith this range (Willan 1983) are thought to indicate zones of localised hydrothermal convection and exhalation. The Auchtertyre horizon showed values of +5 to +11‰ , consistent with a seawater sulphate source for the sulphur. Sulphides in the Ben Challum Quartzite Formation show tightly clustered $\partial^{34}S$ values of around =11 per mill, interpreted as implying a seawater sulphate original source for sulphur with $\partial^{34}S$ being buffered by anhydrite in the underlying calcium-rich rocks.

The contribution of stratabound sulphides to the overall sulphur content of the Dalradian is, then, variable in isotopic composition. Massive Ba/Zn/Pb deposits contribute heavy sulphur whilst minor base metal showings provide relatively light sulphur and stratabound sulphides hosted by volcanogenic formations are characteristically light in isotopic composition. The greatest concentration of sulphide and sulphate mineralization within the Dalradian is within the Argyll Group. The presence or absence of such rocks, and especially any mineralization they contain, on the emplacement path of the appinite will significantly affect the overall isotopic composition of the sulphur available for assimilation on account of the relatively high concentrations of sulphur in such lithologies.

Stratigraphic Distribution Of Dalradian Sulphur Sources

Available data show then that the sulphur content of the Dalradian metamorphic pile is of diverse origins. The database is however incomplete in terms of both along-strike and stratigraphic coverage. The best effort that can be made to build up a picture of the sulphur budget of the metamorphic pile as a whole is to take what is known and, by analogy, broadly predict the isotopic characteristics of the rocks for which no analyses have been done. To this end the various lithologies can be assigned a sedimentary, volcanogenic or mineralised affinity. Sedimentary sulphides from unmineralised lithologies show $\partial^{34}S$ values of 9-22‰ (Hall et al(1987) and Scott at al (1991)) and thus by analogy sulphides from all such hosts are likely to show such signatures. Volcanogenic lithologies host sulphides of $\partial^{34}S$ = -3.5 to+3.9‰ (Scott et al 1991) and so volcanogenic hosted sulphides within the Dalradian as a whole can be assigned this range of values. Sulphide and sulphate mineralizations show two groupings; one showing $\partial^{34}S$ sulphide of +18 to +22‰ and $\partial^{34}S$ baryte of +27 to +36‰ , the other showing $\partial^{34}S$ sulphide of -5.7 to +16‰ (Willan and Coleman 1983), and by analogy all known and as yet undiscovered or subcropping mineralization can be assumed to fall within one or other of these ranges.

With this assumption to hand the overall sulphur content of the crust at the time of appinite emplacement can be assessed by considering the stratigraphic distribution of the various lithologies within the metamorphic pile. Up to Argyll Group times the Dalradian rocks are overwhelmingly, if not exclusively, of sedimentary origin and so the sulphur budget for this part of the pile should have a composition of +9 to +22‰ $\partial^{34}S$. Around Argyll group times crustal breakup was initiated leading to volcanism, with the Ben Lawers Schist Formation the first of the major volcanic units. From this point on an increasing degree of volcanism resulted in greater and greater proportions of volcanogenic material within the metamorphic pile, which continued through the Upper Dalradian. Sulphides hosted by the Ben Lawers Schist show $\partial^{34}S$ of 0 to +4‰ (Scott et al 1991) and this relatively light signature can be assigned to the igneous material in general. This therefore points to a substantial lightening of the bulk sulphur content of the crust during Middle and Upper Dalradian times. The preponderance of stratiform mineralization within the Argyll Group will introduce a component of heavy sulphur of $\partial^{34}S$ and a component of moderately light sulphur of $\partial^{34}S$ to the metamorphic pile at around its stratigraphic middle. The inheritance of sulphur isotopic compositions of premetamorphic origin in what are now greenschist facies rocks (eg sedimentary signatures reported by Hall et al 1987 and 1988 for the Easdale Slate near Oban, igneous signatures in the volcanogenic pyrite horizon (Scott et al 1991), and hydrothermal/sedimentary/bacteriogenic derivation in Ba/Pb/Zn deposits) is evidence that this stratigraphic distribution of isotopic compositions has not been homogenised on the large scale by metamorphic processes.

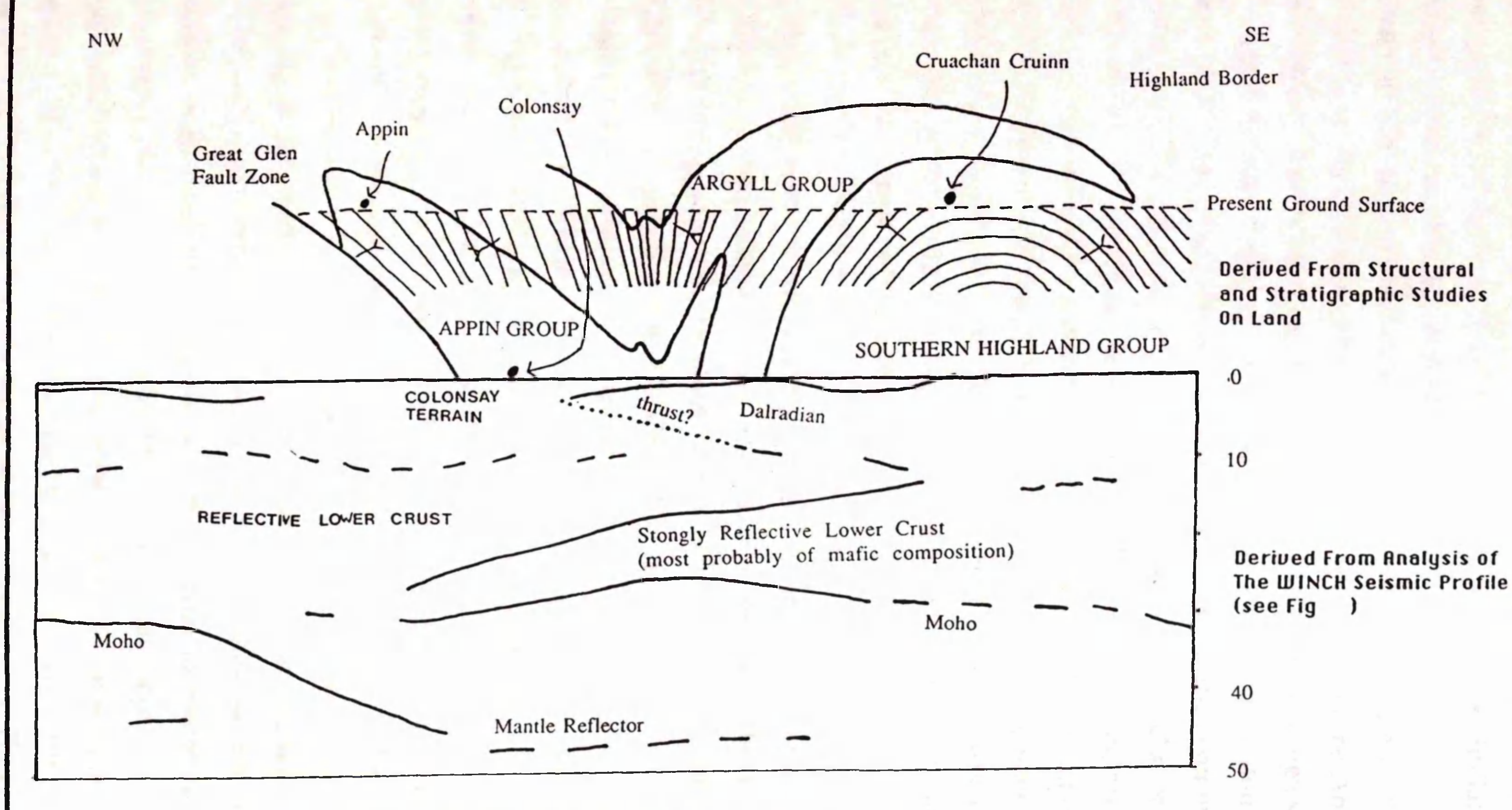
Regional Structural Control On The Dalradian Sulphur Budget

Any igneous body being intruded through the whole package of Dalradian rocks could tap all the sulphur sources identified above. However, structural complexity caused by the Grampian orogeny and subsequent denudation of the metamorphic pile mean that this whole package is nowhere completely preserved, and what lithologies are preserved are juxtaposed in a complex manner. The package of rocks traversed by the appinite will be a function of the large scale structure of the metamorphic pile and the present erosion level. The top part of Fig.6 shows a structural cross-section through the Dalradian according to current structural/stratigraphic studies. The overall picture at the current erosion level is of a large scale antiformal syncline in the SE, a very steeply dipping belt in the centre and a large scale antiformal anticline in the NW near the Great Glen Fault. The implication of this in the present context is that the rocks get stratigraphically younger with depth in the Southern Highlands but generally get older with depth in all other parts. Thus the Cruachan Cruinn appinites have been intruded through Upper Dalradian rocks while the Appin appinites have been intruded through Lower Dalradian lithologies. Colonsay appinites have been intruded through what is known as the Colonsay Terrain and whose affinity is the source of much debate. In sulphur isotopic terms then, Cruachan Cruinn appinites have traversed the volcanogenic rich part of the metamorphic pile whilst those at Appin have traversed the sedimentary dominated part of the Dalradian.

Large scale structure of the Dalradian is less well constrained in Ireland than in Scotland, but correlative structures to the Tay Nappe, the Loch Awe Syncline and perhaps the Islay Anticline are recognisable (Pitcher and Berger 1972). The Donegal appinites can be regarded as occupying a similar stratigraphic/structural position as the Appin cluster. Indeed, individual lithologies hosting the Donegal appinites sampled for this study are able to be correlated directly with Dalradian lithologies of the Ballachuillish area (Pitcher and Berger 1972). In addition, the position of the Donegal appinites with respect to the WINCH seismic profile (Hall 1985) implies that the Dalradian in this part of Ireland overlies a relatively thin, deep crustal mafic wedge. Overall then, the Donegal appinites can be considered to have been intruded through crustal material broadly comparable with that through which the Appin cluster has been intruded.

The lower half of Fig 6. shows the current view of the deep crustal structure beneath the Dalradian. The whole emplacement path of the various appinites is thus shown. Appinite emplacement was demonstrably post Grampian orogenic deformation (Rodgers 1992) and no major crustal deformation has affected the Dalradian metamorphic pile since. Post-deformational modification of the metamorphic pile was restricted to the intrusion of the Newer Granite suite and related hydrothermal activity, which closely followed appinite

FIG. 6 UPPER AND DEEP CRUSTAL STRUCTURE OF THE SOUTHERN HIGHLANDS OF SCOTLAND (modified after Anderton et al 1984 and J.Hall 1985) WITH SCOTTISH APPINITES SAMPLED FOR THIS STUDY MARKED.



Note; lower half of diagram drawn from an analysis of the WINCH seismic profile, shown on Fig. . Colonsay Terrain wedges out along strike into diagram, being replaced by the Dalradian rocks shown on the upper half of the diagram at Appin and Cruachan Cruinn.

emplacement. Fig. 6 is therefore representative of the structural configuration of the metamorphic pile after deformation but before granite emplacement; it can therefore be taken as representative of the state of the metamorphic pile at the time of appinite emplacement, and the analysis which follows is made on this basis. The Scottish appinites sampled for this study are marked on Fig.6, and an assessment of the rocks traversed and their likely sulphur isotopic characteristics can be made from consideration of Fig.6 and the above discussion. An appraisal of the overall sulphur budget available for assimilation by the magmas can thus be made, and this will now be attempted.

This analysis reveals a marked difference in the isotopic nature of the sulphur available for assimilation by the three clusters of Scottish appinites. For the Appin cluster this includes a relatively thinned deep mafic layer and all Dalradian lithologies up to and including the Appin Group, a part of the succession overwhelmingly dominated by isotopically heavy sedimentary and bacteriogenic sulphur. The deep mafic layer provides the only source of light sulphur on this emplacement path. The Colonsay cluster is located above the thinnest part of this mafic layer (Hall 1985) and a metamorphic pile of controversial affinity. Appinites at Cruachan Cruinn on the other hand are positioned above a relatively thick mafic deep crustal layer They are currently exposed in Southern Highland Group rocks which are regionally inverted. They have thus traversed the volcanogenic rich Upper Dalradian and a thick mafic wedge underneath. A relatively large igneous contribution to the sulphur content of this part of the crust is envisaged

A possible explanation for the sulphur isotopic characteristics of the appinites is suggested by this difference in the sulphur content of the crust traversed during emplacement. The crustal contamination which is invoked to produce the heavy signatures for most of the appinites sampled is the result of traversing crust dominated by heavy sulphur. Anomalously light signatures from Cruachan Cruin are the product of emplacement through a package of rocks with much greater proportions of igneous rocks and light sulphur, giving markedly less opportunity for contamination by heavy crustal sulphur and hence allowing preservation of the original mantle signature of the appinite.

The sulphur isotopic systematics of the appinite suite are therefore controlled by the crust through which they have been intruded. Those intruded through the thin mafic deep crustal wedge towards the NW and through a metamorphic pile dominated by sedimentary sulphur show contamination of an original mantle signature by crustal sulphur. Those intruded through the thicker part of the mafic wedge and middle and upper crust with a substantial igneous component show less contamination by heavy sulphur. The distribution of the crustal sulphur budget available for assimilation by the appinites is controlled by large scale tectonic processes. Thus the break-up of the shelf in middle and upper Dalradian times resulted in significant volcanism, now preserved within the metamorphic pile, and in the deposition of these rocks above mafic cumulates and eventually oceanic crust. Subsequent subduction caused underthrusting of a mafic wedge at deep crustal levels. The composition of the middle and upper crust thus changes dramatically across the Mid-Grampian Line and the underthrust mafic wedge thins in the direction of subduction. The resultant overall change in nature of the crust results in a change in its sulphur content which is reflected in the degree of contamination of appinitic rocks intruded through it.

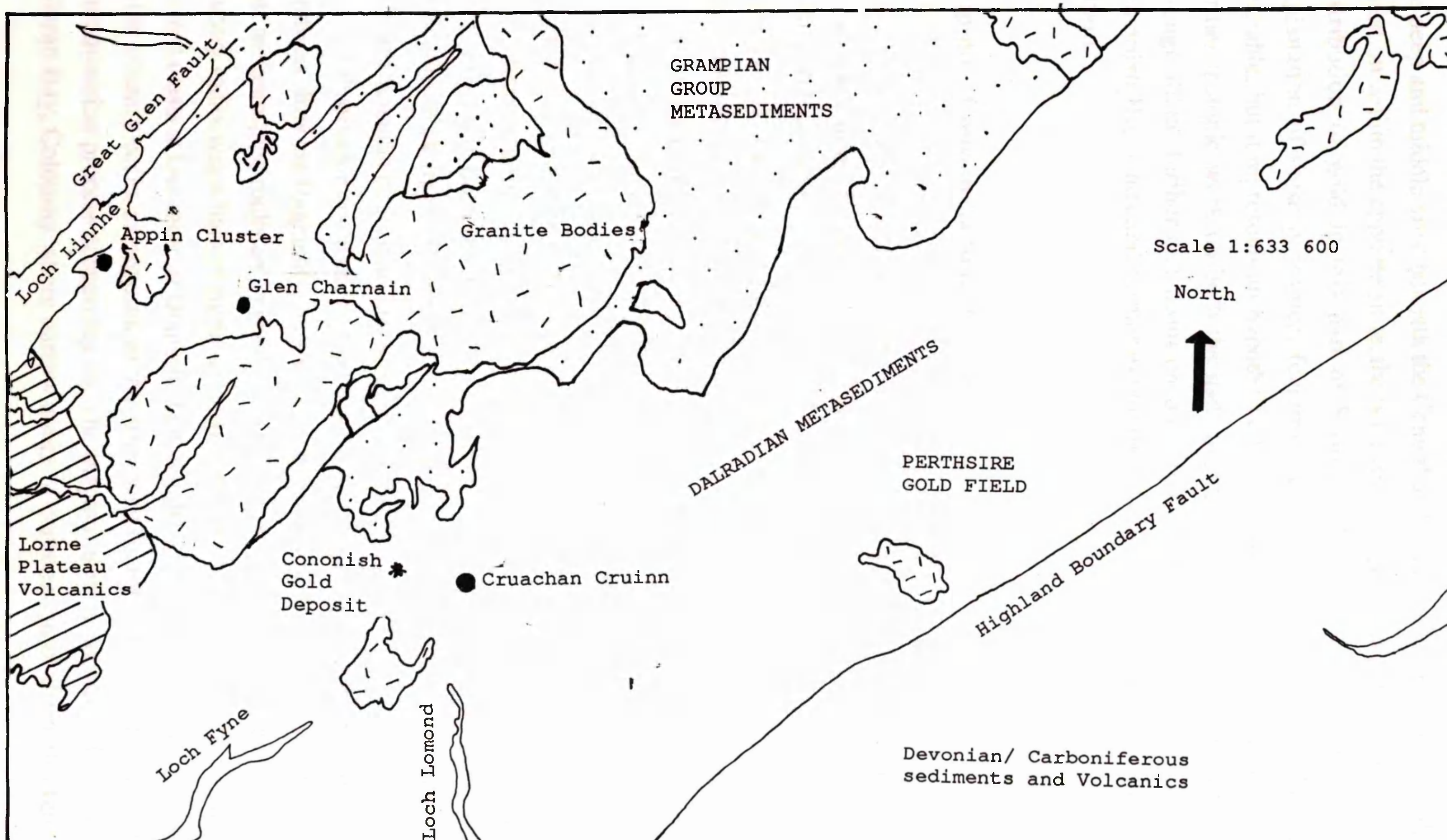
The Link With Gold Prospectivity Of The Appinite Suite

Any suggested link between anomalously light sulphur and anomalous concentrations of gold in breccia pipes at Cruachan Cruinn is very tentative and the database is not sufficiently comprehensive to support any direct link between the two. However it is interesting to speculate on how the differences between the rocks traversed by the appinite might influence whether they carry gold. Russell (1985) mentions how the the start of volcanism in Dalradian times, the subsequent rifting and eventual subduction provided a new source of metals, including gold, for the Scottish metallogenic sub-province. This new igneous material now forms the mafic deep crustal wedge underneath much of the Dalradian, the various volcanogenic lithologies in the Middle and Upper Dalradian and the unexposed plutonic root zones to the Tayvallich volcanics. Such rocks could act as source-rocks for gold, available to be tapped by intruding appinites in the same manner as their isotopically light sulphur content appears to have been tapped. Thus the appinites at Cruachan Cruinn may be anomalously gold bearing on account of their having traversed a greater thickness of potential gold source rock in the form of these basic to mafic crustal components.

This idea that a source rock for gold exists beneath and within the Dalradian of the Southern Highlands is in agreement with an exploration school of thought that predicts that the Upper Dalradian of the southern Highlands is a major prospective belt, evidenced by the existence of the Perthshire Gold Field and the recently found Calliachar deposit (Fig 6A). The subducted mafic wedge can be expected to underly much of the southern Highlands. In this respect it is interesting to consider the extension of the Mid Grampian Line towards the NE in light of the newly found Socach gold deposit in Aberdeenshire (Chapter 3 of this volume) . This lies to the SE of the line and therefore fits the model of overall crustal enrichment in gold during and after middle Dalradian times. The hypothesis does not however explain the presence of the promising Dalnessie Headwaters prospect in Central Sutherland (Chapter 4 of this volume) or other recent finds in the far north of Scotland which lie well to the NW of the Mid Grampian Line.

More recently, a convergent set of ideas has evolved concerning the connection between Devonian magmatism and gold mineralisation in the Scottish Highlands. Curtis et al (1993) have suggested, on the basis of the geochemical similarities between ore fluids at Cononish and those associated with intrusion related mineralisation that the fluids which generated the Cononish deposit were intrusion and possibly appinite derived. Lowry et al (1993, in press) agree with this comparison and suggest that a plutonic body exists beneath the Cononish prospect and that the gold bearing veins represent intrusive related mineralisation developed distally to the intrusion in zones of enhanced crustal permeability. The presence of gold in the Cruachan Cruinn breccia pipes, 4 miles to the SE of Cononish (Fig. 6A) vindicates these ideas and provides a clear link between the processes they

FIG.6b GEOGRAPHICAL LOCATION OF SCOTTISH MAINLAND APPINITE CLUSTERS AND KNOWN DALRADIAN GOLD DISTRICTS



consider; ie. ore forming processes and plutonic intrusive activity. It is considerred here that such intrusive activity, including appinite emplacement, could provide a mechanism for the mobilising of gold from deep crustal regions and its transport to the middle to upper crust. Hydrothermal activity associated with these intruding magmas has the potential to concentrate the gold, and this will be encouraged through breccia formation or the focussing of the fluids in zones of enhanced crustal permeability, such as faults.

The above idea is consistent with both the current knowledge of the composition of the deep and middle crust beneath the Central and Southern Highlands, the sulphur isotopic variation within the appinite suite, the occurrence of gold in appinitic rocks and the general distribution of gold in this part of Scotland. It cannot be proposed as a rigourous explanation of these geological features on the basis of the sparse data-set currently available, but it represents an hypothesis that is testable in future. This test should involve further isotopic work on both the metamorphic rocks and the igneous rocks emplaced through them, further constraint on the middle and deep crustal structure beneath the Grampian Highlands and further exploration for gold within and outwith this immediate terrain.

Appinite Contamination; The Mechanism

The crustal contamination of appinite magmas implied by their sulphur isotopic signatures requires a mechanism for this contamination as well as the availability of crustal sulphur for assimilation. From what is known about appinite emplacement (Bowes and McArthur 1976 and Bowes 1991) the possibilities are;

1) assimilation of country-rock as xenoliths after explosive brecciation.

2) hydrothermal interaction of country-rocks and magma, given that appinites are known to be volatile-rich magmas.

3) interaction between magma and country-rock during crustal ponding beneath the structural trap and in prior uprise through the crust.

Evidence for the operation of the first of these possibilities is abundant in the field., where explosion breccias are seen to be progressively invaded by magma. Volumetrically the country-rock fragments can make up 70vol‰ of these breccias soon after brecciation, so the contamination effect could be substantial.

Observable hydrothermal alteration is not present in or around the majority of appinites. Breccia fragments, wall-rocks to breccia-pipes and contacts between magma and host metamorphic rocks are generally fresh. The only noticeable alteration effect seen in the country rocks was a halo of pyritization around the breccia-pipe and pyritization of locally derived clasts at Dunmore in Donegal. This is indicative of sulphur moving from the magma to the country-rocks as opposed to the other way round so is probably not relevant to the contamination process concerning us. The magma itself is occasionally altered, as seen at Kiloran Bay, Colonsay where narrow zones of carbonation of the mafic igneous phase is seen. The rarity of alteration suggests that this cannot be regarded as an effective means of moving sulphur from the country-rock into the magma in the appinite suite as a whole.

The interaction of hot magma with sulphur bearing country-rocks is analysed by Poulson and Ohmoto (1989) who conclude that contamination of plutons by country-rock sulphur is possible at temperatures as low as 400°C. This mechanism would allow for contamination of the appinite magma by country-rock sulphur both during uprise through the crust and during crustal ponding beneath the structural trap. In the paper it is not mentioned whether the absence of visible contact metamorphic or hydrothermal alteration effects at the margins of the plutons constitutes evidence against the operation of this mechanism, so there is some uncertainty as to the relevance of this mechanism to the appinite suite. The stoping mechanism of emplacement which they conclude as being particularly conducive to this transfer of sulphur may be appropriate to the appinite context where repeated explosive brecciation events are thought to accompany emplacement (Bowes and McArthur 1979 and Bowes 1991).

Thus, the probable mechanisms of contamination of the magmas are assimilation of country-rock xenoliths and interaction between magma and country-rock during crustal ponding and uprise through the crust. The first two of these operate at the structural level at which the appinites are now exposed, whilst the latter operates at a deeper, unexposed level. Without the P/T constraints on the efficiency of sulphur transfer used by Poulsson and Ohmoto, a quantitative comparison of the contributions of these different contamination mechanisms is impossible. At the current exposure level however the relative amounts of crustal sulphur available for assimilation into the magma can be compared for different localities by estimating the amount of sulphide in the host-rocks. At both Cruachan Cruinn and Colonsay, host rocks are sulphide poor whilst the Appin igneous stocks are hosted by pyrite-rich Ballachuillish Slates. Thus the anomalously light sulphur signature at Cruachan Cruinn cannot be explained by the lack of sulphur available for assimilation during crustal ponding, since if this were the case then the Colonsay appinites should show similarly light signatures. This argument can also be applied to the xenolith assimilation mechanism since the bulk of the breccia fragments within breccia pipes are of local country-rocks. It is therefore more likely to be the interaction between the magma and the deeper geology which is responsible for the contamination, supporting the arguments presented for this previously.

These potential mechanisms of sulphur assimilation from country rocks by intruding magmas can be invoked as the means of assimilation of gold and other metals into the appinite igneous/hydrothermal system. Direct assimilation as xenoliths is easily envisaged as a means of metal transfer. Hydrothermal alteration is known to be an effective agent of metal transfer in both enrichment and depletion modes. Poulsson and Ohmoto also maention that the interaction of hot magma with country-rocks can result in metal as well as sulphur transfer between intrusion and country-rock. The latter of these mechanisms of metal transfer is taken as most likely in the present context for the same reasons as argued above for for sulphur contamination. Whether the gold grades observed in breccia pipes can be generated by this mechanism followed by explosive brecciation is indeterminable at the current level of understanding of these processes. The P/T constraints required for a quantitative evaluation of Poulsson and Ohmoto's model are not available, and nor are the gold grades of the crustal gold reservoirs being tapped.(although basic to ultrabasic rocks worldwide have been characterised as carrying gold grades of up to 5ppb (foster 1991). The quantity of gold source rock tapped is not known, and neither is the efficiency of gold precipitation during the explosive brecciation event. The constraints are not available on account of the early stage of development of the model. The model is therefore untestable at this stage by mass-balance calculations of this sort. It should be regarded as purely as conceptual at this stage, but is defendable on the grounds of its success to date as an exploration tool.

The conclusion arrived at by Sasaki and Inshihara (1979) and from a study of the sulphur isotopic signatures of Japanese granites that the emplacement mechanism exerted a strong control over the potential for crustal contamination of the magma and hence its final isotopic signature, can be considered in the context of the appinite suite. Sasaki and Inshihara (1979) proposed that magmas intruded in a fracture-filling fashion would show little crustal contamination and a primitive isotopic signature as a result of the relative lack of crustal interaction between magma and crust during such emplacement. A stoping mechanism of emplacement would on the other hand involve significant crustal contamination and result in significant isotopic crustal contamination. No evidence for a difference in emplacement mechanisms is discernible between the Cruachan Cruinn appinites and the others sampled however. This therefore mitigates against this as an explanation for the contrasting degrees of crustal contamination in sulphur isotopic signatures.

On the other hand it should be pointed out that the Cruachan Cruinn locality sits very close to a postulated deep crustal lineament which runs N-S along the axis of Loch Lomond. Such structures, it has been argued (Russell and Hazseldine 1988), exert a strong control over the localisation of orebodies through, amongst other things, control on the empiacement of magmas and focussing of large scale hydrothermal cells. In this particular context the presence of such a deep crustal structure could facilitate the emplacement of magmas by the fracture-fill mechanism, thus minimising crustal contamination of the magma. In contrast, magmas emplaced remote from such lineaments would be less likely to be emplaced by the fracture-fill mechanism and are therefore more likely to suffer substantial crustal contamination. This is a possible alternative explanation for the contrast in sulphur isotopic signatures between the Cruachan Cruinn appinites and the others sampled. In terms of gold metallogenesis the possible effects of the lineament are less clear. It could be argued that the presence of a zone of enhanced crustal permeability would allow more efficient tapping of the crustal gold reservoirs during emplacement, thus rendering appinites emplaced along these lineaments gold bearing, but those emplaced remote from lineaments barren. More efficient tapping of gold reservoirs by greater interaction between the magma and crust would be accompanied by more efficient homogenisation of sulphur isotopic ratios. This is a possibility, given that efficient homogenisation of $\partial^{34}S$ between magma and crust at Cruachan Cruinn would actually produce primitive signatures whereas at all other localities it would produce more evolved, crustal-type signatures. As is already apparent, however, the arguments about the possible effects of the lineament quickly become circular. It may be that the presence of a deep crustal lineament encourages the emplacement of appinites, as argued by Rock et al (1987) for lamprophyres. During emplacement however, the sulphur isotopic composition and gold content of the appinites will be controlled by the nature of the crust through which they are emplaced.

Process Control on $\partial^{34}S$

A further control on $\partial^{34}S$ in magmas which is liable to be important in the particular context of the appinites is the effect of degassing of sulphur-bearing volatiles. The explosive brecciation event(s) characteristic of appinite emplacement implies a sudden release of volatile pressure once the structural trap has been breached. Intuitively, this pressure release can be expected to result in rapid degassing of the magma, with some of the released volatiles being sulphur bearing. Thus the mechanism described and evaluated by Zheng (1989) probably has an important effect on the sulphur isotopic signature of sulphides precipitated during appinite emplacement.

Pyrite associated with appinitic rocks is hosted both as disseminations through the igneous phase and as part of the matrix to the breccia-pipes. If a sulphur isotopic fractionation does occur in response to explosive brecciation then these two associations of pyrite can be regarded as forming the two end-products of such a process. Disseminations in the igneous stock will contain sulphur with the primary magmatic signature whilst breccia hosted pyrite will have a fractionated signature. Mass-balance considerations of a combined igneous/breccia system would also imply that a fractionation in one direction caused by the brecciation event could produce a fractionation of opposite sense in the magma. Thus, magmas intruded into breccia pipes soon after brecciation may also have a fractionated signature, but fractionated in the opposite direction to the breccia hosted pyrite. This would serve to amplify the difference in sulphur isotopic ratio between the magma and the breccia hosted pyrite.

An evaluation of the effectiveness of this process was attempted by analysing sulphides from from the igneous stock and the associated breccia-pipe for a limited number of localities where both types of pyrite could be sampled. Fig.5 presents this data in histographic form with samples identified as to their locality and their specific host. For each locality an arrow points in the direction of isotopic shift from the igneous to the breccia phase.

Immediately apparent is the fact that there is a difference in isotopic composition between the two associations of pyrite for all the localities studied. This difference amounts to between 1 and 3‰ , which in comparison with the data presented by Zheng (1989) is of the right order to be compatible with the degassing process. Asaki and Inshihara (1979) argue on mass balance grounds that isotopic shifts of around 5‰ $\partial^{34}S$ would be unreasonably large to be explained by an outgassing process. The isotopic shifts observed here between the igneous and directly associated breccia phases are smaller in magnitude and are, as argued by Zheng (1989), explainable by outgassing of sulphur from the magma. The direction of the fractionation can be seen from Fig 5 to be variable, with three localities showing a positive shift and one showing a negative shift. The dominant control on the direction of this shift is stated by Zheng (1989) to be the oxidation state of the magma at the time of degassing. Constraint on this parameter is not available for the localities studied however, so the interpretation can only be taken as far as saying that isotopic fractionation occurs during explosive brecciation and is of a magnitude consistent with a magma degassing mechanism which is expected on geological grounds.

It would be disingenuous at this point to fail to emphasise the fact that without adequate control on the redox state of the magmas involved in these processes, an important aspect of one possible cause of the sulphur isotopic variation in appinitic rocks is incompletely understood. On these grounds it could be argued that the overall sulphur isotopic variation in appinitic rocks could simply be a manifestation of the redox state of the magmas rather than the result of the crustal processes described above. This argument holds for the data relating to the breccia pipes and their relationship in sulphur isotopic terms to the magmas since the differences in isotopic signature recorded are of a magnitude which is explainable by the sulphur degassing process. However, the contrast in signatures between the magmas themselves is too large to be explained in this way. Another explanation for the variation in sulphur isotopic signature of appinitic magmas is therefore required, and on these grounds the argument for a combined mantle/crustal origin of this variation is defendable.

CONCLUSION

In terms of sulphur isotopic systematics then, contamination by crustal material is a feature of appinite emplacement. In the Dalradian of Scotland this contamination is mainly due to interaction between magma and the rocks beneath the current exposure level. Tapping of deep crustal and Dalradian sulphur during uprise through the crust has resulted in a poorly defined provinciality of sulphur isotopic characteristics reflecting the sulphur isotopic budget of the specific rocks traversed during emplacement. Thus the usual mixed mantle/crustal signatures of appinites from Appin, Colonsay and Donegal are the result of mixing of an original mantle signature with sulphur of dominantly sedimentary and bacteriogenic origin within the Dalradian metamorphic pile. Anomalously light signatures at Cruachan Cruinn are possibly the result of uprise of the appinite through a thick mafic deep crustal wedge and overlying Dalradian rocks containing a substantial proportion of igneous material; the relative lack 'crustal' sulphur within this package provided much less opportunity for contamination. Anomalously gold mineralised breccia pipes at Cruachan Cruinn may also be the result of tapping from these large quantities of basic and mafic igneous rocks which could constitute source rocks for gold. More work is required however to quantify the processes of transfer of sulphur from crustal rocks into the magmas, and to extend the database to evaluate the validity of the provinciality suggested. Process control of sulphur isotopic composition is suggested by the isotopic shift seen between pyrite hosted in the the igneous phase and pyrite in the matrix of the breccia-pipes; magma degassing due to pressure release on explosive brecciation is the most likely mechanism for this fractionation.

CHAPTER 3

EXPLORATION FOR GOLD ON THE CUSHNIE PROSPECT, ABERDEENSHIRE, SCOTLAND

The Exploration Hypothesis

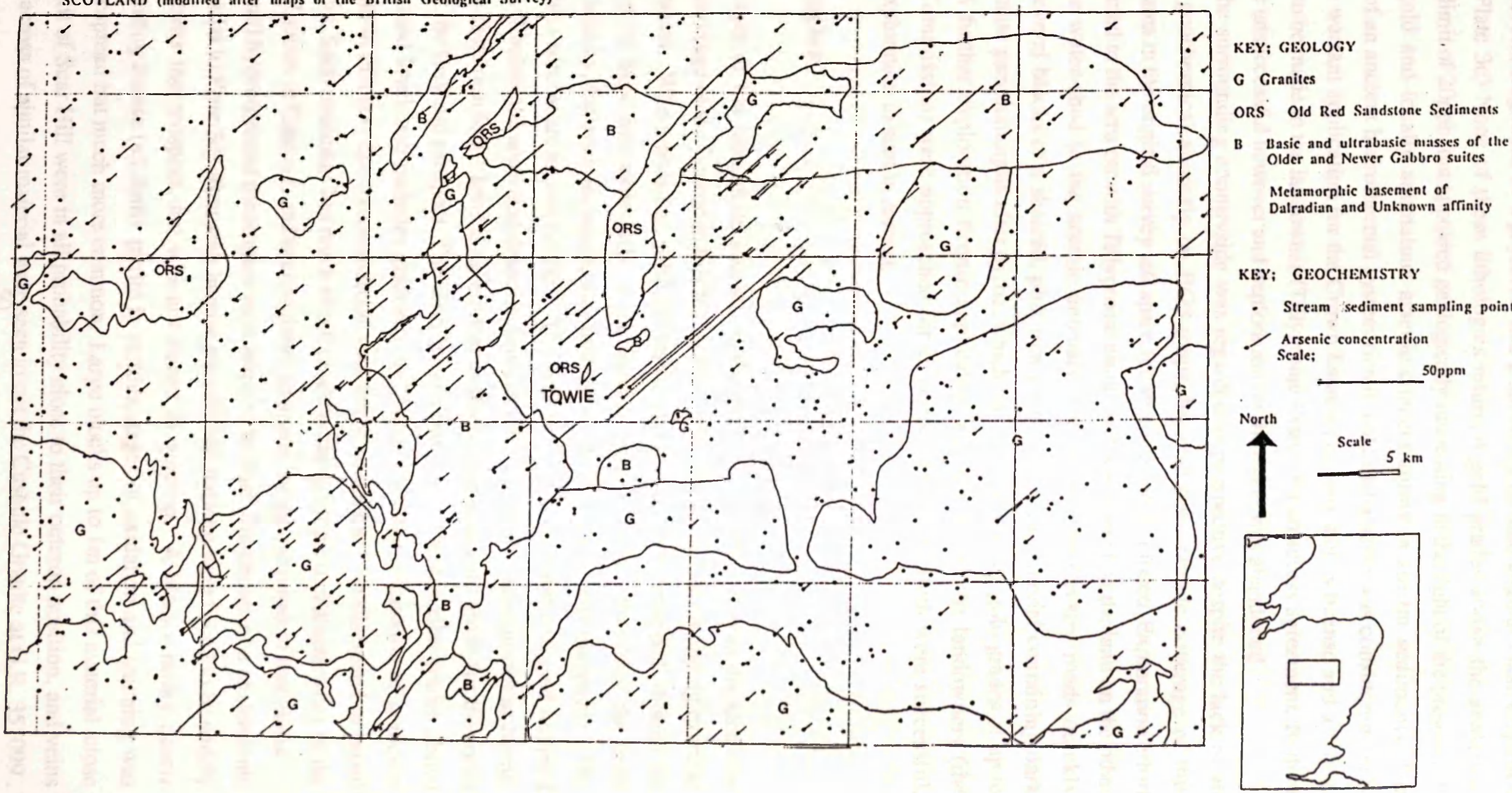
The significance of the Lower Devonian as a period of epithermal activity in Scotland was indicated by Rice and Trewin (1988) and by Nicholson (1988 and 1983) who were interested in exhalative sinters and manganese mineralisation respectively of this age. The work of Rice and Trewin (1988) was important in identifying the surface expression of a gold mineralising epithermal system in Lower Devonian sediments at Rhynie. Previous to this, work by BP Minerals identified mineralisation associated with acid intrusives of Lower Devonian age at Lagalochan, Argyllshire. Research by Zhou (1988 and 1987) and Harris et al (1988) concluded that the mineralisation at Lagalochan was now exposed at a disadvantageous erosion level and that any bonanza style mineralisation was long since eroded. Their estimate of the depth of erosion, based on fluid inclusion work, was 1km. The identification of gold mineralisation at Rhynie raised the possibility that it represented the surface expression of a similar hydrothermal system and that the entire vertical extent of such systems could be preserved in Scotland given a minimum of post-Devonian erosion. However the relatively low gold grades reported from Rhynie suggested that the exhalative parts of such systems were not prospective for economic gold deposits. The prospective erosion level was regarded as being between the two extremes exemplified by Lagalochan and Rhynie.

The thickness of Lower Devonian sediments in the Rhynie Basin is 500-1000m (Rice and Trewin 1988), implying a prospective level either deeper within the ORS sediments or in the underlying Dalradian basement.. The numerous and widely distributed Devonian outliers in northeast Scotland, most of which contain Lower Devonian material, imply that a large part of this region presently lies at an erosion level close to the Devonian palaeolandsurface , and is therefore prospective. Such large areas are deemed necessary in order to increase the probability that it contains a mineralising system. Effective exploration of large areas however require a means of focussing of effort, particularly when exploration budgets are small or time limited. The geochemical maps compiled by the British Geological Survey during the Department of Trade and Industry supported Geochemical Mapping program provided an initial means of doing this. A coherent, three-point arsenic anomaly close to the village of Towie, Aberdeenshire was chosen as an initial target (see Fig.7).

THE EXPLORATION PROGRAM

Exploration as part of this study started in the Towie area of Aberdeenshire with panning of the streams representing the arsenic anomaly on BGS geochemical maps and very brief prospecting of these streams. All four streams with anomalous arsenic showed visible gold in pan concentrates, which in the field appeared flakey and relatively coarse (<0.5mm). Brief prospecting revealed several interesting lithologies ; a pinkish chalcedonic quartz in the form of bladed crystals, typical of the phenomenon of replacement of calcite or baryte by silica- this occurred as rounded boulders up to 30cm across (Plate 3a); milky

FIG. 7 ; KEY ELEMENTS OF REGIONAL GEOLOGY AND STREAM SEDIMENT ARSENIC CONCENTRATIONS IN CENTRAL ABERDEENSHIRE SCOTLAND (modified after maps of the British Geological Survey)



quartz blocks hosting coarse (1cm) pyrite; a very finely pyritic greenish layered chert (Plate 3b), and several fragments of a geyserite-like chalcedony infilled angular clast-supported breccia (Plate 3c) None of these lithologies returned gold grades above the analytical detection limit of 20ppb, but appeared geologically interesting in the light of the presence of alluvial gold and locally anomalous arsenic concentrations in stream sediments. The presence of an ancient hydrothermal system rich in gold and arsenic was considered likely enough to warrant application for the Crown Estates precious metals license and a formal approach to be made to the landowner (Tillypronie Estate) for an access agreement. Both of these were unsuccessful however and exploration on the estate was abandoned.

The surrounding countryside was regarded as prospective despite the lack of an indicated geochemical anomaly on BGS maps, because poor sample coverage of this particular area in the original survey left space for anomalies to be missed. Exploration effort was redirected to the area outwith Tillypronie estate, and was started on the land on the other side of the water-shed to the arsenic anomaly. Prospecting on forestry roads quickly revealed several blocks of a sheared, pink iron stained, sericitic material containing dark grey haematite pseudomorphs after pyrite, which on analysis returned gold grades of up to 6.5ppm. A further exploration license application was made, and the landowners (the Forestry Commission) were approached for an access agreement. Both were successful, allowing exploration to start in earnest.

Float Mapping

In light of the immediate success of the initial prospecting it was decided that complete coverage of the license in this manner was desirable, so a float-mapping exercise was undertaken. Where possible, solid geology was simultaneously mapped, though the extremely poor exposure, especially in the forested ground, meant that only the most obvious boundary, between metamorphics and the Cushnie granite, was mappable. The results of this exercise are shown on Fig.8. The bulk of the float samples analysed returned gold grades of below the analytical detection limit, defined by OMAC laboratories as 20ppb. This 'below detection limit' level is taken here as the background gold grade for the rocks and soils of the Cushnie prospect. The term 'anomalous' is used to describe grades above this background level, and includes grades up to 21ppm. Detailed discussion of grades is inappropriate in this text due to commercial sensitivity, so they will be discussed in broad relative terms. Such treatment has much to tell us about the geological characteristics of the gold mineralisation at Cushnie, and is considered adequate for the purposes of this thesis.

Several hydrothermal lithologies were mapped in float. Fragments of a chalcedonic breccia (similar to Plate 3c) often with intense pink Fe/Mn staining were found to be widely scattered across the prospect, but was not traced to outcrop. A blocky milky quartz lithology hosting coarse (<1.5cm) pyrite in various stages of oxidation and leaching was equally widespread but much more common. Large blocks up to 1m of this material close to the summit of Scar Hill were in all probability close to their outcrop position, and veins up to 30cm across of similar material were seen to cut the Cushnie Granite at G.R. 351099 .

This material was a common and visually obvious component of dry-stane dykes on the prospect. The granite itself was mineralised in places, showing rare disseminations of oxidised pyrite in some exposures in road-cuttings. However, none of these lithologies returned anomalous gold grades . Such grades were restricted to a sheared sericitic material showing pervasive but variously bleached iron staining and hosting haematite pseudomorphs after pyrite in different stages of leaching. This was the same material that returned the initial gold grades found during early prospecting at Cushnie.

The most distinctive common feature of the gold-bearing float samples were the obvious shear fabrics which were highlighted by a thin lining of dark grey haematite. Sawn blocks of this material showed three sets of such fabrics cutting a homogeneous sericitic material displaying varying degrees of iron staining. Intensely stained fragments were a pervasive bright pink colour whilst bleached samples showed patchy and faint development of this staining within creamy white sericite. All gradations between these two extremes were apparent. Cubes after euhedral pyrite were disseminated through the sericitic material and showed 0-100% degree of fill with dark grey haematite. Milky, often vuggy and commonly pale pink stained quartz lenses oriented parallel to the dominant shear fabric were common within float samples. The quartz was also found to host disseminated cubes after pyrite, and to incorporate slithers of sheared, sericitised schistose material.

A crude zonation of the extent to which some of these features were developed was recognisable in the field. At higher topographic levels the degree of iron staining was reduced and pseudomorphs after pyrite were characterised by low degrees of fill. On lower ground, notably on Scar Hill, iron staining was intense and pervasive and 100% degree of fill of pseudomorphs after pyrite was the norm. Gold grades showed a similar crude zonation, with the higher grades being obtained from the samples found at lower topographic levels. This was considered at the time to be the result of supergene alteration, and will be discussed fully in Chapter 6.

The topographic control on gold grades and characteristics of the mineralised rocks can be related to the position of the water-table in the immediate area. A series of springs on the west flank of The Socach is attributed to the intersection of the water-table with the ground-surface, as is the presence of small ponds next to the planted forestry ground on Scar Hill. In addition, the highest topographic level at which water was observed in the streams draining the east side of The Socach can be considered as the highest level attained by the water-table on this side of the hill. On this evidence the water-table can be traced around the hill as shown on Fig.8. Float samples found above this topographic level were of the bleached, leached and gold-poor type whilst those found at and below the postulated water-table were of the stained, unleached and gold-rich type. These features of the float samples, and the degree of topographic control on them exerted by the water-table are symptomatic of supergene oxidation and leaching at and above the water-table respectively.

PLATE 3; DISTINCTIVE FLOAT AND OUTCROP SAMPLES FROM THE CUSHNIE PROSPECT

A) Pink iron stained chalcedonic silica pseudomorphing a bladed mineral, perhaps calcite or baryte.

B) Greenish banded chert hosting rare haematite pseudomorphs after euhedral pyrite. Both found in the Socach Burn.

C) A conspicuous and common float lithology from the Cushnie prospect, an angular clast supported breccia cemented by chalcedonic quartz.

D) Quartzose material displaying abundant cubic porosity after pyrite. Such material returned poor gold grades and is typical of samples located above the topographic level of the current water-table.

E) Large block of mixed hydrothermal and tectonised quartz hosting abundant haematite pseudomorphs after pyrite. located close to the water-table on Scar Hill and highly gold enriched

F) pervasively pink iron stained and sericitically altered schist, typical of the gold enriched material from the Cushnie prospect. Note the abundance of metallic grey haematite and goethite. Typical of the material located at around the topographic level of the water- table on Scar Hill. For further examples see Plate 7 ,Chapter 4


PLATE 3a
scale bar 2cm long


PLATE 3b
scale bar 2cm long


PLATE 3c
scale bar 2cm long


PLATE 3d
scale bar 2cm long

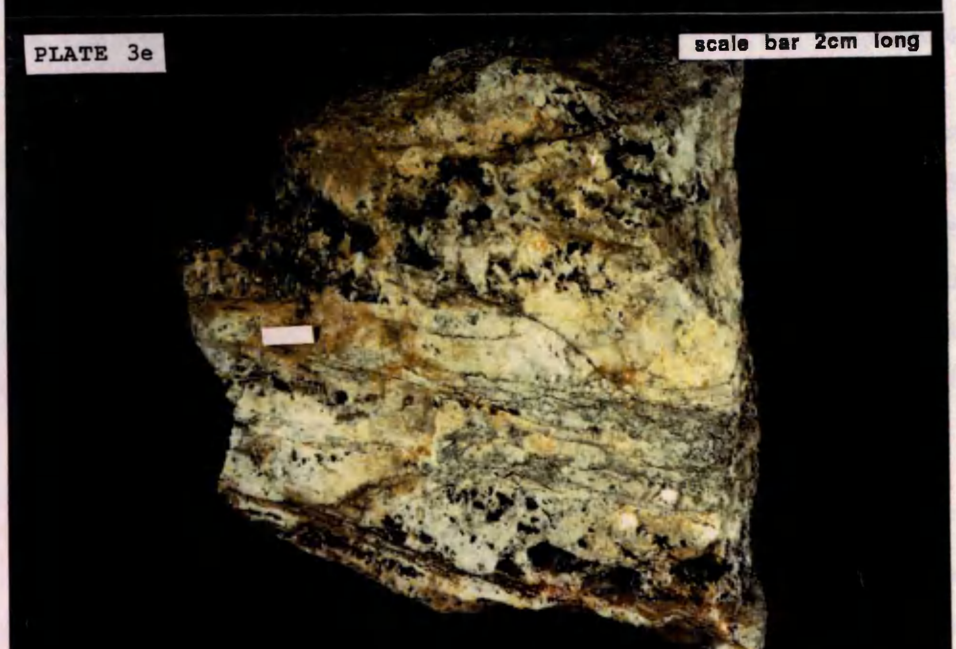


PLATE 3e
scale bar 2cm long


PLATE 3f
scale bar 2cm long

Needs more topographic information, plus cation of Fe alteration + general Au grade.

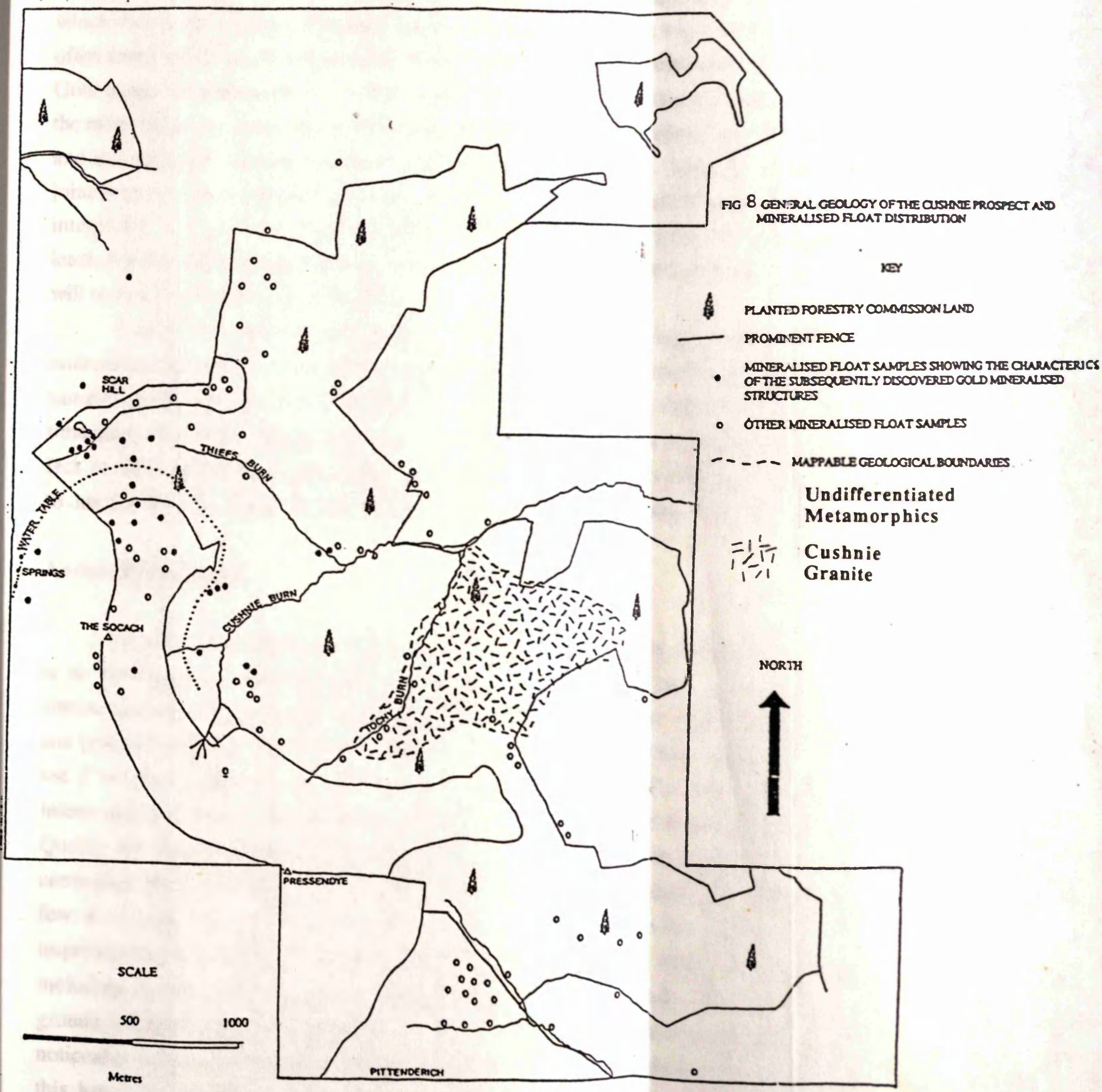


FIG 8 GENERAL GEOLOGY OF THE CUSHNIE PROSPECT AND MINERALISED FLOAT DISTRIBUTION

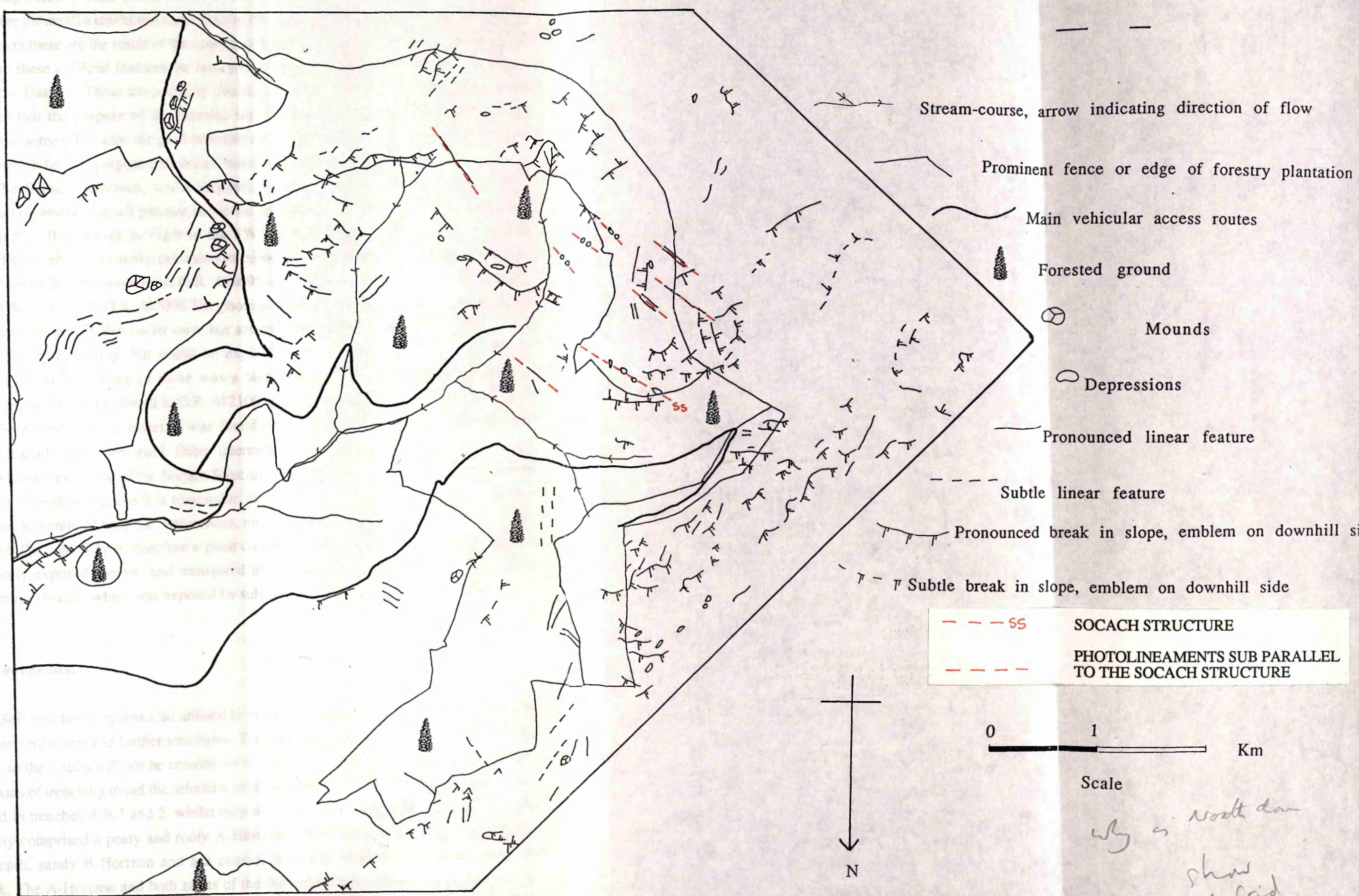
Mapping of this suite of mineralised samples allowed recognition of the SE-NW trending float-train indicated on Fig.8. Closer examination in the vicinity of this float-train located the material in outcrop. This comprised several small exposures arranged in a SE-NW oriented group as shown on Fig 11. The exposures were of a strongly schistose sericitic material with quartz ribs up to 1m wide running parallel to the foliation, and were identical to float samples of the leached, bleached and gold-poor type. Strike direction of the foliation along the length of the outcrop is consistent within 30° (see Fig 12), is sub-parallel to the alignment of the individual exposures and probably represents a C shear fabric (see Chapter 4 for more detail). The outcrops are bounded by steeply dipping joints striking SW which cut the shear fabric. They are characteristically open, with a width of <4mm, and are often lined with a black and orangey brown amorphous ferrugunous/manganiferous wad. Gold grades were generally low in this outcropping material, reflecting the leached nature of the mineralization. Quartz ribs and schistose sericite host negative pseudomorphs after pyrite and this material typically returned grades of less than 0.5ppm. Samples incorporating joint-lining wad gave grades of up to 3.1ppm. The manganiferous/ferrugenous material is interpreted as a product of precipitation from downgoing supergene fluids which have leached gold and other constituents from the bulk of the mineralised outcrop. This process will be dealt with in detail in Chapter 6.

Taking the trend of this group of outcrops as the approximate orientation of a mineralised structure continuous for some distance along strike, the majority of the float samples located are evidently derived from this structure. This was later confirmed by trenching, but a few outlying samples were not consistent with this derivation. A complete lack of exposure in the vicinity of these outlying samples prevented their being traced back to outcrop directly. Aerial photographs were therefore consulted in search of their source.

Aerial Photography

Once the float samples had been traced back to outcrop and the mineralisation proven to be structurally controlled, aerial photographs were consulted in the search for other similar structures which may be mineralised but remain hidden due to poor exposure. Pre and post forestry photographs (of 1: 26562 and 1:24000 scales respectively) were used to see if the thick vegetation cover concealed significant features. The aerial photographic interpretation of the Cushnie prospect is shown on Fig. 9 and will be described here.
Quality and density of observable topographic features is seen be to vegetation and relief controlled. Rich farmland in the NE of the prospect shows very subdued topography with few noticeable features. Open moorland above the current tree-line shows a marked improvement and several forms of linear, curvilinear and point detail are discernible, including breaks in slope, linear features, depressions and mounds. Currently forested ground was previously open moorland and would be expected to show a similar density of noticeable features but the relative lack of clarity of pre-forestry photos mitigates against this, hence the comparative sparcity of data in the forested ground.

FIG 9 : Aerial Photographic Analysis Of The Cushnie Prospect, Aberdeenshire. Scotland.



Some of the features are demonstrably of artificial origin. Most prominent of these are mounds in the SE corner of the area; these are a result of dumping of waste material used during forestry road construction or field clearance for agriculture. Also in this category are the small excavations seen close to the northern corner of the map; according to local farmers these are the result of the hewing of building stone for local farm construction. Other than these artificial features the data shown on Fig.9 represent naturally developed topographic features. These are probably diverse and fairly complex in origin, but in view of the fact that the purpose of the exercise was to identify structures sub-parallel to, or similar to in some other way, the gold mineralised Socach Structure, analysis of the bulk of this data which for this purpose constitutes 'noise' will not be attempted here.

The Socach Structure, where exposed by trenching, is subtly expressed by a colinear arrangement of small pits just above the tree-line at G.R. 485105. Similar trends are highlighted on the overlay to Fig.9 to the SW and NE of here close to the top of The Socach. The southeasterly strike extension of these features may also be represented by the arrangement of depressions around G.R. 485098 and further away by a pronounced linear feature at the tree-line at G.R. 487096 The photogeological evidence for these structures and their extensions is tentative on its own, but several altered and mineralised samples were found during prospecting that could be explained by invoking the presence of these structures. Most interesting of these was a large quartz block with abundant negative pseudomorphs after pyrite found at G.R. 482100 which gave a gold grade of 430ppb. Also, highly Fe-stained sericitic material was found on the forestry track at G.R.488097 and returned a grade of 1.1ppm gold. Other interesting float samples were found well away from the known extension of the Socach Structure, and given the minimal dispersal of float fragments from this structure it is reasonable to expect these outlying samples to originate from other mineralised bedrock occurrences, most probably related to the photolineaments identified. Photogeology is therefore a good complimentary technique to float mapping in such poorly exposed ground, and transpired in this case to be successful in identifying further mineralisation which was exposed by subsequent trenching as described later.

Soil Geochemistry

Soil geochemistry was also utilised in the search for the along-strike continuation of the Socach Structure and further structures. The work was only partially carried out by the author, so the results will not be considered in detail. The technique was used between the two phases of trenching to aid the selection of the second group of trenches. Pilot lines were sampled in trenches A,B,1 and 2 whilst they were open. The soil profile in these trenches generally comprised a peaty and rooty A-Horizon, a dark brown,becoming reddy brown with depth, sandy B-Horizon and a a coarse, generally fresh regolith above coherent bedrock. The A-Horizon and both zones of the B-Horizon were sampled separately at 2m intervals over most of the length of these trenches. Size classification and gold analysis of the various size fractions were performed by OMAC Laboratories, and a decision made to sample the lower B-Horizon and analyse the minus 80 mesh size fraction for gold in subsequent work. Further lines were sampled along forestry rides in planted ground and across photolineaments and expected strike continuations of the Socach Structure, and in the vicinity of unexplained mineralised float samples. Sample spacing on these lines was 25m and the samples collected were split. Combination of consecutive groups of four sample splits was used to reduce the total number of samples prior to gold analysis. The other split from each sample was kept separate and analysed individually in areas where combined samples showed anomalous gold values. This procedure allowed 25m resolution in the soil survey but at the cost, in analyses anyway, of a 100m resolution survey.

The detailed results of this soil survey will not be discussed here, in order to protect commercially sensitive data. It can be stated however that a patchy pattern of anomalous soil values was apparent over the area between Pressendye, Scar Hill and Rough Bank. On mechanical trenching of these anomalies, two main features were observed to be associated with enhanced gold grades. The first of these comprised bedrock mineralisation similar to that seen on the discovery outcrop and as float distributed over the prospect. The second group of soil anomalies was associated with the development of variously orange, yellow and pink stiff but rippable clays containing abundant dark brown ferruginous nodules. Both of these gold enriched materials are described in detail later.

FIELD CHARACTERISTICS OF GOLD MINERALIZATION ON THE CUSHNIE PROSPECT AS REVEALED IN TRENCHES AND OUTCROPS.

Trenching was started in the vicinity of the discovery outcrop in order to expose the mineralization more fully and to trace the extension of the structure along strike. Mineralization intersected is typified by that illustrated on Fig.14 for trench 1. An 11m wide zone comprises quartz ribs up to 1m wide, trending in a NW direction, cutting a sheared and sericitised schistose material. Three prominent quartz ribs are present along with several smaller lens shaped quartz bodies trending parallel to the schistosity in the altered host. Brown iron staining was ubiquitous and patchily pervasive, being better developed in the sericite than in the quartz ribs. The quartz was generally massive and milky but was locally finely vuggy. Slithers of sericitic schist incorporated into the quartz ribs gave them a tiger-striped appearance. Negative pseudomorphs after pyrite were apparent in both the quartz and the sericite, comprising approximately 0.5vol% of the rock-mass within the alteration zone as as a whole. Local concentrations of these pseudomorphs along the foliation in the quartz formed up to 50vol% of the rock at the hand-specimen scale.A Schematic representation of these features of gold mineralisation on the Socach Structure is shown on Fig. 15. The quartz ribs dipped steeply to the SW with both the strike direction and the amount of dip varying in an undulatory fashion across the width of the trench. In the hanging-wall to the uppermost quartz structure a conspicuous orange cohesive clay was developed over a width of 1.5 m; this formed a pronounced dip in the rockhead uphill of the large quartz rib.Late, steeply dipping joints cutting the quartz ribs and sericitic material show a concentration of dark iron and blue/black manganese staining along them, similar to that seen on the

PLATE 4; THE DISCOVERY OUTCROP OF THE SOCACH STRUCTURE

A,B) Discovery Outcrop of The Socach Structure at G.R. 485105 For exact position see Fig. 9 Note pervasive sericitically altered host and parallel alignment of quartz ribs. Prominent fabric controlling orientation of the quartz ribs is a C shear foliation. Note also the relative lack of pervasive pink iron staining (c.f. Plate 7d,3f), a feature typical of mineralisation exposed at this structural level and the result of wholesale supergene leaching of the mineralised structure in the zone above the water-table.

PLATE 5; CONSPICUOUS SURFICIAL MANGANESE STAINING ON THE SOCACH STRUCTURE.;

Surficial manganese staining of sericitically altered schist at the intersection of the Socach Structure with the water-table on Scar Hill. Intense staining of this sort occupies a 5 m wide zone in Trench B straddling the outcrop of the Socach Structure, and is best developed on the immediate footwall to the structure. Gold grades within this zone are the highest obtained from the Socach Structure, suggesting a link between gold and manganese mobilities in the supergene environment.

PLATE 6; DEVELOPMENT OF PINK CLAYS IN TRENCH 3

Typical of the several occurrences of such material on the Cushnie prospect.


PLATE 4a


PLATE 5


PLATE 4b


PLATE 6

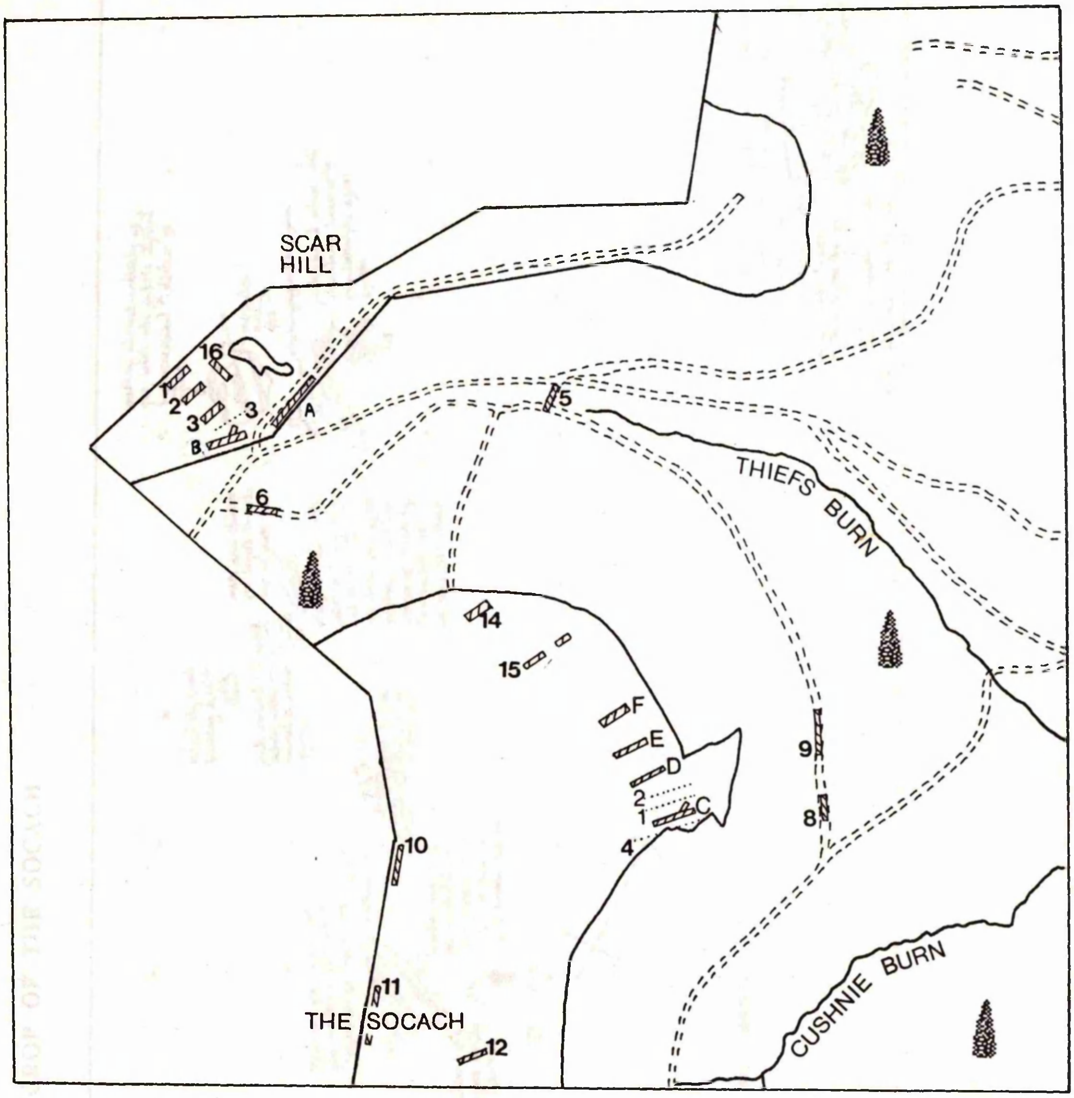


FIG 10 LOCATION OF TRENCHES AND GEOPHYSICAL TRAVERSES ON THE CUSHNIE PROSPECT

NORTH

KEY

PROMINENT FENCE/BOUNDARY

PLANTED FORESTRY COMMISSION LAND

FORESTRY RIDES

TRENCH, with number

GEOPHYSICAL TRAVERSE, with number

SCALE

0 100 200

METRES

FIG. 11 ; SKETCH MAP OF THE DISCOVERY OUTCROP OF THE SOCACH STRUCTURE AT G.R.

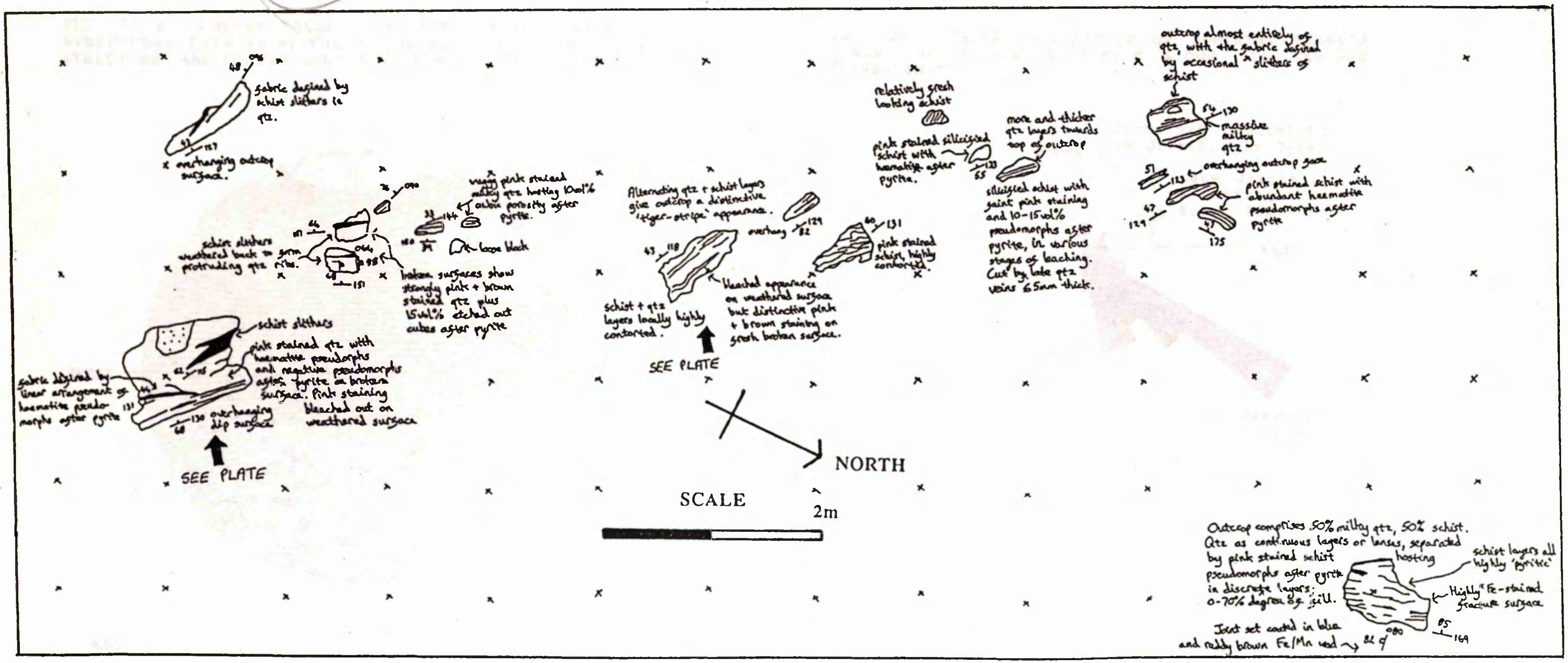
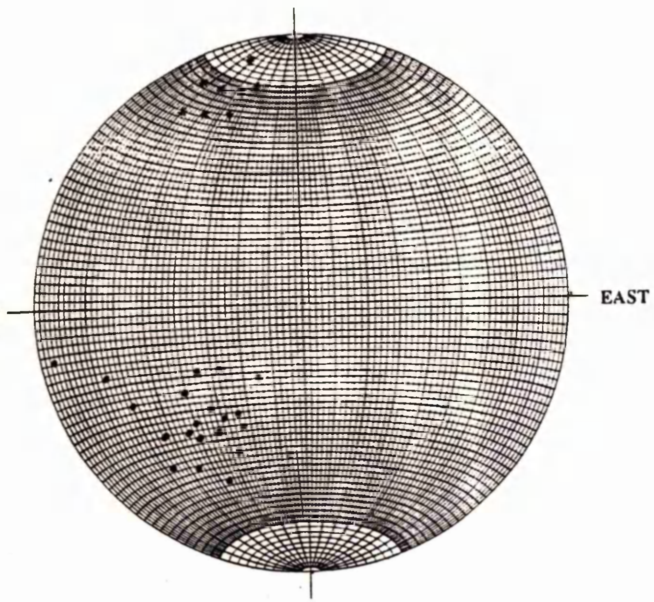


FIG 12 B+C; STRUCTURAL ORIENTATIONS OF THE DOMINANT FABRICS WITHIN THE SOCACH STRUCTURE.

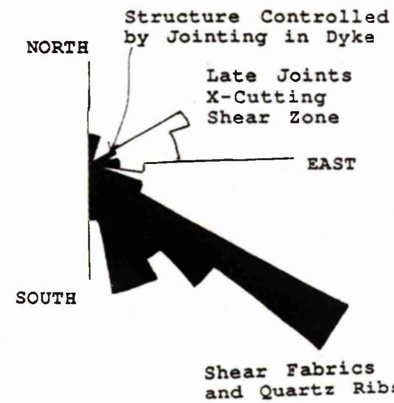
FIG 12 B; LAMBERT EQUAL AREA STEREOGRAPHIC PROJECTION OF STRUCTURAL DATA FROM THE DISCOVERY OUTCROP OF THE SOCACH STRUCTURE AND ITS EXPOSURE IN TRENCHES ALONG STRIKE



KEY

• Foliation * Late Joints

FIG. 12C; STRIKE ORIENTATION OF DOMINANT FABRICS WITHIN THE SOCACH STRUCTURE ALONG ITS EXPOSED STRIKE-LENGTH



1cm diameter = 4 measurements

use scale bar

FIG. 13 ; GEOLOGY OF THE NARROW PART OF THE SOCACH STRUCTURE ON SCAR HILL, CUSHNIE PROSPECT

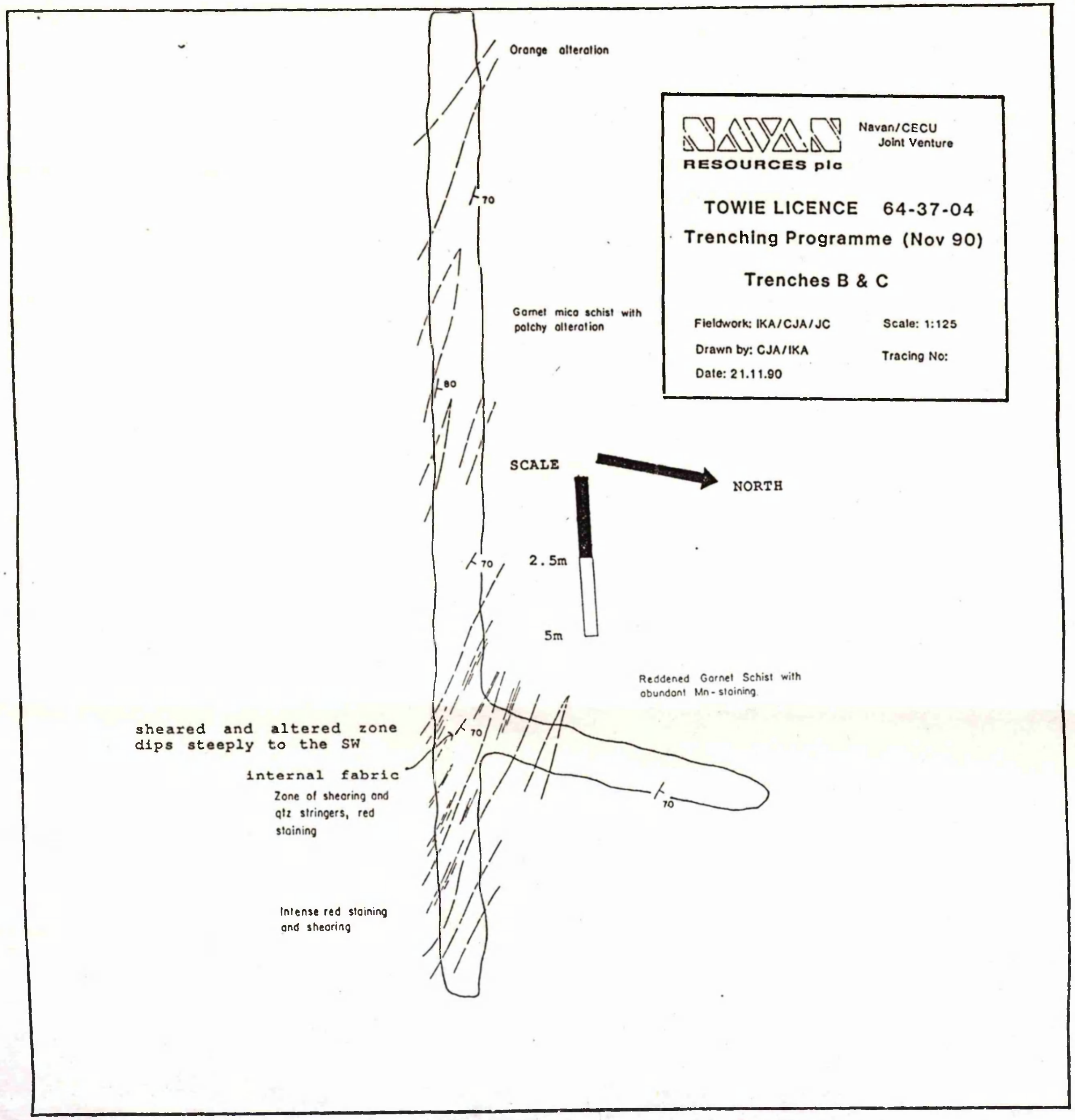


FIG. 14 ; GEOLOGY OF THE WIDE PART OF THE SOCACH STRUCTURE, CLOSE TO THE DISCOVERY OUTCROP, CUSHNIE PROSPECT.

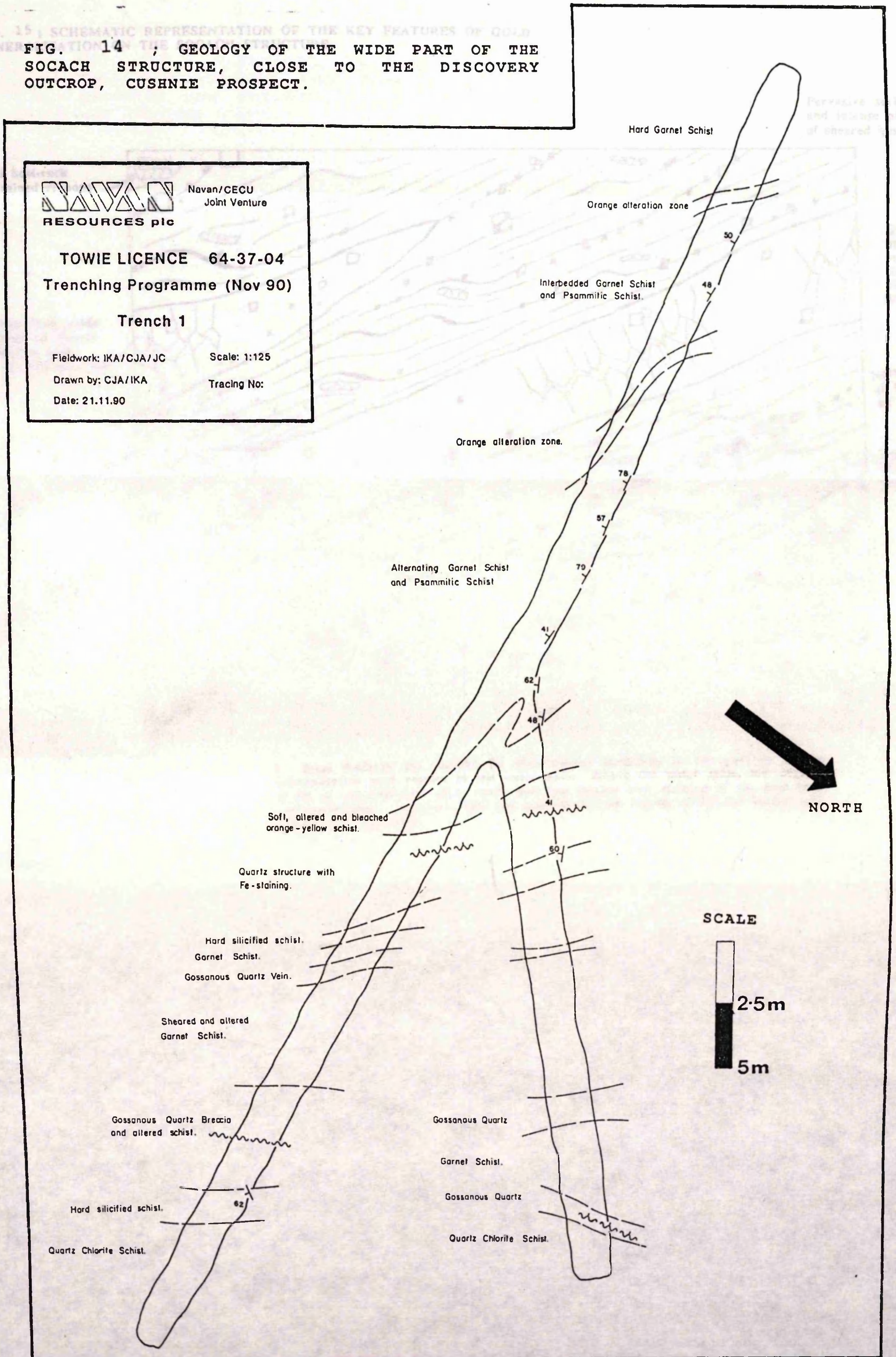
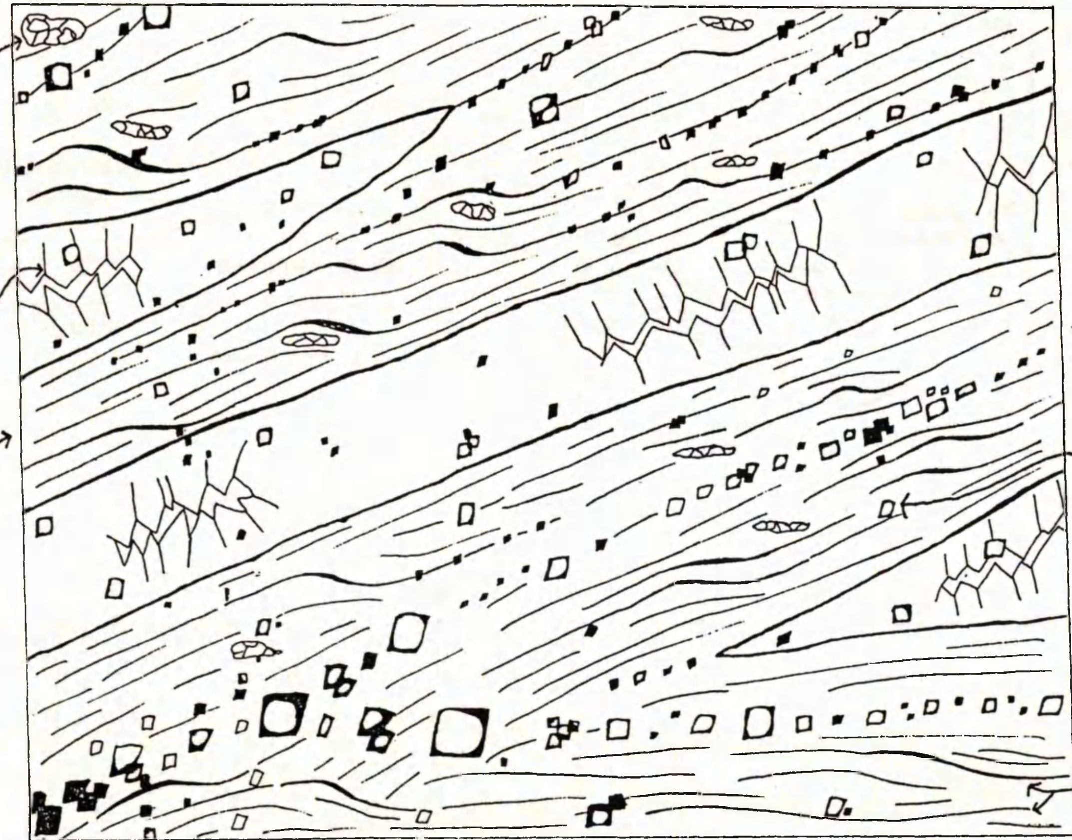
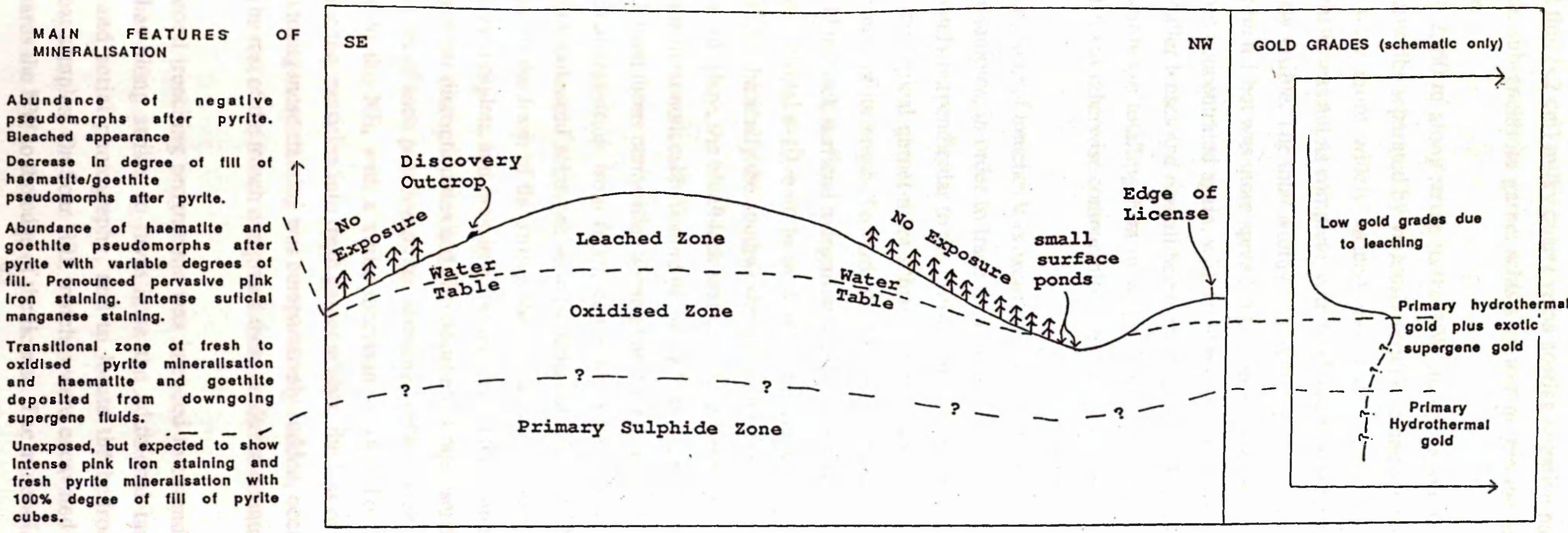


FIG. 15 ; SCHEMATIC REPRESENTATION OF THE KEY FEATURES OF GOLD MINERALISATION ON THE SOCACH STRUCTURE



* these features are variable in development according to the position of the mineralisation with respect to the water-table. Above the water table, low degrees of fill of pseudomorphs after pyrite and less intense iron staining of the host rock and quartz ribs apparent. Near the water-table high degrees of fill and intense iron staining are the norm.

FIG. 16 ; SCHEMATIC STRIKE-SECTION ALONG THE SOCACH STRUCTURE AND INTERPRETATION OF THE TEXTURES AND GRADES IN GOLD MINERALISED FLOAT AND OUTCROP SAMPLES.



discovery outcrop. Outwith the main alteration zone, narrow zones of orange and brown alteration and thin (<2 cm) milky quartz veins hosting negative pseudomorphs after pyrite cross-cut fresh, sub-gneissose garnet schists up to 8 m into the hanging-wall of the main alteration zone.

Trench 2, 50 m along strike to the NW showed a similar configuration of three prominent quartz ribs separated by variously sericitised and brown iron stained schist. The quartz veins were more widely spaced and slightly narrower, and alteration of the intervening schists was not as complete, with fresh interbanded psammite and garnet schist being frequently visible. The total width of altered rock and quartz ribs was comparable to that seen in Trench 1 but was more spread out. Trench 3 showed the alteration and veining to become more concentrated again, with three prominent quartz ribs up to 0.75 m across and several smaller lenses and ribs all being enclosed by a sheared, sericitic envelope with the whole assemblage totalling 6 m in width. The appearance of the mineralization in trenches 2 and 3 was otherwise comparable to that seen in trench 1.

Another group of trenches was excavated on Scar Hill in the vicinity of the cluster of gold-rich float samples, in order to trace them to source. Two trenches (A and B) were dug, approximately perpendicular to the overall strike direction of the float-train. Trench A went through the typical garnet-mica schist country-rock of the area, with little sign of alteration over most of its length. Towards the SW end of the trench however, a patchy pink staining and a blue/black surficial manganese staining became apparent, both being faintly discernible over the final 8-10 m of the trench and increasing slightly in degree towards the SW. Trench B was basically the southwesterly continuation of trench A on the other side of the forestry road. Here, the blue/black surficial manganese staining was developed to the point of being the most noticeable feature of the rock, affecting regolith material and the top of bedrock with ubiquitous permeation along joints in the latter. Broken bedrock fragments showed a gradual transition from fresh, coherent garnet schist to a blocky cream and occasionally pink coloured schistose sericitic material. Near the NE end of trench B the schistosity took on the form of the strong shear fabrics previously seen in float samples, sericitization was complete and pink iron staining was intense and pervasive. Iron oxides lined the strong shear discontinuities and also occurred as rare pseudomorphs after euhedral pyrite, and clusters of such pseudomorphs, showing 100% degree of fill. The shear fabric dipped steeply to the NE, with a strike direction of 140° To the SW of this narrow mineralised zone the transition into fresh garnet schists, the loss of pervasive iron staining and of surficial manganese staining was comparatively sudden, occurring over a 1m length of the trench. The rest of the trench comprised these unaltered country-rocks.

The second trenching programme was intended to extend the findings from the original trenches along strike, to investigate the additional targets outlined by soil geochemistry and aerial photography, and to locate the bedrock source of outlying mineralised float samples. On Scar Hill, trenches were excavated along the strike of the shear zone towards the NW to the edge of the license. The mineralization in these trenches differed from that in trench A in several respects. Firstly, in all subsequent trenches the centre of the shear zone was occupied by a 30cm wide blocky, highly pink stained and often slickensided quartz rib. The total width of the mineralised zone stayed consistent at around 1m despite this additional component. In trench 3 the quartz rib and sericitic envelope were hosted by a highly weathered intrusive body, and the orientation was deflected to a less steeply dipping one, being strongly controlled by the prominent jointing in the intrusive material. In all other trenches the host-rock was interbanded psammite and garnet schist and no such joint control existed. The degree of surficial manganese staining and pervasive iron staining and the degree of fill of the pseudomorphs after pyrite decreased towards the NW and in a slightly uphill direction; this will be considered in a broader context later in this chapter.

Trench 8 was excavated to investigate the locally anomalous soil geochemistry and to see if its causative body was related to the faint photolineament visible on aerial photographs of this vicinity. (see Fig 9) The mineralization intersected was comparable to that seen in trench 2 but its orientation could not be ascertained due to the instability of the trench walls. The relationship of this structure to the photolineament is therefore unproven. The nearby trench 9 went through a sheared, patchilly pink iron stained granitic material reminiscent of the stained material seen in the footwall of the Socach Structure in trench B. No stronger signs of mineralization were encountered in this trench however.

Trench 12 was excavated to locate the source of a large outlying mineralised float sample and to investigate one of the photolineaments identified in its vicinity. A quartz rib 40 cm across with a narrow (30cm either side) sericitic alteration envelope was intersected. The structure trends 145° , sub-parallel to the Socach Structure, and is hosted by sub-gneissic garnet mica schists. It shows the development of negative pseudomorphs after pyrite which comprise 0.5vol% of the rock, but only poor development of the sheared wallrock textures typical of the Socach Structure.

Along Strike Correlation Of Mineralised Structures

In correlating the Socach Structure along strike between trenches, the scale of observation of the shear zone proved to be an important consideration. Local strike directions of either the foliation or the quartz ribs within the discovery outcrop (Fig. 11) show an undulation of +/- 30° along the 10 m strike length of the outcrop, even though the overall trend of the outcrop is reliably 135° Trenches were excavated to a width of only 1m however, so this undulation could not be observed at the scale of the individual trench. Trends measured in trenches, then, are an unreliable indicator of the strike direction of the shear zone because this larger scale undulation is not visible. Also, en-echelon offsets are a characteristic feature of shear zones and could further complicate this picture. The development of one such feature was observed on the base of trench 1 where the quartz rib occupying the centre of the shear zone is offset by 45 cm along a discontinuity trending at a high angle to the shear zone. No other such features were observed, but the possible effect of these offsets on the overall trend of the Socach Structure cannot be ignored.

With these complications in mind it is relatively easy to correlate the structure along strike in most cases. Between trenches C and D , measurements from the trenches gave very poor correlation, but if the overall trend of the intervening exposure was used instead, correlation was exact. This trend could be extrapolated along strike to give exact correlation with mineralization exposed in trench E . On Scar Hill, poor correlation is apparent using the only data available, ie. from trenches, but the similarity of the single structure in each of the trenches and their broadly similar trends, forces the conclusion that they do in fact correlate. A degree of along-strike undulation in trend and/or the development of en-echelon offsets is necessary to explain the poor apparent correlation. Since evidence for both is present within the Socach Structure, correlation on this basis is considered reasonable.

Correlation is difficult between trenches E and F. In the former the Socach Structure is similar to that seen in trenches to the SE and on the discovery outcrop in terms of the width of the alteration zone and the size and number of the quartz ribs present it is a substantial mineralised zone. In trench F however the alteration zone has a width of 1.5 m and includes a single 30cm wide quartz rib; it has narrowed significantly over an along-strike distance of 100m. Further to the NW this narrow width is a consistent feature of the Socach Structure.The trend of the shear zone can be correlated between these two trenches despite this change in width. This sudden change in width remains unexplained.

Correlation of the structure between Scar Hill and the slopes of The Socach above the tree-line is less well constrained than elsewhere in view of the lack of trenches within the forested ground. The overall trend of the structure running across the hillside above the trees is consistent with its re-emergence from the forested ground close to the position of trench A however, where the mineralised shear zone was intersected. Thus, the Socach Structure can be correlated from the edge of the license on Scar Hill to the position of the discovery outcrop, with the only inconsistency being a rapid change in width towards the SE end of its exposed strike length.

Supergene Alteration Of Gold Mineralisation

Mineralization exposed in trenches showed the same effects of supergene alteration as were apparent in float samples during prospecting, with the geographical distribution of these effects also being very similar. Thus, material exposed on The Socach in trenches C, D, .E, F, 12, 14 and 15 showed the characteristics best seen on the discovery outcrop; namely low degree of fill of psuedomorphs after pyrite, bleaching of iron staining in quartz ribs and sericitically altered host rocks, and low gold grades. Material exposed on topographically lower, and flatter ground on Scar Hill showed high (up to 100%) degrees of fill of haematite/goethite pseudomorphs after pyrite, pervasive and intense iron staining of host rocks and to a lesser extent the quartz ribs, and generally higher gold grades. The close spacing of trenches on Scar Hill allows the transition from the oxidised to the leached state to be examined in more detail. Over a vertical interval of 5 m and a horizontal distance of 70 m both the above end members are developed along with the intermediate stages in the process. The oxidised but unleached end-member is seen in trench A where the Socach

Structure returns a gold grade of 21ppm over 1m width from intensely iron stained material showing no porosity development at the expense of oxidised pyrite cubes. Trench 3, 20m to the NW and elevated 1.5 m above trench B shows the same degree of pervasive iron staining but with incipient development of porosity after euhedral pyrite. Incomplete oxidation of the pyrite is evidenced by the occurrence of pyrite cores to coarse (<2 cm across) aggregates of euhedral cubes. Further uphill and to the NW oxidation is complete and the development of porosity after pyrite becomes more pronounced in trench 2 and achieves completeness in trench 1. Iron staining is noticeably less intense and less pervasive in these latter trenches, and gold grades decline rapidly as leaching progresses; from 21ppm in trench B to 2.65 ppm in trench 1.

Other evidence for the operation of the supergene processes considered responsible for this oxidation and leaching comes from the occurrence of manganiferous/ferrugenous staining seen along joint planes exposed on trench walls, similar in fact to the material seen on the discovery outcrop which returned enhanced gold grades. A very prominent blue/black surficial manganese staining is developed on regolith and bedrock in trench B and to a lesser extent in trench A. It occupies 4 m of the trenches on the hanging-wall side of the Socach Structure and is the most notable feature of both trenches. The two occurrences of manganese oxides are most easily explained as the result of downward percolation of supergene fluids along permeable joints with gradual precipitation of dissolved manganese oxides followed by sudden precipitation of these dissolved materials at the water-table in trench B. This aspect of the supergene process will be considered in more detail in Chapter 6. The overall picture of the Socach Structure that can be constrained by fieldwork is illustrated by the left hand parts of Fig. 16.

Other, separate mineralised structures intersected during the trenching programmes can be fitted into this supergene framework on the basis of the degree of development of the characteristics described above and their topographic setting. The structure intersected near the summit of The Socach, targetted by the coincidence of a photolineament and a large outlying float sample, showed complete leaching and bleaching and returned relatively low gold grades. This is consistent with its high topographic position which would place it at an elevated level within the leached zone above the water table. Mineralization intersected on Rough Bank, targetted largely on the basis of anomalous soil geochemistry but also detected during aerial photographic work, showed leaching and (unsurprisingly) low gold grades but with the preservation of pervasive pink iron staining. This is comparable to the Socach Structure as intersected in trench 2, which lay only a few metres above the water-table. Its occurrence at a topographic level shown of Fig 8 to be below the local water-table is considered to be due to the steepness of the slope it lies on and the behaviour of the water-table in areas of high relief. It is known that in such circumstances the water table typically lies at a short distance beneath the ground-surface and asymptotic to it. Thus this structure is actually exposed in a position a few metres above the water table and shows the characteristics typical of such a structural position. Its situation differs from that seen on Scar Hill where the relative flatness of the terrain allows the water-table to reach the ground surface to form small ponds.

Host Rocks To Mineralised Structures And Other Country-Rocks Of The Cushnie Prospect

Host -rocks to the mineralised structures as exposed in trenches are dominantly of one single but transitional lithology. It can be described as a garnet mica schist showing incipient to partial development of gneissic characteristics, and as such includes unsegregated and segregated sub-lithologies. The unsegregated lithology is a muscovite schist hosting up to 5vol% pink to brown garnets up to 7 mm across. These garnets show evidence of preferential weathering resulting in float-samples and outcrops frequently displaying rounded negative pseudomorphs after garnet whilst the host schist appears fresh and retains its characteristic micaceous sheen. Segregation involves the progressive development of lens and augen-shaped quartzo-feldspathic partings parallel to the foliation in the host schist. In trenches these partings were between 5 and 50 mm wide and locally comprised anything up to 40% of the rock. Outwith the trenches the segregation was seen in various stages of development, and was seen to progress by a widening of the quartzo-feldspathic partings and an increase in their number and density to form a rock of dominantly granitic gneiss with isolated pockets of relict garnet muscovite schist. The two end-member rock types formed by this change are very distinctive, but their transitional nature and the poor exposure on the prospect make it un-mappable. A fairly rapid transition is seen in loose blocks along the forestry track on Scar Hill where the change from the unsegregated to the completely segregated lithology is apparent over a 150 m traverse. The transition is not however mappable through the forested ground. The various lithologies within this transition formed the country-rocks over much of the prospect. A variation on the fully segregated gneiss

Intruded into these country-rocks were a range of mafic to felsic, hypabyssal and plutonic rocks. The most extensive of these is the Cushnie granite, a pink leucocratic medium grained unfoliated granite mappable by the presence of exposures in stream-beds and the red sandy soil developed above it. The nature of its contact with the country-rocks is not discernible due to poor exposure. Where exposed in road-cuttings the granite is in a highly weathered and oxidised state, and hosts rare but coarse (<5mm) disseminations of haematite after euhedral pyrite.

Intermediate hypabyssal rocks are detectable by the numerous clusters of felsite boulders by roadsides and in dry-stane dykes, but they are nowhere exposed in-situ and the loose material is not mappable for any distance. Basic hypabyssal rocks are detectable in a similar manner but were also found in-situ in trenches. One large body was excavated in trenches 3 and 16 where it was recognisable by its homogeneous blocky nature and the presence of white feldspar phenocrysts. It was completely decomposed to a compact crumbly coarse sand at surface, and excavation down to a depth of 5m showed no decrease in the degree of weathering. A less weathered basic intrusive body was intersected in trench F where it was exposed close to mineralised and hydrothermally altered rocks. It comprised a 2m wide dyke of dark, fine grained equigranular doleritic material showing distinctive onion-skin weathering, but with relatively fresh core-stones. The extreme weathering of intrusive material seen in trenches 3 and 16 is thus unusual, and points to a period of intense weathering after exposure; this will be dealt with in more detail in Chapter 6.

A curious feature of several trenches was the development of cohesive yellow and pink clays often containing irregular nodular and occasionally cubic accumulations up to 1cm across of iron and manganese oxides. These were well developed in trench A where a pink and a yellow clay occurred in close proximity to highly altered rocks associated with the Socach Structure, leading to the suggestion that they were a product of hydrothermal alteration. Similar materials were however developed in trenches 10 and 11, where no signs of hydrothermal alteration or mineralization were seen despite the anomalous soil geochemistry above these trenches. The nodular nature of these materials is suggestive of their development by saprolite forming processes. Such processes are known to be capable of remobilising gold in the supergene environment and reconcentrating it in regolith or soil materials. Such a mode of formation could explain the anomalous geochemistry of these materials as revealed during the soil survey. Field evidence was however unable to conclusively resolve the origin of these deposits, but they will be considered in later chapters. For the moment they are considered anomalous.

GEOPHYSICAL EXPRESSION OF THE SOCACH STRUCTURE

In view of the extremely poor exposure typical of most of Aberdeenshire, and with the supposition that the oxidised and leached state of the mineralisation on Socach is likely to be typical of other mineralised bodies in areas of NE Scotland affected by Tertiary weathering, it was deemed worthwhile to search for a geophysical expression that could be used to follow the structures along strike or discover further unexposed structures. Knowledge of such an expression would be of benefit in further evaluating the Cushnie prospect and in exploration elsewhere in NE Scotland.

The Self-Potential method was chosen on account of the availability of appropriate equipment and the depiction in the literature of significant anomalies developed over conducting bodies which traverse the water table (eg. Keary and Brooks 1985). This is a broadly similar geological configuration to that expected at depth at Cushnie, and similar anomalies were expected. The VLF EM method was chosen for its ability to detect structural offsets in subsurface geology and also the presence of sulphides; the combination of these two characteristics at Socach was therefore expected to produce a significant and traceable VLF EM anomaly. Details of the theoretical and practical aspects of both techniques can be found in Keary and Brooks (1985).

The Self Potential Survey

In order to evaluate the effectiveness of the method for detecting mineralisation typical of that on the Cushnie prospect, the strongest part of the Socach Structure, close to the discovery outcrop, was chosen for a pilot-study. Correct operation of the equipment was checked by placing the electrodes 20 cm apart and taking a reading. This gave potential differences of up to 0.4 mV, which is within the tolerances quoted in the literature. Electrode placement was in the peaty layer beneath the heather after digging the latter away; this was found to give consistent readings as long as the base of the electrode was not sitting directly on top of boulders. Profiles were run using the fixed base-station and single roving electrode method, with station spacings of 5 m, 2.5 m and 1m to check for reproducibility of results and to determine the optimum station interval. Lines were consistently perpendicular to the strike direction of the Socach Structure.

Differences between readings from original and repeat traverses ranged from 0 mV to 7 mV. This is attributed to the quality of the placement of the roving electrode since it was noticed in the field that stoney placements resulted in readings up to 20mV greater than peaty placements. The maximum of these differences was defined as the amplitude of the noise factor for the technique at this locality. It is also noticeable from Fig. 17 LINE 1 that the 2.5 m electrode spacing traverse revealed fluctuations of a greater amplitude than this noise factor which were not picked up by the 5 m spacing traverse. On the other hand the additional fluctuations detected by the 1m spacing traverse are of lower amplitude than the noise level. Thus no enhancement in detail of the SP profile is obtained using electrode spacings of less than 2.5 m, and this therefore constitutes the optimum electrode spacing.

The SP profiles across the Socach Structure close to the discovery outcrop are shown on Fig.17, with the position and orientation of the mineralised body overlain. Line 1 shows a negative anomaly of around 20 mV magnitude on the down-dip side of the mineralised outcrop, and a further similar anomaly of 25 mV magnitude at the 16-20 m point on this line. Whilst the former lies in a fortuitous position to be explainable as a negative centre directly overlying the down-dip intersection of the Socach Structure with the water-table the size of the anomaly is an order of magnitude smaller than those reported in the literature. The anomaly at 16-20 m does not match up with a known mineralised body, but no exposure of bedrock was achieved at this position during trenching to verify this. Line 4 was run 30 m to the SE along the strike of the Socach Structure, and two anomalies found on this line, at 7.5-10 m and at around 50-55 m can tentatively be correlated with the anomalies on Line 1. Again, the anomalies are of very low order (20 mV) and the latter is poorly defined due to forested ground which made it impossible to keep the electrode spacing consistent over this part of the line. Line 3 was run 30 m to the NW of Line 1 and records no coherent anomalies with a magnitude greater than the noise level. Also, the tentative correlation of anomalies between Lines 1 and 4 does not continue to this line. Line 2 was run for comparison purposes over the Socach Structure where it was exposed in trenches on Scar Hill. In view of the reduced width of the mineralised structure at this locality the electrode spacing was reduced to 1m. The profile is comparable to Line 3 in that no coherent anomalies of greater amplitude than the predetermined noise level of 20mV are apparent.

Very few positive conclusions can be drawn from the results of the SP work. Anomalies are of very low amplitude and are discontinuous along strike, and this is true

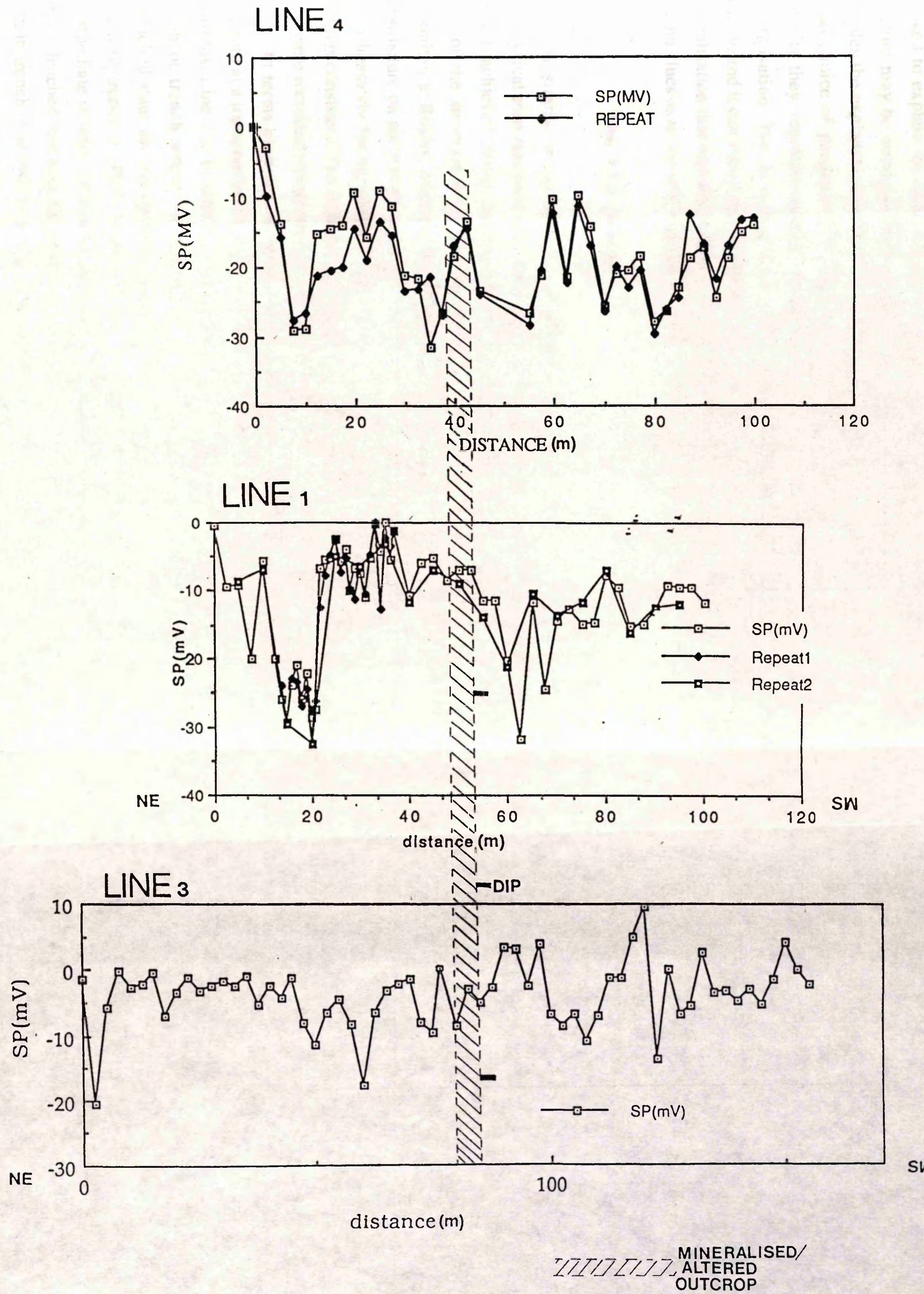


FIG 17 SELF POTENTIAL PROFILES ACROSS THE SOCACH STRUCTURE CLOSE TO DISCOVERY OUTCROP AT GR NJ486104

where the profiles were run at both the level of the water table and at the higher structural level where the mineralisation is leached. Whether the low order anomalies are due to mineralised bodies is impossible to say with any certainty. Initial explanation of these negative results was that the mineralisation is not adequately sulphide rich to produce a detectable SP anomaly. Additionally, for Lines 1,3 and 4 the depth of leaching can be invoked to explain the lack of a detectable surface anomaly even where the mineralised structure may be strong enough to create an anomaly at depth. However, Corry (1985) provides the explanation that the lack of a significant anomaly is entirely due to the poor initial choice of geophysical method. In controlled experiments over porphyry copper deposits they reported complete destruction of the SP anomaly on oxidation of the mineralisation. This is a more likely explanation of the failure of the technique at this locality, and it can therefore be assumed that if such oxidation is a common characteristic of mineralisation that has undergone Tertiary weathering then the SP geophysical method will give no clues as to the whereabouts of further, unexposed mineralised bodies.

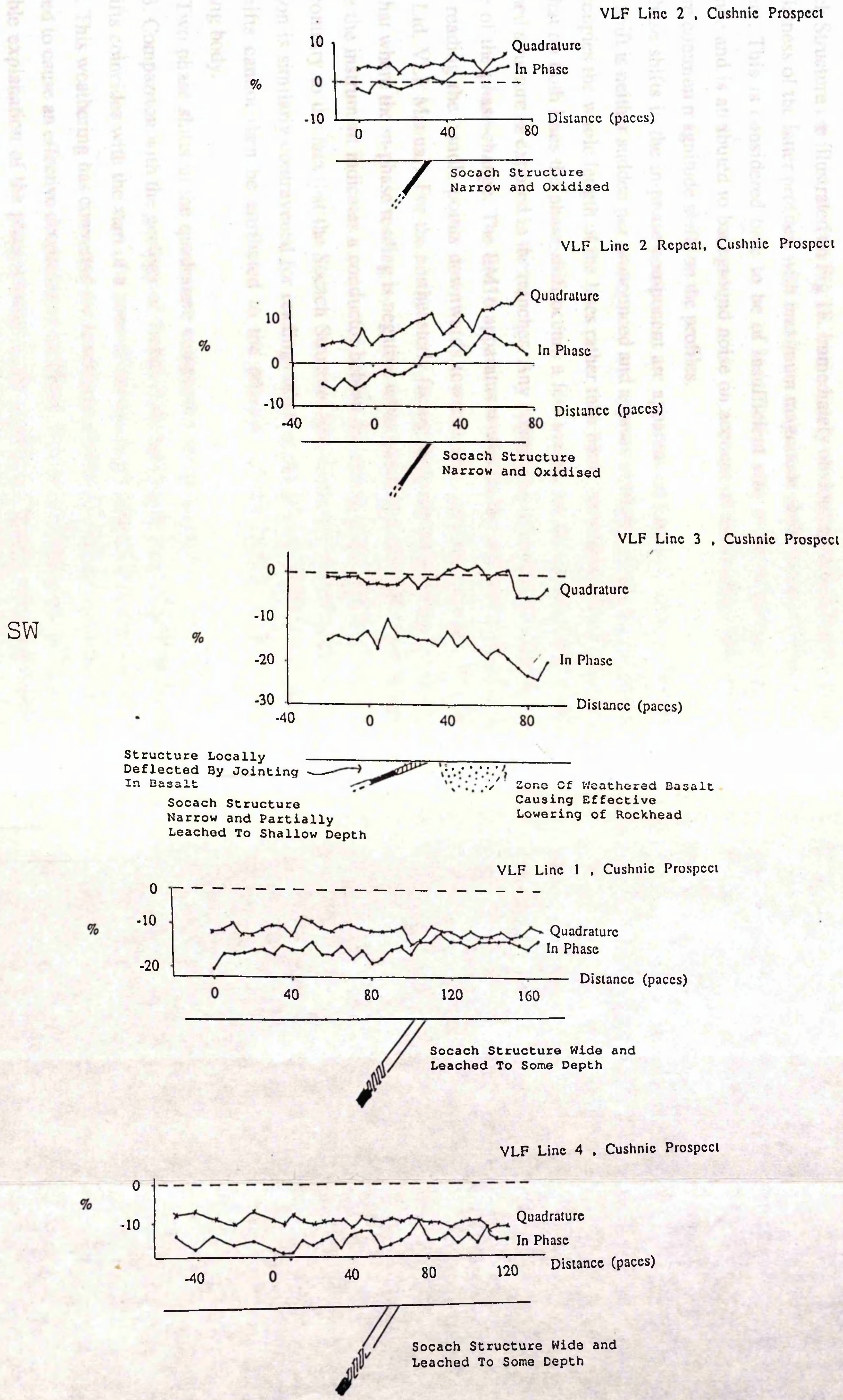
The VLF Survey

A similar set of lines were used for the VLF survey as for the SP survey. Geophysical traverses were run across the Socach Structure at positions of good geological control, achieved during trenching, and the positions of the lines were chosen to include parts of the structure known to be oxidised and leached respectively. The 16.0 kHz transmitter at Rugby, England was used as the signal source, providing good coupling with the structure on account of its position only slightly off the strike direction of the shear zone. A northeasterly facing direction was used on all lines in order to keep the polarity of all readings consistent. The in-phase and quadrature components of the vertical electromagnetic field were recorded simultaneously, and the results are plotted on Fig.18 .

In terms of structural position, Lines 1 and 4 cross the widest part of the Socach Structure at a topographically high level, and the structure is in a highly leached state in such positions. Line 2 is situated at around the level of the water table, and was run along the length of trench where the mineralization was exposed in a completely oxidised but unleached state and occupying a significantly narrower width. Line 3 was run along the length of trench 2, 50 m to the NW and 5 m vertically above trench A and as such is intermediate in terms of structural position. Mineralization in trench 2 was observed to be largely leached, but with the expectation that oxidised but unleached material similar to that seen in trench A would be present at a shallow depth on account of the water-table being present at this level. Part of the remit of this study was to investigate what effect the supergene alteration responsible for oxidation and leaching has on the geophysical signature of the Socach Structure.

VLF electromagnetic anomalies resulting from the presence of structural discontinuities and/or conducting bodies in the subsurface characteristically take the form of phase and/or magnitude shifts in either or usually both components of the vertical field. Examples of the size and disposition of such anomalies and their known or postulated

FIG 18; VERY LOW FREQUENCY ELECTROMAGNETIC PROFILES ACROSS THE SOCACH STRUCTURE, AND RELEVANT BEDROCK GEOLOGY.



signal comprises merely background noise. Few positive conclusions can be drawn from the VLF work then. The two characteristics of the structure, ie. its conductivity due to its hosting disseminated sulphide mineralization at depth and its presence as a structural discontinuity, have proven to be transparent to VLF electromagnetic waves. Where the shear zone is strongly developed but leached of sulphide and oxide minerals to some depth, ie. close to the discovery outcrop, the discontinuity is not apparent on VLF profiles. This may be a result of the similarity of host-rocks (interbanded psammites and garnet schists) on both sides of the structure; their similar geophysical properties may be preventing the shear zone showing up as a surface of geophysical contrast. Where the structure is mineralised with oxides at the surface and sulphides at depth but the structure is thin, its conductivity is transparent to the VLF technique. It may be that the metallic minerals are too sparsely disseminated to form a coherent conducting body; the mineralization could not be described, after all, as being sulphide-rich. Whatever is the cause of the transparency of the Socach Structure to VLF electromagnetic waves, the technique is not a useful one to detect mineralization as exposed in any of the trenches to date.

In conclusion, the Socach Structure has proven awkward to characterise by the types of geophysical methods which could cheaply and rapidly provide the large amounts of ground coverage required in the search for further mineralised structures or to follow known structures along strike. This difficulty is largely attributed to the fact that the potentially anomalous characteristics of the mineralization are not exposed together. Where the shear zone is developed to substantial width, any metallic minerals that may render it anomalously conducting have been leached out to some depth. The wide conductor is only then present at depth. Where the mineralization is unleached it is only developed over a very narrow width and the conductor is therefore volumetrically very small. It is interesting to speculate that were the Socach Structure exposed in an unleached state and developed to the widths seen near the discovery outcrop it would be geophysically distinctive. Since such a mineralised body constitutes the real exploration target at Cushnie, the constraint on this signature would be invaluable. The results above do not contradict the notion that such mineralization will be present at the downdip intersection of the Socach Structure near the discovery outcrop with the water-table, but they do mean that the depth and degree of leaching will prevent its detection by either SP or VLF geophysical methods.

These findings (or rather, the lack of them) are consistent with the work of Leslie (pers. comm.) who used ground magnetic data for the purposes of geological mapping in areas of poor exposure in the Grampian Highlands. The rocks in areas affected by Tertiary weathering exhibited subdued geophysical characteristics. Mapping of geological boundaries through such areas was possible by interpolation of geophysical data from outwith the area affected by deep weathering. On the basis of data collected from solely within the weathered area these boundaries could not be constrained. This latter situation is analogous to that on the Socach Structure and provides an explanation of its lack of geophysical expression.

CONCLUSIONS

A combination of float mapping, aerial photography, soil geochemistry and mechanical trenching has succeeded in locating several gold mineralised structures on the Cushnie prospect. At least one of these structures is traceable for a minimum of 1.5 km along strike, and the mineralised float distribution suggests that others will extend over similar lengths. Widths of mineralised zones is variable between 1m and 11m. The structures show distinctive shear fabrics, pervasive to patchy pink iron staining, pervasive sericitic alteration and the development of quartz ribs up to 1m wide, a combination of features indicative of ductile deformation and hydrothermalism. Topographic control on gold grades obtained from these structures defines a leached zone above the present water table and an oxidised zone at around the level of the water table. Textural characteristics of the mineralisation show pervasive oxidation at lower topographic levels and varying degrees of leaching of both sulphides and iron staining at higher levels. Such features are indicative of intense supergene alteration of the mineralised bodies. Attempts at characterising the main mineralised structure by geophysical means failed, probably due to a combination of relatively low primary sulphide content, leaching of these sulphides to significant depths and inadequate width of the mineralised body where it is actually exposed beneath the leached zone.

Field characteristics of the gold mineralisation provide evidence for the operation of processes of ductile deformation, hydrothermalism and supergene alteration in the generation of the auriferous structures on the Cushnie prospect. These aspects are dealt with in turn in subsequent chapters; Chapter 4 deals with the structural control of the mineralisation; Chapter 5 considers the hydrothermal processes; and Chapter 6 deals with the supergene alteration effects. The information provided by these specific studies is used in Chapter 7 to characterise the geological setting of the mineralisation within the context of the regional geology of NE Scotland, and to glean information which may be useful in the exploration for further such mineralised bodies. In these following chapters the material studied came chiefly from the series of trenches excavated to extend the exposure of the discovery outcrop towards Scar Hill. The mineralisation so exposed is believed to represent a single structure which can be correlated for 1.5 km along strike. This structure, denoted here the 'Socach Structure' provides the best opportunity for the study of the main characteristics of the mineralisation, since other structures were only exposed in single trenches and their extension along strike not investigated during trenching.

CHAPTER 4

STRUCTURAL CONTROL OF THE SOCACH GOLD DEPOSIT, ABERDEENSHIRE, SCOTLAND

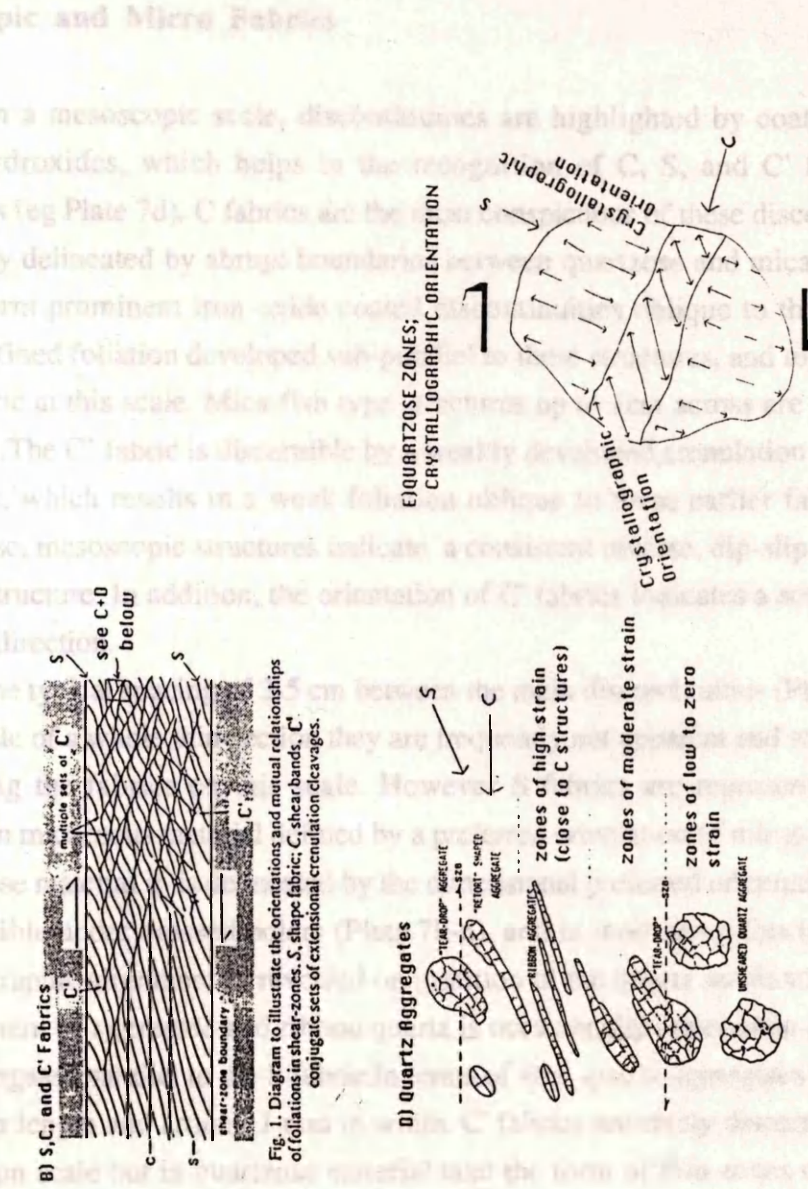
Introduction

The general nature of the structure hosting gold mineralisation at Socach was discernible even during the initial stages of prospecting. Shear fabric planes coated with iron oxides were visible on weathered surfaces of float samples and were unmistakable on sawn slabs of mineralised float. This early recognition assisted exploration slightly by confirming the original supposition that the mineralisation would be structurally controlled. Little could be gleaned concerning the detail of this structural control however until oriented sections from in-situ mineralised material were available and so structural analysis proceeded in earnest only when the float samples had been traced back to outcrop and the mineralisation exposed along strike by mechanical trenching.

Oriented sections were cut perpendicular to the foliation and parallel to the lineation in the sheared material. In addition slabs with a similar orientation permitted study of the fabrics on a mesoscopic scale. Strike coverage was good; samples were available from most of the trenches shown on Fig.10 as well as from the discovery outcrop. In all, 25 oriented sections and slabs were cut and studied.. They were examined for fabrics that would establish the sense of shear on the structure and for evidence of the relationship between deformation and mineralisation. Whether the ductile deformation played an active or a passive role in the mineralising process is critical for an understanding of the genesis of the deposit.

The ductile deformational fabric within the Socach Structure included S, C, and C' structures (Harris and Cobbold 1984, White et al 1980), which were associated with a combination of mica-fish, dimensionally and crystallographically oriented quartz, development of aggregate to ribbon quartz textures, imbrication of fractured quartz fragments and quartz horse development.This list includes components of both the type I and type II S-C mylonites of Lister and Snoke (1984); different components of the two types being recognisable at different scales of observation. Since it is the kinematic information that is important to this study rather than the origin of these features they will be described together without distinction and the kinematic information extracted following the framework of Lister and Snoke (1984). Identification of the above features was facilitated on the one hand by infilling of voids in the shear fabric by iron oxides of hydrothermal/supergene origin which enhanced the optical contrast in PPL between pale quartz and mica and the contained dislocations. On the other hand, intense sericitic hydrothermal alteration often homogenised the micaceous material to an amorphous fine grained sericitic aggregate, obscuring cleavage and related structural discontinuities. The information provided by these fabrics is presented here as a series of 'photosequences' where the rocks are analysed on increasing scales from the hand-specimen to the whole thin-section to the microscopic scales.

FIG. 19 ; SCHEMATIC DIAGRAM SHOWING RELATIONSHIPS BETWEEN KINEMATIC INDICATORS WITHIN THE SOCACH STRUCTURE. (modified after Platt (1983), Simpson (1983) and Lister and Smoke (1984).



Mesoscopic and Micro Fabrics

On a mesoscopic scale, discontinuities are highlighted by coatings of grey iron oxides/hydroxides, which helps in the recognition of C, S, and C' fabrics in certain specimens (eg Plate 7d). C fabrics are the most conspicuous of these discontinuities and are commonly delineated by abrupt boundaries between quartzose and micaceous domains. S fabrics form prominent iron oxide coated discontinuities oblique to the C fabric, with a poorly defined foliation developed sub-parallel to these structures, and together they define the S fabric at this scale. Mica-fish type structures up to 1cm across are occasionally seen (Plate 7g).The C' fabric is discernible by a weakly developed crenulation of earlier S and C structures, which results in a weak foliation oblique to these earlier fabrics. In terms of shear sense, mesoscopic structures indicate a consistent reverse, dip-slip movement on the Socach Structure. In addition, the orientation of C' fabrics indicates a southeasterly bulk transport direction.

The typical spacing of 2-5 cm between the main discontinuities (Plate 7d) means that on the scale of a whole thin-section they are frequently not apparent and so do not contribute to defining the fabrics on this scale. However S fabrics are represented by a distinct foliation in micaceous material defined by a preferred orientation of micas (plate 7a-c), while in quartzose material it is delineated by the dimensional preferred orientation of small quartz grains visible under crossed polars (Plate 7k-n), and in most cases this is accompanied by crystallographic alignment as revealed on insertion of the quartz sensitive tint (Plate 7f,l,n). Development of aggregate and ribbon quartz is occasionally observable at this scale (Plate 7b,c), elongated parallel to the S fabric.In terms of size, quartz aggregates reach a maximum of 4mm in length and around 1 mm in width. C' fabrics are rarely discernible on the whole thin-section scale but in quartzose material take the form of thin zones of high strain and dimensional realignment of quartz in an attitude antithetic to the S fabrics (Plate 7j,n).That these features develop in an orientation consistent with all other shear fabric elements within the Socach Structure is taken as evidence that they formed during shearing on that structure rather than being relict features of any earlier deformation such as regional metamorphism. The pattern of fabric elements visible on this scale is identical to those observed on the mesoscopic scale, and the tectonic implications are therefore identical.

Microstructures visible in thin section at 2.5X to 10X magnification exhibit a greater variety and clarity of shear fabric elements than all other scales. C fabrics are represented by sharp discontinuities, frequently with abrupt boundaries between quartzose and micaceous domains (Plate 7e) and commonly occur close to zones of high strain in altered host rocks. The latter are recognised by the development of densely packed mica-fish adjacent to the discontinuities. The S fabric in micaceous material is represented by pronounced alignment of micas, and discontinuities are frequently present sub-parallel to this (Plate 7b.f) These discontinuities are usually associated with mica-fish, either as discontinuity surfaces within the fish or as surfaces along which stair-stepping mica-fish are connected (using the stair-stepping analogy, the 'flats' define the C fabric while the 'steps' define the S fabric) While

PLATE 7; MESO AND MICROFABRICS WITHIN THE SOCACH STRUCTURE AND THEIR KINEMATIC SIGNIFICANCE

A) Sample LS21B Looking Southeast

Whole thin-section scale; C fabric defined by weak foliation, horizontal on photograph. Stronger foliation created by preferred alignment of micaceous material and dimensional preferred orientation of ribbon quartz aggregates defines the S fabric. Angle between C and S fabrics is very acute implying a high degree of strain, consistent with the presence of ribbon quartz. From the Socach Structure on Scar Hill where the shear zone is only one metre wide, implying a higher concentration of strain where the deformation zone is narrower.

B) Sample LS21B Microscopic Scale Looking Southeast

C fabric defined by major dislocation just off the lower edge of the picture. S fabric defined by dimensional elongation of quartz aggregate and by preferred orientation of platey micas. Quartz aggregate shows broad sweeping undulose extinction and relatively coarse grain size indicative of low amount of strain; insertion of quartz sensitive tint shows no crystallographic alignment of the quartz within the aggregate. Incipient mica-fish development in centre of picture is consistent with shear direction indicated by C and S fabrics. Note hydrothermal alteration of mica fish which partially obscures dislocations and opaque zones representing iron oxides/hydroxides of hydrothermal/supergene origin.

C) Sample LS21B Microscopic Scale Looking Southeast

C fabric parallel to lower edge of photograph. S fabric defined by preferred orientation of micas and dimensional orientation of ribbon quartz aggregate. Note high strain state of quartz in ribbon, with small grain size and ubiquitous undulose extinction; insertion of quartz sensitive tint shows a high degree of crystollagraphic alignment of this quartz. Note ubiquitous alteration of muscovite to sericite and the opaque patches representing iron oxides/hydroxides of hydrothermal/supergene origin.

Fabrics at the whole thin-section and microscopic scales give consistent indications of shear sense on the Socach Structure. The presence of indicators of high strain (ribbon quartz) and indicators of relatively low strain (incipient mica fish development and crystallographically unaligned quartz aggregates) in the one thin section implies that strain was inhomogeneous and locally highly concentrated.

D) Sample JC2 Whole Rock Scale Looking Southeast

C fabric defined by prominent sub-horizontal discontinuities. S fabric defined by prominent continuous discontinuities oblique to the C fabric. C' fabric defined by discontinuous discontinuities arranged antithetically to the S fabric. Note lining of shear fabric discontinuities with dark grey iron oxides/hydroxides, and pervasive iron staining in

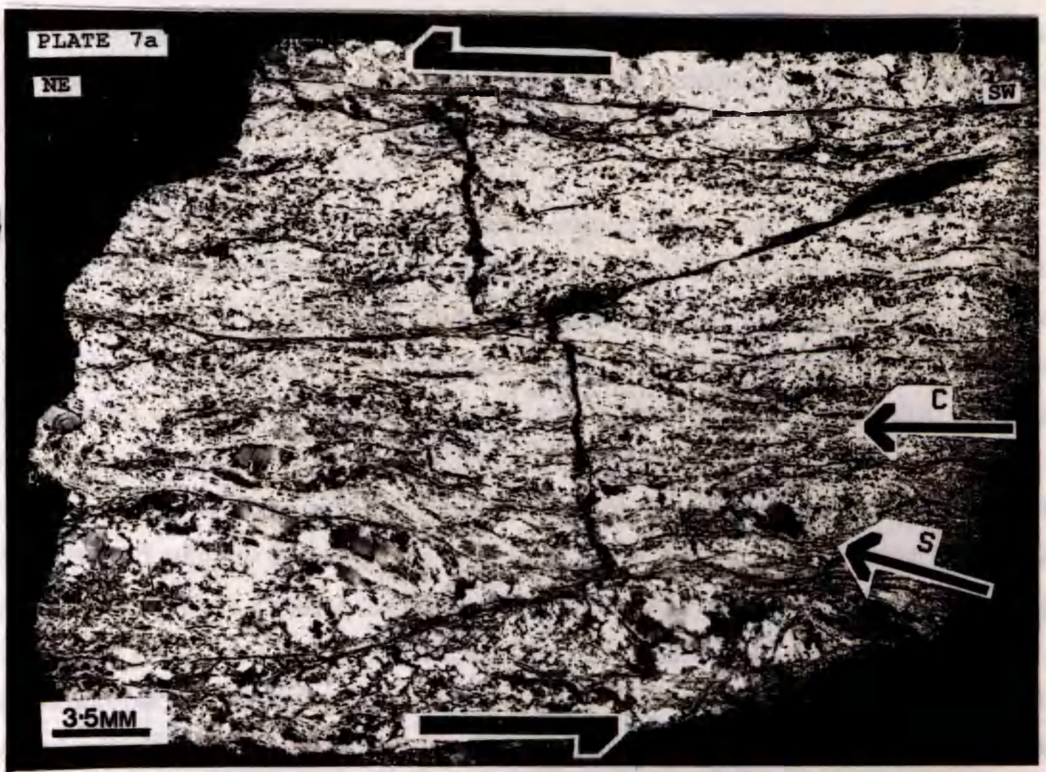


PLATE 7a
NE
SW
C
S
3·5MM

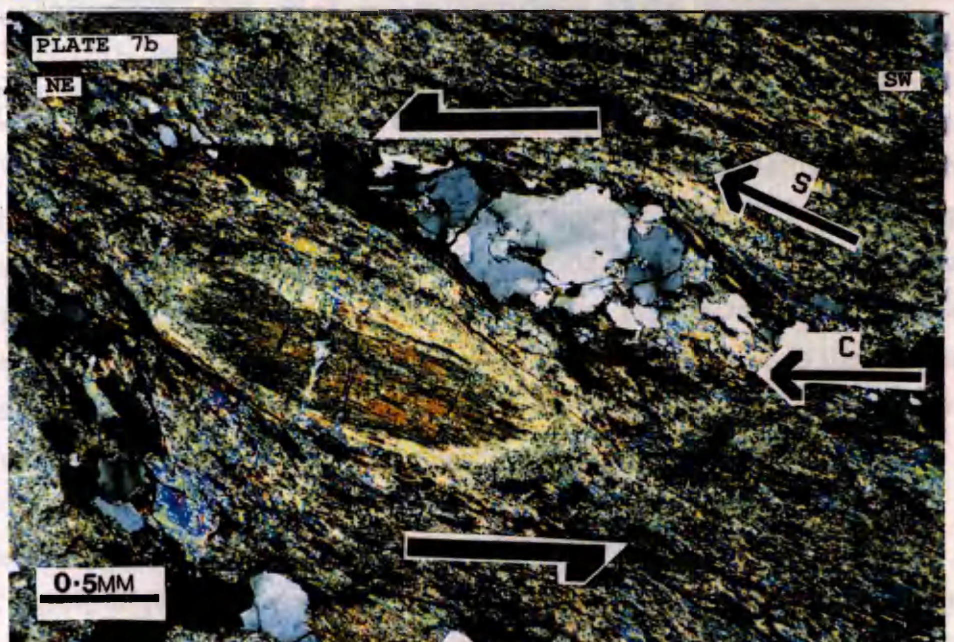


PLATE 7b
NE
SW
S
C
0·5MM

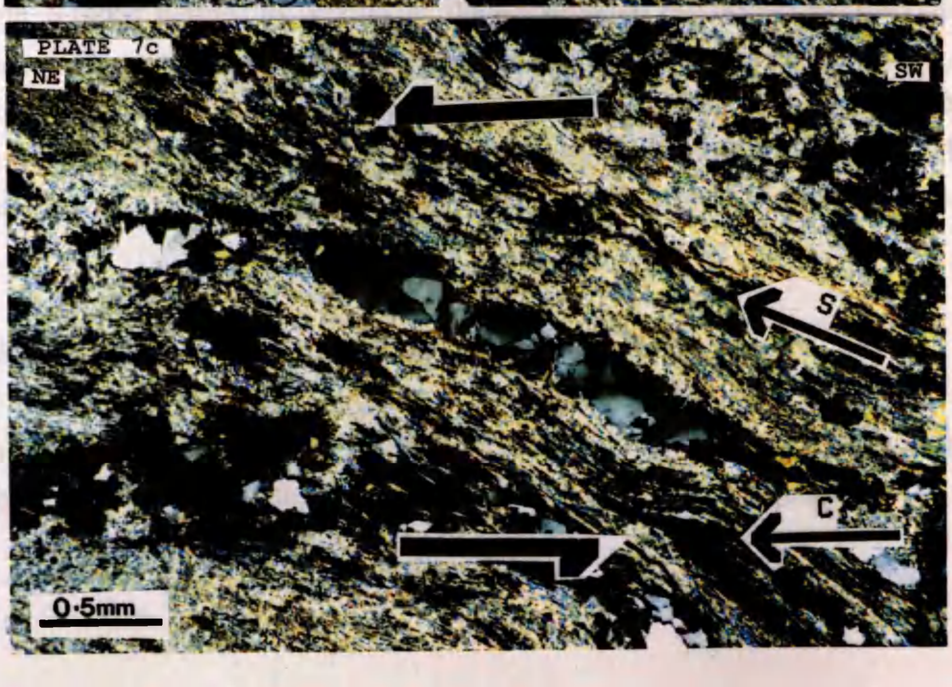


PLATE 7c
NE
SW
S
C
0·5mm

between the discontinuities. Note also the hydrothermal quartz lens near the top of the rock, aligned and bounded on both sides by prominent C fabric discontinuities. All point to strong control of hydrothermal fluid passage by shear fabric permeability, but not complete control, hence the pervasive iron staining.

E) Sample JM2 Whole Thin Section Scale Looking Northwest

C fabric defined by major dislocations running horizontally across the middle of the photograph. S fabric defined by well developed foliation in micaceous/quartzose material in lower part of photograph. Note prominent quartz domain occupying top of photograph, the quartz being unstrained, relatively coarse grained and subhedral in habit; this represents hydrothermal quartz.. Note parallelism of the edge of this quartz domain to C fabric. Subordinate quartz domain in centre of photograph shows strong control by C fabric on its location and shape, indicating a strong control by C fabrics over the passage of hydrothermal fluids. Opaque areas are iron oxides/hydroxides of hydrothermal/supergene origin and these also show overall C fabric control. Note also late fractures cutting hydrothermal quartz domain; these are lined with vuggy quartz and iron oxides of hydrothermal/supergene origin, indicating the brittle regime prevalent during hydrothermal activity.

F) Sample JM2 Microscopic Scale Looking Northwest

C fabric parallel to lower edge of photograph. S fabric defined by foliation in micaceous/quartzose material. Note the extremely fine grain size of the strained quartz in comparison with hydrothermal quartz on Plate 8. Good development of mica fish in centre of photograph with transport of fish in a stair-stepping manner upwards and rightwards, consistent with the shear sense indicated by C and S fabrics. Note also the localisation of haematite pseudomorphs after pyrite along S fabrics, indicating that S fabrics also exerted some control over the passage of hydrothermal fluids.

G)Sample LS8B Whole Rock Scale Looking Southeast

C fabric defined by prominent discontinuities running horizontally across the photograph. S fabric defined by prominent oblique foliation and occasional discontinuities. Note good development of mica-fish at the gross scale at the centre left of picture and the greater degree of iron staining in and around prominent C and S fabrics. Note also the small lens of hydrothermal quartz lying along the C fabric near the centre of the picture. The latter two points indicate strong control by shear fabrics on the localisation of hydrothermal minerals.

H) Sample LS8B Whole Thin Section Scale Looking Southeast

C fabric defined by most prominent, undulatory discontinuities running roughly horizontally across the photograph. S fabric defined by dimensional alignment of quartz in lower half of photograph. Opaque material is iron oxide/hydroxide of


PLATE 7d
scale bar 2cm long
NE
SW
C'
C
S

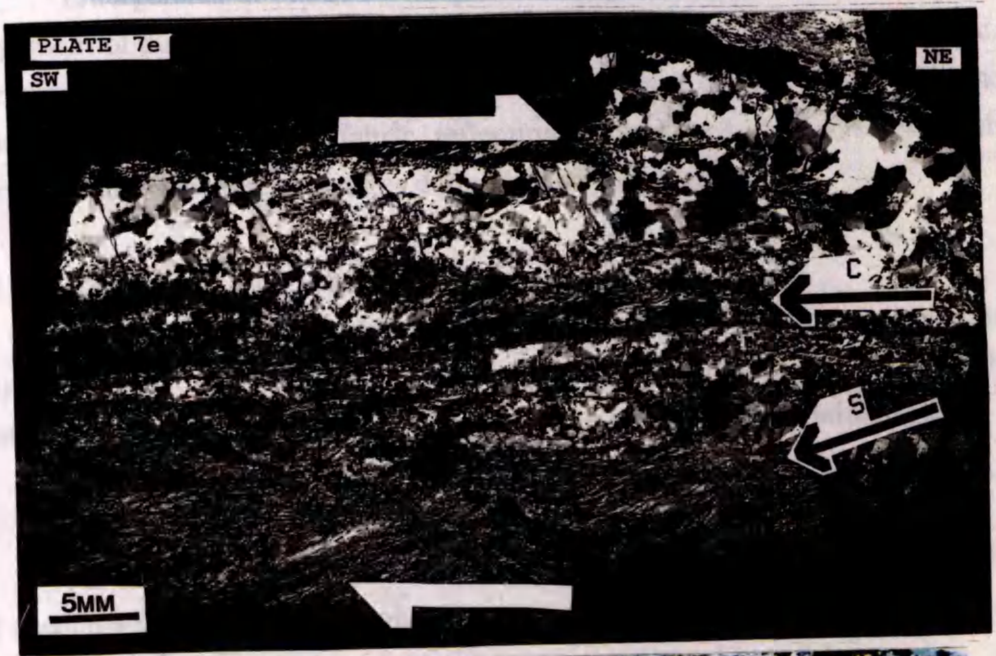


PLATE 7e
SW
NE
C
S
5MM

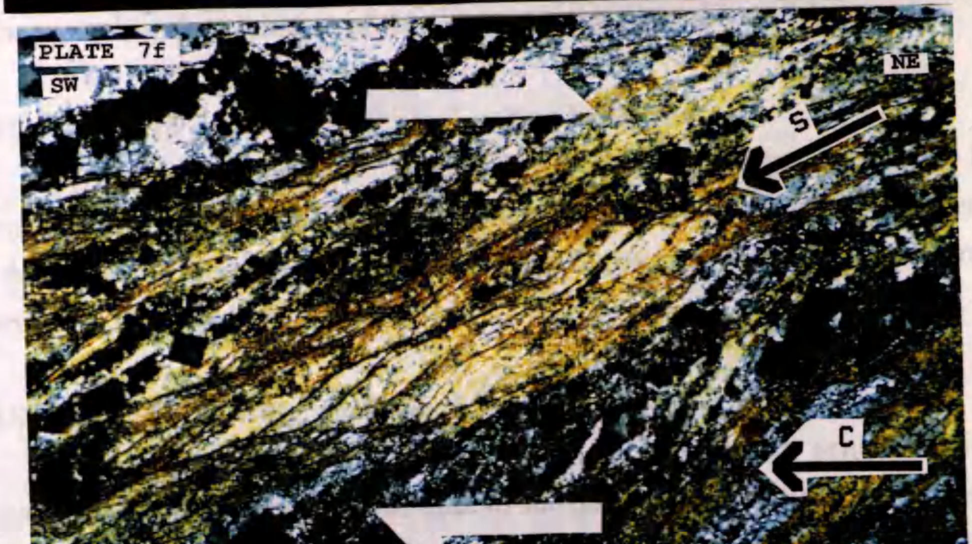


PLATE 7f
SW
NE
S
C
0·5mm

hydrothermal/supergene origin and shows strong C fabric control on its distribution. Note good development of mica fish near top of photograph, highlighted by the contrast between mica and iron oxide/hydroxide, and indicating a shear sense consistent with that implied by the S and C fabrics.

I) Sample LS8B Microscopic Scale Looking Southeast

C fabric defined by undulatory iron oxide lined shear gash at top of picture. S fabric defined by dimensional alignment of quartz masses which on insertion of the quartz sensitive tint also shows up as a crystallographic alignment (see Plate 7i)." C' " fabric defined by parallel fractures which cut the quartz masses at an angle antithetic to their direction of elongation. Fractures have broken the large elongate quartz grain into 'books' which have become imbricated by further shearing of a sense similar to that which affected the bulk rock, consistent with the fractures representing a C' fabric.

J) Sample LS8B Microscopic Scale Looking Southeast

Enlargement of Plate 7i with quartz sensitive tint inserted. Shows crystallographic alignment of dimensionally elongate quartz (yellow) which defines the S fabric. Note also the change in crystallographic alignment in fine grained quartz (blue) within the antithetic fractures defining the" C' " fabric, reflecting the localised oblique sense of shear which occurred across the microfractures during late stages of shearing..

K) Sample LS16 Whole Thin Section Scale Looking Northwest

Typical sheared quartzose domain. C fabric defined by faint discontinuities cutting horizontally across the photograph. S fabric defined by prominent directional alignment of quartz crystals. C' fabric defined by zones of high strain oriented antithetic to the S fabric.

L) Sample LS16 Microscopic Scale Looking Northwest

Insertion of quartz sensitive tint shows dimensional alignment of quartz crystals to be accompanied by crystallographic alignment. Discontinuity cutting diagonally across slide is the typical weak expression of the C fabric in this type of material.

M) Sample LS16 Microscopic Scale Looking Northwest

Close-up of antithetic zone of high strain defining C' fabric. Pronounced dimensional grain alignment within the zone of high strain indicates a shear sense the same as that affecting the bulk rock, implying that it formed under the same stress regime and is therefore a true C' fabric.

N) Sample LS16 Microscopic Scale Looking Northwest

Same field of view as Plate 7m with the quartz sensitive tint inserted. Crystallographic alignment of the bulk of the quartz which defines the S fabric shows up


PLATE 7m
SW
NE
S
C
0·5MM


PLATE 7n
SW
NE
S
C
0·5mm


PLATE 7k
SW
S
C
2MM

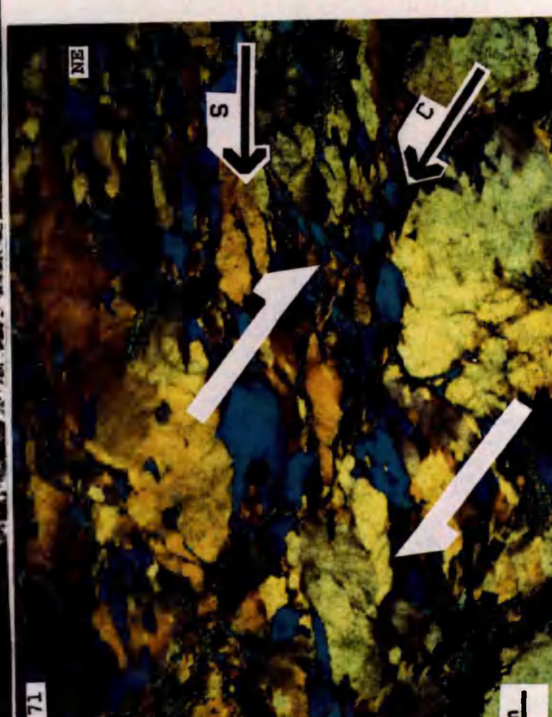
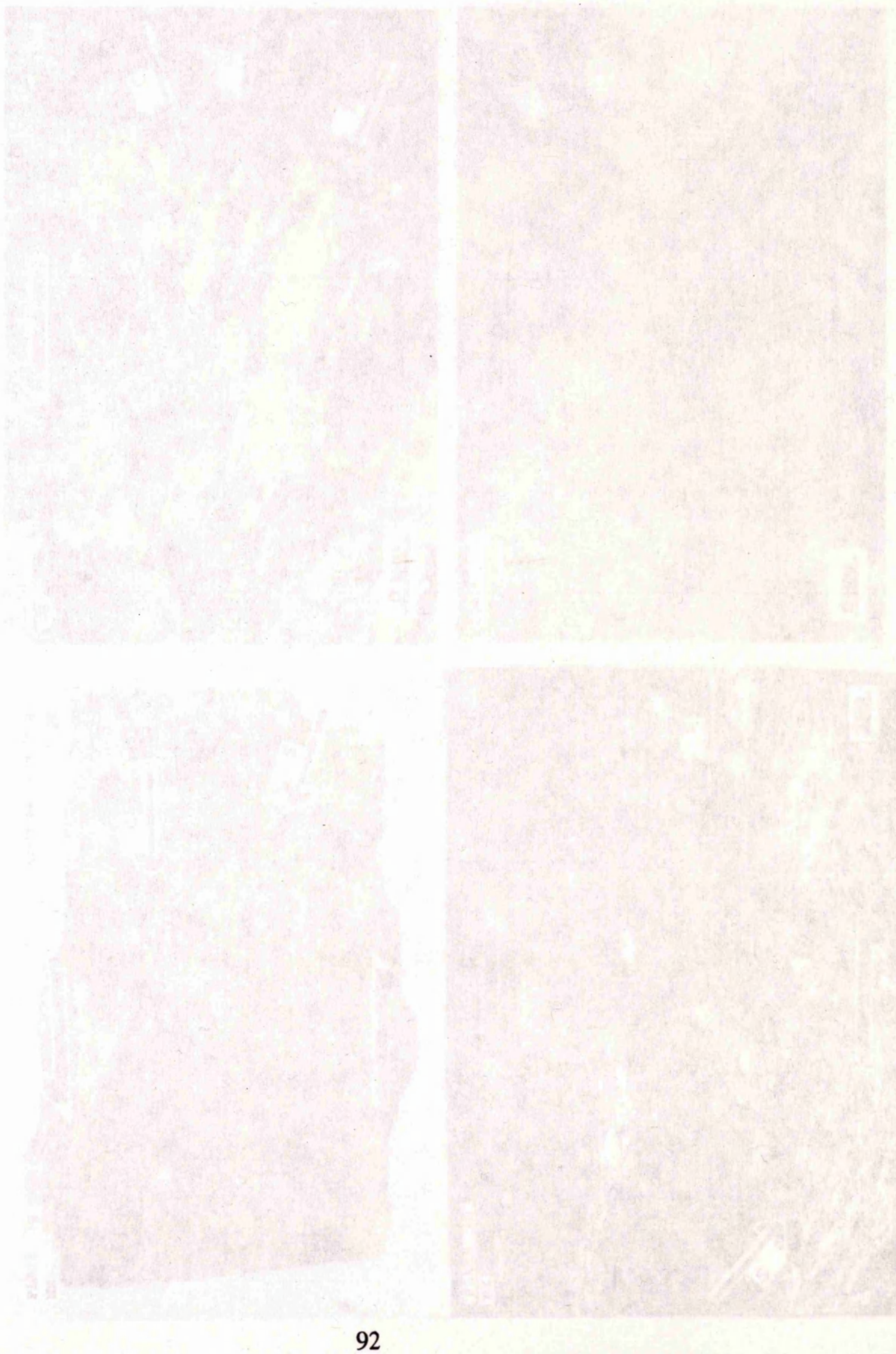


PLATE 7l
SW
NE
S
C
0·5mm

well. Zone of high strain shows crystallographic re-alignment antithetic to that in the bulk rock, in a similar manner to the dimensional alignment.



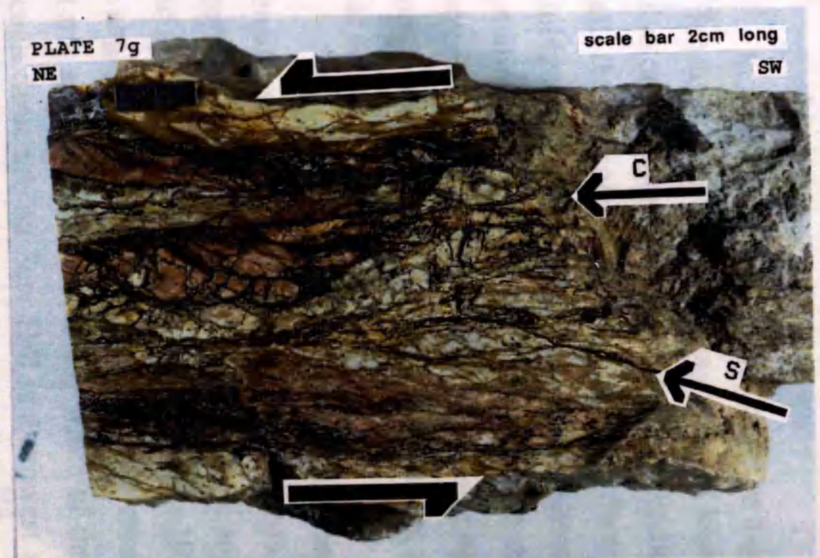


PLATE 7g
NE
scale bar 2cm long
SW
C
S

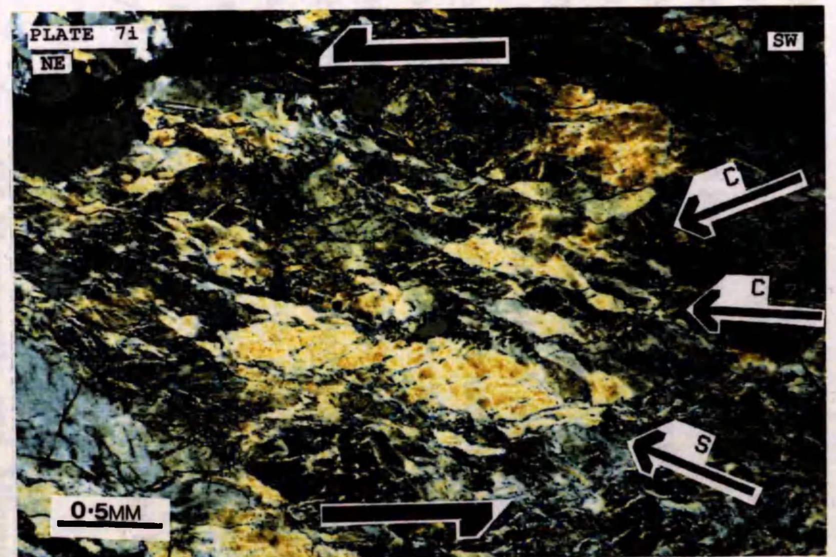


PLATE 7i
NE
SW
C
C
S
0·5MM

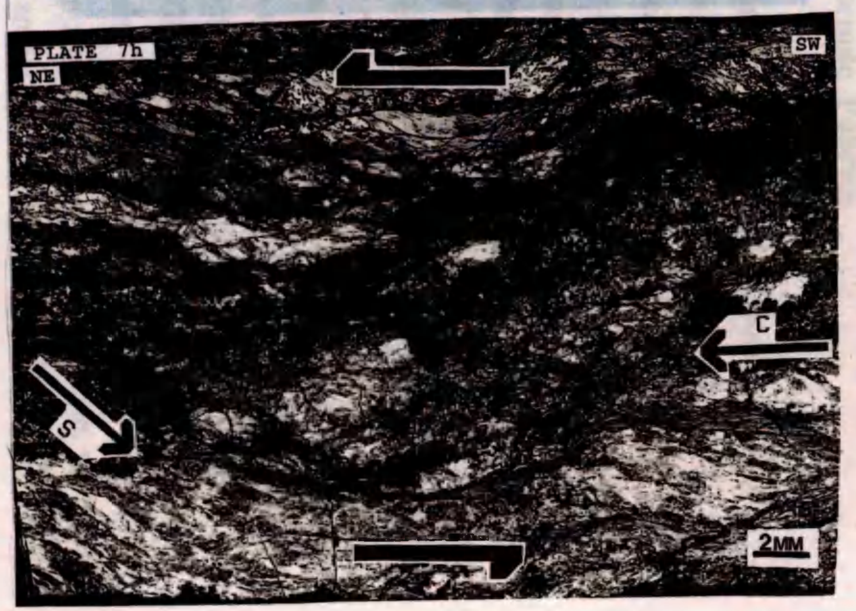


PLATE 7h
NE
SW
C
S
2MM

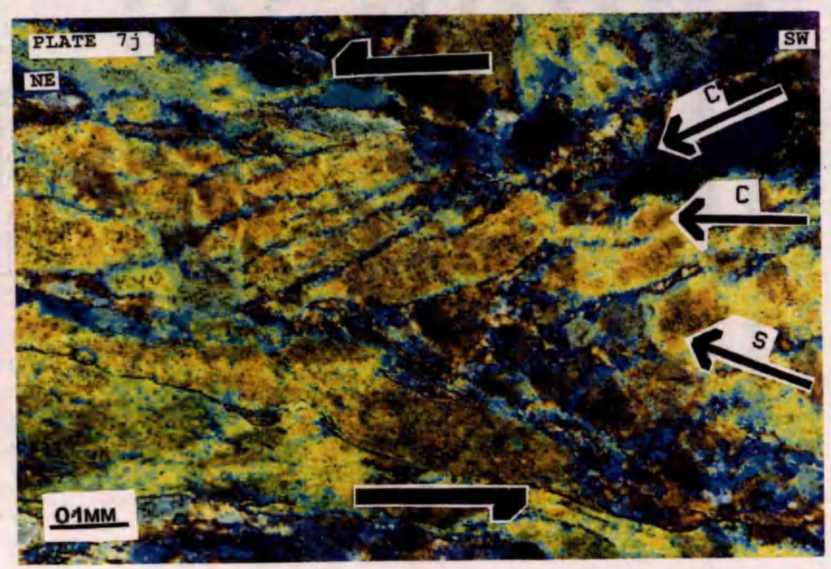


PLATE 7j
NE
SW
C
C
S
0·1MM

the orientation of these 'steps' is more undulatory than the foliation, their overall attitude is very similar, so they are regarded as partially defining the S fabric.In quartzose material the dimensional and crystallographic alignment of quartz grains is even more obvious than on the whole thin-section scale (Plates 7i-n). Mixed quartzo/micaceous domains show good development of quartz aggregates and ribbons (Plates 7b,c), with the elongation direction being parallel to the foliation in surrounding micas. In slightly elongate aggregates quartz is relatively coarse grainedand only slightly strained while in the ribbons it shows evidence of recrystallisation to a finer grain size with some degree of crystallographic re-orientation within the ribbon. Mica-fish are present in most thin sections and demonstrate all stages in development from in-situ masses of mica, broken up by listric type discontinuities (Plate 7b) but with no movement across them, to clusters of individual fish which display evidence of relative transport, ie. offset of cleavage in micas across listric discontinuities and stair-stepping fish joined by by elongate discontinuities sub-parallel to the gross S fabric (Plate 7f). The shapes of individual fish and direction of offset between the fragments on listric discontinuities is consistent with shear sense deduced from S and C fabrics at all scales. On a microscopic scale in quartzose material, C' fabrics are revealed by thin to very thin zones of high strain oblique to and cross-cutting the S fabric foliation (Plate 7l,7m). Within these high strain zones, quartz recrystalisation to finer grain size with dimensional and crystallographic re-orientation show up well (PLATES 7l,m,n) and indicate a similar shear sense in the bulk rock. The orientation of these features and the sense of shear they imply are similar to that shown by C' fabrics in adjacent micaceous material, thus confirming that they do in fact represent C' fabrics developed in a mechanically distinct material.

Implications Of Mesoscopic and Microscopic Fabrics

In addition to defining the rocks as a product of processes of ductile deformation, the fabrics discussed above may serve as kinematic indicators. As mentioned earlier, the relative orientations of C and S fabrics can indicate the shear sense (Lister and Snoke 1984). In all the samples from the Socach Structure in which C and S fabrics can be unambiguously defined the shear sense indicated is reverse dip-slip in nature. The relative orientations of the fabrics are consistent on the mesoscopic rock, whole thin-section and microscopic scales, and confirm this sense of movement on the structure. Mica-fish are commonly observed at the microscopic scale, and their shapes give further evidence of this shear sense.

The degree of development of the shear fabrics may provide some indication of the intensity of ductile deformation. At the gross scale, the angle between C and S fabrics is known to decrease as shearing progresses, sometimes with a concomitant decrease in the spacing of S surfaces (Lister and Williams 1979). On the Socach Structure, comparison of the angle between C and S fabrics and the spacing of both fabrics reveals decreasing angles but not spacing, with decreasing width of the zone of ductile deformation, ie. where the Socach Structure on Scar Hill is narrowest angle(CS) is very small (15-25) (Plate 7a) whereas close to the discovery outcrop where the structure is substantially wider the angles approach 45°.

The homogeneity of the ductile deformation may also be revealed from the study of shear fabrics. The presence of C, S, and C' surfaces, (see Plate 7), implies that the bulk of the deformation occurred along these features. Dense packing of adjacent mica-fish testify to the relatively high strain experienced at the margins of these discontinuities. The pattern of strain was therefore inhomogeneous on the gross scale, being concentrated along what are now iron oxide coated shear gashes. On a slightly smaller scale this inhomogeneity is recognisable by the juxtaposition of quartz aggregates/ribbons of widely different elongations, eg. Plates 7b,c come from the same thin-section, only 5mm apart. The low degree of overall elongation, individual grain recrystallisation and crystallographic alignment in the former compared with the latter are indicative of widely different degrees of strain even on this scale. Between the two areas depicted there is a C fabric dicontinuity, so it can be seen that as well as concentrating strain these discontinuities separate low from high strain domains. Strain is therefore inhomogeneous at all observed scales. At only one point on the Socach Structure could the variation in strain across the width of the shear zone be observed. Samples LS21B and JC2, from the centre and margins of the zone respectively, show angle(CS) to be more acute in the middle of the zone, indicating a greater degree of strain. However, in view of the inhomogeneity of strain identified on smaller scales it is very unlikely that this represents any sort of gradual increase of strain towards the middle of the Socach Structure. Strain can only be described as inhomogeneous on the microscopic to macroscopic scales.

Structural Control of Hydrothermal Processes

The spatial relationship between hydrothermal quartz, the iron oxides/hydroxides of hydrothermal/supergene origin, and the shear fabrics is informative on the control exerted on the hydrothermal processes by the deformation fabrics. The most noticeable feature is the almost ubiquitous coating of C and S surfaces by dark grey iron oxides/hydroxides (Plate 7d,e). Such coatings are not a typical feature of shear zones. The other forms of iron oxide/ hydroxide hosted by the Socach Structure (pseudomorphs after pyrite and pervasive iron staining) are considered to be the products of hydrothermal followed by supergene processes. It is therefore very likely that the discontinuity coatings are also of such an origin.

Prominent hydrothermal quartz domains in rocks of the Socach Structure are characteristically bounded by C fabrics (Plates 7d,e), and this is observable on all scales examined from mega to microscopic. On a mesoscopic scale this phenomenon is responsible for the distinctive banding of quartz and altered host rock which trends in the strike direction of the outcrops. On smaller scales, unstrained hydrothermal quartz is bounded by zones of particularly high strain in sericitised host rock, the strain being suggested by the dense packing of mica-fish and the presence of strong discontinuities parallel to the C fabric. The degree of strain decreases away from these abrupt boundaries and the sericitised host rock becomes more homogeneous and less broken up into mica-fish. Zones of hydrothermal pyrite (now pseudomorphed by haematite and goethite) enrichment show similar but weaker control by C fabrics (Plate 7e); in this instance the boundaries are more diffuse and significant amounts of pyrite are disseminated through the host rocks outwith the C fabric discontinuities. This forms zones of iron oxide/hydroxide enrichment oriented sub-parallel to the C structures/surfaces/shear bands, with most of the opaque minerals lying between the C fabric discontinuities and substantial dissemination outwith these structures.

S fabric control on the location of hydrothermal minerals is indicated by the frequent occurrence of euhedral pseudomorphs after pyrite aligned along the foliation which defines the S fabric. This is only apparent in micaceous host rocks where the foliation is partly defined by discontinuities oblique to the C structure and subparallel to the preferred orientation of the micas; here opaques with cubic form are seen to be distributed along the discontinuities (Plate 7f) No iron oxide/hydroxide enrichment occurs in the coherent micas whose alignment further defines the S fabric. In quartzose hosts where the S fabric foliation is defined entirely by dimensional and crystallographic alignment of the quartz mass no enrichment of opaque minerals occurs parallel to the S fabric. It is therefore the discontinuity aspect of the S fabric rather than the mineral alignment component which exerted a control on hydrothermal fluid flow.

The coating of C' discontinuities with iron oxides/hydroxides (Plate 7d) is the only observable control of this structure on the siting of opaque minerals These iron oxides/hydroxides do not display the pseudomorphic habit after pyrite. The poor development of hydrothermal minerals (ie.quartz ribs and pyrite) along C' fabrics constitutes evidence that these fabrics did not provide significant permeability to hydrothermal fluids. In addition, this discontinuity lining is only apparent within micaceous material, as the crystallographic and dimensional fabric of quartz seen elsewhere defining the C' fabric is not accompanied by opaque mineral enrichment. C' fabrics cutting micaceous material can on these grounds be argued to have provided better permeability than those cutting quartzose domains. The tightness of the shear discontinuities would render them relatively impermeable to downward percolating hydrothermal fluids, so a supergene origin for the discontinuity lining iron oxides/hydroxides can be discounted. Hydrothermal fluids under pressure could penetrate along such discontinuities. The discontinuity lining can therefore be assigned a hydrothermal origin, with its degree of development reflecting the relative permeabilities of the different fabrics to hydrothermal fluids. C' fabrics provided less permeability to these fluids than C or S fabrics, particularly in quartzose materials.

Late cross-cutting fractures provide an additional site for hydrothermal minerals. These are lined with vuggy quartz and iron oxides/hydroxides, the former being diagnostically hydrothermal in origin. Such fractures are rare and tend to transect shear fabrics and hydrothermal quartz lenses at a high angle. They are typically thin, reaching a maximum of 2 mm wide, highly irregular and distinctly brittle in character. The development of euhedral quartz along these fractures also implies a degree of dilational movement across them, to create space for quartz crystallisation. The occurrence of these fractures is restricted to rocks and thin sections where hydrothermal quartz lenses are well developed but they do extend beyond the quartz domains themselves.

In order of importance the structures developed in the mineralised zone are C, S, late brittle fractures, then perhaps C'. The order of importance of the ductile fabrics is the same as their degree of development in the Socach Structure; C structures form the major continuous discontinuities, S structures form significant and continuous but less pronounced discontinuities and a well developed foliation oblique to the C fabric, while C' fabrics are poorly and discontinuously developed. The correlation between quality/continuity of fabric development and the degree of hydrothermal mineralization implies that the primary control on the latter is the permeability created by the shear fabrics. Thus, continuous, interconnected C and S structures formed the major pathway exploited by invading hydrothermal fluids while the weakly developed, discontinuous C' fabrics provided permeability to these fluids to a much lesser degree. Additionally, some degree of passage of hydrothermal fluids through the bulk rock away from these discontinuities is evidenced by the pervasive nature of the sericitic alteration and the iron staining so characteristic of the Socach Structure. Thus while the microstructure concentrated and directed fluid flow it did not completely control it. This applies also to the larger scale,where sericitic alteration and iron staining are observed in the field to extend outside the zone of ductile deformation. Thus whilst the above descriptions categorise the deposit as structurally controlled, it is not 100% so.The bulk of the hydrothermal fluid flow would appear to have been controlled and focussed by shear-induced permeability in the rock, but the extent of pervasive sericitic alteration in the immediate wall-rocks indicates a degree of penetration of fluid through unsheared rock in the vicinity of the Socach Structure. Shear induced permeability constituted the primary control on fluid flow, but fluid penetration into surrounding country-rocks was also significant.

The generally pronounced contrast in strain states between hydrothermal and tectonic minerals in the Socach Structure imply that the hydrothermal activity post-dated tectonic movement on the shear zone. Plates 7i-7n however clearly show quartz domains within the Socach Structure which have undergone significant strain, and S, C and C' fabrics are all discernible within these domains. Strained quartz domains such as these were exclusively situated immediately adjacent to strongly developed C fabric discontinuities.This strained quartz was observed to be transitional with unstrained hydrothermal quartz situated away from the prominent C fabric discontinuities. This spatial relationship is suggestive of syn or post hydrothermal reactivation of the dominant lines of weakness within the Socach Structure. C, S and C' fabrics within strained quartz domains indicate that movement on the Socach Structure during reactivation was in a similar direction and attitude to that involved in the initial pre-hydrothermal movement. Relative volumes of strained and unstrained quartz are variable and reflect the degree of development of C fabric discontinuities, but on the bulk rock scale the unstrained variety is generally significantly dominant. The above observations therefore point to some degree of overlap between hydrothermalism and shear deformation, most probably as a result of late reactivation of the Socach Structure along the dominant lines of weakness, the C fabric discontinuities. Given that the bulk of the quartz within the Socach Structure is of the unstrained hydrothermal variety and is therefore post shear deformation, it is envisaged that hydrothermal fluids invaded a pre-existing shear zone, exploiting the permeability provided by the shear fabrics. It is however difficult to imagine how the space now occupied by quartz lenses could have formed. Individual lenses can be 5cm or more wide and outcropping material shows them to be developed to lengths exceeding 75 cm. A possibility exists that the hydrothermal quartz ribs are developed in the open space produced by the development of tension gashes during shearing. However the typical form of such features, as tapering S-shaped bodies (when viewed looking along the strike of the shear zone) is inconsistent with the 3D shape of the quartz ribs on the Socach Structure (Fig.15). The variation in dip and thickness along the length of such tension gashes is not apparent on the quartz ribs. Rather they form lens-shaped bodies, elongate along the strike direction of the shear zone and with a consistent dip in the same direction as the plunge of the Socach Structure. The thicknesses of some of the hydrothermal quartz ribs is also inconsistent with the idea that they represent hydrothermally infilled tension gashes. An alternative means of generating these voids would be by hydraulic jacking of the shear fabrics by hydrothermal fluids. Such fluids under pressure could at shallow crustal levels overcome the lithostatic pressure holding the shear fabrics tightly together, creating void space along the planes of permeability being exploited by the fluids. Subsequent quartz crystallization from hydrothermal fluids while the shear fabrics were still jacked open would create the quartz lenses seen in outcrop today.

Mineralization of shear fabrics by quartz and pyrite would eventually result in the partial destruction of the originally exploited permeability, ie. the shear zone would 'clog up' with hydrothermal minerals. In such instances the only possibility for hydrothermal fluids attempting to migrate along the shear zone would be to create their own permeability. This is envisaged as the cause of the late brittle mineralized fractures, which formed by hydraulic fracturing once the shear zone permeability had been locally reduced by mineralization from earlier fluids. A late 'crack and seal' mechanism of mineralization therefore replaced the earlier hydraulic jacking and subsequent void infilling mode of mineralization.

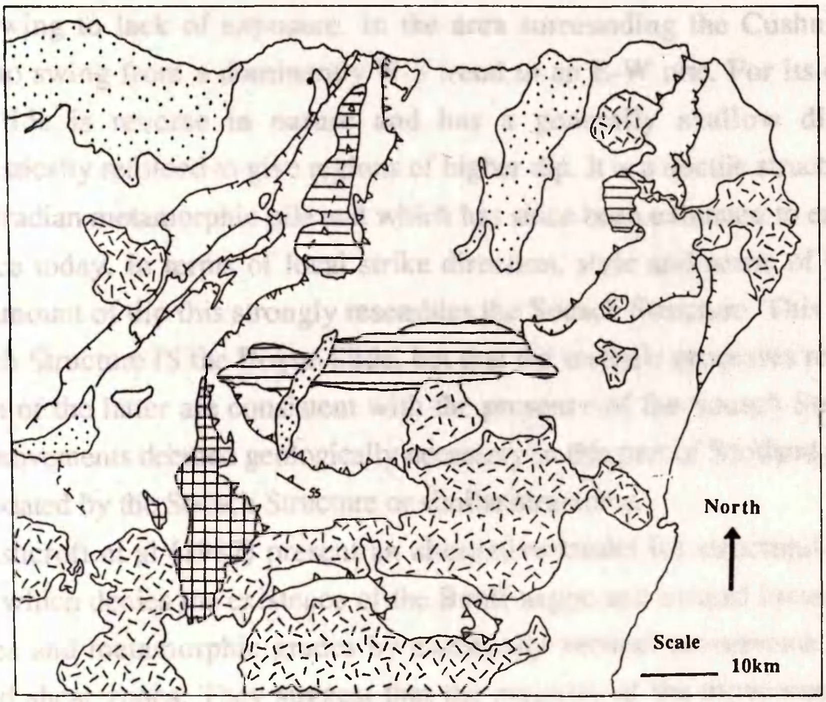
Towards A Structural Setting For The Socach Gold Deposit

Resolving the structural evolution in an area as poorly exposed as the NE of Scotland is extremely difficult and it is still the subject of much debate. In attempting to integrate an isolated structure into the regional framework, where time is not available for structural mapping, the best that can be done is to fit it into the most compatible setting using the models that are available. Thus if the Socach Structure, its attitude and sense of movement, can be slotted into a tectonic model without modification then it is deemed compatible with it.

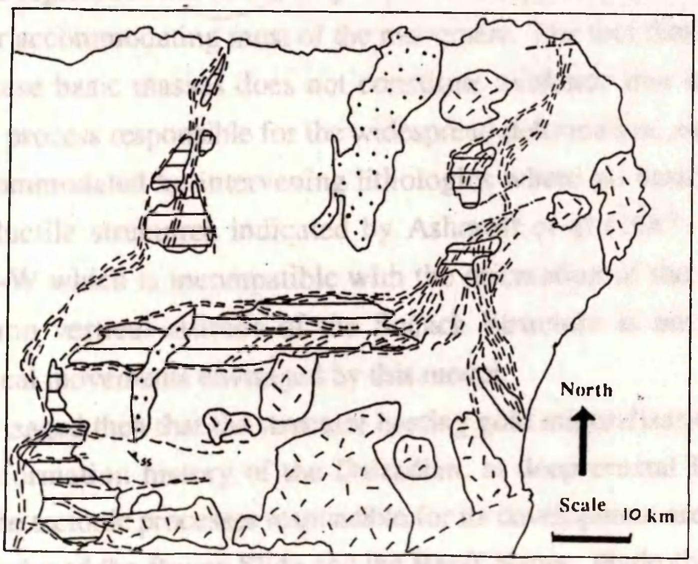
Hypotheses for the structure and evolution of NE Scotland fall into two broad groups; a) The nappe models and b) The shear zone models. In this respect the work of Read (1956), and later Ramsay and Sturt (1979), in making a case for the existence of the

FIG. 20 A,B; THE STRUCTURAL SETTING OF THE SOCACH STRUCTURE; COMPETING MODELS FOR THE REGIONAL STRUCTURE OF THE NE GRAMPIAN HIGHLANDS

A; PRE-DEVONIAN STRUCTURES ASSOCIATED WITH THE BANFF NAPPE (modified after Ramsay and Sturt 1987)



B; THE STEEPLY DIPPING SHEAR ZONE MODEL OF ASHCROFT ET AL (modified after Ashcroft et al 1984)



KEY

Devonian Sediments

Newer Granites

Basic/Ultrabasic Rocks Of The Newer and Older Gabbro Suites

Metamorphic Basement

SS Socach Structure (as identified by the author)

Banff nappe and its lower boundary surface, the Boyne slide, is relevant. Read (1956) proposed that the structure of the Buchan region is dominated by the Banff Nappe, the northeasterly extension of the Tay Nappe. The major structures inferred by the nappe model are illustrated on Fig 20a, which is a compilation of Ramsay and Sturt (pers. comm.) The upper limb of the Banff nappe is variably excised by a major tectonic slide which Read named the Boyne Slide. The outcrop of the slide is loosely constrained for much of its course, owing to lack of exposure. In the area surrounding the Cushnie Prospect it is believed to swing from a dominantly N-S trend to an E-W one. For its entire length the Boyne Slide is reverse in nature and has a generally shallow dip, though it is characteristically refolded to give regions of higher dip. It is a ductile structure, formed deep in the Dalradian metamorphic pile and which has since been exhumed to expose the slide at the surface today. In terms of local strike direction, style and sense of deformation and perhaps amount of dip this strongly resembles the Socach Structure. This is not to say that the Socach Structure IS the Boyne Slide, but that the tectonic processes responsible for the formation of the latter are consistent with the presence of the Socach Structure. Thus the tectonic movements deemed geologically necessary in this part of Scotland could be partially accommodated by the Socach Structure or similar structures.

Ashcroft et al (1987) present an alternative model for structural evolution of NE Scotland which denies the existence of the Banff nappe and instead juxtaposes the various lithologies and metamorphic grades by essentially vertical movements along regionally developed shear zones. They suggest that the majority of the movement occurred along shear zones developed in the Older and Newer Gabbros. These basic rocks are thought to have constituted regional zones of ductility within a comparatively competent metamorphic pile, hence their accommodating most of the movement. The fact that the Socach Structure does not cut these basic masses does not constitute evidence that it was not part of the overall tectonic process responsible for the widespread deformation, since movement would need to be accommodated by intervening lithologies where no basic rocks were present. However the ductile structures indicated by Ashcroft et al (1987) around the Cushnie Prospect run E-W which is incompatible with the orientation of the Socach Structure. In addition, the non vertical attitude of the Socach Structure is not consistent with the essentially vertical movements envisaged by this model.

It is envisaged then that the structure hosting gold mineralization at Cushnie formed early in the deformation history of the Dalradian, at deep crustal levels and by ductile deformation. The tectonic processes responsible for its development are liable to be the same as those that produced the Boyne Slide and the Banff Nappe. Hydrothermal invasion of the Socach Structure was demonstrably post shearing. In order to determine the time lapse between deformation and hydrothermalism, other lines of evidence relating to the hypogene mineralising processes must be pursued.

CHAPTER 5

HYPOGENE PROCESSES IN THE GENESIS OF GOLD MINERALIZATION ON THE CUSHNIE PROSPECT, ABERDEENSHIRE, SCOTLAND

A Fluid Inclusion Study Of Hydrothermal Quartz From The Socach Structure

Introduction

Hydrothermal quartz ribs within the Socach Structure are mainly composed of unstrained sub- to euhedral milky quartz with distinctive intergranular iron staining (Plate 8). Some slightly strained quartz is also present, showing broad sweeping undulose extinction but no recrystallisation effects. This hydrothermal quartz is easily distinguishable from the earlier 'tectonized' quartz which occurs as aggregates, ribbons and occasional ribs in the shear zone and takes the form of corroded quartz in strained to highly strained states. The hydrothermal quartz is contemporaneous with pyrite precursors to goethite and haematite and their contained gold and the pervasive sericitic alteration, as justified in Chapter 4. Since it is the gold mineralising processes in which we are interested and since the quartz was precipitated by the same hydrothermal fluids that precipitated pyrite and gold, the fluid inclusion study is restricted to the hydrothermal quartz..

Petrography of Inclusion Populations

The principles of inclusion petrography used for this study are those described by Wilkins (1989). In terms of form and disposition, fluid inclusions in hydrothermal quartz show two contrasting types. Large (<25mm) $H_20 + C0_2$ + NaCl inclusions are randomly dispersed through the quartz vugs and show a transitional range of forms and compositions (see Plate 9) whilst smaller H_20 + NaCl inclusions are located in planar arrays cutting the quartz crystals. The former are regarded as primary in origin on the basis of their random distribution and location away from fractures. The latter are demonstrably secondary in origin, being hosted by later fractures which cross-cut the quartz crystals and the primary inclusion population.The primary inclusions constitute substantially the most abundant population and therefore will tell us most about the hydrothermal processes responsible for quartz precipitation and the deposition of the coeval pyrite and gold. It has already been argued (Chapter 3) that the later leaching and oxidation of the mineralization was not a result of later hydrothermalism, so the secondary inclusions are not relevant in this respect.On these grounds, emphasis was placed on the study of the primary inclusion population as a means towards the end of understanding the gold mineralising hydrothermal processes.

Within this primary inclusion population, a range of inclusion forms and fill types and ratios are evident which together constitute an obvious visual heterogeneity in this population (see Plate 9). The thermometric data presented below provide confirmatory evidence for this heterogeneity. The data will be presented, the heterogeneity characterised and the data interpreted within the context of this heterogeneity.

PLATE 8; PHOTOMICROGRAPHS OF HYDROTHERMAL QUARTZ FROM THE SOCACH STRUCTURE

A,B) Combined Plane Polarised Light and Crossed-Polar image of typical hydrothermal quartz from the Socach Structure. Note the presence of intercrystalline iron oxide crystal coatings and the characteristic unstrained nature of the quartz. Compare to Plate 7b,c,j which shows the characteristic undulose extinction pattern of the 'tectonised' quartz.

PLATE 9; PHOTOMICROGRAPHS OF FLUID INCLUSIONS IN HYDROTHERMAL QUARTZ FROM THE SOCACH STRUCTURE

A) Inverse crystal shaped inclusions showing low degree of fill and dark internal appearance due to high vol% of CO_2 .

B) Intermediate inclusion forms showing variable degree of fill and variable H_2O/CO_2 ratios within the inclusion cluster.

C) Intermediate inclusion forms within hydrothermal quartz. Notice regular shapes and moderately high degree of fill by $H_2O+NaCl+CO_2$ fluids.

D) Rounded, regular shaped $H_2O+NaCl+CO_2$ inclusion, intermediate in form and degree of fill between C and E .

E) Rounded, $H_2O+NaCl$ only type inclusions showing high degree of fill near the tip of a quartz crystal, and highly irregular inclusions hosted in quartz immediately adjacent to haematite/goethite filled vug.

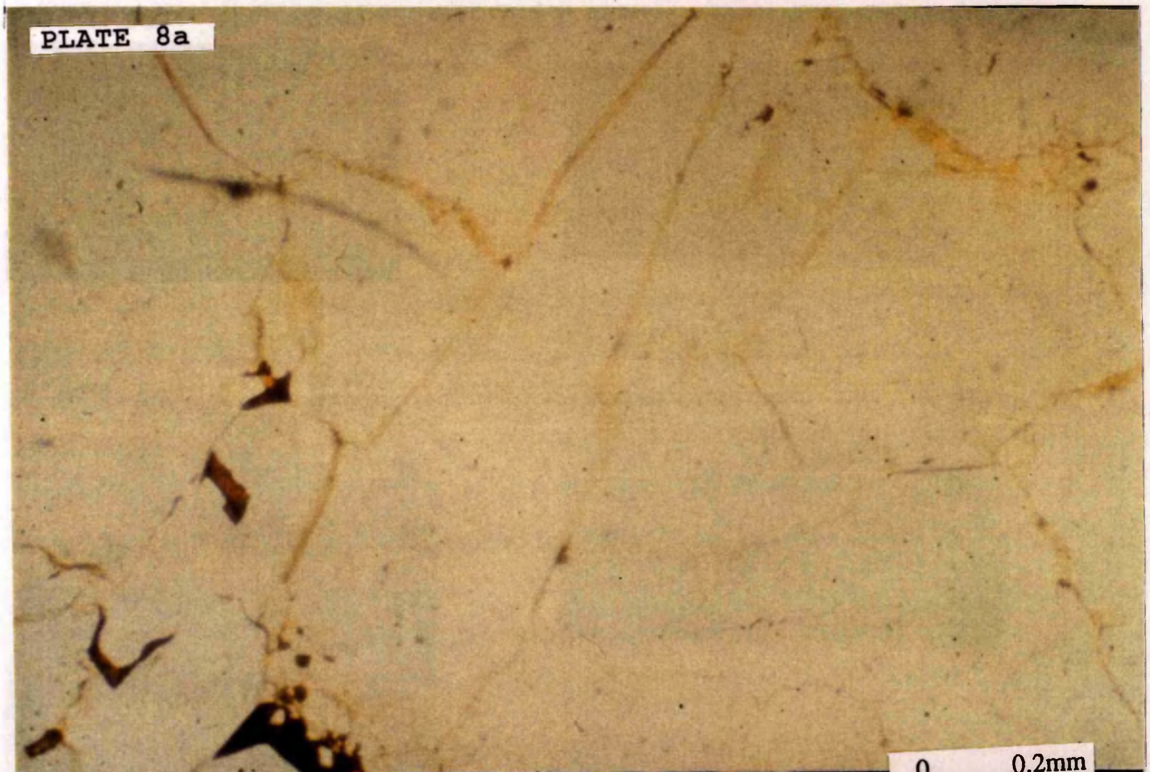


PLATE 8a

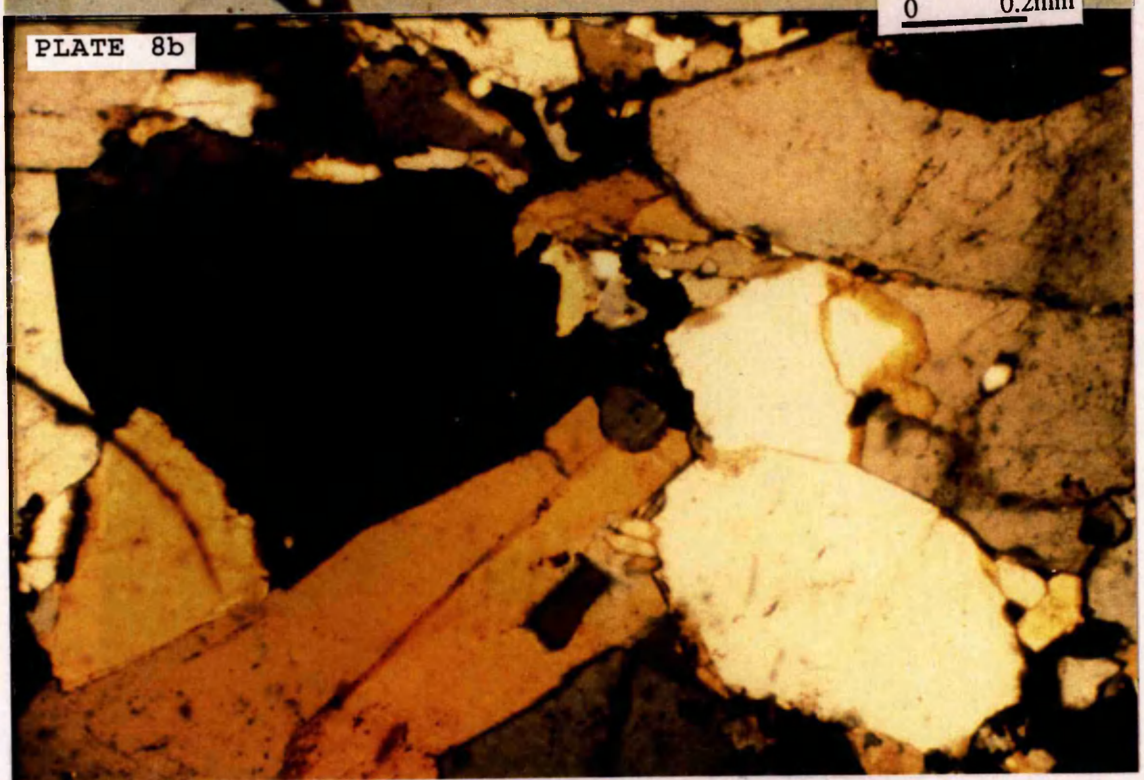


PLATE 8b

PLATE 9a 10µm

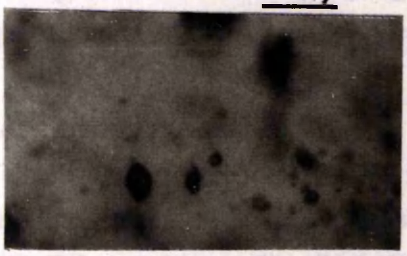


PLATE 9b 10µm

PLATE 9c 10µm

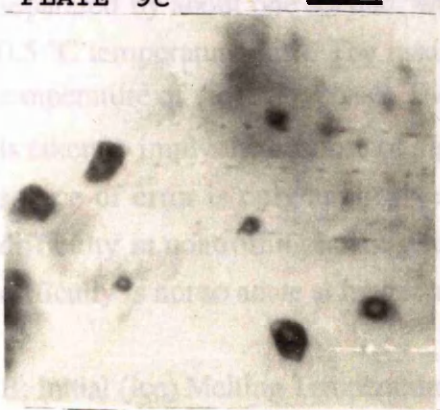
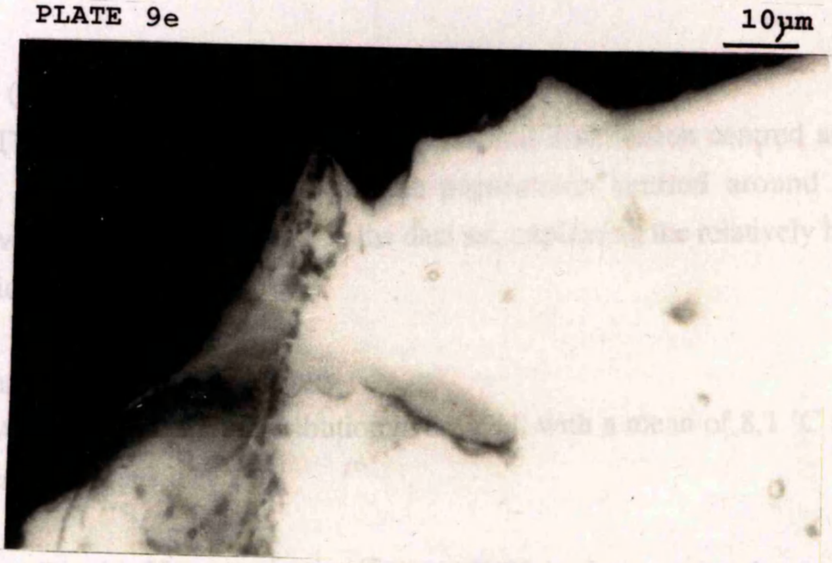


PLATE 9d 10µm

PLATE 9e 10µm



Thermometric Data

Fluid inclusion data for primary inclusions in hydrothermal quartz from the Socach Structure are tabulated in Appendix 6 and shown in histographical form in Figs. 21a-f along with the accompanying summary statistics. The characteristics of the various populations are now briefly described;

A; Carbon Dioxide Melting

Data form one strongly skewed population tightly clustered approximately around the melting point of CO_2 . Skewness is positive, towards higher temperatures (mean -55.9 °C, CO_2 melting point -56.6 °C). This shift is considered to be the result of analytical error whereby the witnessing of the melting event and the recording of temperature were separated by about one second, which at an approximate heating rate of 25 °C/min gave a 0.5 °C temperature shift. The results are therefore taken to represent the expected melting temperature of the CO_2 phase. The lack of any other unusual melting events above -120 °C is taken to imply the absence of significant proportions of other gaseous phases. The above source of error is only applicable to melting events at very low temperatures due to the difficulty in controlling heating rates at these temperatures with the equipment used; this difficulty is not so acute at higher temperatures.

B; Initial (Ice) Melting Temperatures

An unusually wide data-spread is apparent, between -38 and -18 °C. Sub-populations within this broad spread are present, centred on -20.5, -26 and, possibly, -31 °C.

C; Final (Ice) Melting Temperatures

The data define a broad, roughly normal distribution centred around -10 °C and ranging from -15 to -3 °C. Two sub-populations centred around -13.5 and -9 °C respectively can be seen to make up the data set, explaining the relatively broad spread of the population.

D; Clathrate Melting Temperatures

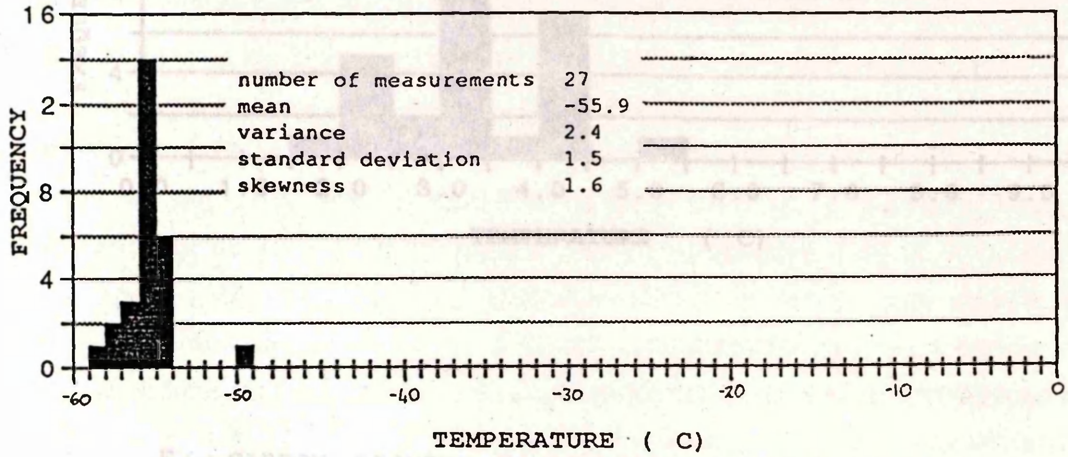
A roughly normal distribution is defined, with a mean of 8.1 °C and a range 2 to 3 °C either side of this mean.

E; Carbon Dioxide Homogenisation Temperatures

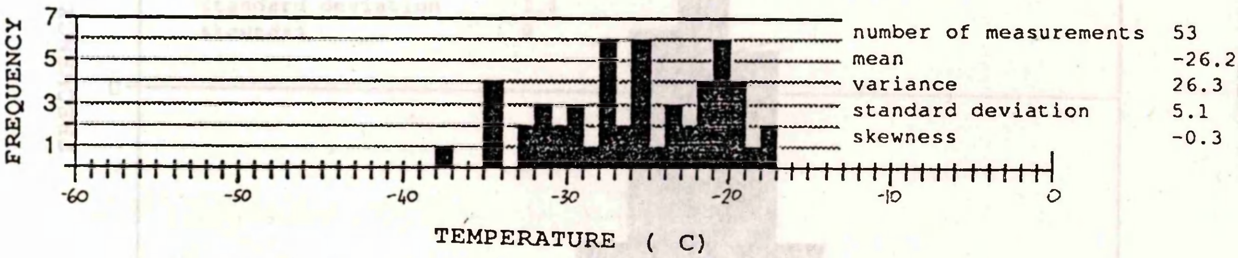
The inclusion population defines a normal population with a mean, median and mode of 31 °C. Data range up to 3 °C either side of this mean, but are concentrated within 1 °C of the mean. This is entirely consistent with the dominant mode of homogenisation of the CO_2 phase (by fading of the liquid/vapour meniscus) which implies critical behaviour and density of the CO_2; the critical point of CO_2 is 31.1 C, consistent with the mean of the data-set.

FIG. 21 A-F ; FLUID INCLUSION THERMOMETRIC DATA FOR PRIMARY INCLUSIONS IN HYDROTHERMAL QUARTZ FROM THE SOCACH STRUCTURE; FREQUENCY HISTOGRAMS

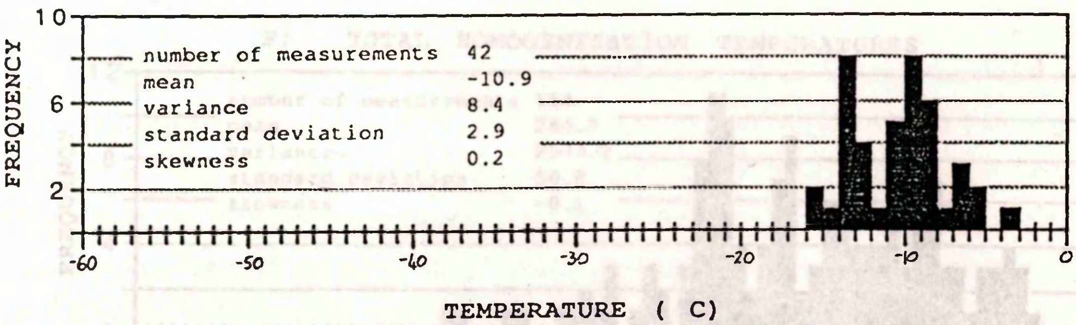
A; CARBON DIOXIDE MELTING TEMPERATURES



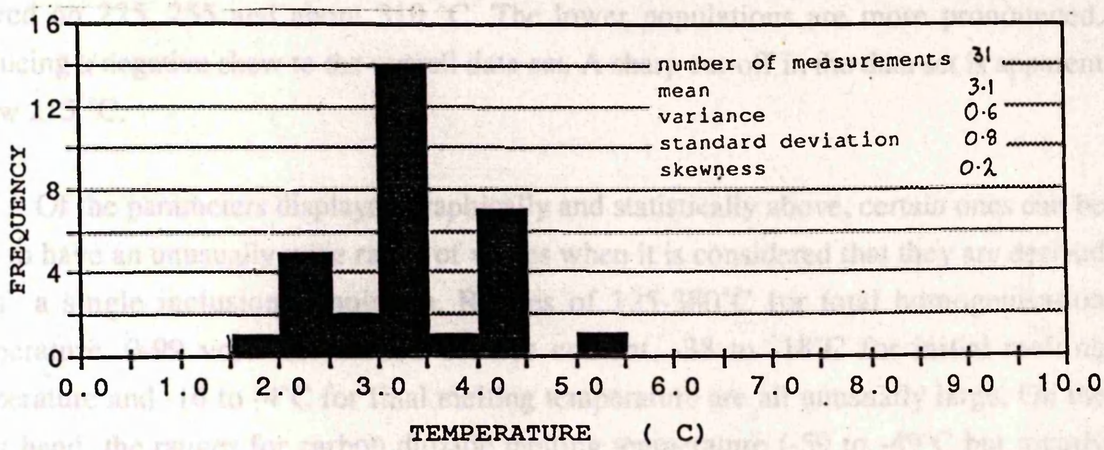
B ; INITIAL MELTING TEMPERATURES



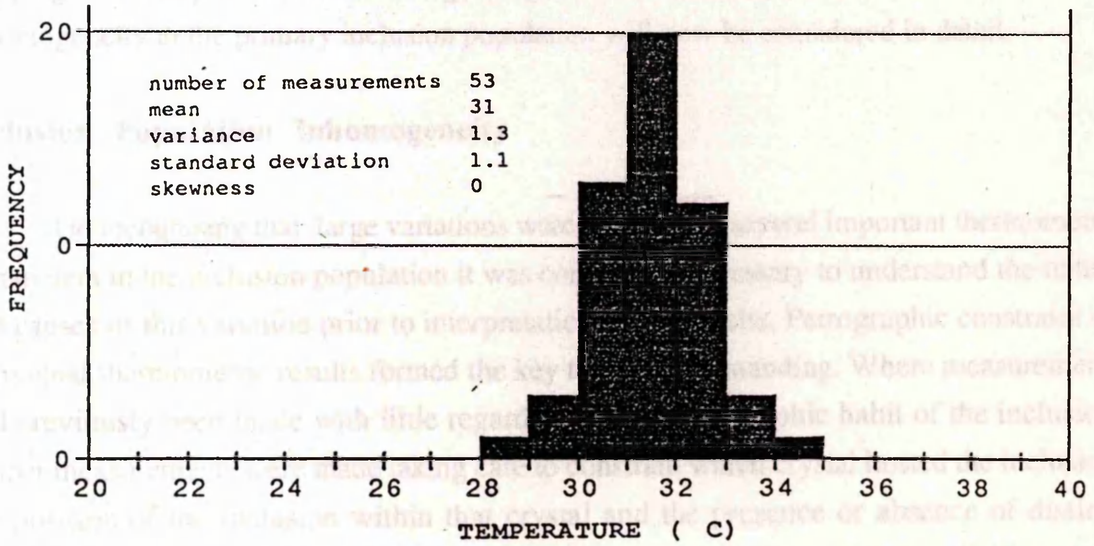
C ; FINAL MELTING TEMPERATURES



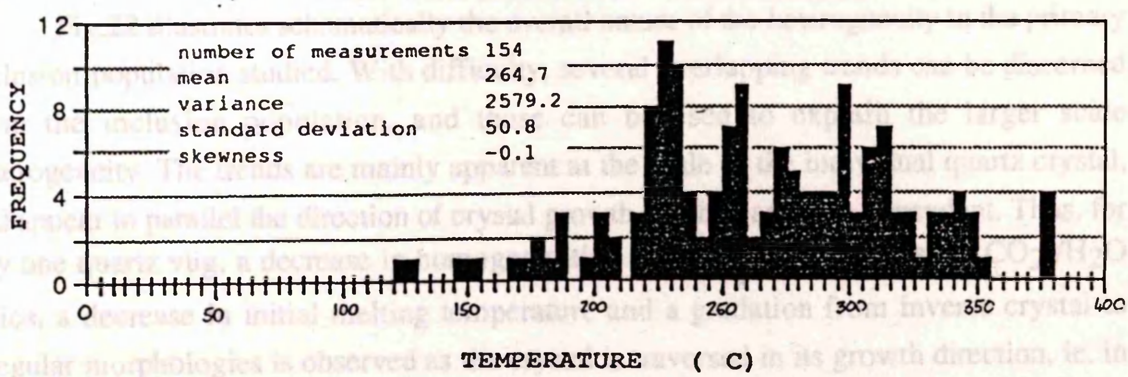
D; CLATHRATE MELTING TEMPERATURES



E ; CARBON DIOXIDE HOMOGENISATION TEMPERATURES



F; TOTAL HOMOGENISATION TEMPERATURES



F; Total Homogenisation Temperatures

A wide spread of homogenisation temperatures is apparent, from 130-380 °C. The bulk fall within the 215-355 °C range, within which three sub-populations are discernible, centred on 225, 255 and about 310 °C. The lower populations are more pronounced, producing a negative skew to the overall data-set. A sharp cut-off in the data set is apparent below 215 °C.

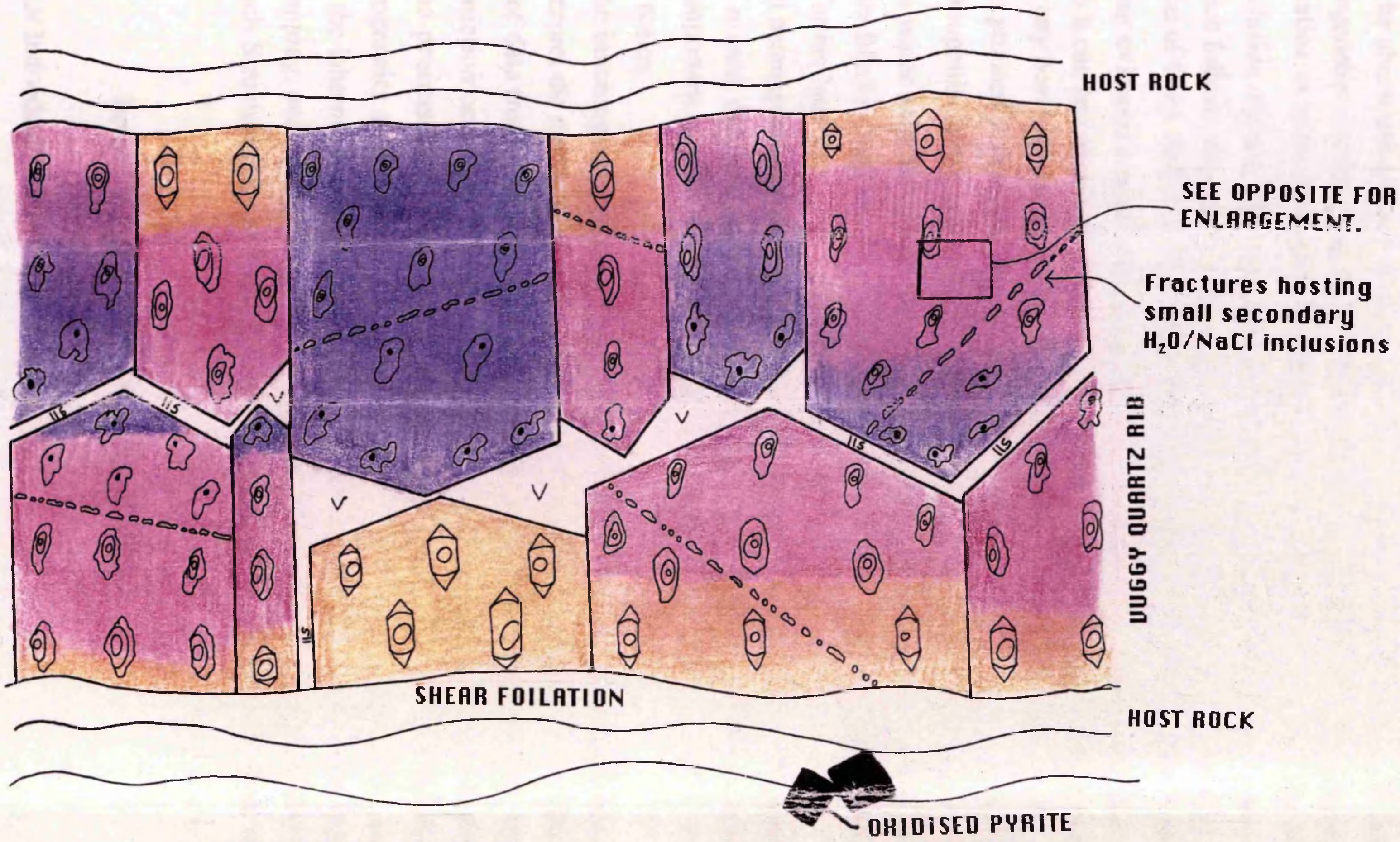
Of the parameters displayed graphically and statistically above, certain ones can be seen to have an unusually wide range of values when it is considered that they are derived from a single inclusion population. Ranges of 125-380°C for total homogenisation temperature, 0-99 vol% for carbon dioxide content, -38 to -18°C for initial melting temperature and -16 to -4°C for final melting temperature are all unusually large. On the other hand, the ranges for carbon dioxide melting temperature (-59 to -49°C but mainly below -54°C) clathrate melting temperature (1.5 to 5.5°C) and carbon dioxide homogenisation temperature (28 to 35°C) are comparatively narrow. A narrow range in thermometric properties is the expected situation for inclusions which have trapped a single, homogeneous, stable fluid. Wide ranges in these parameters are likely to be the result of the trapping of multiple and/or inhomogeneous and/or unstable fluids. The nature of the inhomogeneity in the primary inclusion population will now be considered in detail.

Inclusion Population Inhomogeneity

On recognising that large variations were apparent in several important thermometric parameters in the inclusion population it was considered necessary to understand the nature and causes of this variation prior to interpretation of the results. Petrographic constraint on individual thermometric results formed the key to this understanding. Where measurements had previously been made with little regard to the crystallographic habit of the inclusion, further measurements were made taking care to constrain which crystal hosted the inclusion, the position of the inclusion within that crystal and the presence or absence of distinct inclusion clusters. This petrographic constraint on thermometric measurements facilitated the understanding of the inclusion population inhomogeneity and the interpretation of the thermometric results described below.

Fig.22 illustrates schematically the overall nature of the heterogeneity in the primary inclusion population studied. With difficulty, several overlapping trends can be discerned from the inclusion population, and these can be used to explain the larger scale heterogeneity. The trends are mainly apparent at the scale of the individual quartz crystal, and appear to parallel the direction of crystal growth, ie. they are time dependant. Thus, for any one quartz vug, a decrease in homogenisation temperature, a decrease in CO_2 /H_2O ratios, a decrease in initial melting temperature and a gradation from inverse crystal to irregular morphologies is observed as the crystal is traversed in its growth direction, ie. in the time dimension. These three trends are illustrated on Fig.22 by a change in colour (=temperature), a variation in degree of fill (=CO_2 /H_2O ratio) and a gradational

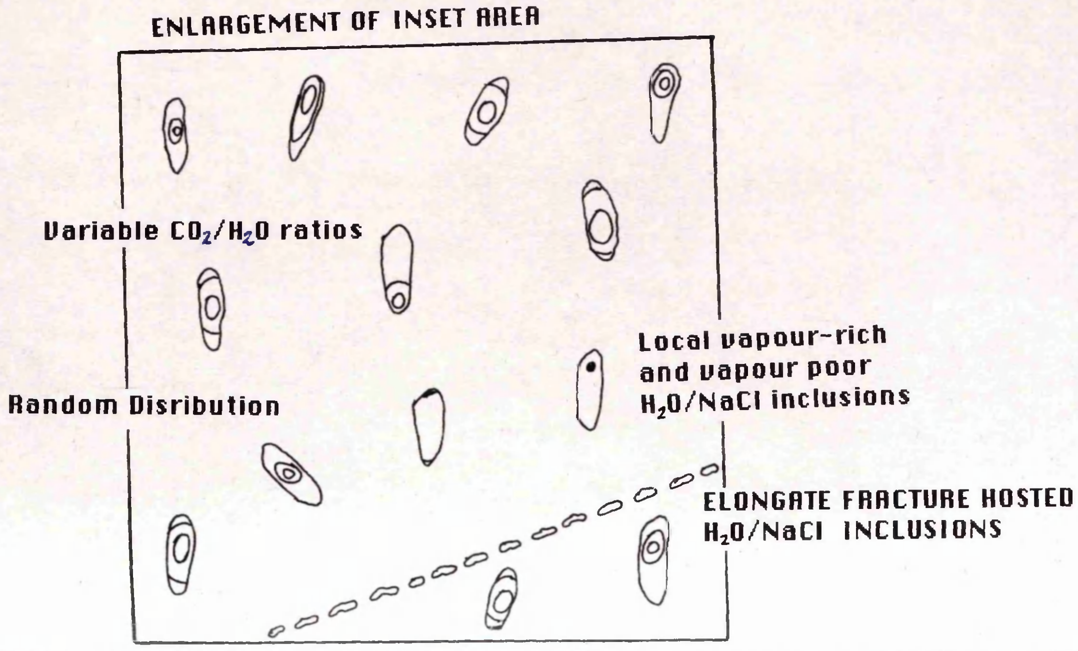
FIG 22 ; SCHEMATIC REPRESENTATION OF FLUID INCLUSION INHOMOGENEITY IN HYDROTHERMAL QUARTZ RIBS FROM THE SOCACH STRUCTURE.

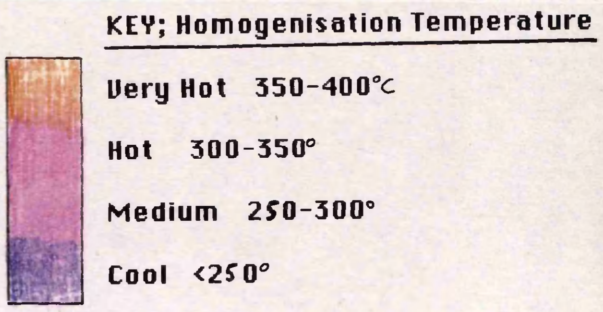


V=POROSITY BETWEEN VUGS

IIS=INTERCRYSTALLINE IRON OXIDE GRAIN COATINGS

ENLARGEMENT OF INSET AREA





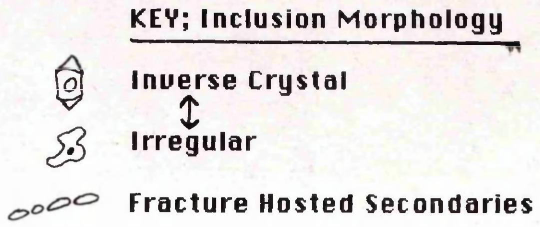
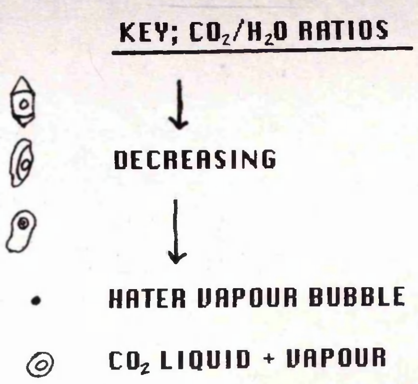


FIG 22. KEY CHARACTERISTICS

1) Decrease in homogenisation temperature in growth direction of quartz.
2) General decrease in CO_2/H_2O ratio in growth direction of quartz.
3) Gradation in forms of primary inclusions from inverse crystal shaped to irregular in growth direction of quartz.
4) Variable starting point with respect to 1,2,and 3 above for each quartz crystal in different parts of the quartz rib.
5) Inhomogeneity in CO_2/H_2O ratios on the microscopic scale.
6) Occasional H_2O only inclusions with variable liquid/vapour ratios.
7) Later secondary inclusions hosted by fractures crosscutting the quartz vug and the primary inclusion population.
8) Intercrystalline iron staining and gold bearing oxidised pyrite coeval with primary inclusion population. No iron staining along later fractures.



morphology, as explained on the individual keys for these parameters. Intra-crystalline variation is also apparent; it manifests itself as a different starting and finishing point with respect to the three trends described for each quartz crystal. Thus inclusions in the roots of the individual quartz vugs within a cluster of crystals will not necessarily exhibit the same Th, CO_2 /H_2O ratio or morphology. The same applies also to the tips of quartz crystals; the end-point of the above three trends is not consistent at the intra-crystalline scale.A smaller scale of heterogeneity is observed in the inclusion population, and takes the form of variable H_2O/CO_2 ratios in inclusions from a single cluster. It is apparent at the scale of the individual inclusion cluster, and is superimposed onto the larger scale trend in this very parameter which follows the crystal growth direction as described above. It is noticeable due to the presence of CO_2 rich and CO_2 poor inclusions adjacent to one-another within a cluster. No clear evidence is seen for the necking down of parent inclusions to produce this assemblage so it can be concluded that the inhomogeneity relates to the fluid being trapped rather than to any post-entrapment modification of the inclusions. Separation of CO_2 and H_2O is seen to proceed to completeness in places where nearby CO_2 only (recognisable by their total homogenisation temperatures of around 31^0C) and H_2O only inclusions are present. In the water only inclusions, phase separation occasionally gives rise to adjacent steam and water filled inclusions. This small scale heterogeneity is complex in itself and will be discussed further later on.

Overall heterogeneity is thus the result of several overlapping trends which manifest themselves at several different scales. Microscopic, individual crystal and intracrystalline scales are all important, and Th , CO_2 /H_2O ratio and morphology are all variable at one or more of these scales.

With the inhomogeneity in the inclusion population now understood an attempt can be made to interpret the thermometric data within this context. Two options are available for the treatment of data from such a heterogeneous population. Detailed analysis may reveal data whose variation occurs on a scale smaller than that of the primary heterogeneity, in which case the processes responsible for these variations will not be obscured by the primary heterogeneity as long as the scale of reference is chosen to exclude the latter. Alternatively, the inhomogeneity can be treated as the manifestation of one or more trends, perhaps overlapping, and the data interpreted within the context of these trends. The data from the Socach Structure are conducive to, and indeed require, treatment by both these means.

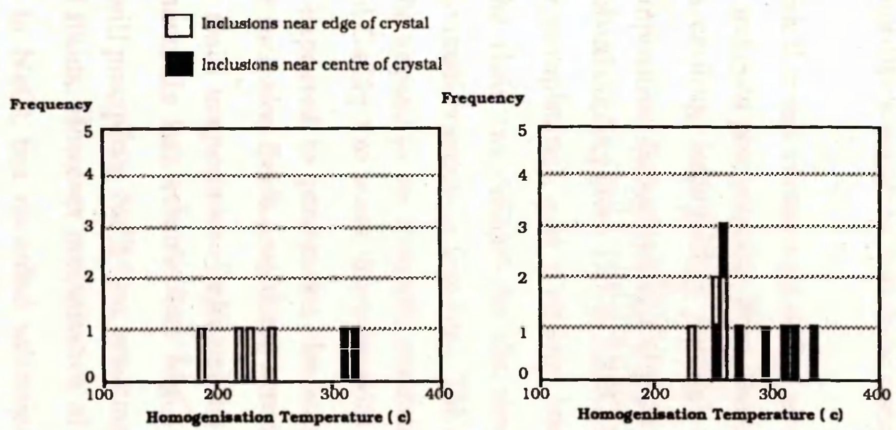
Interpretation Of Thermometric Data

Interpretation Of Individual Thermometric Parameters

The trend of decreasing homogenisation temperature in the direction of crystal growth is explainable as the result of precipitation of quartz from a cooling fluid.

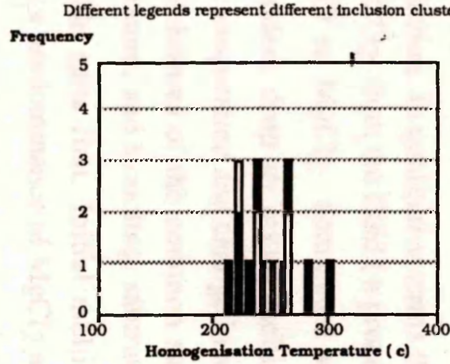
Figs 23 A-E; HOMOGENISATION TEMPERATURE VARIATIONS OF PRIMARY INCLUSIONS WITHIN INDIVIDUAL QUARTZ CRYSTALS FROM HYDROTHERMAL QUARTZ HOSTED BY THE SOCACH STRUCTURE

A+B Variations from the centre to the edge of individual crystals.



C; Variation within individual inclusion clusters

Different legends represent different inclusion clusters



D+E; Diagramatic representation of variation in homogenisation temperature and carbon dioxide content within individual crystals

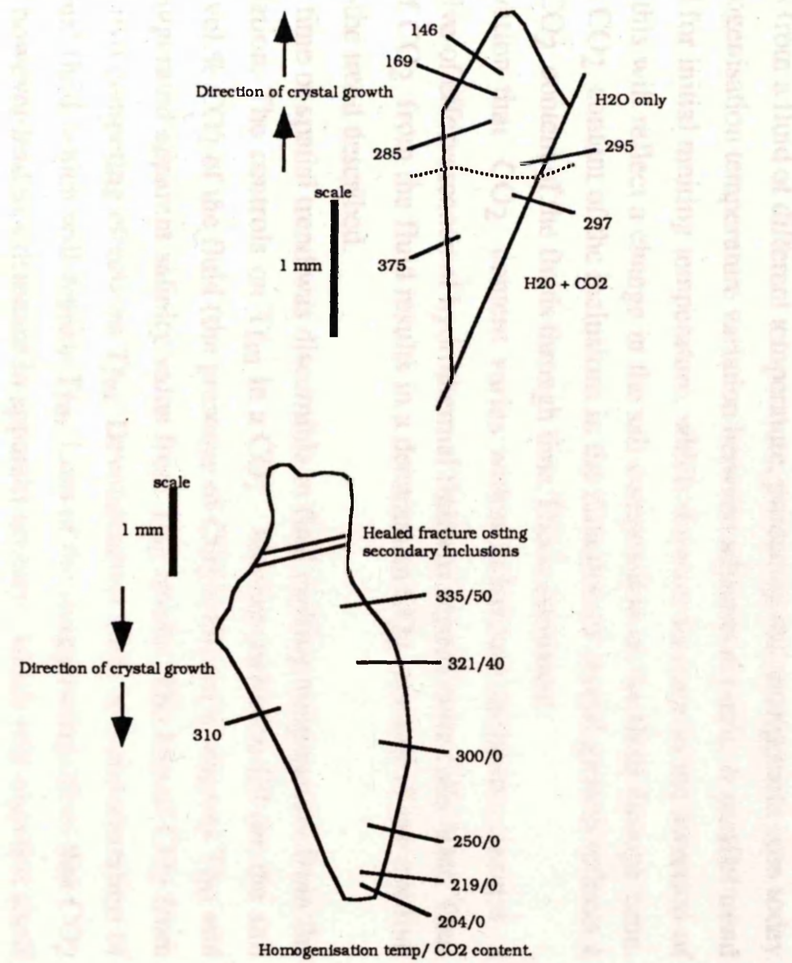


Fig 23

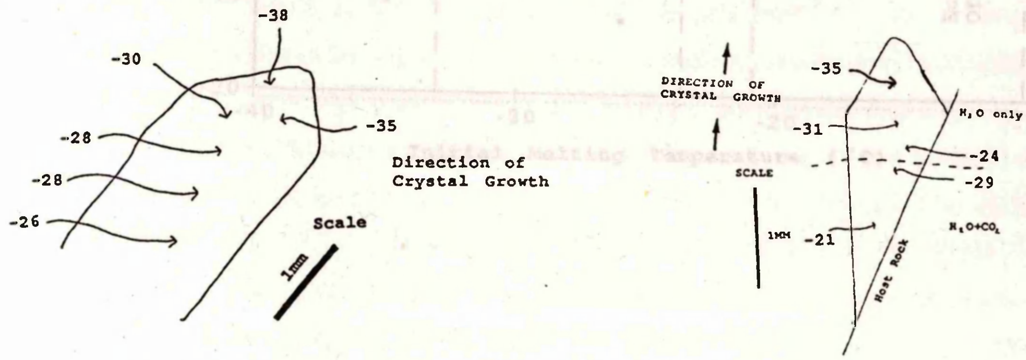
Intergranular variations will, in this context, be a result of inconsistency in the timing of quartz nucleation. This would result in the trapping of inclusions in similar positions within adjacent crystals from a fluid of different temperature, producing the arrangement seen today in terms of homogenisation temperature variation between adjacent crystals. A parallel trend is also observed for initial melting temperature, which shows a decrease in the direction of crystal growth; this will reflect a change in the salt composition of the fluid through time. The decrease in CO_2 content of the inclusions in the direction of crystal growth reflects a decrease in the CO_2 content of the fluids through time.This is consistent with the observation that CO_2 content varies within individual inclusion clusters, a situation indicative of effervescence of hydrothermal fluids as argued more fully later. Thus effervescence of CO_2 from the fluid results in a decrease in CO_2 content of the residual fluid to produce the trend described.

No clear time or spatial trend was discernible in final melting temperatures from the inclusion population. The controls on T_{fm} in a CO_2 - bearing inclusion fill are the salt content and the vol.% CO_2 of the fluid (the presence of CO_2 is known to depress T_{fm} and thus give an exaggerated apparent salinity value from T_{fm} results. The loss of CO_2 from such a fluid has two competing effects on T_{fm}. Devolatisation leads to a concentration of salts in the residual fluid, which will depress T_{fm}. Loss of the exaggerating effect that CO_2 has on T_{fm} will however lead to a decrease in apparent salinity , which will manifest itself as a rise in T_{fm}. The lack of temporally or spatially dependant variability in Tfm in the present inclusion population suggests that these competing influences are approximately in balance.

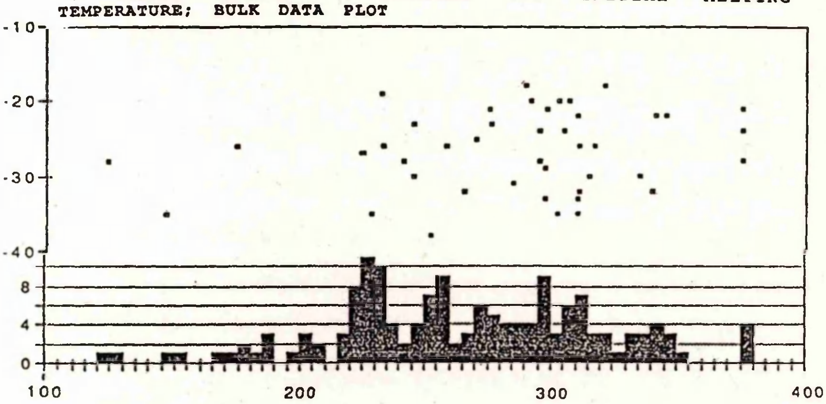
These individual trends collectively define an evolutionary path for the hydrothermal fluid during quartz and gold precipitation. Thus, the hydrothermal fluid responsible for gold mineralisation was cooling, losing CO_2 through effervescence, and, could have been changing in salt composition during quartz and gold precipitation. In qualitative terms this fluid evolution involved cooling from 375 to 220°C, loss of CO_2 from the fluid (a process that often went to completion), and a change from NaCl to $MgCl_2$ dominated salt compositions in the fluid (as defined by the time-dependent drop in initial melting temperatures in individual crystals eg. Fig.24a). The drop in temperature and change in salt compositions can be argued to be mutually consistent. Solubilities of the common salts (NaCl, $MgCl_2$, and $CaCl_2$) in water decrease with temperature, and a cooling, saturated fluid can thus be expected to precipitate the least soluble salts first. Initial melting temperatures for the inclusion fluids considered here indicate a predominance of $MgCl_2$ and NaCl salts. At the fluid temperatures indicated by homogenisation temperatures (375-220°C), NaCl is markedly less soluble than $MgCl_2$. Thus a fluid cooling through this temperature range will precipitate NaCl first, resulting in the residual fluid evolving to more $MgCl_2$ dominated fluids. However precipitation of NaCl from the fluid requires that the fluid be saturated in NaCl, but recorded salinities argue against this state of affairs. Alternatively, the evolution in salt composition could be a post-entrapment phenomenon resulting from the formation of clathrate. In a hypothetical case, partitioning of $MgCl_2$ into the clathrate would cause a shift towards more NaCl dominated salt compositions in the

FIGS 24 A-C; VARIATIONS IN INITIAL MELTING TEMPERATURES OF PRIMARY INCLUSION FLUIDS IN HYDROTHERMAL QUARTZ FROM THE SOCACH STRUCTURE.

A; DIAGRAMATIC REPRESENTATION OF VARIATION IN INITIAL MELTING TEMPERATURE WITHIN INDIVIDUAL CRYSTALS



B; HOMOGENISATION TEMPERATURE VS. INITIAL MELTING TEMPERATURE; BULK DATA PLOT



C; HOMOGENISATION TEMPERATURE VS. INITIAL MELTING TEMPERATURE; DATA ITEMISED BY HOST CRYSTAL

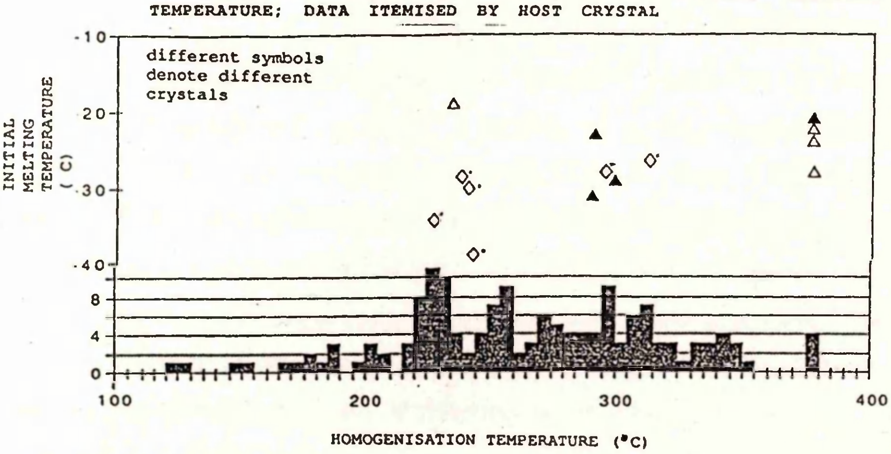
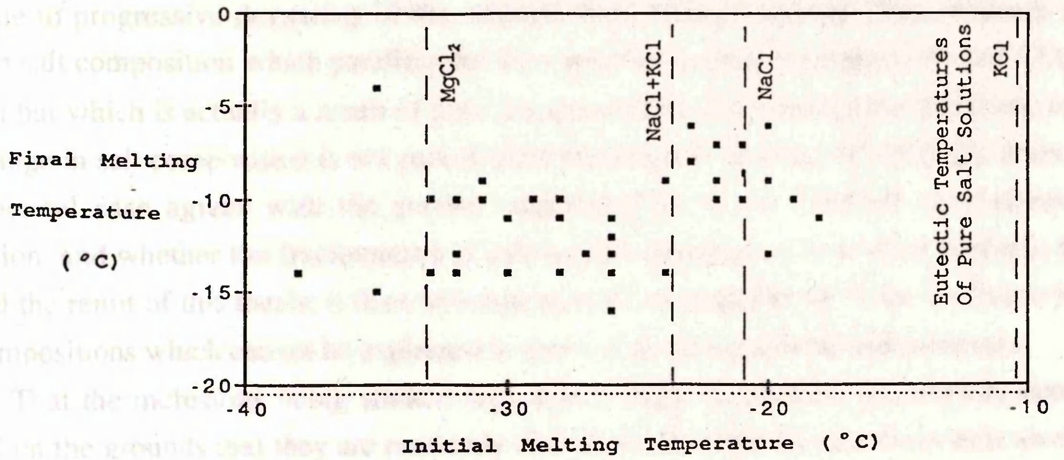


FIG. 25 INITIAL VS. FINAL MELTING TEMPERATURES FOR FLUID INCLUSIONS IN HYDROTHERMAL QUARTZ FROM THE SOCACH STRUCTURE.

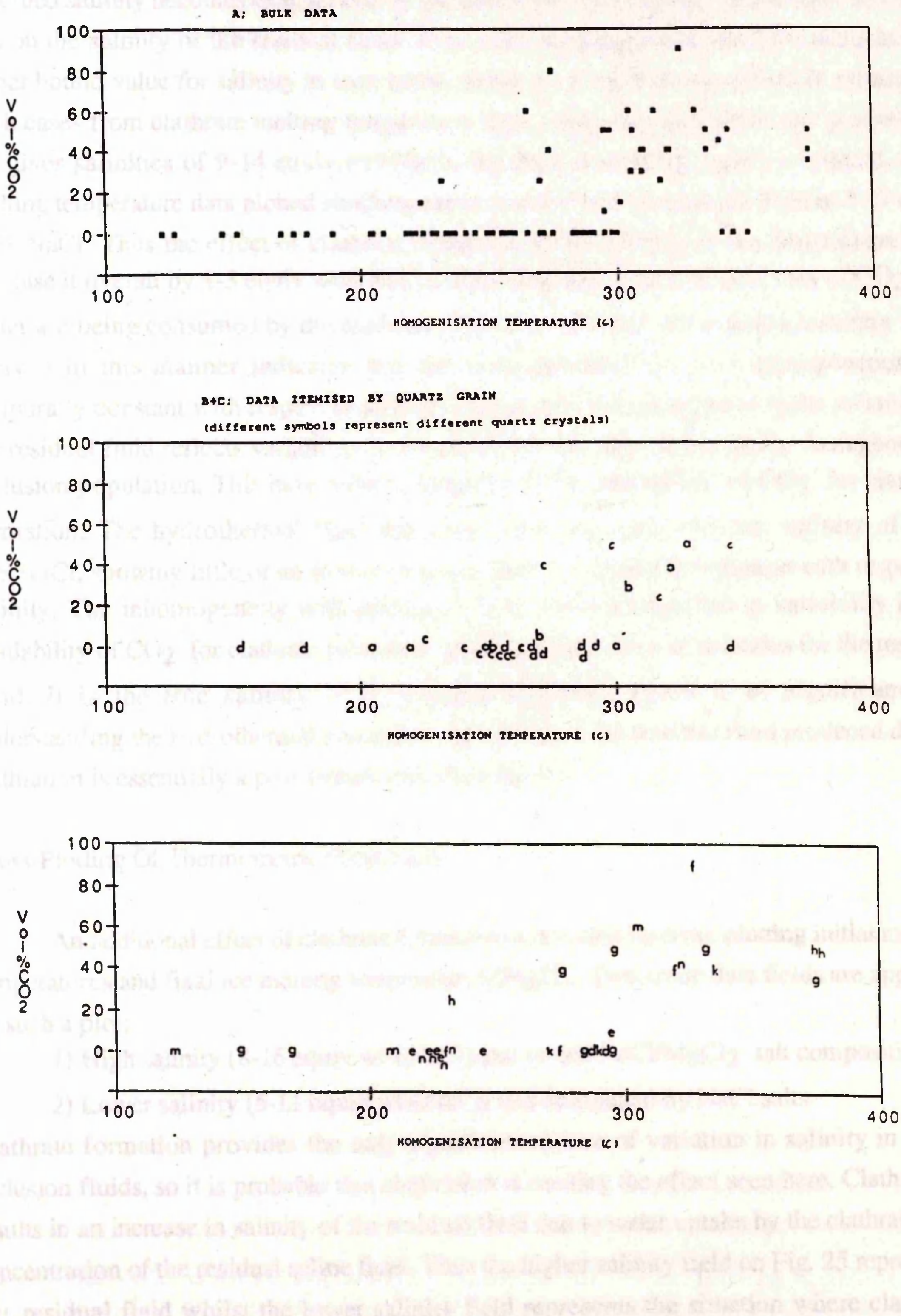


residual fluid. Clathrate formation will be more significant in the early, CO_2 rich inclusions so this partitioning will be more effective in these inclusions. Thus the residual phase in paragenetically early inclusions will be dominated by NaCl salt compositions and will evolve towards more $MgCl_2$ dominated compositions as the CO_2 content of the inclusions falls due to progressive degassing of the original fluid during trapping. This produces a trend in salt composition which parallels the time dependent drop in temperature and CO_2 content but which is actually a result of post-entrapment processes within the inclusion, ie. the change in salt composition is not part of the hydrothermal process. Whether the above hypothetical case agrees with the current understanding of the controls on clathrate formation, and whether the fractionation of salt species described is a realistic scenario is beyond the remit of this thesis; it does however provide an explanation of the evolution in salt compositions which cannot be explained in terms of simple hydrothermal processes.

That the inclusions being studied represent a single population has already been argued on the grounds that they are randomly distributed through the quartz crystals away from fractures and display similar forms within any given part of the crystal. The variation in CO_2 /H_2O phase ratio must therefore reflect a characteristic of a single fluid. Inhomogeneity of this type can be produced by the separation of immiscible phases from a previously mixed fluid. In this specific case, separation of CO_2 and H_2O will occur through effervescence of the hydrothermal fluid during trapping. This produces pockets of CO_2 rich and CO_2 poor fluid which on trapping give a similar configuration of CO_2 contents in the inclusions. Other means to this end include necking down of parent inclusions with partitioning of the different phases into separate daughter inclusions. Textural evidence for the operation of such a process is however not apparent in the inclusions studied. Therefore the presence of variable phase ratios within a single inclusion population which show similar homogenisation temperatures within clusters of inclusions is taken as evidence for effervescence of CO_2 from the fluid. As described above, this results in depletion of the residual fluid in CO_2 , and a temporal evolution of the fluid to lower CO_2 contents during quartz and gold precipitation.

The large variation in certain thermometric parameters now explained as a result of fluid inhomogeneity and evolution, it remains to explain the data for the parameters which do not show such wide variation in values. CO_2 melting, final melting, clathrate melting and CO_2 homogenisation temperature data define tight clusters rather than wide spreads. CO_2 melting temperatures show tight clustering around the known melting point of CO_2 of -56.6 °C, with experimental error accounting for a slight skew towards higher temperatures. This simply reflects the purity of the CO_2 phase, which contains no contaminants, and therefore shows no depression of freezing point. Thus the CO_2 phase is pure, and the lack of any other melting events between -120°C and -50°C implies the absence of any other obvious gaseous phases in the inclusion fluids. Similarly, CO_2 homogenisation temperatures show tight clustering around the CO_2 triple point, indicating that the gaseous

FIG 26 A-C: HOMOGENISATION TEMPERATURE VS. CARBON DIOXIDE CONTENT FOR PRIMARY INCLUSIONS IN HYDROTHERMAL QUARTZ FROM THE SOCACH STRUCTURE



phase is present in the inclusions at close to its critical density. This is consistent with the dominant mode of homogenisation of the CO_2 phase by fading of the liquid/vapour meniscus, which also implies that CO_2 is present at close to its critical density. Thus the thermometric behaviour of the CO_2 phase indicates that the phase is pure and is present at close to critical density, and that these properties are homogeneous throughout the inclusion population and show no temporal evolution during hydrothermalism.

Final melting and clathrate melting temperature data also show tight clustering. Final melting temperature records the degree of depression of freezing point of water by dissolved salts, from which can be derived the salinity. In the presence of gas hydrates however this recorded salinity becomes exaggerated by the effect that water uptake for clathrate formation has on the salinity of the residual fluid. Thus, final melting temperature provides only an upper bound value for salinity in such cases. Salinity can be derived with more certainty in such cases from clathrate melting temperature data. Using this method on the present data set gives salinities of 9-14 equiv.wt%NaCl, the data again being tightly clustered. Final melting temperature data plotted similarly shows a salinity of the residual fluid of 8-17 equiv wt% NaCl. Thus the effect of clathrate formation on the salinity of the water phase is to increase it overall by 1-3 equiv.wt% NaCl., indicating that significant amounts of CO_2 and water are being consumed by the clathrate. That true salinities show tight clustering when derived in this manner indicates that the hydrothermal fluid was homogeneous and temporally constant with respect to salinity. The greater spread apparent in the salinities of the residual fluid reflects variability in the efficiency of clathrate formation throughout the inclusion population. This may reflect variability in the availability of CO_2 for clathrate formation. The hydrothermal fluid was, then, of a relatively constant salinity of 9-14 wt%NaCl, showing little or no spatial inhomogeneity or temporal evolution with respect to salinity. The inhomogeneity with respect to CO_2 contents resulted in variability in the availability of CO_2 for clathrate formation, giving a wider range of salinities for the residual fluid. It is the true salinity of 9-14 equiv.wt%NaCl which is of significance to understanding the hydrothermal processes; the salinity of the residual fluid produced during clathration is essentially a post-entrapment phenomenon.

Cross-Plotting Of Thermometric Parameters

An additional effect of clathrate formation is revealed by cross-plotting initial melting temperatures and final ice melting temperatures (Fig25). Two crude data fields are apparent on such a plot;

1) High salinity (8-16 equiv.wt%NaCl) and mixed $NaCl/MgCl_2$ salt compositions

2) Lower salinity (5-11 equiv.wt%NaCl) and dominated by NaCl salts

Clathrate formation provides the only significant source of variation in salinity in these inclusion fluids, so it is probable that clathration is causing the effect seen here. Clathration results in an increase in salinity of the residual fluid due to water uptake by the clathrate and concentration of the residual saline fluid. Thus the higher salinity field on Fig. 25 represents this residual fluid whilst the lower salinity field represents the situation where clathrate formation has not occurred. Partitioning of $MgCl_2$ into the clathrate leaves the residual fluid depleted in $MgCl_2$ and therefore the proportion of the other contained salts, in this case NaCl, increases. The result is a rise in salinity in the residual fluid and a change in salt composition to more NaCl dominated ones during clathration, as observed here. This is consistent with the previous argument for the origin of the apparent temporal variation in salt compositions.

Cross-plotting of initial melting temperature against total homogenisation temperature shows a lack of any clear data grouping. This is surprising given the evidence presented earlier for a variation in salt composition in the direction of crystal growth, a trend which was observed to parallel the decrease in total homogenisation temperature in this direction. This would be expected to produce a positive correlation between initial melting and total homogenisation temperatures. The existence of an intercrystalline inhomogeneity in the inclusion population provides an explanation for this. Subtle trends could be obscured by plotting the data en masse as a result of this larger scale heterogeneity.

Itemising the data according to the host crystal from which it was derived provides a means of seeing through this intercrystalline heterogeneity. This is done on Fig.24 for the total homogenisation versus initial melting temperature plot. The data is sparse due to the difficulty in collecting an adequate quantity of data of this type from individual quartz crystals, and the data are fewer than for the non-itemised plot on account of the initial measurements being made without detailed petrographic constraint..Nonetheless, itemisation of the data does reveal individual weak trends between a hot, NaCl dominated fluid and a cooler more $MgCl_2$ dominated fluid. Where the data can be itemised further according to position within the host crystal the trend can be shown to indicate evolution of the fluid towards the lower temperature, more $MgCl_2$ rich end member in the direction of crystal growth. Thus the expected correlation is observed once a means of seeing through the larger scale heterogeneity is found, and the correlation is consistent with the previous arguments for clathration in CO_2 rich inclusions causing an apparent but false temporal variation in salt composition.

Cross-plotting of total homogenisation temperature against salinity, both true salinity as derived from clathrate melting temperatures and apparent salinity as derived from final melting temperatures, illustrates the lack of variability in salinity during hydrothermalism. No CO2 - variation of data is apparent, revealing a lack of temporal evolution of salinity or evidence for the mixing of fluids during this evolution. The lack of significant variation in Tm and Tim within the inclusion population overall makes it very unlikely that a plot of the data itemised according to host quartz crystal will be any more informative.

In the cross-plots analysed thus far, the larger scale intercrystalline heterogeneity has obscured the subtle trends apparent at the scale of the individual crystal. Plotting CO_2 content against Th however shows a clear but broad trend in the bulk data as well as in the itemised data plot (Fig. 26). Thus the parallel trend between CO_2 content and temperature of the fluids is strong enough to remain apparent on the bulk scale. Thus the overall correlation between these parameters is stronger than that between other parameters. The process which caused this stronger covariation can thus be argued to have operated more vigorously than the other processes which produced weaker covariations. Simultaneous fluid cooling and effervescence was thus the most vigorous process in the evolution of the fluid. The change in salt composition during this evolution occurred with less vigour.

In summary then, thermometric data from fluid inclusions in hydrothermal quartz constrain several characteristics of the fluid responsible for quartz and gold precipitation on the Socach Structure. This fluid evolved during hydrothermalism in terms of temperature and CO_2 content. The starting point of this evolution was a CO_2 rich fluid at a temperature of around 350-375°C, dominated by $MgCl_2$ and NaCl salts which contributed to an effective salinity of 9-14equiv.wt%NaCl. Loss of CO_2 through effervescence, and rapid cooling resulted in a temporal shift towards CO_2 poor (or CO_2 free) fluids of 220°C. Salinity remained fairly constant during this evolution. The relevance of this fluid evolution to gold metallogenesis on the Cushnie prospect will be discussed later.

Variation In Inclusion Morphology

A further aspect of the heterogeneity of the inclusion population relates to the shape of the inclusions. As illustrated on Fig.22 the primary inclusions show a transition in forms from regular inverse crystal shapes to highly irregular ones, a trend that occurs in the direction of crystal growth. This parallels the trends in decreasing homogenisation temperatures and CO_2 contents of the inclusion fills. Regular inverse crystal shaped inclusions characteristically contain large amounts of CO_2 and total homogenisation occurs at temperatures towards the higher end of the observed 375-220°C range. Indeed many of these high temperature, high CO_2 content, regular shaped inclusions decrepitate before the homogenisation temperature is reached; this is taken as symptomatic of the high internal pressure of these inclusions which in turn is a result of their high CO_2 contents. Highly irregular inclusions occur close to the tips of quartz crystals, show low CO_2 contents (or, more usually, an absence of CO_2), and homogenise at the lower temperatures within the 220-375°C range. Inverse crystal shaped inclusions are transitional with slightly elongate oval shaped forms via a gradual loss of angularity of the inclusion walls. These oval shaped inclusions gradually become less regular in shape towards the tip of the crystal. Thus the inclusion population can be regarded in terms of shape as one transitional population.

Inclusion form represents the final product of both entrapment and post-entrapment processes (Wilkins 1989). An inclusion can be trapped in a high or low energy form, and can subsequently evolve to lower energy forms. By 'energy' here is meant the degree of equilibrium with the host crystal lattice. Thus inverse crystal shaped inclusions are in equilibrium with the host crystal structure and therefore represent low energy forms. Highly irregular inclusions are far from this state of equilibrium and represent high energy forms. Thus the trend in the inclusion population studied here is from low to high energy forms in the direction of quartz crystal growth.

The attainment of the low energy, equilibrium, state from a highly irregular one is kinetically controlled, and involves the movement of host material from one position on the inclusion walls to another to eventually even out the inclusion shape. It therefore takes time for this to occur. It can be argued then that slow crystallisation will encourage the formation of inverse crystal forms whilst rapid crystallisation will preclude this from happening. The implication for the inclusions studied here then is that slow quartz crystal growth from hot (375-325°C), CO_2 rich fluids resulted in the trapping of these fluids in inverse crystal shaped inclusions. Gradual acceleration of the rate of crystallisation accompanied the cooling of the fluid and loss of CO_2, resulting in progressively cooler, less CO_2 rich fluids being trapped in progressively more irregularly shaped inclusions. However the previously implied vigorous CO2 devolatisation of the fluids would result in rapid reduction in silica solubility and therefore rapid quartz precipitation. The possibilities for slow quartz crystal growth producing low-energy inverse-crystal shaped inclusions are therefore limited.

Alternatively, post-entrapment readjustment of inclusion shapes could be responsible for the observed trends. This would imply more efficient redistribution of host material around the inclusion walls in CO_2 rich inclusions than in CO_2 poor inclusions. Quartz is known to be more soluble in CO_2 rich fluids (hence quartz precipitation from hydrothermal fluids on CO_2 loss through effervescence), so this is a possibility. The implication of a degree of post-entrapment resetting of inclusion shapes is significant to the validity of the thermometric measurements made on these inclusions (Roedder 1984). Increased burial of inclusions is known to produce a change in volume and measured total homogenisation temperature due to post-entrapment increase in pressure and temperature (Osborne and Haszeldine 1993). Without increased burial no source of increased pressure and temperature is available to produce the volume change, so no change in the thermometric properties of the inclusion fluid will occur (Osborne, pers. comm.). No evidence is available for post-depositional deep burial of the Socach Gold Deposit; rather the deposit has most likely been progressively unroofed since formation (erosion has been the overwhelmingly dominant geological process in NE Scotland since the postulated Lower Devonian age of formation of the deposit - see Chapter 7). On these grounds the resetting of inclusion shapes can be assumed to have occured at constant volume, so no resetting of total homogenisation temperature will have occurred. Variations in inclusion shapes can therefore be explained by internal, volume-constant redistribution of silica, without invalidating the thermometric measurements made. The kinetics of this post-entrapment process are likely to be rather involved however, and beyond the scope of this work. The mechanism is regarded as a possible explanation of the observed trends in inclusion form and the parallelism with trends in fluid temperature and CO_2 content, but its proof is beyond the scope of this work.

Geobarometry

The previous section has dealt with the temperature and compositional variations in hydrothermal fluids during quartz and gold mineralization on the Socach Structure. A further factor that comes into play is the ambient pressure at any given point in the hydrothermal system and the evolution of this pressure during the lifetime of hydrothermalism. Pressure affects the density of the fluids and influences processes such as effervescence and boiling. It is a function of several interacting factors including the nature of the hydrothermal fluid, the structural depth within the hydrothermal system and the permeability and availability of open space within the hydrothermal system.

Two methods are available for the deduction of barometric data from measurable inclusion parameters. In an inclusion population showing variable CO_2/H_2O ratios, the inhomogeneity results in CO_2-rich and CO_2-poor inclusions within individual inclusion clusters which show similar total homogenisation temperatures. Plotting CO_2 content and total homogenisation temperature for inclusions within such a cluster on the P-X plot shown on Fig.28b allows the ambient pressure at the time of trapping to be deduced. Alternatively, where fluid separation has gone to completion to produce CO_2 only and H_2O only inclusions, the method of intersecting isochores can be used.

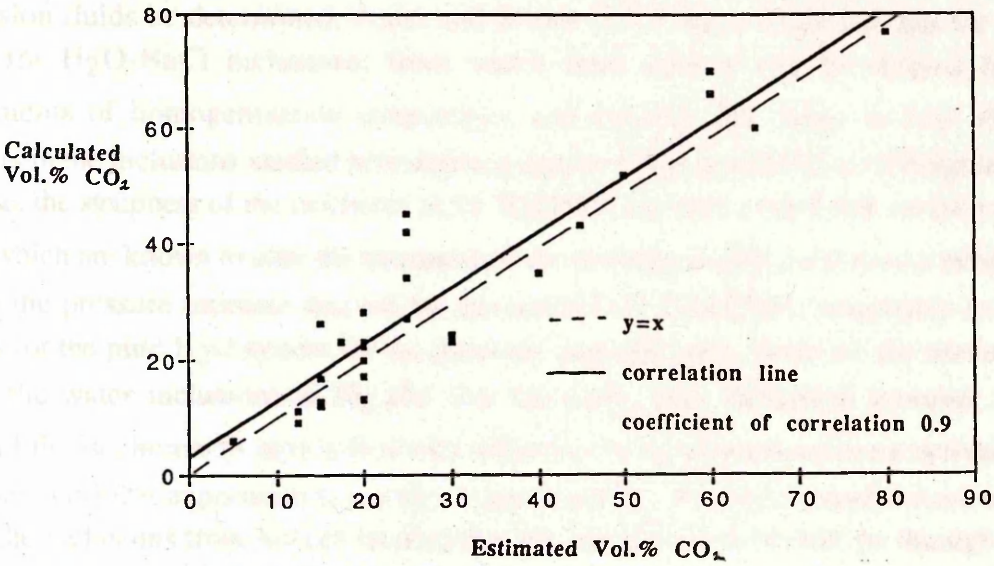
Determination Of CO_2 /H_2O Phase Ratios and Inclusion Densities

Proper utilisation of both the above methods depends on correctly determining the CO_2 content of the inclusions. Charts are available for this purpose which show the size of the CO_2 bubble within the inclusions and give the calculated vol% CO_2 for those inclusions. Experience is required for the use of these charts however. For the purposes of this work a pilot study was carried out to determine how accurate the author's visual estimates of CO_2 contents were.

A set of inclusions showing variable CO_2 /H_2O ratios were chosen, and visual estimates of these ratios were made by comparison with the aforementioned charts. For comparative purposes, accurate measurements were made of the relevant dimensions of the inclusion and the CO_2 bubble and the volumes calculated. For any estimation of vol%CO_2 made according to the relative areas of the CO_2 bubble and the inclusion, the major source of error results from the fact that the depth dimension may differ from the length and breadth as measured in the plane of focus. In order to overcome this error, inclusions were chosen for both the pilot study and the geobarometric study which showed small depth dimensions, as determined by racking the microscope focus up and down and observing the 3D shape of the inclusion. Thus, the inclusions used were observed in an orientation where measurements of relative areas of bubble and inclusion are representative of relative volumes. The results of this pilot study in terms of estimated and calculated Vol%CO_2 are tabulated and analysed on Fig.27. The relative spreads in the data for both estimated and calculated CO_2 contents indicate that visual estimates do give a reasonably reliable estimate

FIG. 27 DATA PERTAINING TO THE VOL.% CO_2 ESTIMATION PILOT STUDY

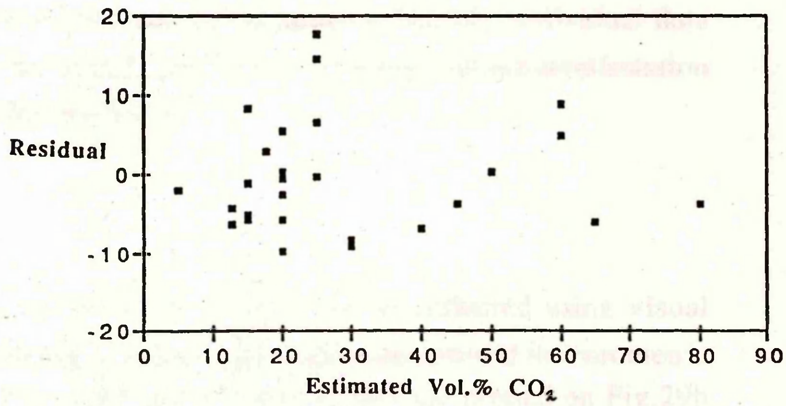
B; SCATTER PLOT OF ESTIMATED VERSUS CALCULATED VOL.% CO_2



A: RAW DATA

Estimated Vol.% CO_2	Calculated Vol.% CO_2
15	26
12.5	11
20	17
20	28
20	22
20	20
15	12.5
17.5	23
5	6
25	45
60	66
20	23
60	70
20	28
30	24
25	34
40	35
80	77
45	43
20	13
25	27
50	52
12.5	9
15	16.5
65	60
30	23
25	42
25	34
15	12

C; PLOT OF RESIDUALS



of the actual phase ratios of the inclusions studied. Visual estimates can therefore be utilised further for the purposes of geobarometry.

In addition, the use of the intersecting isochore method requires that the densities of the inclusion fluids be determined. Potter and Brown (1977) have compiled data for this purpose for H_2O-NaCl inclusions, from which fluid density can be derived from measurements of homogenisation temperature and salinity. The range in both these parameters in the inclusions studied here define a density range from 0.686 to 0.939g/cm^3 . In practise, the steepness of the isochores in the H_2O/NaCl system is such that variations in salinity, which are known to alter the steepness of the isochore slightly, will have a minimal affect on the pressure estimate derived by this method. It is therefore reasonable to use isochores for the pure H_2O system for the purposes intended here. These are the isochores used for the water inclusions in Fig.28a. For the CO_2 only inclusions however, the gradient of the isochore will have a profound influence on the pressure estimate derived. It is therefore of critical importance to use the correct isochore. The near critical behaviour of CO_2 in the inclusions from Socach implies that the relevant isochore will go through the CO_2 critical point on Fig.28A . This still leaves much choice in terms of the gradient of the isochore used however. Measurement of the density of the inclusion fluids via calculation from estimated liquid/vapour phase ratios and the known density of liquid CO_2 allow the choice of isochores to be narrowed down slightly. Ranges in degrees of fill of CO_2 only inclusions of 30-60% correspond to fluid densities of 0.33-0.66g/cm^3 . The correct isochores will thus be within this density range, as indicated on Fig.28a. Individual data points plotted on Fig.28a show a wide range in pressure estimates as a direct manifestation of this variability in CO_2 density in the inclusions.

Geobarometric Data

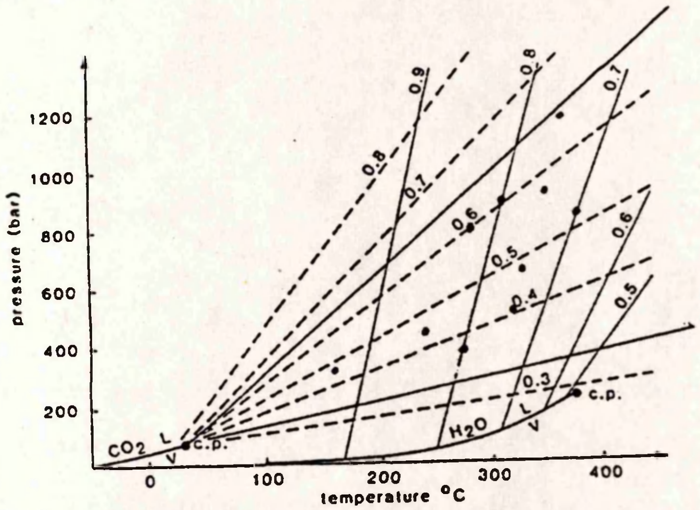
With confirmation that reliable phase ratio data can be collected using visual estimates, and the relevant inclusion densities could be adequately determined the barometric study was carried out. For mixed CO_2 /H_2O inclusions the data are plotted on Fig.29b whilst data derived from H_2O only and CO_2 only inclusions are plotted on Fig.29a .

Extracting pressure estimates from both Figs. 29a and 29b allows them to be displayed more simply in histographic form, see Fig.29c. This shows a wide spread in pressure estimates from 200 to 1250bars. Wide spreads in thermometric data were ascribed to temporal evolution of an inhomogeneous fluid, and are interpretable within this context. The wide spread in geobarometric estimates also therefore requires interpretation within this context.

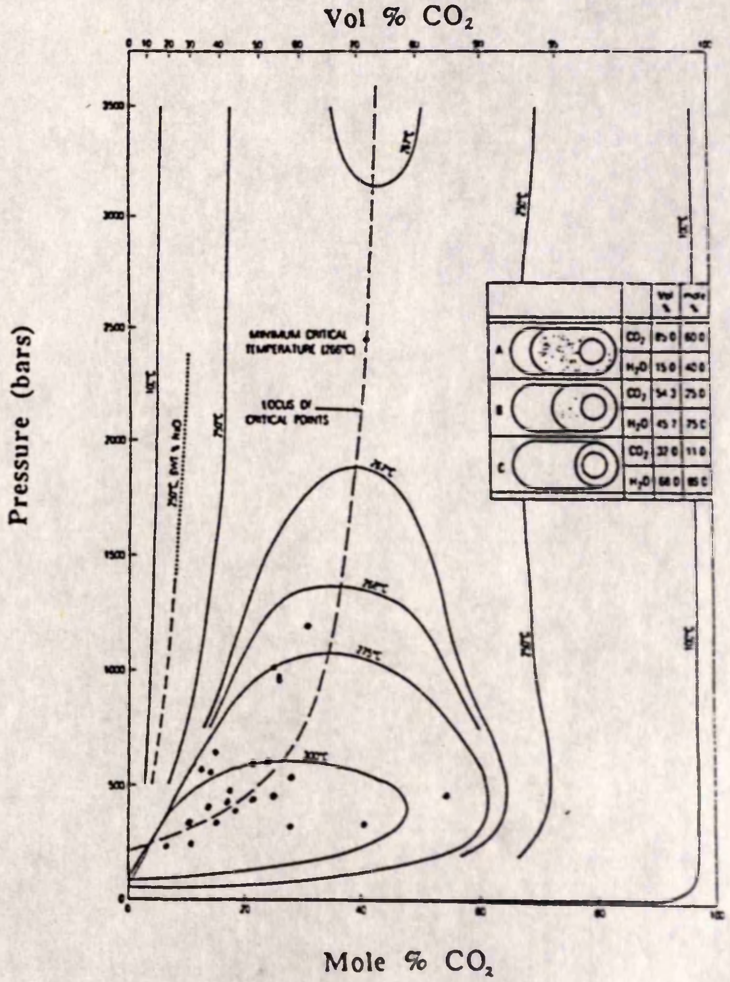
With respect to Fig.29b, it should be borne in mind that the immiscibility phenomena it depicts relate to the H_2O/CO_2 system. The effect on CO_2/H_2O immiscibility of the addition of NaCl to the system has been described by Bowers and Helgeson (1983). Addition of 6, 20 and 35 wt.% Nacl is shown to expand the immiscibility field substantially at temperatures around 500 C. Data specifically relating to the 9-14wt.% NaCl salinities and

FIG. 28 A-C; GRAPHICAL REPRESENTATION OF BAROMETRIC DATA DERIVED FROM FLUID INCLUSIONS IN HYDROTHERMAL QUARTZ FROM THE SOCACH STRUCTURE

A; THE INTERSECTING ISOCHORE METHOD (after Shepherd et al 1985)



B; THE ISOTHERMAL METHOD (after Roedder 1984)



C; HISTOGRAPHIC REPRESENTATION OF GEOBAROMETRIC DATA DERIVED FROM A AND B ABOVE

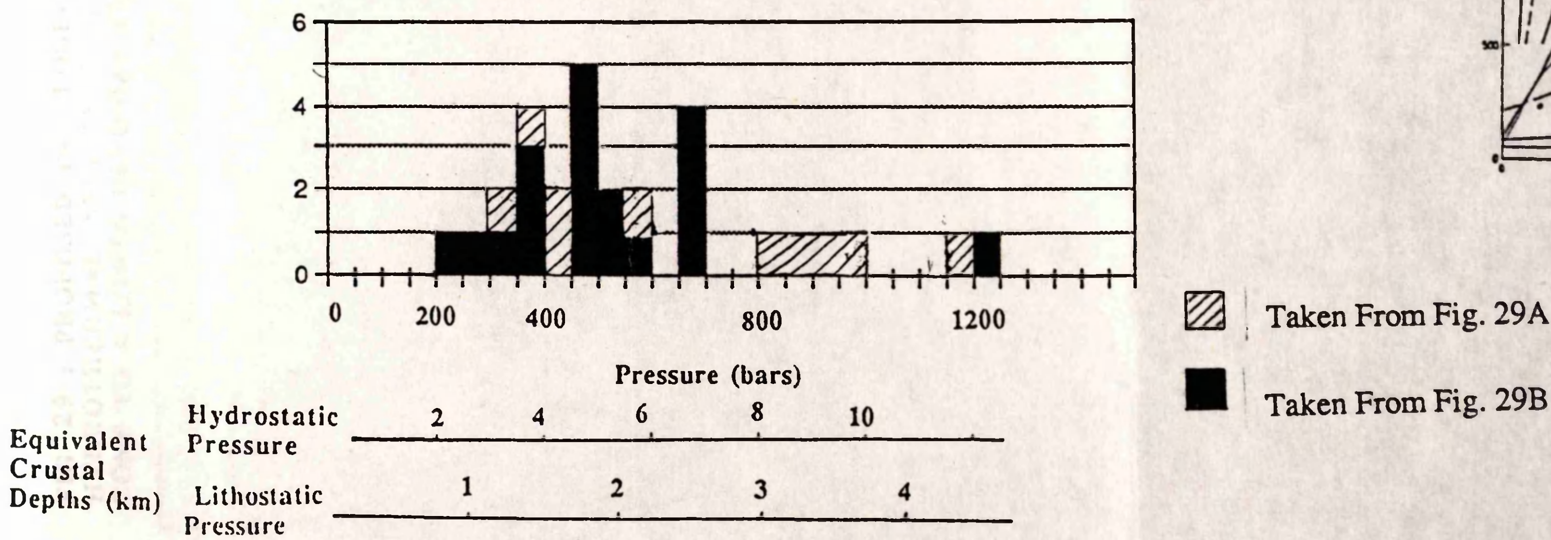
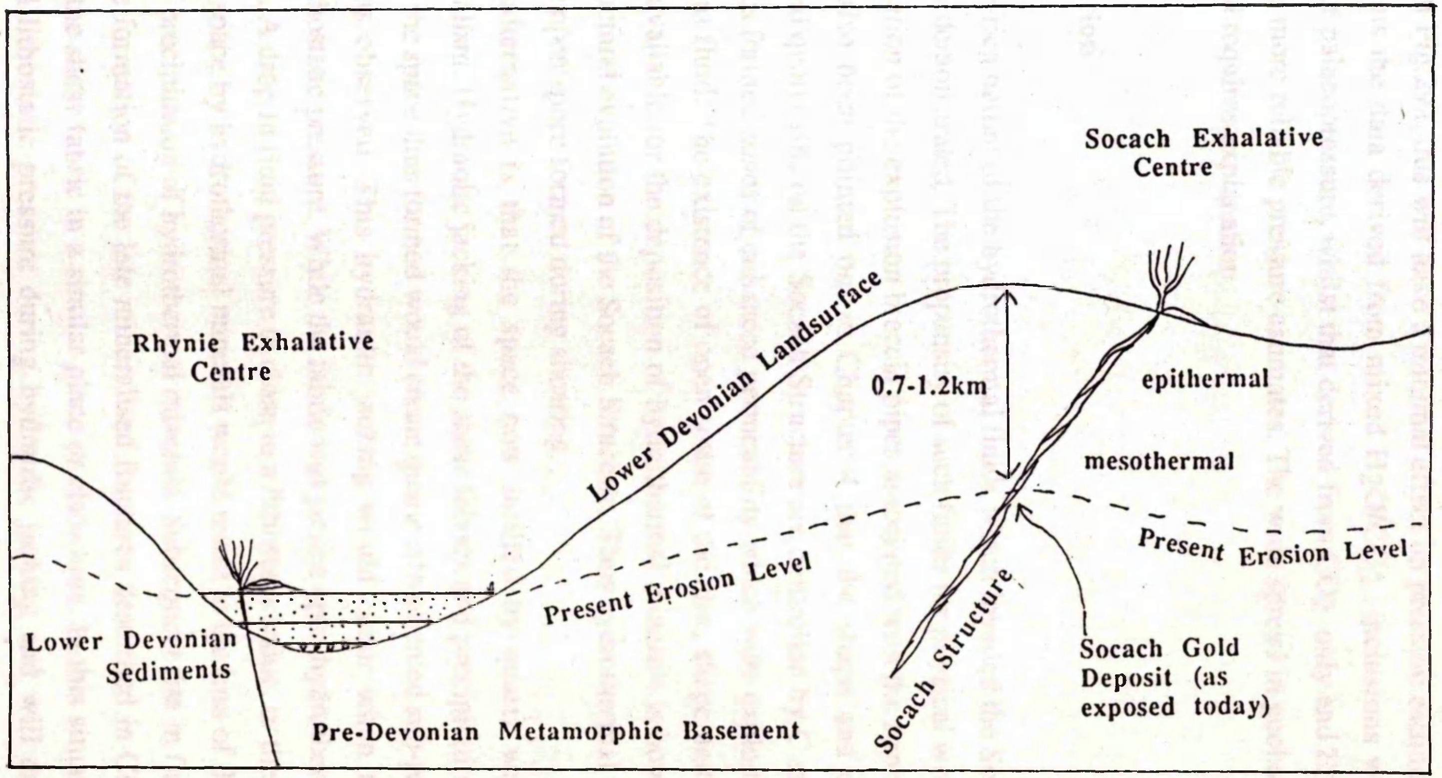


FIG 29 ; PROPOSED PALAEOGEOGRAPHICAL SETTING FOR THE SOCACH HYDROTHERMAL SYSTEM; THE UNROOFED MESOTHERMAL FEEDER ZONE TO A LOWER DEVONIAN EXHALATIVE SYSTEM.



220-380 C temperatures of concern here are not available in detail, but the conclusion that the immiscibility fields will be expanded must be taken into account. Expanding the immiscibility fields on Fig.29b and replotting the data will produce higher pressure estimates. The pressures derived from the method of Fig.29b, interpretted within the context of the H_2O/CO_2 system will be under-estimates if any NaCl is also present, as it is here. The effect of the addition of salt to pressure estimates derived by the intersecting isochore method of Fig. 29a will be less pronounced. The gradients of the isochores for pure H_2O change gradient slightly on addition of NaCl. In view of the already steep nature of these isochores on Fig.29a, this will have a minimal effect on pressure estimates derived by this method. Thus the data derived from mixed H_2O/CO_2 inclusions will provide under-estimates for palaeopressure, whilst that derived from CO_2 only and H_2O only inclusions will provide more reliable pressure estimates. The wide spread in geobarometric estimates remains, and requires explanation.

Interpretation

The volatile-rich nature of the hydrothermal fluids which invaded the Socach Structure has been clearly demonstrated. The propensity of such fluids for physical work is demonstrated by the formation of the explosion breccia pipes associated with the appinite suite (Chapter 1). It has also been pointed out in Chapter 4 that the shape and orientation of the hydrothermal quartz ribs on the Socach Structure are controlled by C and S shear fabrics. These fabrics formed zones of enhanced permeability which were exploited by the invading hydrothermal fluid. The existence of open space of the size, shape and orientation of the quartz ribs available for the deposition of hydrothermal minerals is however inconsistent with the structural evolution of the Socach Structure.`Thus hydrothermal not precipitated in pre-existing open space formed during shearing.

An alternative is that the space now infilled by quartz was formed during hydrothermalism. Hydraulic jacking of the shear fabrics and precipitation of hydrothermal minerals in the space thus formed would create quartz ribs oriented sub-parallel to the C and S fabrics, as observed. This hydraulic jacking would occur when the fluid pressure exceeded lithostatic pressure. While the fabric was jacked open hydrothermal mineralisation could occur. A drop in fluid pressure to close to a lithostatic value, or the complete infilling of the open space by hydrothermal minerals would result in the loss of this open space and cessation of precipitation of hydrothermal minerals. Subsequent rise in fluid pressure would result in the formation of the late mineralised fractures described in Chapter 4 or the re-opening of the shear fabric in a similar place or elsewhere. In this situation fluid pressure will exceed lithostatic pressure during hydraulic jacking and will drop to closer to a lithostatic value as mineralisation proceeds and the open space closes again.

The fluid pressures derived from inclusions in hydrothermal quartz are likely to reflect this process of hydraulic jacking and subsequent mineralisation. The higher pressures derived will relate to the hydraulic jacking phase whilst the lower ones will record the drop towards lithostatic pressure during mineralisation. By this reasoning the lower of the pressure figures will reflect lithostatic pressure whilst the higher ones will reflect the degree of over-pressuring. The appreciation that the data derived by the intersecting isochore method will provide more reliable pressure estimates should also be borne in mind here. Thus, using the minimum pressure of 300bars, this corresponds to a crustal depth of 1.0 - 1.5km during hydrothermalism, if it is assumed that the pressure is lithostatic in origin. This assumption is defendable on the grounds that the relatively tight shear fabrics typical of the Socach Structure are unlikely to allow uninhibited hydraulic contact with the contemporaneous land surface.This palaeodepth derived for auriferous hydrothermalism allows the mineralisation to be placed in the palaeogeographical setting depicted by Fig. 29, which will be discussed further in Chapter 7.

Hydrothermal Gold Transport and Deposition

Sulphur and chloride complexes are considered the most common gold complexing agents in hydrothermal fluids on account of their availability in most such fluids and their ability to form stable complexes with gold over a range of hydrothermal pressure, temperature and chemical conditions. The availability of sulphur for this purpose in the mineralising fluids considered here is evidenced by the abundance of pyrite within the Socach Structure. Chloride availability can be argued on the grounds of the high salinity of the hydrothermal fluids. Both chloride and sulphur are therefore considered to be available and able to carry gold in the present context and on these grounds are considered the most likely complexing agents responsible for gold hydrothermal transportation.

The most obvious hydrothermal fluid processes in evidence on the Socach Structure are the cooling and effervescence of the fluid. Seward (in Foster 1991) considers the effect of both processes on the stability of sulphur and chloride complexes of gold. He collates data relating to the stability of the $AuCl_2^-$ complex at different temperatures and pressures. Of note is the drop in stability of this complex over the 375-220°C temperature range of relevance here. Similar collation of data for the $Au(HS)_2^-$ complex shows a parallel trend to that for chloride complexes, with stability decreasing with temperature over the range 375-220° C. Hence it can be concluded that gold carried as either type of complex will show a tendency towards precipitation on cooling of the hydrothermal fluids.

Seward (in Foster 1991) also considers the effect of boiling and/or effervescence on the solubility of gold as the $Au(HS)_2^-$ complex, and concludes that the process exerts a strong control over gold solubility to the point that precipitation can quickly follow the onset of phase separation. In his specific example he considers closed system adiabatic boiling as a very efficient means of precipitating gold carried as the $Au(HS)_2^-$ complex, and concludes similarly for the $AuCl_2^-$ complex. He compares the effect of this process with that produced by the cooling of the hydrothermal fluid from 311-180°C, and concludes that the overall effect on gold complex stability is similar.Open system boiling is also shown to be a very efficient mechanism of gold precipitation where gold is carried as these complexes. Effervescence and cooling of the gold mineralising solutions have been shown to have occurred together at Cushnie, and on the above grounds the combined effects will constitute a very effective mechanism for precipitating gold. Thus it can be argued that cooling and effervescence of the hydrothermal fluid was responsible for deposition of gold being carried as either chloride or sulphur complexes or both.

Hydrothermal Fluid Sources On The Cushnie Prospect

Hydrothermal fluids responsible for gold mineralisation on the Cushnie prospect were hot (220-375 °C), CO_2 bearing and highly saline (9-14 equiv.wt%NaCl). In deducing the source of these fluids the high salinity can be used to narrow the possibilities. Meteoric water is usually considered to possess a salinity of around 0 equiv.wt%NaCl, whilst sea-water world-wide has a salinity of 3.5equiv.wt%NaCl. Neither of these fluids in their unmodified form could form hydrothermal fluids of the observed salinity. Intense evaporation of either or both of these fluids could produce salinities of 9-14 equiv.wt%NaCl. However the presence of such highly evaporative marine or terrestrial environments does not figure anywhere in the geological history of NE Scotland, so both these fluid sources can be discounted on the grounds of unavailability. Igneous and metamorphic fluids can, and frequently do, attain salinities similar to those of the inclusion fluids studied here. The movement of igneous fluids through the crust will be accompanied by igneous emplacement. The presence of the Cushnie Granite within the prospect therefore provides a potential source for such igneous fluids. Gold mineralisation associated with metamorphic fluid flow is considered by Craw and others to be a result of regional uplift of the metamorphic pile. That such uplift has occurred at some time in the geological evolution of the Cushnie prospect is evidenced by the presence of outcropping medium to high grade metamorphic rocks which must have been uplifted into their present position. Thus, the first deduction can be made that the geology of the Cushnie prospect has the potential to provide either (or both) igneous and metamorphic fluids as potential carriers of gold. This choice will be narrowed further once the geological setting of the Socach gold deposit is more fully understood.

CHAPTER 6

SUPERGENE ALTERATION OF THE SOCACH GOLD DEPOSIT, ABERDEENSHIRE,SCOTLAND

Introduction

One of the most distinctive features of the mineralisation at Socach is the wholesale oxidation and leaching of the pyrite. The understanding of such later supergene effects is important to the economic evaluation of mineral deposits because they characteristically involve grade redistribution. In this particular case it is also important scientifically since it is the first reported occurrence of supergene alteration of this intensity in mineralisation in Scotland.Fig.30 presents a schematic representation of the paragenesis of this oxidation as deduced through textural analysis. The order of events depicted by Fig. 30 will be followed here but in more detail.

Textural Analysis Of Oxidised Gold+Pyrite Mineralisation

Primary sulphides are represented by individual euhedral crystals and crystal aggregates of pyrite with individual cubes ranging from 0.5mm to 1cm across, and cube clusters up to 2 cm across. In the field they were only encountered in trench 3 where they occurred within intensely oxidised material. Other occurrences found later in polished sections comprise very fine cubes completely enclosed in individual quartz crystals that in all probability protected the pyrite from oxidation. Also found in this position are very fine blebs of chalcopyrite; this is the only habit of chalcopyrite in this mineralisation, no secondary copper minerals or coarser grained equivalents were found. Grain boundary fractures within pyrite crystal aggregates are characteristic and are most probably a primary crystallisation phenomenon, but the more intense, random fracturing of pyrite cubes (Plate 10a) is later. Both these types of discontinuity in the primary sulphides provided permeability along fractures up to 1.5mm wide which later facilitated access by downgoing supergene solutions.

Infilling of fractures cutting fresh pyrite by goethite and hematite is alluded to by the slithers of these minerals preserved along the fractures. Preservation of these infilling secondary minerals in polished blocks is poor due to the hardness difference between them and the pyrite and the less coherent nature of the goethite and haematite. In order to achieve a good polish on the relatively hard pyrite a longer polishing polishing period is required and this gives more opportunity for plucking out of secondary minerals. Nevertheless finely banded goethite and haematite are seen lining fractures in fresh pyrite, thus constraining the timing of this infilling as before wholesale oxidation of pyrite.

Wholesale oxidation of pyrite to haematite and goethite formed euhedral pseudomorphs (Fig 10b,c). On polished blocks these occur as cubes of amorphous looking iron oxide which characteristically takes on a poor polish due to its ubiquitous pitted nature and is dull grey in colour, cut by fractures lined by the earlier secondary minerals which take on a markedly better polish. The earlier secondary minerals are better preserved in the completely oxidised material due to the reduction in hardness and competence contrasts which facilitates polishing without plucking of softer less coherent material. Wider fractures

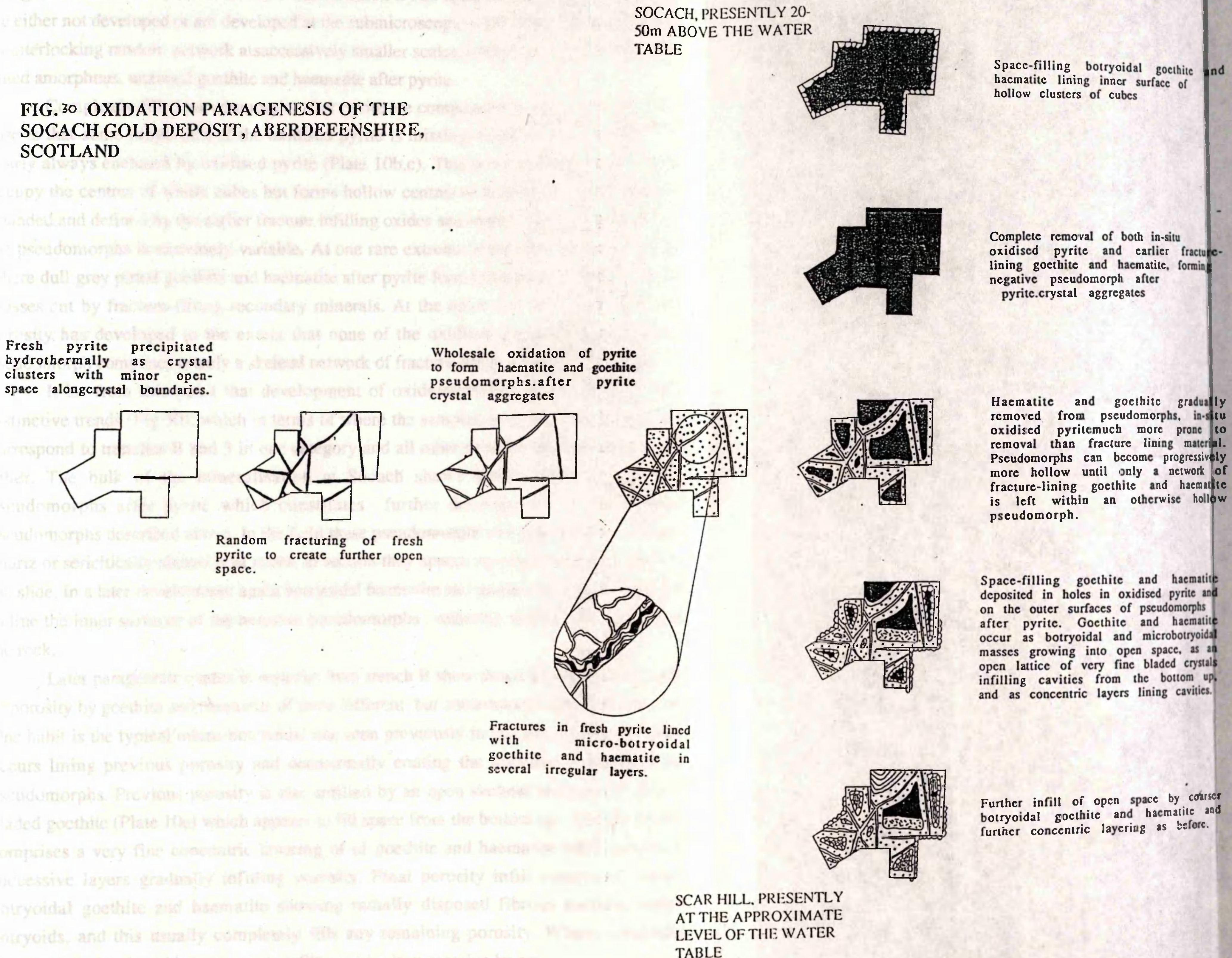


FIG. 30 OXIDATION PARAGENESIS OF THE SOCACH GOLD DEPOSIT, ABERDEEENSHIRE, SCOTLAND

show botryoidal shapes, convex out from the fracture walls, and an alternation between goethite and haematite which results in roughly parallel zones of different brightnesses lining the fracture. In narrower fractures this zonation is still apparent but botryoidal textures are either not developed or are developed at the submicroscopic scale. The fractures occur as an interlocking random network atsuccessively smaller scales, enclosing zones of dull grey pitted amorphous, unzoned goethite and haematite after pyrite.

Completely filled pseudomorphs after pyrite are comparatively rare, the more usual case is that some proportion of the oxidised pyrite is missing, forming porosity which is nearly always enclosed by oxidised pyrite (Plate 10b,c). This porosity does not normally occupy the centres of whole cubes but forms hollow centres to irregularly shaped masses bounded and defined by the earlier fracture infilling oxides and hydroxides. Degree of fill of the pseudomorphs is extremely variable. At one rare extreme is the case described above where dull grey pitted goethite and haematite after pyrite form irregularly shaped coherent masses cut by fracture-filling secondary minerals. At the other end of the spectrum the porosity has developed to the extent that none of the oxidised pyrite remains and the pseudomorph comprises merely a skeletal network of fracture-lining secondary minerals.

It is from this point that development of oxide/hydroxide textures shows two distinctive trends (Fig 30), which in terms of where the samples were obtained in the field correspond to trenches B and 3 in one category and all other trenches and outcrops in the other. The bulk of the mineralisation at Socach shows development of negative pseudomorphs after pyrite which constitutes further development of the skeletal pseudomorphs described above. In the field these pseudomorphs comprise hollow cubes in quartz or sericitically altered host rocks; in section they appear as euhedral shaped holes in the slide. In a later development again botryoidal haematite and goethite are again observed to line the inner surfaces of the negative pseudomorphs , reducing slightly the porosity of the rock.

Later paragenetic events in material from trench B show much greater variety. Infill of porosity by goethite and haematite of three different but contemporaneous habits occurs. One habit is the typical micro-botryoidal one seen previously in fracture linings; here this occurs lining previous porosity and occasionally coating the outsides of some of the pseudomorphs. Previous porosity is also infilled by an open skeletal boxwork of micro-bladed goethite (Plate 10e) which appears to fill space from the bottom up. The third habit comprises a very fine concentric layering of of goethite and haematite which grows in successive layers gradually infilling porosity. Final porosity infill comprises coarser botryoidal goethite and haematite showing radially disposed fibrous textures within botryoids, and this usually completely fills any remaining porosity. Where concentric layering was developed it continues to infill porosity in successive layers.

PLATE 10; REFLECTED LIGHT AND SEM PHOTOMICROGRAPH SEQUENCE SHOWING THE OXIDATION PARAGENESIS OF GOLD PLUS PYRITE MINERALISATION ON THE SOCACH STRUCTURE

A) Fractured pyrite grain clusters.

B) Oxidised pyrite grain clusters. Note amorphous, dull grey haematite/goethite forming hollow cubes, interpreted as insitu oxidised pyrite. Note also lining of cubic crystal boundary fractures and outside of grain clusters with clean, more highly polished grey haematite showing botryoidal textures in places, interpreted as material precipitated from supergene fluids. Gold grain hosted by exotic supergene material. Note also hollow individual cubes between fractures, evidence that leaching postdated fracture infill.

C) Largely fine grained dirty grey haematite and goethite showing evidence of leaching in the form of large hollows. Cut by large fracture partially infilled by grey and white botryoidal goethite and haematite interpreted as of exotic supergene origin. Small gold grains near centre of photograph actually hosted by tiny anastomosing fractures branching off the main fracture. Note that these small gold grains occupy the entire width of the fractures, evidence of chemical gold transport and deposition since it would be difficult for grains of particulate gold to get into such a position.

D) Highly leached amorphous haematite and goethite hosting gold grains near the centre of the picture. Cut by prominent fracture partially infilled by poorly developed botryoidal haematite.

E) SEM photomicrograph of late porosity infilling iron oxides. Negative pseudomorph after pyrite, the result of complete leaching, partially infilled by bladed haematite growing in from the edges of the pseudomorph. Later partial infill of remaining porosity by boxwork haematite in a geopetal manner.


PLATE 10a
0 1mm

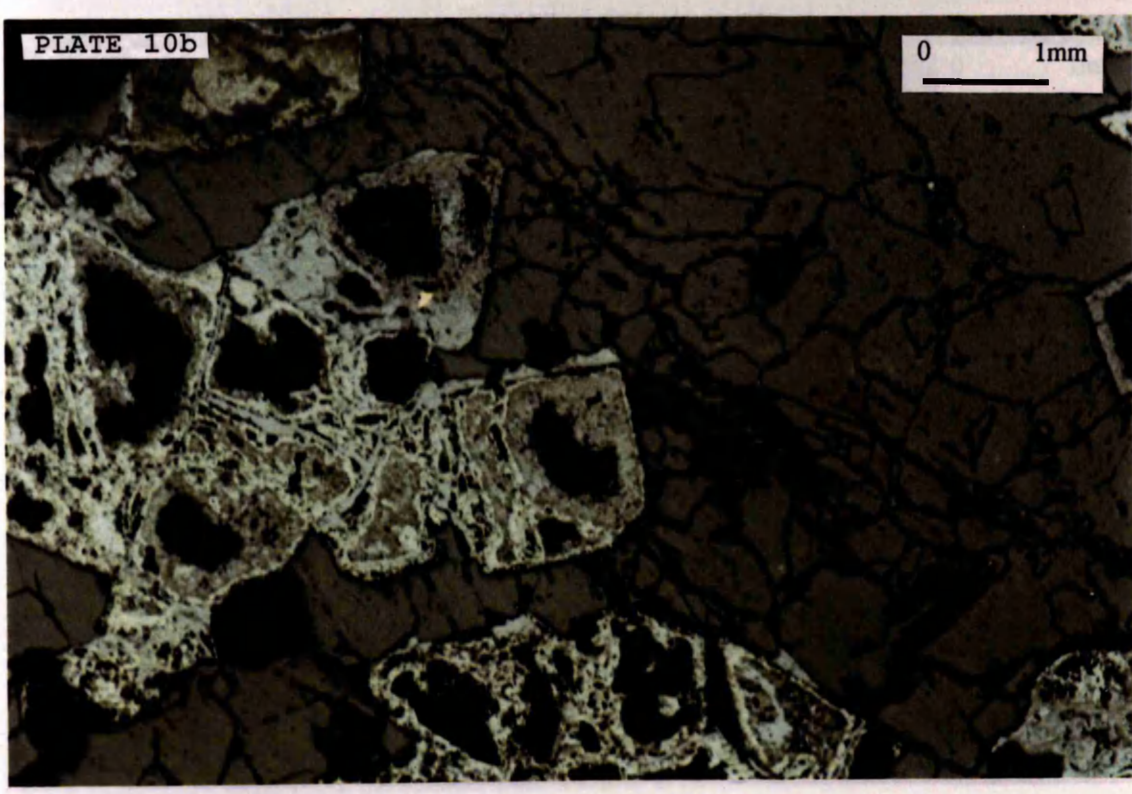


PLATE 10b
0 1mm

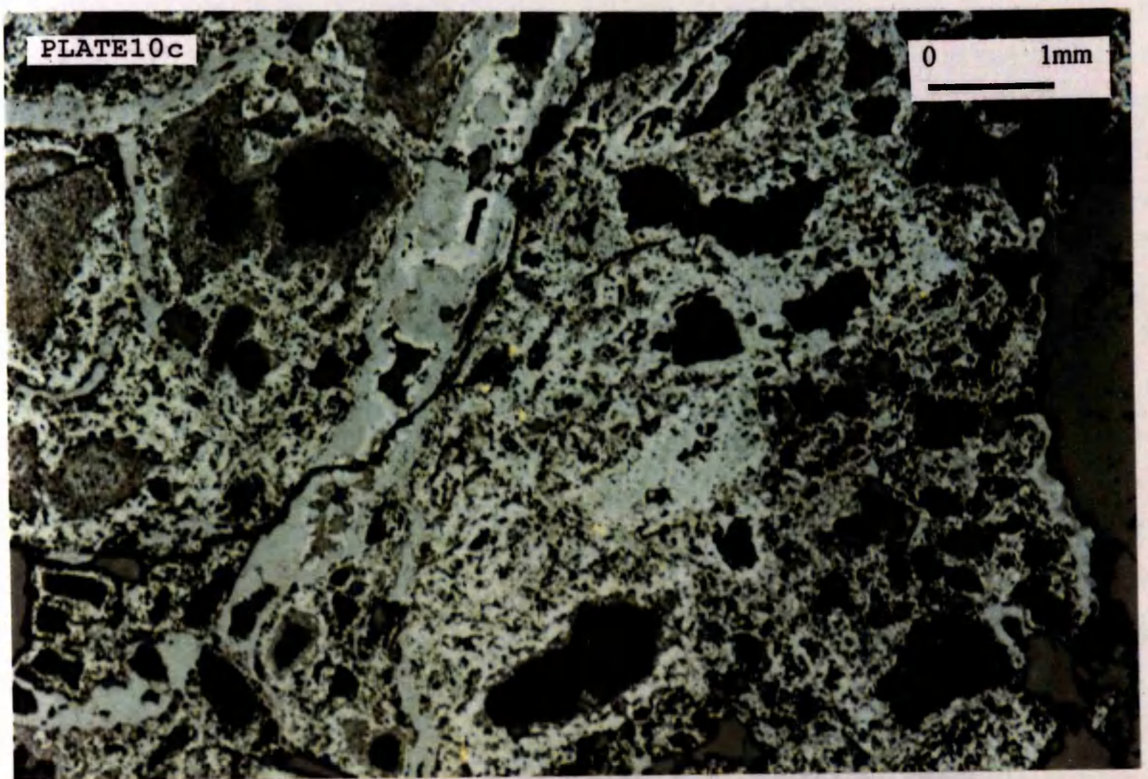


PLATE10c
0 1mm

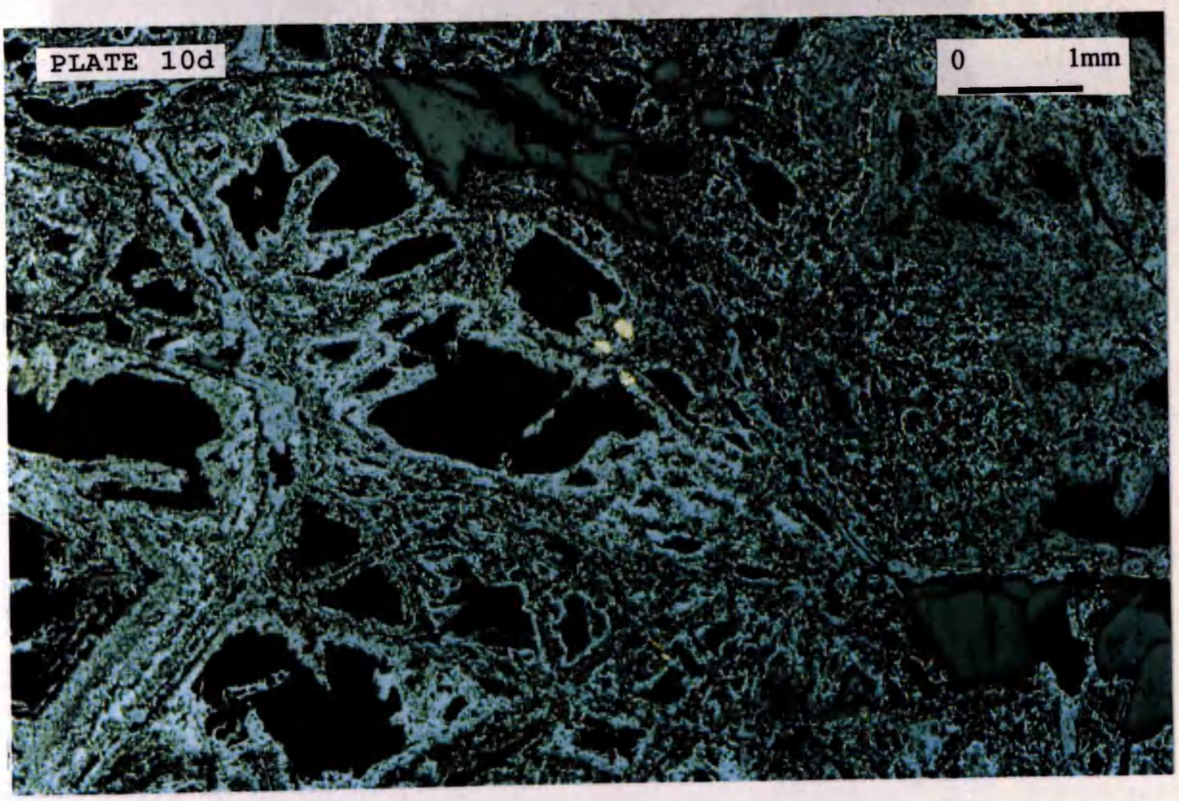


PLATE 10d
0 1mm

PLATE 10e

Interpretation of Textural Characteristics

On the basis of textures and their relative chronologies a picture can be developed of the sequence of oxidation events that occurred on the Socach Structure. Firstly, the different textures can be assigned an in-situ or exotic origin, the former refering to those that have developed in place without movement of the material and the latter refering to textures that have formed from material that has been brought in from elsewhere ('elsewhere' and 'exotic' in this context means outwith the area represented by the scale of observation. Thus, exotic iron oxides/hydroxides are most likely to originate from elsewhere on the Socach Structure, probably in the up-dip direction, as a result of oxidation and leaching of sulphides.). The latter category will include all the space-filling textures, namely the fracture-lining goethite and haematite and the botryoidal, boxwork and concentrically zoned secondary minerals seen infilling both early and late porosity. The dull grey amorphous pitted goethite and haematite is assigned an in-situ origin. An exotic origin is unlikely because it shows none of the space-filling characteristics of zonation or 'convex into porosity' botryoids possessed by both earlier and later exotic secondary minerals. The timing of its formation and the lack of evidence for previous porosity in the position this material currently occupies also mitigates against an exotic origin.

Basically then, the mineralisation contains, in various proportions, material of both in-situ and exotic origins, interpreted to be material that has oxidised in-situ and material that has been introduced by downgoing supergene solutions respectively. The latter material is divided into two stages, the first being the infilling of fractures and the second being the infilling of later porosity. These constitute two stages of precipitation from downgoing supergene fluids, and are separated by a porosity forming, or leaching, event. From previous studies of the supergene alteration of sulphide deposits(eg.Emmons 1912), precipitation of iron oxides and hydroxides is known to occur where acid, oxidising supergene fluids meet the redox front represented by the water-table, and leaching is known to occur in the aerated zone above the water-table. Thus these events indicate that the mineralisation was originally beneath the water-table, then was exposed above it, undergoing leaching, before being submerged again. The most likely scenario is that the deposit hosting the hydrothermally precipitated pyrite gradually made its way to the surface by means of erosion of overlying rocks. At relatively shallow levels the pyrite came into contact with downgoing supergene fluids beneath the water table and these precipitated their dissolved oxides and hydroxides in fractures. On further erosion and/or a drop in the level of the water-table the mineralisation moved to a position above the water-table, initiating wholesale oxidation and eventually leaching. Around the present positions of trenches B and 3 the water-table then rose to submerge the mineralisation and precipitation from downgoing supergene fluids resumed, filling in the porosity formed during the leaching stage. The water-table never rose enough to submerge the full strike-length of the Socach Structure, thus everywhere else but trenches B and 3 , leaching continued and is still active today. The legacy of these events is a mineralised body which at the current erosion level is almost entirely exposed within the leached zone except where it is briefly exposed at the level of the present water table where the upper levels of the oxidised zone are exposed. By this reasoning the oxidised zone should be found at depth over the rest of the strike-length of the Socach Structure, and under this oxidised zone should be the zone of primary sulphides. The lack of carbonate minerals in the mineralisation or host rocks means that the oxidised zone may be fairly thick due to the lack of a means of quickly neutralising the downgoing fluids, as described by Emmons (1912).

Gold Redistribution By Supergene Processes

When dealing in any kind of commercial capacity with ores that have been subjected to supergene alteration processes it is necessary to understand how these processes have affected the grades in the material and to predict from grade redistibution patterns evident at exposure level how the grades might vary with depth. For the Socach deposit it is necessary to know whether the gold is in supergene material or in pyrite that has oxidised in-situ since in the former case the grade will be a result of supergene enrichment and will not be maintained at depth whilst the latter scenario predicts no supergene enrichment and therefore vertical continuity of gold grades. At Socach reasonable control on supergene processes can be achieved because the mineralisation outcrops both above and at the level of the water-table so providing a good opportunity for such a study.

Once the oxidation paragenesis was constrained by textural analysis, meticulous search for gold grains in polished blocks and textural study of the host iron oxides and hydroxides was used to categorise each gold grain found into insitu or supergene origin. Of the seventy gold grains examined , twenty six were found to be hosted by highly polished goethite and haematite infilling fractures with one found on late botryoidal material coating the outside of a pyrite pseudomorph. The diagnostic feature of infilled fractures was taken to be matching walls that could reasonably be fitted back together again after removal of the infilling oxides and other late oxides which were identified by their higher polish and unpitted appearance. Another six gold grains were found along primary pyrite grain boundaries but with no accompanying iron oxide/hydroxide infill; Gold in these habits was assigned a supergene origin. The remainder of the gold grains were found away from fractures in in-situ oxidised pyrite and were therefore assigned a primary, non-supergene origin.

Gold grains located in polished blocks prepared from mineralised outcrop and loose local blocks from the Socach Structure on Scar Hill were generally roughly equant in dimension and rounded to sub-rounded (see Table 2). The minority of elongate grains showed maximum aspect ratios of 2:1 and 3:1 in insitu and exotic supergene hosted grains respectively but in general there was no noticeable shape difference between the two categories of grains. Some rare irregular shaped grains were the result of inverse botryoidal or lath shaped re-entrants caused by competition for space with goethite and haematite. Summary statistics of grain dimensions on Table 3 indicate that grains hosted by insitu oxidised pyrite were on average slightly larger, by 29% in length and 43% in breadth, reflecting the greater number of large grains in the insitu host. Textural differences between the two categories of grains, such as evidence of fine euhedral or dendritic gold in exotic grains were not apparent on polished blocks. Extraction of individual grains from the rock mass for textural analysis was not attempted since it was considered that any such extraction (eg. crushing, leaching) would have been destructive of the textures of interest. It is considered here that the control on the development of both insitu and exotic gold grains would have been the competition for space with iron oxides and hydroxides; a textural difference reflecting the space-filling botryoidal and boxwork habits of exotic iron oxides and hydroxides and the amorphous nature of the insitu oxidised material would therefore be anticipated if gold grain separation from these hosts could be achieved non-destructively.

In order to evaluate the relative contributions of the gold from the two types of host the individual grains were measured and assigned a nominal shape (see Table) The area of each grain was then calculated using the formulae;

$A=lXb$ for equant grains
$A=lXb$ for elongate grains
$A=\pi r^2$ for circular grains
$A=0.8(lXb)$ for elongate rounded grains
A=visual estimate for irregular grains

(where A=area, l=length, b=breadth, r=radius)

It should be pointed out that these calculations do not take into account the third dimension of the gold grains, which is unmeasureable on polished blocks. The random orientation of the polished blocks with respect to host pyrite crystals and the fractures therein should however randomise and essentially eliminate any bias this creates in the results. It should nevertheless be borne in mind that the calculated areas give only a rough estimate of the relative quantities of gold present and the conclusions drawn from them are only semi-quantitative. In addition, the calculations performed take no account of the possibility that gold could occur in invisible form, perhaps as a result of original solid-solution gold in unweathered pyrite, or as colloidal particles within or attached to iron oxide/hydroxide minerals. As such, the results relate to particulate gold only. Given that solid solution and colloidal gold are generally not recoverable by normal metallurgical methods, the results of this analysis can be considered to approximately relate to recoverable gold; in this sense the approach is defendable since the remit of this part of the study is to assess the effect of the oxidation process on gold grade redistribution, and the consideration of recoverable gold is more appropriate in assessing the implications this has for the economics of the deposit.

The areas calculated are shown on Table 2. When the areas of the grains from the insitu oxidised pyrite and those hosted by fracture and porosity filling iron oxides/hydroxides of exotic supergene origin are totalled they reveal that the former constitutes 72.6% of the total. Examination of the areas of individual grains on Table however reveals that a few large grains from both hosts dominate the a real totals. When the

TABLE 2 Grain Size Data For Gold Grains Found In Polished Blocks Prepared From Outcrop and Loose Blocks Of The Socach Structure On Scar Hill, Cushnie Prospect, Aberdeenshire, Scotland.

A) Gold Grains Hosted By In-Situ Oxidised Pyrite

Polished Block	Shape	Dimensions um	Area (um)
4	equant,irreg.	50x40	2000
4	rounded	10diameter	78.5
4	rounded	10diameter	78.5
4	elong,rounded	20x15	280
4	rounded	10diameter	78.5
4	elongate	35x20	700
4	equant	10x10	100
4	elogate	75x40	3000
4	equant	10x10	100
4	equant	10x10	100
4	equant	10x10	100
2	elong,rounded	30x15	400
2	irregular	20x15	280
2	rounded	10diameter	78.5
2	rounded	20diameter	314
3	equant	10x10	100
3	equant	10x10	100
3	irregular	20x15	280
3	rounded	10diameter	78.5
3	regular	20x15	280
3	regular	10x8	80
3	elongate	25x15	375
3	elongate	30x20	600
6	equant	30x30	900
6	rounded	10diameter	78.5
1	rounded	5diameter	19.6
1	equant,angular	15	200
1	irregular	10x10	80
1	rounded	3.3diameter	35.2
1	elong,rounded	15x10	120
5	equant	50x50	2500
1	elong,rounded	15x10	120
5	elongate	30x15	450
5	equant	10x10	100
5	rounded	5diameter	19.6
5	rounded	5diameter	19.6
5	rounded	5diameter	19.6

B) Gold Grains Hosted By Fracture and Porosity Filling Iron Oxides And Hydroxides Of Exotic Supergene Origin.

	Polished Block	Shape	Dimensions um	Area (um)
1	4	equant	30x30	900
2	4	rounded	10diameter	78.5
3	2	rounded	20x15	280
4	2	rounded	5diameter	19.6
5	3	elongate	15x10	150
6	6	elongate	50x25	1250
7	1	rounded	6.7diameter	141
8	1	elong,rounded	20x10	180
9	1	irregular	10	75
10	1	rounded	10diameter	78.5
11	1	elong,rounded	10x5	40
12	1	irregular	25	200
13	1	rounded	10diameter	78.5
14	1	rounded	10diameter	78.5
15	1	rounded	10diameter	78.5
16	1	elong,rounded	10x5	40
17	1	elong,rounded	10x5	40
18	1	elong,rounded	10x5	40
19	1	elong,rounded	10x5	40
20	1	elong,rounded	5x2.5	10
21	1	elong,rounded	5x2.5	10
22	1	rounded	5diameter	19.6
23	5	rounded	10diameter	78.5
24	5	rounded	10diameter	78.5
25	5	rounded	10diameter	78.5
26	5	rounded	10diameter	78.5
27	5	rounded	5diameter	19.6
28	5	elongate	40x20	800
29	5	equant	10x10	100
30	5	elongate	30x10	300

C) Gold Grains Hosted By Iron Oxides And Hydroxides Of Dubious Affinity.

Polished Block	Shape	Dimensions um	Area (um)
4	elongate	20x10	200
4	elongate	20x10	200
4	elongate	20x10	200
5	rounded	10diameter	78.5
5	rounded	10diameter	78.5
5	rounded	10diameter	78.5

TABLE 3. Summary Statistics Of Grain Size Data For Gold Grains Found In Polished Blocks Prepared From Outcrop and Loose Blocks Of The Socach Structure On Scar Hill, Cushnie Prospect, Aberdeenshire, Scotland.

	minimum	maximum	median	mean	variance	std. deviation	skewness	kurtosis
LENGTH	3.3	75	10	18.2	225.2	15.0	1.9	3.8
WIDTH	3.3	40	10	14.6	93.2	9.7	1.5	1.4
LENGTH	5.0	50	10	14.1	117.0	10.8	1.8	2.6
WIDTH	2.5	30	10	10.2	44.7	6.7	1.5	1.5

TABLE 4. Contributions Of Supergene Enrichment And Primary, Insitu Components To Gold Grades On The Socach Structure At Scar Hill, Cushnie Prospect, Aberdeenshire

	TOTAL AREA	% OF TOTAL	TOTAL AREA excluding grains >1000 um	% OF TOTAL AREA excluding grains >1000 um
SUPERGENE	5365.8	27.4	4115	37.9
INSITU	14244	72.6	6744	62.1

largest of these grains (>1000 mm) are excluded from the calculations the figure alters to 62.1% of the total being hosted by insitu oxidised pyrite.

This modification to the calculation can be considered to minimise the 'nugget effect'. Thus, between 62.1 and 72.6% of the gold is hosted in insitu oxidised pyrite, which represents primary hydrothermal gold, whilst the remainder represents the supergene enrichment component. The significance of this in economic terms is that the former is very likely to be sustained beneath the zone of supergene oxidation and enrichment, and a rapid grade cut-off below this zone is thus not expected. This is encouraging since it points to moderate and sustained gold grades in the down-dip direction on the Socach Structure.

It is evident then that gold grades from material close to the water-table on Scar Hill comprise a primary and a supergene component, with the former being dominant. It is also possible to use the textural information to predict what will happen to these components and therefore the overall gold grade at depth. Firstly, the material which is missing from the centres of pyrite pseudomorphs is volumetrically similar (by visual estimate) to the first stage supergene material introduced along fractures and grain boundaries. The introduction of this later gold bearing material in itself is a gold enrichment event. The material which has been removed in all probability contained gold so this constitutes a grade reducing process. The hollow centres to these cubes have in places been infilled by 2nd stage supergene oxides/hydroxides ,in which material no gold grains were found, and so the gold removed is not replaced during this second supergene event. Since the material being removed was constrained as being the most gold-rich whilst others were either subordinately gold-rich or barren, the overall effect at this structural level is of grade reduction. It will be the vertical extent and effectiveness of these different events that will determine whether the overall effect has a grade reducing or grade increasing effect.

The degree of leaching of oxidised pyrite is observed to decrease with topographic level, being complete on the flanks of Socach hill and on top of Scar Hill but being incomplete beside the forestry on Scar Hill where the mineralisation outcrops at the level of the water-table. It can be predicted that it will continue to decrease at depth and the grade-reducing effect will become less pronounced, until it becomes non-existant at a level corresponding to the water-table at the time of this leaching. The depth of this level is not determinable from the data available but going by the high degree of fill of some of the pseudomorphs it is unlikely that the material on Scar Hill has ever been substantially above the water-table. First-stage fracture-filling supergene oxides are observed with fresh pyrite from trench 3 so this implies that the downward percolating solutions got below the water table before depositing their dissolved contents, including gold. How far they penetrated is impossible to say but it is expected that their effect will gradually decrease with depth and the grade-increasing effect they caused will tail off. Below this zone gold grades in primary sulphides are not affected by supergene redistribution and will remain at their original hydrothermally derived levels. These levels are likely to be similar to the gold content in the in-situ oxidised pyrite on Scar Hill.

The overall vertical grade variations will depend on how these grade reducing and grade increasing events overlap. In the case of Scar Hill grade should increase downwards at shallow levels until the leached zone is left behind and should then gradually decrease as the amount of supergene material introduced by downgoing solutions decreases. This reduction in grade will span the oxidised zone and the zone of fresh pyrite invaded by oxides, beneath which grades should level out. as the effects of supergene redistribution die out. On Socach the story will be similar except that there is a much thicker and more advanced leached zone to traverse first. Grades will remain constant and poor until the structure intersects the water-table and then the story for Scar Hill will be repeated. The implication of this is that the full strike-length of the Socach Structure is prospective for gold grades similar to those obtained from trench B, but not at the level of present exposure. The down-dip intersection of the Socach structure with the water table remains an untested target except in one trench on Scar Hill, and remains highly prospective.This overall picture is illustrated on Fig. 16.

The means of redistribution of gold by supergene processes is discernible on a qualitative basis. The first clue comes from the observation that the gold hosted by fracture-filling supergene oxides often occupies the entire width of the fracture. It is difficult to imagine how a piece of particulate gold could find its way into such a position and it therefore suggests that gold movement was not on particulate form. Chemically transported gold could however nucleate in such a position and grow to completely fill any available space. This requires a means of chemical transport of gold, a subject we will come back to later in this chapter.

Towards A Model For Supergene Gold And Silver Transport On The Cushnie Prospect.

Given that petrographic evidence exists for gold and silver mobility in the supergene environment at Cushnie, some attempt should be made to understand the mechanisms and driving force behind the redistribution of these metals on the Prospect. Petrographic evidence suggests chemical transport of gold, but this still leaves several options (Emmons 1912, Bowell 1992, and Boyle 1979). The following attempt at addressing this question is is largely based on field evidence which is used to develop a model within the context of what is known to be chemically possible. As such the evidence is circumstantial and the model is tentative and qualitative at best. Attempts at generating less circumstantial evidence failed due to the unsuitability of the materials available for study, as described later. Also, quantitative constraint on the various chemical parameters mentioned in the model, such as pH, Eh, chloride content and manganese content of groundwaters is not a practical option at the present stage in the work. The development of the model is however defensible as it forms the best working hypothesis currently available, with the only alternative being to ignore the issue altogether. The approach adopted by Webster and Mann (1984) who considered the overall effects of individual factors such as climate and host geology will be used here in formulating a model for the supergene alteration observed at Cushnie. The relevant individual factors will be described first, and a synthesis of the overall process presented later.

Composition Of The Gold Grains

Gold/silver ratios of selected gold grains were determined by EDX analysis on a Cambridge Instruments Stereoscan F360 SEM, using as standards pure gold and silver. The average grain size of 16 x 12 mm was close to the reliable instrumental resolution; despite the electron beam width of 1mm, wandering of this beam over an 8 mm radius during analysis made this latter resolution the one that determined the overall instrumental spatial accuracy. In most grains therefore only one measurement was possible and this was made as close to the centre of the grain as possible (to avoid interference in the result as a consequence of dilution by host iron oxides/hydroxides) and the result taken as the bulkcomposition of the grain.The results are quoted in terms of wt% on the right-hand side of Table 5. Wandering of the beam across the gold grains and outwith the grains resulted in a variable degree of interference from host haematite/goethite being recorded in these analyses. Hence in terms of wt%, the total for gold and silver ranges between 74 and 88.7% for insitu grains and between 74 and 88.7% for exotic grains, rather than the expected 100%. This interference will result in some inaccuracy in the calculations of mole% (or the equivalent atom%), but this inaccuracy will be similar for both sets of grains so will not affect the final conclusion of this part of the exercise.

Data for gold and silver contents are shown on Table 5 and are analysed statistically on Table 6 after grouping according to the origin of the host iron oxides/hydroxides. Noticeable during analysis, and statistically significant, is the difference in silver and gold contents between gold grains hosted by insitu oxidised pyrite and those hosted by fracture-lining/porosity infilling oxides/hydroxides of exotic supergene origin, illustrated on Fig. 31.. The former show consistently lower weight percentages of silver, with no overlap of the silver contents of the two populations. On average the difference amounts to 10.7 wt%, with a range of 2 to 12 wt% for insitu hosted gold and 14 to 24 wt% for supergene hosted gold. Also apparent is the lack of significant, consistent within-grain variability of silver content at the resolution studied; differences between central and outer parts of grains are up to 7wt% silver and do not show any consistent pattern; grain rims can be relatively depleted or enriched in silver. The magnitude of these within-grain variations is also substantially smaller than the magnitudes of both the inter-grain variations and the inter-grain-population variations.

Data for gold and silver contents are shown on Table 5 and are analysed statistically on Table 6 after grouping according to the origin of the host iron oxides/hydroxides. Noticeable during analysis, and statistically significant, is the difference in silver and gold contents between gold grains hosted by insitu oxidised pyrite and those hosted by fracture-lining/porosity infilling oxides/hydroxides of exotic supergene origin, illustrated on Fig.

TABLE 5 : Gold And Silver Contents Of Gold Grains From The Socach Structure At Scar Hill, Cushnie Prospect

A) Grains Hosted By Insitu Oxidised Pyrite

Au Mole%	Ag Mole%	TOTAL Mole%	Au Wt%	Ag Wt%	TOTAL Wt%	SHAPE	SIZE (um)
87.8	12.2	100	76.4	6.3	82.7	rounded	50x40
86.2	13.8	100	80.3	7.6	87.9	rounded	50x40
87.3	12.7	100	77.6	6.7	84.3	rounded	50x40
93.8	6.2	100	79.8	3.1	82.9	rounded	10diameter
82.2	17.8	100	74.7	9.6	84.3	elongate	20x10
80.5	19.5	100	72.2	10.2	82.4	elongate	20x10
89.8	10.2	100	82.8	5.6	88.4	equant	20x20
82.1	17.9	100	71.7	9.3	81.0	rounded	5diameter
81.6	18.4	100	76.7	9.4	86.1	rounded	75x40
87.3	12.6	100	80.9	6.4	87.3	equant	50x40
78.7	21.3	100	76.2	11.3	87.5	rounded	45diameter
77.7	22.3	100	74.5	11.7	86.3	rounded	45diameter
93.3	6.6	99.9	84.5	3.3	87.8	elongate	20x10
77.2	22.8	100	70.7	11.4	82.1	angular	30x2

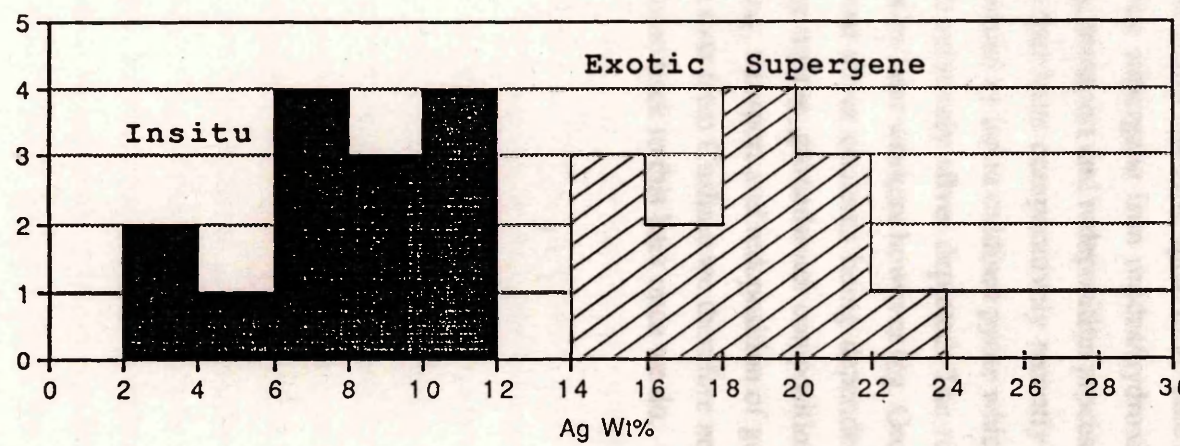
B) Grains Hosted By Fracture Lining And Porosity Infilling Iron Oxides/Hydroxides Of Exotic Supergene Origin.

Au Mole%	Ag Mole%	TOTAL Mole%	Au Wt%	Ag Wt%	Total Wt%	SHAPE	SIZE (um)
63.0	36.9	99.9	61.4	19.76	81.24	rounded	10diameter
61.7	38.3	100	61.4	20.8	82.2	rounded	10diameter
71.0	29.0	100	69.0	15.4	84.4	elongate	20x10
70.3	29.7	100	67.7	15.7	83.4	rounded	10x7.5
66.9	33.0	99.9	58.3	15.7	74.0	equant	10x10
64.4	35.6	100	63.7	19.3	83.0	angular	15x10
69	31	100	66.6	17.8	84.4	equant	30x30
70.6	29.4	100	71.1	17.6	88.7	equant	30x30
63.8	36.2	100	60.4	20.4	80.8	elongate	5x2.5
68.8	31.2	100	67.5	18.2	85.7	elongate	30x10
67.3	32.7	100	65.4	18.9	84.3	elongate	30x10
62.3	37.7	100	60.9	21.9	82.8	rounded	10diameter
61.6	38.4	100	59.2	22.0	81.2	rounded	10diameter

TABLE 6 :Summary Statistics Of Gold And Silver Contents Of Gold Grains From The Socach Structure At Scar Hill, Cushnie Prospect.

VARIABLE	N	MINIMUM	MAXIMUM	MEDIAN	MEAN	VARIANCE	STD. DEVTN.	SKEWNESS	KURTOSIS	
Mole% Au	13	61.6	71.0	66.9	66.2	12.6	3.6	0.0	-1.8	A) Grains Hosted By Insitu Oxidised Pyrite
Mole% Ag	13	29	38.4	33.0	33.8	12.6	3.5	0.0	-1.8	
Wt% Au	13	58.3	71.1	63.7	64.0	16.8	4.1	0.2	-1.5	
Wt% Ag	13	15.4	22.0	18.9	18.7	5.1	2.3	-0.1	-1.4	
Mole% Au	14	77.2	93.8	84.2	84.7	30.0	5.5	0.2	-1.4	B) Grains Hosted By Fracture Lining And Porosity Infilling Iron Oxides/Hydroxides Of Exotic Supergene Origin.
Mole% Ag	14	16.2	22.8	15.8	15.3	30.1	5.5	-0.2	-1.4	
Wt% Au	14	70.7	84.5	13.8	77.1	17.5	4.2	0.1	-1.2	
Wt% Ag	14	3.1	11.7	8.4	8.0	8.2	2.9	-0.3	-1.3	

FIG 31 : Frequency Histogram Of Silver Contents Of Gold Grains From The Socach Structure,



31.. The former show consistently lower weight percentages of silver, with no overlap of the silver contents of the two populations. On average the difference amounts to 10.7 wt%, with a range of 2 to 12 wt% for insitu hosted gold and 14 to 24 wt% for supergene hosted gold.
Also apparent is the lack of significant, consistent within-grain variability of silver content at the resolution studied; differences between central and outer parts of grains are up to 7wt% silver and do not show any consistent pattern; grain rims can be relatively depleted or enriched in silver. The magnitude of these within-grain variations is also substantially smaller than the magnitudes of both the inter-grain variations and the inter-grain-population variations.

A commonly used rule of thumb states that the longer a gold/silver grain spends in the supergene environment the more depleted in silver it will become, due to the generally greater solubility of silver in this environment (eg.Hallbauer and Utter 1987). The data presented above are at odds with this in that the gold grains that have spent more time in the supergene environment (ie. those hosted by exotic supergene iron oxides/hydroxides), having gone through the whole oxidation, leaching, transport and redeposition process, are relatively richer in silver. In addition, the grains that have comparatively recently been introduced into the supergene environment, those hosted by insitu oxidised pyrite which has not gone through further supergene processes, are relatively silver depleted. The rule of thumb has been shown to be an over-generalisation by later workers however (eg. Groen et al 1990), with the actual configuration of gold and silver contents being dependent on specific local circumstances such as the weathering regime, groundwater composition and host geology which more directly affect the leaching, transport and redeposition of gold in the supergene environment. In order to explain the data from Cushnie we therefore need to know more about these other factors, and we will come back to this later once we do.

The Supergene Weathering Regime; Evidence From Soil Developments At Cushnie

Assessment of the weathering regime responsible for the supergene alteration of the gold mineralisation presents a problematic choice. The intensity and vertical extent of the alteration are quite unique in Scotland; no other mineralised bodies have been reported that show anywhere close to the 25 vertical metres of leaching and the indeterminately thick oxidised zone seen on the Socach Structure. This leads to the conclusion that the mineralisation has been subjected to an unusual weathering regime at some time. North-east Scotland is noted for its well preserved Tertiary weathering mantles (eg. Hall 1984) The effect of this weathering is commonly described as including the complete disintegration of certain lithologies such as dolerite dykes to a compact coarse sand. This is very reminiscent of the situation encountered in trench 16 on Scar Hill where 5 vertical metres of such doleritic material were excavated with still no sign of coherent bedrock. Despite the weathering the material remained recognisable as a dolerite by the ghost blocky structure and the 5mm scale mottling representing ghost phenocrysts. Host sub-gneissic garnet schists and psammites were relatively fresh and coherent bedrock was encountered beneath 1-1.5 m of soil, peat and regolith, illustrating the lithology-specific nature of this weathering.

Somewhat similar to this are the zones of pink and yellow clay encountered in trenches B and 3. During mapping of the trenches these were assigned a hydrothermally altered dyke origin in view of their narrow widths and apparent linear configuration. In addition, soil geochemical surveys commonly showed gold anomalies of the order of 50-200 ppb which on trenching were found to be associated with these materials, thus adding weight to the idea that they were a product of auriferous hydrothermalism. The alternative idea, that they represent confined zones of intense weathering, perhaps Tertiary in age, was more plausible and was also consistent with the degree of supergene alteration of the gold mineralisation however, so the actual origin of these materials required further investigation.

Thin sections were prepared from the pink and yellow clays in order to search for relict or derived textures that would pin down the origin of the deposits. Relict igneous textures (eg. ghost phenocrysts or trachytic texture) would point to a precursor igneous rock, and the alteration of the various phases should be of similar type (ie. sericitic with iron staining) to that encountered within the Socach structure if the clays were the products of hydrothermal alteration. In contrast intense weathering would replace any original texture with fabrics associated with soils, and alteration of constituent minerals would be distinguishable from sericitic hydrothermal alteration. Examination of the sections showed aspectrum of fabrics whose end-members are taken to represent primary, insitu rock textures and completely derived soil fabrics. In dealing with such materials, the most appropriate descriptive terminology comes from the literature on soil science, eg. Brewer 1964, and this will be used here for both description and interpretation of these materials. They are described here in roughly the order of increasing decomposition.

PLATE 11; PHOTOMICROGRAPHS OF THE SOIL TEXTURES IN PINK/YELLOW CLAYS OF THE CUSHNIE PROSPECT

A-D) SKELETAL AND PLASMA FABRICS

A) Corroded quartz skeletal grains supported by a bright clay plasma with weak unistrial fabric. Sample T627, Crossed Polars.

B) Corroded quartz grains set in a clay plasma with lattisepic overall texture. Also poorly developed, localised skelsepic texture around edges of large quartz grain. Sample T627, Crossed Polars.

C,D) Corroded quartz skeletal fragments set in a bright clay plasma with lattisepic overall texture. Extensive void development with occasional vosepic plasma fabric on their margins. Note also preferential iron oxide cementation of plasma close to voids. Sample T3YC, Plane Polarised Light and Crossed Polars respectively.

E-I) BIOTURBATION AND SESQUIOXIDE CEMENTATION TEXTURES.

E) Sesquioxide nodule formation by localised haematite cementation of plasma. Note also void and cutan development in plasma. Sample T622, Plane Polarised Light.

F) Void development and localised haematite cementation around the margins of the voids forming opaque and reflective concentrations. Sample T622, Plane Polarised Light.

G) Sample T37 Plane Polarised Light; Haematite cemented burrow-like feature in asepic plasma. Note curvilinear textures perpendicular to the axis of the burrow, reminiscent of the internal fabric of skolithos burrows.

H) Sample T37 Plane Polarised Light; Haematite cemented zone within asepic plasma showing curvilinear internal zonation reminiscent of those seen in Skolithos burrows. Interpretted as a short section of an infilled escape burrow within a soil.

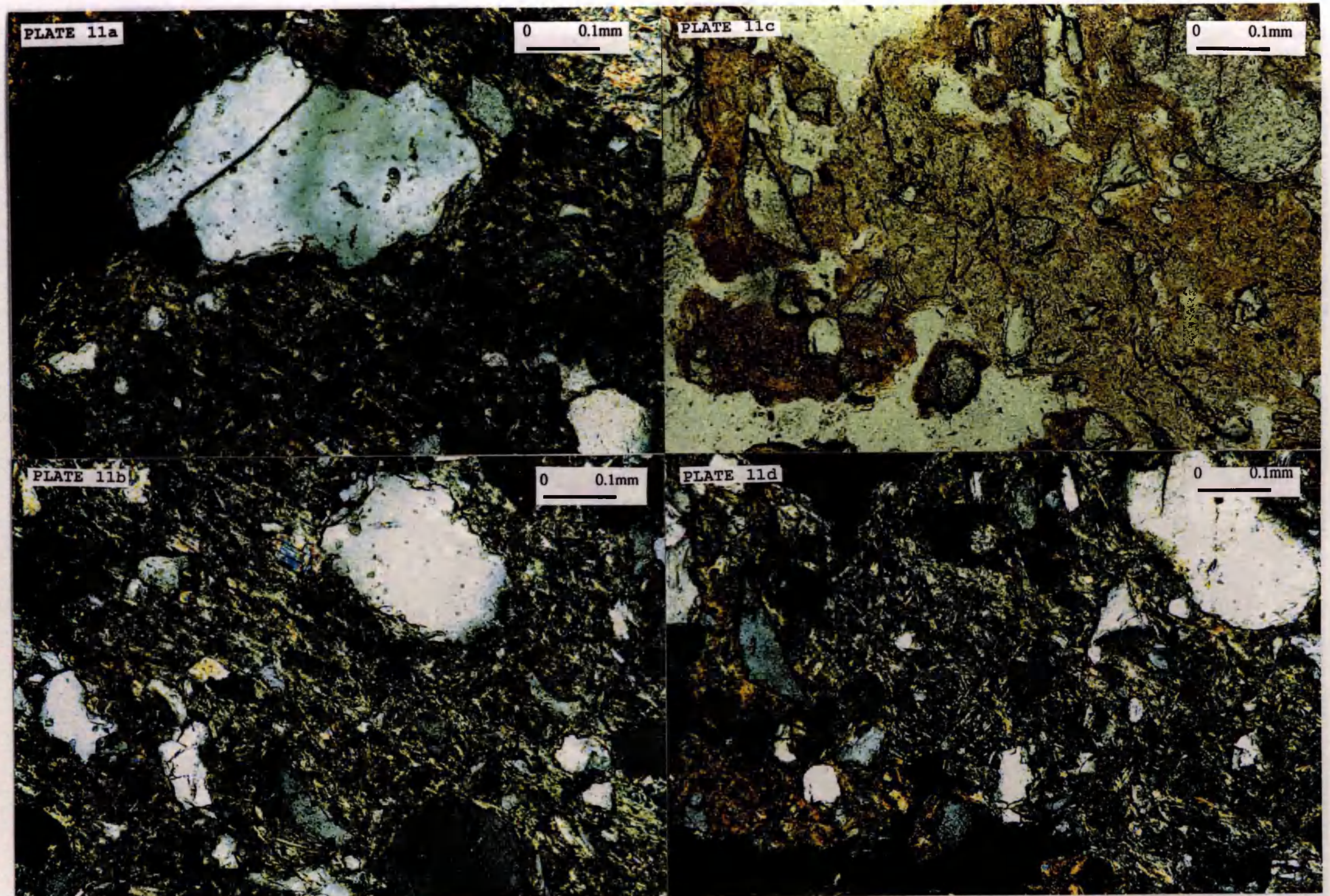


PLATE 11a
0 0.1mm
PLATE 11c
0 0.1mm
PLATE 11b
0 0.1mm
PLATE 11d
0 0.1mm

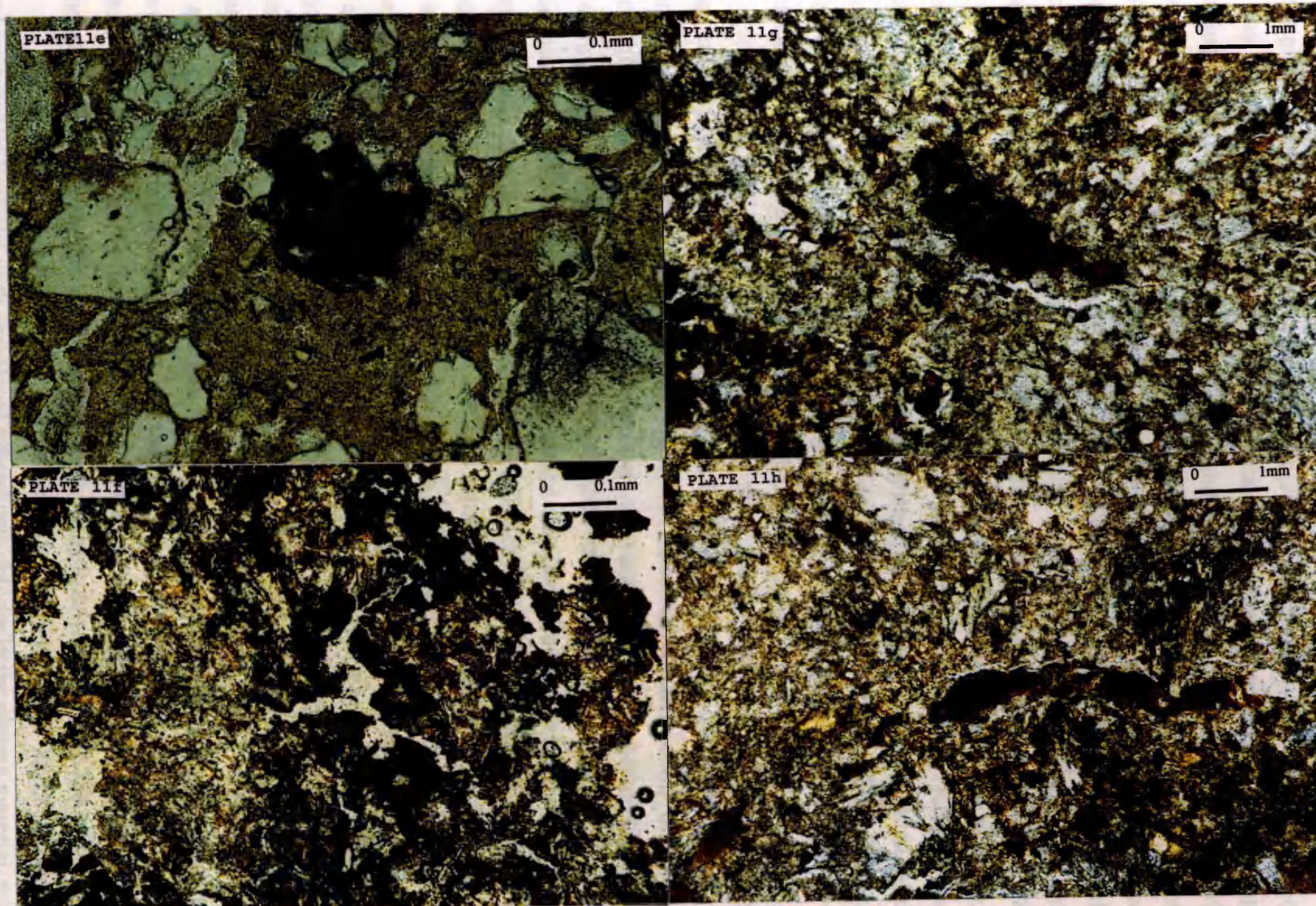


PLATE11e
0 0.1mm
PLATE 11g
0 1mm
PLATE 11f
0 0.1mm
PLATE 11h
0 1mm

Section T622, prepared from the yellow clay found in trench 6 comprised a very weathered but still recognisable garnet schist. Preservation of schistosity, defined by alignment of muscovite flakes, showed the material to be insitu rather than colluvial. Garnets were the most weathered phase, showing complete decomposition to haematite with development of botryoidal textures, and partial leaching of the iron oxide. Elsewhere, iron oxides are largely restricted to porosity between mica flakes. In fresh garnet schists such porosity does not exist and it would appear that swelling of micas during weathering creates the porosity which is subsequently infilled with iron oxides/hydroxides formed by the breakdown of other phases. Section T627 was sampled from close to T622 and shows a complete absence of any relict metamorphic texture. In gross terms it comprised a quartz clast assemblage floating in a dark mottled clay matrix. Skeletal materials comprise a highly corroded, poorly sorted (0.1-1 mm) angular quartz of slightly strained to highly strained nature. This formed 25-30 vol% (by visual estimation) of the slide and was supported by a pale yellow/brown (PPL) non-pleochroic clay matrix. Under cross-polars the s-matrix showed an overall sub-lattisepic fabric withskelsepic fabric developed around occasional quartz grains, and occasional weakly developed unistrial fabric in areas where grain density was greatest. The insipient development of sesquioxide nodules is indicated by local concentrations up to 2 mm across of iron oxides/hydroxides cementing . cementing the plasma. The fabrics in this section are not in any way reminiscent of relict igneous textures, and the dark mottled nature of the clay matrix is dissimilar to the high interference colours and general high brightness seen in sericitically altered specimens from the Socach structure. They are however consistent with the operation of soil forming processes.

Sections T36 and T37 were prepared from the intense pink and orange clays respectively from trench 3. Both show complete breakdown of any precursor fabric with no ghost igneous or metamorphic textures visible.In T36 the skeletal material comprised poorly sorted (0.1-1 mm) angular quartz in all states of strain and rare, highly altered plagioclase and muscovite laths. T37 was similar with a skeletal composition of quartz and mica. Both were matrix supported, and this matrix comprised a randomly mottled very fine clay, ie. an asepic plasmic fabric. Sesquioxide nodule formation is confined to very small (<100 mm) opaque blotches of deep red haematite, and some cubic examples in T36 suggest the development of pyrite (or alternatively, salt) during soil formation and subsequent pseudomorphing by haematite. T37 shows evidence of bioturbation in the form of haematitic pedotubules showing the characteristic curved infill textures typical of these features. These are diagnostic of the operation of surface processes during the formation of these materials. Section T3YC is from the yellow clay in trench 3 and has a similar asepic plasmic fabric to the others from this trench but with no skeletal material. Nodule formation is most complete in this sample with sesquioxides becoming opaque and reflective. Development of voids in the plasma is apparent, but without the formation of a vosepic fabric, and iron oxides/hydroxides are most crystalline along the margins of these voids where they develop cocentric botryoidal fabrics growing in towards the void space.

Mineralogical analysis of the cohesive clay materials by XRD showed a predominance of kaolinite with occasional subordinate chlorite in the plasma material, with quartz forming the skeletal fraction. It has been surmised (Lasalle et al 1985) that kaolinite in saprolitic profiles is the result of either very long weathering cycles or weathering under warm and humid, probably tropical conditions. Further, they suggest, using examples from Quebec, that interglacial periods would not provide the necessary conditions for the formation of deep saprolite profiles dominated by kaolinite and gibbsite clay fractions, and that preglacial, probably Tertiary, weathering needs to be invoked for this purpose. By similar reasoning it can be argued that the mineralogy of the cohesive soil profiles at Cushnie is the result of deep weathering during Tertiary times, when the climate in Scotland was warm, humid and tropical in character (Anderton et al 1985).

Significant evidence exists then that the wholesale alteration observed on the Cushnie prospect not directly spatially related to gold mineralisation is the result of intense weathering and soil formation. By analogy with other documented examples of such weathering in NE Scotland(eg. Hall 1991) and Quebec (Lassale et al 1985) these soils are here assigned a Tertiary age. Such weathering is known to be capable of remobilising gold and concentrating it in deeply weathered soils and saprolites (eg. Bowell 1992). Thus, the gold enrichments found in the soil materials could be the result of lateral supergene redistribution from gold bearing structures on the prospect and re-concentration in these soils. This would be directly analogous to the situation described by Bowell (1992) at the Ashanti mine, which is currently undergoing supergene alteration under conditions not dissimilar to those proposed for the Cushnie prospect during Tertiary times. Thus, leaching and oxidation of bedrock gold concentrations, formation of deeply weathered soils and wide secondary dispersion of gold therein are all consistent with the idea that the Socach deposit and its host rocks have undergone intense supergene alteration during Tertiary times.

A single inconsistency upsets the idea that weathering of a Tertiary age was solely responsible for the oxidation and leaching of the Socach Structure however. The fact that the present-day water-table separates the oxidised and leached zones is evidence that the present climatic regime is responsible for the supergene alteration of mineralisation. The present climate has not affected sulphide mineralisation in this way elsewhere in Scotland (eg. at Cononish the discovery outcrop occurs high on a hill, well above the water-table and contains fresh sulphides showing very minor surface oxidation) and it has to be concluded that it is incapable of doing so at least in the post-glacial time-scale. Tertiary weathering is thus most likely to be responsible for the supergene effects seen at Cushnie This would also explain the rarity of such alteration in Scotland in that more intense glacial erosion has elsewhere removed the Tertiary mantle whereas the relatively benign glacial activity characteristic of the northeast has allowed its preservation. The fluctuating behaviour of the water-table during oxidation and leaching described earlier has probably resulted in the positions of the Tertiary and Recent water-tables coinciding.

The Tertiary climate in Britain was characterised by warm, humid, tropical conditions, evidenced by the development of thick lateritic deposits between Tertiary lava flows on Skye and the fact that lotus grew in the caldera lakes of Skye (Anderton et al 1985). This is consistent with the extreme decomposition of intrusive material on parts of the Cushnie prospect and also with the development of thick nodular clay soils. The high rainfall and consequently voluminous groundwater flow associated with such a climate is liable to be important in the supergene leaching of gold mineralisation and will be considered again later.

The Role Of The Mineralisation, Gangue and Host Rocks In The Supergene Process

The nature of the mineralisation itself and of the host geology exert an influence on the effectiveness and type of supergene processes by determining and controlling the chemistry of the fluids involved. Highly acidic fluids are known to be conducive to the solution of gold and silver, and the simplest way of producing such low pH is by generation of sulphuric acid during sulphide oxidation. In mineralisation where the gold and silver are exclusively hosted by pyrite, as at Cushnie (where it has since been oxidised) this process will be locally concentrated within pyrite crystals, ie. around the gold grains. Dissolution of gold in supergene fluids during oxidation is therefore not difficult to conceive, given the presence of a suitable complexing agent.

The reactivity of the gangue minerals or host rocks to these acidic fluids influences how long the gold and silver will remain in solution. The presence of (especially) carbonate in either is known to rapidly neutralise the solutions causing re-precipitation of the precious metals (Emmons 1912). This results in spectacularly rich but vertically discontinuous gossans overlying much lower grade sulphide mineralisation. This appears to have occurred at Colby Gold's Calliachar prospect in Perthshire, Scotland, where shallow bonanzas are associated with intense supergene alteration and a calcite gangue. Photographs of gold-rich material containing much carbonate, and the rapid vertical grade cut-off on the prospect Pattrick 1991) are indicative of extremely effective gold precipitation from downgoing supergene fluids by the carbonate gangue. Such is the effectiveness of this as a gold precipitation mechanism that very little of the dissolved gold penetrates to any depth during migration in the supergene environment, thus forming shallow bonanzas. At Cushnie, carbonate has not been recorded on XRD or observed petrographically in gangue, alteration or host rocks. Such sudden vertical grade cut-offs are therefore not to be expected here, a conclusion backed up by the earlier one that 60-70% of the grade on the Socach Structure is due to primary hydrothermal gold, with the remainder being due to supergene enrichment. The mineralogy of the host rocks to the Socach Structure (quartz + muscovite + garnet + chlorite + feldspar) do not include any significantly reactive phases, so the rocks will be relatively benign in this respect. In addition, the sericitic alteration envelope around the mineralisation constitutes an unreactive lithology and will render these host rocks even more benign in this respect. The mineralisation itself is therefore conducive to the dissolution of the contained precious metals during oxidation while the host rock and alteration minerals and the gangue minerals are not effective reprecipitants of gold and silver. The latter must be controlled by other factors.

A striking feature of the Socach Structure where it was exposed in trenches B and 3 at and just above the water-table respectively was the presence of intense blue/black surficial manganese staining on the footwall to the mineralised structure. This extended up to 5 m away from the shear zone itself and both the coherent bedrock and the overlying regolith were stained. The staining was found to be non-pervasive except in zones of particularly fractured and permeable bedrock. In this respect it contrasts with the pervasive iron staining observed in mineralised material at this structural level and is therefore regarded as a supergene rather than a hydrothermal effect. At higher structural levels this wholesale manganese staining was not apparent, but localised staining was present along joints exposed on trench walls. Also, originally sampled manganiferous material lining late joints cutting the discovery outcrop of the Socach Structure gave gold grades of up to 2.5ppm, exceeding those from the leached host. Thus gold grades at this structural level are restricted to manganiferous material while at lower levels intense surficial manganese staining occurs in the same vicinity as the jump in gold grades at the water-table. The coincidence points to a link between gold and manganese mobilities in the supergene environment.

A direct parallel can be drawn between the origin of this manganese staining and the distribution of the pervasive pink iron staining observed to be better developed at lower topographic levels.Hydrothermal fluids were iron-bearing - hence the deposition of pyrite. It is however difficult to reconcile the precipitation of pyrite with the deposition of iron in its oxidised form immediately adjacent to this pyrite. The contrasting chemical states of the iron implies that they were precipitated by different processes. This leaves a supergene origin for the pervasive iron staining as the most likely, an idea supported by its topographic distribution. Leaching of iron above the water table and its reprecipitation close to the water table, with fluid flow focussed along the Socach Structure, provide an explanation for the iron staining seen on the structure close to the water table. The contrast between the pervasive nature of the iron staining and the superficial nature of the manganese staining remain unexplained however.

Gold enrichments at the level of the water-table on the Socach Structure are demonstrably the product of gold remobilisation in the supergene environment. The coincidence of gold and iron and manganese oxide enrichments in this context implies that all three metals have been mobilised in the supergene environment. Nicholson (1983, 1987) suggests that deep weathering of the Dalradian metamorphic pile caused iron and manganese remobilisation at the Lecht deposit. Subsequent re-precipitation in near-surface breccias formed iron and manganese oxide cemented breccias which have been mined for both metals. A similar remobilisation of manganese and iron from the sub-gneissic garnet schist host rocks at Cushnie can be invoked as a source of these metals in the enrichments described on the Socach Structure. In this respect it is interesting to investigate another conspicuous field observation concerning the weathering state of the garnets in these schists. The garnets in this material appear to have suffered a similar fate to the pyrite in the Socach Structure. In thin-sections prepared from trenches B and 3 the garnets are seen to be partially to completely oxidised to haematite which shows well developed micro-botryoidal textures mimicking textures in the precursor garnet. At higher topographic levels, loose boulders and outcrops of garnet schist found during float-mapping commonly showed complete leaching of the garnets, leaving roughly spherical negative pseudomorphs within a schistose host.(see Plate 12). These are directly comparable to the cubic negative pseudomorphs after pyrite seen in mineralised material at such topographic levels. In fresh samples, chemical analyses of these garnets by SEM showed them to be manganese as well as iron bearing. It is considered that the same weathering regime invoked to oxidise and leach the mineralised structures on the Cushnie prospect also weathered and leached these manganiferous garnets. This could enrich the groundwaters in manganese and iron, and thus provide a potential source of these metals in the enrichments described.

Further evidence was sought that the invoked source and sink for manganese were directly related. Nicholson (1992) reviews mineralogical and geochemical means of distinguishing the origin of manganese oxides. He also mentions (Nicholson 1992) that the mineral lithiophorite forms as a product of weathering manganiferous garnets. An attempt was made to apply the methodology of Nicholson (1992) to determine if the manganese oxide mineralogy was consistent with the supergene terrestrial nature of the Socach mineralisation, and also to confirm (by identifying lithiophorite in the local manganese budget) the intuitive notion that the source of the manganese in the staining was the local garnet schists. Unfortunately the materials available for this study, whilst being intensely manganese stained were not conducive to mineralogical analysis. Manganese oxides are characteristically difficult to characterise due to their typically poor crystallinity. Also, the staining comprised a microscopically thin coating of manganese oxides of very low crystallinity. X-ray diffractograms showed a higher than normal background level, suggestive of the presence of manganese oxides, but interference from other constituent minerals and low oxide crystallinity prevented identification of distinctive peaks and made identification impossible. Interference was a result of the extreme thin-ness of the manganiferous coating which prevented its sampling in anything close to pure form (ie. without heavy contamination by the material beneath this coat), so diffractograms became crowded with quartz, sericite and kaolin peaks from the rock itself. Low crystallinity was also a result of the thin coating. The materials present at Cushnie are therefore not conducive to simple mineralogical study and characterisation by such means, and confirmation of the source of supergene manganese was not achieved.To summarise the evidence then before going on to attempt to synthesize the supergene processes responsible for gold and silver redistribution on the Socach Structure, the following statements can be made;

1) Gold hosted by insitu oxidised pyrite has greater fine-ness than that hosted by exotic fracture and porosity infilling iron oxides/hydroxides of supergene origin. In qualification however, the former do not necessarily reflect the gold/silver ratios of primary hydrothermal gold since some modification has probably occurred during oxidation. Information on this starting-point to the supergene processes is unavailable at the present time due to the lack of exposure of the primary sulphide zone.

2) 60-70% of the gold grades at the level of the water-table on Scar Hill is attributable to primary hydrothermal gold, with the remainder constituting the supergene enrichment component.

3)Weathering of pyritic mineralisation and garnet schist host rocks provided acidity and unusual manganese and iron concentrations in downward percolating supergene fluids.

4)Within the time scale of downward percolation of these supergene fluids, gangue minerals and host rocks were inert and provided little opportunity for sudden neutralising of the fluids and subsequent rapid gold re-precipitation. Gold therefore remained relatively mobile in the downward percolating fluids.

5) The weathering regime responsible for deep weathering and leaching of the deposit and its host rocks was characterised by warm humid tropical conditions which would have resulted in intense weathering and voluminous groundwater flow.

6)Late brittle iron oxide/hydroxide lined fractures associated with hydrothermal processes, and post-hydrothermal jointing within the shear zone provided the permeability necessary for passage of supergene fluids down-dip on the Socach structure.

7) Intense surficial manganese staining in the footwall to the Socach Structure is associated with a jump in gold grades at the level of the water table.Within the leached zone, the highest gold grades were returned from samples containing manganiferous wad materials lining late joints cutting the Socach Structure. Both are considered as supergene effects and point to a direct link between manganese and gold mobilities in the supergene environment. The geographical distribution of pervasive pink iron staining is seen to be very similar to that of the surficial manganese enrichment.

PLATE 12; PHOTOMICROGRAPHS OF THE WEATHERING STATE OF GARNETS WITHIN MUSCOVITE GARNET SCHISTS OF THE CUSHNIE PROSPECT

A) Largely in-place but fractured garnet with narrow haematised zones along fractures. Note chloritised margin and relatively blocky nature of garnet. Plane Polarised Light.

B) Advanced alteration of garnet to haematite with semi-blocky garnet core cut by wide haematised fractures giving way to massive haematite away from the core and partially leached haematite close to the edge of the grain. Notice also intact quartz plus muscovite host and inclusions of this material within the garnet. Crossed Polar view.

C) Advanced leaching of garnet showing large central and several satellitic voids separated by a skeletal framework of fracture-filling haematite and inclusions of host schist. Plane Polarised Light.


PLATE 12a
0 0.2mm

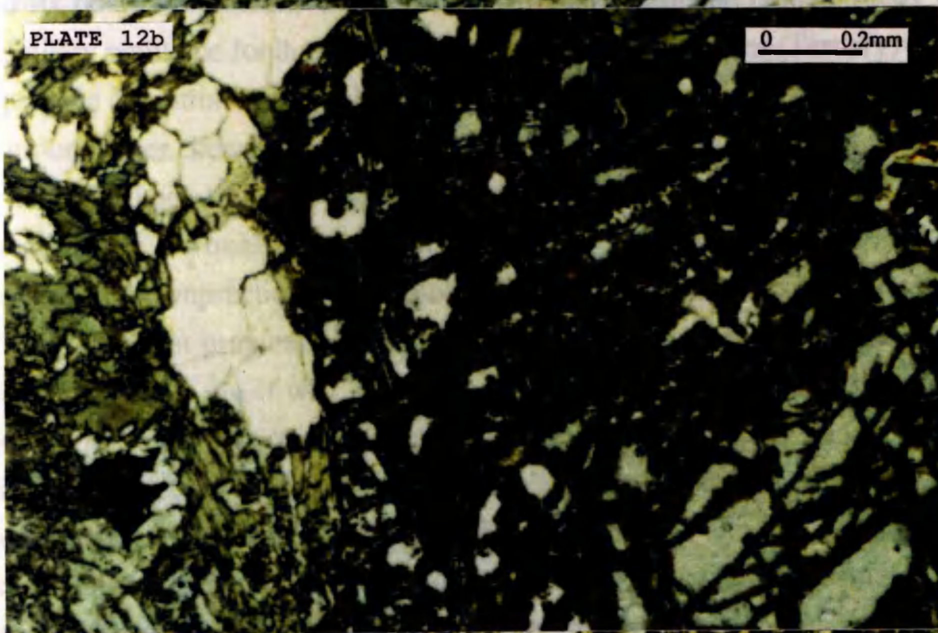


PLATE 12b
0 0.2mm

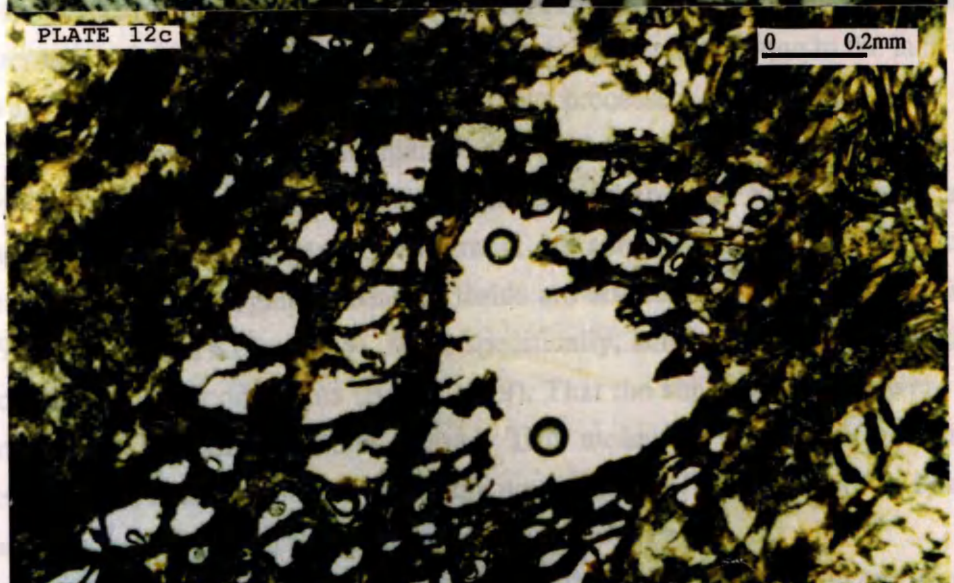


PLATE 12c
0 0.2mm

SYNTHESIS

Emmons (1912) takes an empirical and pragmatic approach to the subject of supergene enrichment of gold deposits without getting too bogged down in the intricacies of the chemistry and the quantitative analysis of the supergene processes he invokes. This is regarded here as a useful and appropriate approach to the study of mineralisation as poorly exposed and little studied as that on the Cushnie prospect, and is therefore adopted in this synthesis. The incomplete record of the supergene processes, caused by the almost complete lack of exposure of the primary sulphide zone (only one hand-specimen hosting pyrite was recovered from trenches and even it displayed oxidation effects along fractures and on the outsides of grain clusters) means that we have very little information on the true starting point of the supergene processes. More specifically, no gold grains were observed in fresh pyrite, so no information is available on the starting point of the supergene process in terms of gold morphologies, grain sizes or compositions. The poor exposure of the mineralisation and its host-rocks means that quantitative analysis of the contributions of both to fluid chemistry would be foolhardy. In addition, the fact that ancient (Tertiary) rather than present supergene conditions are invoked as the main agent of alteration means that parameters such as groundwater chemistry and flow rates relevant to supergene processes are not measurable in the field. Lack of permeability data on the host rocks and mineralised structure are also unobtainable. A qualitative appraisal of the supergene processes is defensible on the grounds of the impracticality and foolhardiness of the quantitative approach.

A similar pragmatic and qualitative approach to that used by Eamons will therefore be adopted here, but it will be checked for consistency with the ideas presented in more modern literature where the chemistry of the processes is better understood. The analysis will concentrate on the role of manganese in the transportation and precipitation of gold in the supergene environment since specific field evidence exists for a direct link between Au and Mn mobilities. Extensive literature exists on several alternative means of gold transportation and deposition in the supergene environment; the existence of these alternatives is acknowledged but not considered in detail here due to the lack of specific field evidence for the operation of these alternative processes

The coincidence of manganese and gold enrichments on the Socach Structure at the level of the water table and the implication taken from this that gold and manganese mobilities in the supergene environment are somehow linked can be reconciled by the knowledge that manganese bearing fluids are effective transporters of gold (eg. Emmons 1912, Cloke and Kelly 1964). More specifically, acid manganiferous fluids can transport gold as chloride complexes (Boyle 1979). That the supergene fluids were manganiferous and acidic has already been argued. This means of supergene gold mobilisation is considered the most probable one in the present context on account of its compatibility, thus far, with the field observations.

Thus, it is envisaged, gold was mobilised in the supergene environment in acidic, manganiferous fluids. pH is considered by Emmons (1912)to be the most important factor controlling the solubility of manganese and gold in such fluids, such that both can be carried effectively at low pH but loss of acidity will cause both to precipitate. The highest acidity in the present context will be achieved close to the Socach Structure itself as a result of the weathering of sulphides, and it therefore follows that this zone will show enhanced gold and manganese mobility. Where a drop in acidity occurs the gold and manganese will be reprecipitated. The most likely mechanism for such a pH change, given the unreactive nature of the host rocks and gangue minerals in this respect, will be by dilution of fluids as they reach the water-table. Thus, enhanced acidity and hence metal mobility at high levels on the Socach Structure and subsequent loss of this acidity and metal mobility through dilution at the water table formed localised and striking manganese enrichments and increased gold grades at the intersection of the Socach Structure with the water table. The downward movement of the metals in supergene fluids would have been incremental; metals will be repeatedly dissolved and reprecipitated on their way down, and only when conditions become permanently less acidic will gold and manganese be fixed permanently. This finally occurs at the water table, whilst the incremental stages beforehand give rise to the gold bearing manganiferous/ferrugenous wad materials coating late joints in the Socach Structure at higher levels.

Boyle (1979) also points out an alternative role of manganese in the precipitation of gold from supergene fluids. Gelatinous manganese oxides can absorb and co-precipitate gold. Thus the loss of pH of the supergene fluids on dilution at the water table, resulting in the precipitation of manganese oxides can result in the co-precipitaion of gold, producing the association between gold grade and manganese enrichment seen on the Socach Structure. Again this process can occur incrementally, through repeated dissolution and re-precipitation of gold and manganese resulting in localised gold enriched manganiferous wad materials lining late joints cutting the Socach Structure within the leached zone.This ability of manganese to promote the dissolution and precipitation of gold is also possessed by iron, though to a lesser degree (Boyle 1979). A similar argument to the above can be presented linking the precipitation of iron oxides to the precipitation of gold. Where present however, the effect of manganese in this respect overwhelms that of iron (Boyle 1979), so the remainder of the argument will concentrate on the role of manganese in this process.

Emmons describes the solution and precipitation mechanisms of gold and silver separately and points out the overall similarity in their behaviour in the supergene environment. In particular, he remarks;

"If the deposits contain manganese, gold may be carried downward and be redeposited below. Thus there may be a zone at and near the surface in which silver is concentrated, whereas gold will become increasingly greater in quantity with increase in depth, as at the Exposed Treasure mine, near Mojave, Cal. At Creede, Colo. in the Amethyst vein, where manganese is abundant and carbonates are rare, silver is most highly concentrated a short distance below the surface. Although the chloride in this deposit is not so important as native silver, gold is nevertheless found in greatest concentration below the zone where silver is most abundant."

The inference is that in these particular circumstances, silver precipitates out from downgoing supergene fluids more readily than gold. This is particularly relevant to the situation on the Socach Structure where inert wallrocks and gangue and manganese rich fluids are envisaged as encouraging gold and silver to stay in solution and be transported some distance in the supergene environment. It provides a mechanism which can be invoked to explain the lower fine-ness of the gold grains that have been precipitated from downgoing supergene fluids compared with those that have remained insitu.

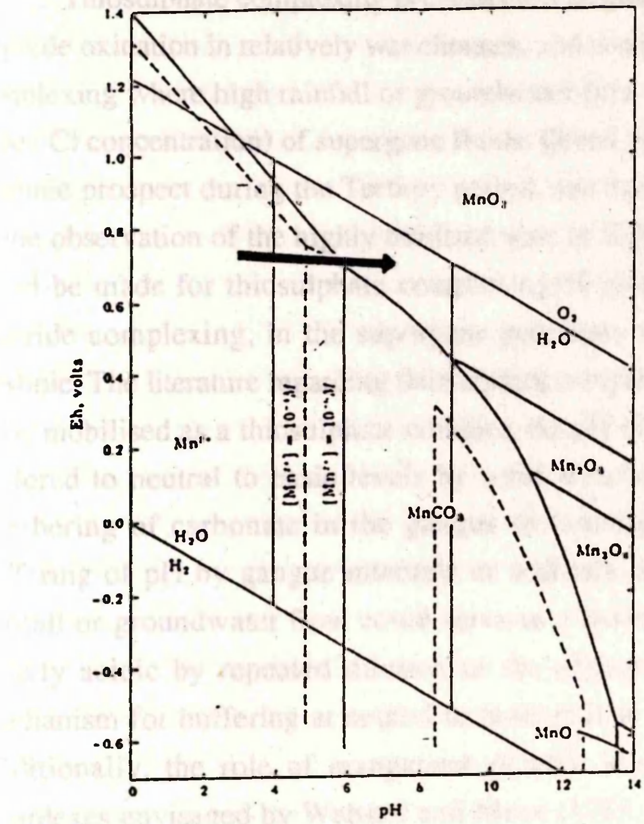
pH Versus Redox Control On Supergene Mobility Of Gold And Manganese

The process of manganese mobilisation and re-precipitation envisaged can be illustrated on the Eh/pH diagram of Fig.32. The dominant chemical changes will relate to acidity, so the processes described will follow the arrow on Fig.32., which delineates a shift from the field of aqueous manganese stability to the field of manganese oxide stability, ie. from dissolved manganese to precipitated manganese oxides.

The water-table is also generally considered to represent a redox boundary separating oxidising conditions above from relatively reducing conditions below. Redox control on manganese solubility is considered to be subordinate to pH control in this particular case, largely on the grounds of field evidence. It can be seen from Fig.32 that a shift from oxidising to reducing conditions would not be conducive to precipitation of manganese oxides. Rather, the opposite holds whereby manganese rich groundwaters beneath the water table will become oxidised in the aerated zone close to the water table and will precipitate manganese as oxides. This results in the widespread manganese enrichments at the level of the water table which are a common feature of any ground excavation. The important difference between this situation and the present context is in the abundance and very localised distribution of the manganese oxides on the Socach Structure. A more localised process must be invoked to explain these characteristics. Supergene metal transport, it can be conclusively stated, has been downwards on the Socach Structure, and the supergene fluids responsible for this transport have also been percolating downwards. The chemical means of re-precipitation of metals at the water table must be consistent with these facts, and the above model is both consistent and chemically feasible. A strong case can then be argued for the predominance of pH as a control on manganese and gold mobility, with redox control being relatively minor. Loss of acididty results in the precipitation of manganese oxides. The removal of this effective oxidising agent from the supergene fluids destabilizes $AuCl_2$ resulting in gold precipitation. Alternatively, precipitation of manganese oxides directly results in the co-precipitaion of gold.

More up-to-date work on supergene gold transportation has revealed a greater diversity of chemical means of mobilising gold in supergene fluids. Hydrolysis, thiosulphate complexing and organic complexing are considered important in certain contexts, and their potential role in the present situation needs to be evaluated.

FIG. 32 : Eh/pH DIAGRAM SHOWING STABILITY FIELDS FOR THE COMMON MANGANESE MINERALS (after Krauskopf 1979)



Postulated change in Eh/pH conditions of supergene fluids during downwards transport and dilution at the water-table. Note qualitative shift from Mn (aq) stability field to field of manganese oxide precipitation on dilution and loss of acidity.

Speciation of dissolved gold in the absence of other ligands can be achieved by hydrolyzed species such as $AuOH(H_2O)^0$ (Vlassopoulos and Wood 1990). This mechanism of supergene remobilisation will be addressed later in the event that no alternative more effective means are deemed available in the present context.

Thiosulphate complexing is considered an effective means of mobilising gold during sulphide oxidation in relatively wet climates, and is commonly cited in preference to chloride complexing where high rainfall or groundwater flow are thought to reduce the salinity (and hence Cl concentration) of supergene fluids. Given the evidence for deep weathering on the Cushnie prospect during the Tertiary period, and the high rainfall that this implies, as well as the observation of the highly oxidised state of sulphides on the Socach Structure, a case could be made for thiosulphate complexing of gold playing a part, in competition with chloride complexing, in the supergene processes responsible for gold redistribution at Cushnie. The literature regarding thiosulphate complexing emphasises however that for gold to be mobilised as a thiosulphate complex the pH of the transporting fluid must be locally buffered to neutral to basic levels by some means, the most commonly cited being the weathering of carbonate in the gangue or host-rock. That little opportunity exists for buffering of pH by gangue minerals or wallrock has already been discussed.Very high rainfall or groundwater flow could serve as a buffer, keeping the fluids either neutral or weakly acidic by repeated dilution of the acidity generated by sulphide oxidation. A mechanism for buffering at neutral to basic pHs is not available by this means however. Additionally, the role of manganese dioxide in gold precipitation from thiosulphate complexes envisaged by Webster and Mann (1983) is as an oxidising agent, as illustrated thus;

$$2Au(S_2O_3)_2^{3-} + MnO_2 + 4H^+ \dashrightarrow 2Au^0 + 2S_4O_6^{2-} + Mn^{2+} + 2H_2O$$

This involves the breakdown of MnO_2 on gold precipitation, which is contrary to the field evidence which suggests that downward percolating supergene fluids co-precipitate MnO_2 and gold at the water-table. This considerably weakens the case for thiosulphate complexing as the primary means of supergene gold mobility.

The role of chloride complexing in the present context is also called into question however by the idea that it will predominate in arid conditions chloride contents will be high. High chloride contents will be unattainable in the wet, humid conditions prevalent during Tertiary times on the Cushnie prospect. It is considered by the author however that, given the low quantities of gold requiring mobilisation during the weathering of a gold deposit, only low quantities of chloride are required to this end. A dilute source of chloride and an extended period of weathering are considered here as capable of remobilising the low quantities of gold envisaged in the model. The case for chloride complexing is strengthened by the lack of any requirement for medium to high pH in the supergene fluids. Chloride complexing in the presence of manganese requires fluids of high acidity. This acidity is achievable through the generation of sulphuric acid during sulphide oxidation. High rainfall could quickly dilute this locally high acidity however. A mechanism is therefore envisaged involving repeated sulphide oxidation, local acidification of the fluid, gold dissolution, dilution, gold reprecipitation, oxidation of further sulphides, re-acidification and so on. This process will have occurred along a front within the Socach Structure which gradually advanced downwards as weathering proceeded. As the fluids percolate downwards they encounter fresh sulphides at depth which on oxidation cause acidification of the fluid and a repeat of the process. The process will be repeated iteratively until the fluids become permanently diluted at the water-table, and gold transport will halt at this level. On these grounds, chloride complexing is regarded as more likely than thiosulphate complexing in explaining supergene gold remobilisation at Cushnie.

A range of organic compounds possess the propensity to mobilise gold in the supergene environment. Such substances could well have been available during the weathering of gold mineralisation on the Cushnie prospect on account the warm humid climatic conditions which would have supported lush vegetation. Cyano complexing, humic, fulvic and amino acids (Bowell 1992) may have played a role in gold mobilisation at Cushnie. No specific field evidence exists for the involvement of such substances however, so their specific role cannot be evaluated in detail. The specific field evidence for the role of manganese in the process of supergene gold remobilisation justifies the above emphasis on this and related mechanisms in preference to organic acids.

Invoking gold mobilisation in the supergene environment by chloride complexing in acidic fluids to explain the grade redistribution effects along the Socach Structure also provides a means of explaining the presence of gold in the nodular palaeosoil materials located remote from primary gold mineralised structures. Mann (1984) states that the oxidation of iron to hydroxide causes reduction of the AuCl complex and precipitation of gold and iron oxides together. The formation of ferruginous and manganiferous nodules in the palaeosoils will therefore be accompanied by co-precipitation of gold from supergene fluids, by either the above mechanism or through colloidal absorption on iron oxides.(Enzweiler and Jokes). Gold mobilised in acidic supergene fluids will migrate laterally and will be reprecipitated in deeply weathered soils by the above mechanisms (for a more detailed discussion of this process see Chapter 9). Chloride complexing of gold can therefore explain both vertical and lateral migration of gold from primary sulphide mineralisation in the supergene environment on the Cushnie prospect.

In summary then, supergene alteration of the Socach Gold Deposit was the result of deep weathering in the warm, humid climatic conditions prevalent during Tertiary times. Gold remobilisation was in acid, manganiferous fluids, the acidity arising from the weathering of sulphides and the manganese being mobilised from the country rocks by deep weathering. Acidity and manganese/gold mobility were locally enhanced in the vicinity of the Socach Structure. Downward percolation of these acid , metal bearing fluids and dilution at the water table resulted in loss of acidity and gold and manganese precipitation. In this way, gold and manganese were transported downwards to produce an upper leached zone and a zone of gold and manganese enrichment at the water table. The Socach Structure is currently exposed dominantly within the leached zone. The presence of the zone of enrichment and the underlying gold bearing primary sulphide zone on the downdip extension of the Socach Structure over its entire strike length is implied. This constitutes a significant exploration target which awaits evaluation by drilling.

Quantification Of The Model

Chloride complexing, manganese and organic acids may all have played a role in the supergene remobilisation of gold at Cushnie. Specific field evidence exists for the role of manganese in the dissolution and reprecipitation of the gold, and this idea has been shown above to be both chemically feasible and consistent with current ideas on supergene gold mobility. Gold was carried as chloride complexes in manganese enriched groundwaters and was subsequently co-precipitated with manganese and iron oxides as a result of loss of acidity of the fluid through dilution at the water-table.Modelling of the chemistry of the supergene alteration of a mineral deposit is an inexact science, more so in this instance where specific parameters such as rainfall, manganese content, salinity, pH, and Eh are not accurately known. The best that can be done is to develop a model which is consistent with the observations available and is chemically plausible. The model developed is consistent with the characteristics of the mineralisation on the Socach Structure described earlier. Coincident manganese, gold and silver enrichments (in particular at the level of the water-table), a consistent oxidation paragenesis and availability of all the necessary constituents of the supergene fluids envisaged, all contribute towards a reasonably consistent qualitative model for supergene alteration. It therefore represents a working hypothesis which is testable through quantification of the important parameters. Quantification of the model would involve;

1) estimation of precipitation rates and subsequent groundwater flow during the Tertiary weathering regime.

2)calculation of the amounts of garnet available for leaching (and their manganese contents) and the quantities of manganese available from deep weathering of the country-rocks as a whole; calculation of the quantities of pyrite available for oxidation and the dilution factors of the groundwater flow to give actual pH and manganese content of the supergene fluids.

3)measurement of the permeability of the Socach Structure to the downgoing fluids.

4)evaluation of the dilution factor and Eh change at the water table which cause gold and silver re-precipitation.

CHAPTER 7

THE GEOLOGICAL SETTING AND EXPLORATION SIGNIFICANCE OF THE SOCACH GOLD DEPOSIT

Introduction

The Socach gold deposit shows a diversity of geological characteristics which point to a multi-faceted and protracted history of development of the deposit. The structural control, hydrothermalism and supergene alteration involved in its formation and the preservation of the effects of these processes all occurred within the broad context of the geological evolution of NE Scotland. Understanding the deposit within this context will help identify the geological coincidences that gave rise to the mineralisation, which in turn will assist the search for other such deposits. An attempt will be made to place the deposit in a regional context and assess the implications this has for the exploration for other similar deposits.

Geological Setting

The host rocks to the Socach gold deposit have been described as sub-gneissic interbedded garnet schists and psammites, reminiscent in many respects of some typical middle Dalradian lithologies exposed in the southern and central Highlands, but also showing affinities with the Strathdon gneisses of Ramsay and Sturt (1979). The transitional nature of these rocks from garnet schists and psammites through to granitic gneisses via the progressive development of quartzo-feldspathic segregations as illustrated on Plate 13 would argue for these rocks representing the transition from typical unsegregated Southern Highland type Dalradian lithologies to the migmatites and gneisses of Donside. Ramsay and Sturt however envisage the Strathdon Gneisses as representing a distinct thrust sheet made up of pre-Dalradian lithologies. The dispute remains unresolved and, in terms of regional setting, the gneisses are generally considered as 'Dalradian of unknown affinity' on regional geological maps of North East Scotland. These host rocks have been deformed by a series of NW-SE trending, SW dipping shear zones across which movement of a reverse sense has occurred. The rocks and structures were later invaded by hydrothermal fluids to form the deposit seen today.

The work of Read (1956) in unravelling the geological structure of NE Scotland provides a framework for a plausible tectonic setting for the Cushnie prospect. The emplacement of a large nappe structure (the Banff nappe) is used to explain the relative juxtaposition of the various pre-Devonian lithologies. The bounding surfaces of this nappe are conjectural but are locally consistent with the orientation and movement sense deduced for the Socach Structure. Thus the Socach Structure can be envisaged as developing in response to the stresses set up during nappe emplacement. The accommodation of the induced strains along such structures resulted in the juxtaposition of the lithologies seen on the regional scale today.

Thus the Socach gold deposit is situated within the Dalradian metamorphic pile, but in a geological terrain whose exact affinity is not clear. It lies in rocks that would have been below the extension of the Banff nappe but close to the bounding surfaces of the nappe, and

PLATE 13; A-C; THE COUNTRY-ROCKS OF THE CUSHNIE PROSPECT

Plate A; Typical garnet muscovite schist; the unsegregated lithology described in the text.

Plate B; Muscovite garnet schist displaying incipient segregation of quartz and feldspar to produce a sub-gneissic texture.

Plate C; Local development of the completely segregated lithology, a granitic gneiss.

A,B, and C above are transitional lithologies on the Cushnie prospect.


PLATE 13a
scale bar 2cm long


PLATE13b
scale bar 2cm long


PLATE 13c
scale bar 2cm long

is hosted by structures which developed in response to the stresses set up during emplacement. These processes all occurred during pre-Devonian times and provided a setting for later hydrothermalism and gold mineralisation.

Thermometric and barometric data derived from fluid inclusions in hydrothermal quartz from the Socach Structure suggest that the gold mineralising processes were mesothermal in character and their effects are now exposed at a structural level corresponding to a palaeodepth of 1 - 1.5km at the time of hydrothermalism.This information allows the auriferous hydrothermalism to be placed in the palaeogeographical setting illustrated by Fig. 29. Exhalation would have occurred at the contemporaneous land surface, which in terms of present topography would have been at about 1500-1900m above sea level. (present elevation plus palaeodepth). The Rhynie chert, 10 miles to the north, is a product of such exhalation onto a Lower Devonian land surface. The geographical proximity and geochemical similarity of the two deposits suggests that some form of analogy can be drawn between them. The analogy envisages exhalation from the Socach hydrothermal system during Lower Devonian times. The two contemporaneous exhalative centres would then be 15 km apart and have a vertical disparity of about 1200-1600m.

This scenario needs to be considered within the context of the Devonian palaeogeography of NE Scotland (Bluck et al 1988). Devonian outliers resting upon metamorphic basement are widespread in the eastern part of Scotland. The Devonian period involved the initial phase of denudation of the Caledonide orogen, producing extensive molasse deposits.which are preserved as the ORS sediments of NE Scotland. The agents of this denudation and molasse accumulation were dominantly fluviatile, and major river and basin systems developed. A dissected peneplain was formed, with molasse sediments accumulating in the basinal and valley areas which are now preserved as ORS outliers. Tectonic stability and little subsequent erosion since Devonian times has preserved these sediments in topographic lows throughout NE Scotland (eg. the Rhynie basin and the Cabrach outlier).

The palaeotopography described above could well have sufficient undulation to accomodate the 1200-1600m of vertical separation between the Rhynie and the postulated Socach exhalative centres. The former is located within one of the said basinal areas, whilst the latter can be envisaged as exhaling onto the relatively elevated peneplain. Thus the original analogy between the two deposits, constructed on geochemical grounds, and the implications of fluid inclusion data for temperature and palaeodepth of hydrothermal activity can be reasonably accommodated within a Lower Devonian palaeogeographic setting. The Socach gold deposit can be considered as the medium level exposure of a hydrothermal system similar to that preserved at Rhynie; it represents an unroofed remnant of a structurally controlled Lower Devonian hydrothermal system.

Given the postulated Lower Devonian age of gold mineralisation at Cushnie, and again using the analogy with Rhynie, a hydrothermal fluid source related to emplacement of the Newer Granite suite into the Caledonide metamorphic pile can be envisaged. The presence of a medium sized granite body (the Cushnie Granite) within the prospect itself provides further weight to this idea. The affinity of this granite is as yet indeterminate due to the complete lack of exposure of fresh rock; the material is generally completely weathered to a sandy soil or to an incoherent crumbly texture and is therefore inconducive to geochemical characterisation. Texturally it appears as an unfoliated coarse grained muscovite granite, and the exposure pattern is suggestive of a batholithic form which is in the early stages of unroofing. This is not inconsistent with its belonging to the Newer Granite suite, but hardly constitutes substantial proof of the fact. The association of the Newer Granite suite with gold as well as Cu, Mo, As, Pb, and Zn mineralisation throughout Scotland is well documented (Pattrick et al 1991, Alderton 1988, Boast et al 1990, Harris et al 1988, Zhou 1987, 1988). Lowry (1993, in press) distinguishes hydrothermal fluids associated with plutonic and porphyry systems in Scotland. CO_2 rich fluids homogenising at <400^0C are considered typical of the deeper-seated plutonic systems, whilst porphyry systems are typified by CO_2 deficient fluids boiling at 320-560^0C. The Socach hydrothermal fluids are therefore typical of Lowry's plutonic systems. It is not unreasonable then to suggest that the Socach gold deposit is a further example of Newer Granite related metallic mineralisation of the plutonic variety. Emplacement of the Cushnie Granite could provide a fluid and heat source for a hydrothermal system which utilised crustal permeability along pre-existing shear zones. The hydrothermal system would have exhaled onto a Lower Devonian land surface. At higher structural levels than are exposed today, ie. close to the Devonian land surface, this hydrothermal system may have entrained meteoric water as has been suggested for Rhynie hydrothermal system. The level of intrusion of the Cushnie Granite is not known (but by analogy with the plutonic systems of Lowry (1993, in press) a depth of 3-5km is possible), nor is the nature of any related hydrothermal activity outwith the Socach Structure; the above is therefore presented as an analogy with other Newer Granite related mineralisation elsewhere in Scotland rather than as a rigourous metallogenic model.

Metamorphic fluids provide an alternative hydrothermal fluid source for gold mineralisation under certain tectonic conditions. Craw and Koons (1989) and Craw et al (1989) invoke the release of metamorphic fluids close to the brittle/ductile crustal transition during rapid uplift of the metamorphic pile to explain the distribution and genesis of gold deposits in South Island, New Zealand. The lack of granite batholiths and the evidence for very rapid uplift in South Island support his assertion that metamorphic rather than igneous derived fluids were responsible for this gold mineralisation.Craw (1990) applies this idea in a study of barren and metal bearing quartz veining in the western Central Highlands of Scotland. Basal Devonian sediments in NE Scotland commonly show conglomeratic facies, indicative of relatively rapid vertical crustal movements and rapid erosion. Metamorphic fluid expulsion during this Lower Devonian uplift could be argued to have played a part in the hydrothermal activity associated with the Rhynie chert for example. However, the lack of evidence for uplift rates of the magnitude required by Craw's model affecting the Dalradian rocks of NE Scotland (Dempster 1985) argues against the application of Craw's model to this terrain and also argues against the possibility of sufficient fluid volumes being generated by this means. This, together with the abundance of granite bodies intruded through the metamorphic pile, gives weight to the idea that igneous rather than metamorphic derived fluids were responsible for gold mineralisation at Cushnie.

Subsequent erosion progressively unroofed the deposit, removing the upper epithermal part and exposing the deeper, mesothermal mineralisation to surface weathering effects. Between hydrothermal activity and exposure to weathering, net erosion of 1 - 1.5km must have taken place.

The intensity and vertical extent of supergene alteration recorded at Cushnie are unique in Scotland. The leached zone is developed to a thickness of 10-15 m and is characterised by complete leaching of gold and host sulphides, porous textures and low gold grades. The underlying oxidised zone is developed to an indeterminate depth. Nowhere else in Scotland is this depth of leaching apparent. (At the Aberfeldy baryte deposit, oxidation of sulphides is apparent to some depth, but wholesale leaching is not seen. The nearby Calliachbhar gold prospect shows intense oxidation of sulphide mineralisation at shallow depths but none of the vertically extensive leaching seen at Cushnie (Pattrick 1991). At Cononish, exposures of vein sulphide mineralisation near the top of a hill show only surficial oxidation effects) This uniqueness points to a unique agent of supergene alteration having operated at Cushnie. The development and patchy preservation of palaeosoils over weathered bedrock and the degree of weathering of basic intrusives on the Cushnie prospect is also unusual and needs explaining.

Further examples of such intensity of supergene alteration are well documented in mine reports and research publications on mineral deposits situated in tropical latitudes. The warm humid climate in these regions is considered conducive to the deep weathering, oxidation and, where appropriate, leaching, of sulphide ores. This deep weathering is also responsible for the development of thick lateritic soil profiles and the underlying weathered regolith materials.

Records of intense and vertically extensive weathering of bedrock abound in engineering geological reports and palaeogeographical literature pertaining to NE Scotland(eg. Hall 1984, 1985). On the local scale the phenomenon is normally attributed to the effects of deep Tertiary weathering. The geographical distribution of these and other effects provide the basis for palaeogeographical reconstructions which imply that such deep Tertiary weathering was effective over a large part of NE Scotland (Hall 1984).

By comparison with these separate examples then, the main effects of surface weathering seen at Cushnie can be attributed to tropical weathering and Tertiary weathering. The climate during Tertiary times in Scotland has been shown to have been hot and humid, approximating that seen in sub-tropical latitudes today. Similar climatic conditions are also believed to have prevailed during some of the numerous interglacial periods. It has been argued (Lassale et al 1985) that the development of deeply weathered soil profiles to a kaolinite and/or gibbsite dominated clay fraction mineralogy requires prolonged periods of such weathering. The palaeosoil profiles at Cushnie are indeed kaolinite dominated (see Chapter 6), suggesting that they formed over such a prolonged period of time, which is more consistent with their formation during the longer duration Tertiary weathering period than with formation during the relatively short interglacial periods.

It can be concluded then that erosion of 1 - 1.5km of rock between Devonian and Tertiary times resulted in the unroofing of the Socach gold deposit and its exposure to surface weathering effects. Deep weathering of country rocks and supergene remobilisation of gold from auriferous structures proceeded under a warm, humid climate approximating that seen in subtropical latitudes today.

The preservation of the Socach gold deposit in its largely pre-glacial form and of the other Tertiary weathering effects on the prospect implies minimal glacial erosion of the area. This aspect of the evolution of the prospect is consistent with the regional glacial history of this part of Scotland. The intensity of glacial erosion is shown by Sissons (1976) to decrease across Scotland in a broadly easterly direction, giving rise to the contrasting geomorphology of the east and west Highlands. A highly dissected mountainous landscape in the west is the result of aggressively erosive glaciation, whilst the undulatory landscape of the NE Highlands resulted from the relatively benign glacial activity characteristic of these parts. This less aggressive regime resulted in the preservation of pre-glacial features on the Cushnie prospect and in the widespread preservation of such features in NE Scotland.

In summary, a long and protracted geological history is recorded by the Socach gold deposit and its surrounding country-rock. Pre-Devonian tectonism, Lower Devonian granite emplacement with associated hydrothermalism, subsequent unroofing and deep Tertiary weathering , and non-erosive glaciation all played a role in producing the deposit seen today. The exploration significance of this history will now be outlined.

EXPLORATION SIGNIFICANCE

The formation of the Socach gold deposit and its discovery and subsequent study have several aspects of relevance to gold exploration in Scotland. They are basically two-fold, relating to the potential of the deposit itself as a resource and to the the exploration for further such deposits respectively. The former has largely been dealt with in Chapter 6 which describes and predicts the gold grade distribution within the Socach Structure. This section deals with the potential for discovery of new deposits of a similar type. The deposit itself represents the fortuitous combination and relative timing of the geological processes described above, and the equally fortuitous preservation of their effects. Exploration for other such deposits involves looking for other similar geological coincidences, by direct analogy with the known deposit. Several of the characteristics of the Socach gold deposit and the geological processes responsible for their development provide information which can be used either directly or indirectly to aid this search.

The host structures to gold mineralisation on the Cushnie prospect were instrumental in allowing and also focussing hydrothermal fluid flow and in so doing concentrating the gold mineralising effects of this hydrothermal activity. The hydrothermal system exploited pre-existing permeability along the shear zones, and any other such systems can be expected to exploit whatever structures are present. Given the postulated Lower Devonian age of auriferous hydrothermalism at Cushnie, it will be pre-Devonian structures that exert this control on gold mineralisation. Knowledge of the dominant pre-Devonian structures within a prospect will therefore aid the search for further such deposits by, for example, enabling geophysical lines and soil traverses to be designed to cut these trends at optimum angles. At Cushnie the major structures are considered to be associated with the emplacement of the Banff nappe; such structures are thought to trend NW-SE locally, so this forms the dominant trend of mineralised bodies located to date, and others not yet found are likely to follow this trend also. Elucidation of such details for the specific prospect of interest could constitute a valuable exploration tool. In this respect the work of Read (1956), Ramsay and Sturt (1979) and Ashcroft et al (1987) provide good starting points for deciding on relevant structural trends for the specific area of NE Scotland of interest.

The case put forward for a Lower Devonian age for the hydrothermal activity at Cushnie, and the analogy with the nearby Rhynie chert deposit are important in exploration terms. The Rhynie chert represents the exhalative epithermal manifestation of a Lower Devonian hydrothermal system, whilst the Socach gold deposit represents a deeper level, mesothermal part of such a system. Direct comparison of gold grades obtained from both deposits obtained by mapping/drilling at Rhynie and mapping/trenching at Cushnie, shows the latter to constitute a superior exploration target once the effects of supergene alteration (present at Cushnie but not at Rhynie) are considered. The implication then is that the deeper, mesothermal feeder zones to such hydrothermal systems are more prospective than the exhalative epithermal zone. This is possibly a direct manifestation of the gold depositional processes involved in these hydrothermal systems. Effervescence of these fluids is a pressure controlled phenomenon and will be encouraged by a gradual decrease in lithostatic pressure as the fluids penetrate upwards through the crust. Effervescence will result in gold precipitation, and both will be initiated when the hydrothermal fluid reaches a crustal level where fluid pressure exceeds lithostatic pressure. Thus gold precipitation will be initiated at some depth. It is conceivable that the bulk of the gold carried by the hydrothermal fluids is deposited soon after initiation of effervescence, resulting in a depletion of the residual fluid in gold. This depleted fluid will then be involved in mineralising processes at shallower crustal levels, producing the lower grades of mineralisation at these levels. Thus the mesothermal parts of these hydrothermal systems may be more prospective because they occur close to the point of initiation of effervescence.

NE Scotland during Lower Devonian times comprised a dissected peneplain, and this land surface is preserved within and around the numerous Devonian outliers present in the regional geology. Exhalative systems will be preserved on this land surface, as is the case with Rhynie. The more prospective parts of such hydrothermal systems will however be found at some depth beneath this palaeolandsurface. Taking the thickness of Lower Devonian sediments within the Rhynie basin as 500-1000m (Rice and Trewin 1987, Gould 1990) and the palaeodepth derived from fluid inclusion work for the Socach deposit (1 -

1.5km), implies a prospective structural level close to the base of the Devonian sediments and within the underlying Dalradian. Mesothermal gold-rich deposits will be exposed where the current erosion level is close to or a short distance beneath the Devonian land surface. The prospective areas will therefore be within very basal Devonian sediments within the Devonian outliers of NE Scotland or in the metamorphic basement to the outliers, and deposits will be found where the present erosion level coincides, by geological good luck , to a gold-rich part of the hydrothermal system, as at Cushnie. The wide distribution of Devonian outliers in NE Scotland suggests that the relevant palaeolandsurface is regionally not far removed from the present erosion level. Large parts of NE Scotland are therefore likely to be exposed at, or close to, the prospective erosion level. The coincidence of a hydrothermal system and a prospective erosion level remains a distinct possibility, and further deposits could be awaiting discovery. Exceptions to the above rule could occur where large thicknesses of Lower Devonian sediments are (or were prior to later erosion) present within an outlier; the desired erosion level of the hydrothermal system could then be preserved within this sedimentary pile, ie. within the outlier. The presence of a potential heat and fluid source for the hydrothermal systems envisaged would also enhance an area's prospectivity. Thus the presence of Newer Granites in the local geology, either exposed or inferred at depth, can be taken as encouragement.

Appreciation of the possible effects of supergene alteration on the grade characteristics of gold deposits was instrumental in maintaining interest in the Cushnie prospect despite the original low grades obtained during the float-mapping exercise. These grades were attributed to supergene leaching of gold and host sulphides, producing the porous textures observed. Follow-up exploration was justified on the grounds that any magnitude of anomalous gold grade reporting from such material implied the presence of higher grades at depth or at lower topographic levels beneath the upper leached zone. This idea was verified during subsequent trenching programs, and the expected higher grades intersected. A lack of appreciation of the above factors would have resulted in the exploration effort being curtailed too soon. This lesson is relevant to any prospect where low gold grades are reporting from leached or oxidised material. Tertiary weathering has been deemed responsible for these effects on the Cushnie prospect, and therefore any exploration effort in terrains affected by such weathering should take the above lesson on board from the start. NE Scotland is known to have been affected by deep Tertiary weathering on the regional scale, so the above is directly relevant to that part of Scotland. In the absence of oxidised or leached sulphides, the likelihood that such weathering has occurred can be assessed by the consistency of the local bedrock; anomalously rippable intrusives as on the Cushnie prospect should immediately ring alarm bells and prompt close attention to the textures of any mineralisation subsequently found. Deep weathering results in poor exposure however, and the presence of Tertiary weathering may not become apparent until trenching proceeds. Only once the effects of deep weathering have been considered in such areas can the exploration potential of the prospect be properly appreciated.

Supergene alteration has been observed at Cushnie to affect the geochemical and geophysical expression of gold mineralised bodies. Lateral migration of gold in supergene fluids and re-precipitation in deeply weathered soils gives rise to soil geochemical anomalies remote from bedrock gold mineralisation, as described in Chapter 3 and 6. Soil surveys can be complicated by this phenomenon. Distinguishing deeply weathered soils from hydrothermally altered wallrocks therefore becomes important in guiding trenching (or drilling) programs in order that effort is not wasted following a patchilly preserved palaeosoil in the mistaken belief that it indicates incipient hydrothermalism. Textural examination for sesquioxide nodules and other soil textures hold the key to this distinction.

Leaching of metallic minerals by deep weathering renders geophysical prospecting less effective than in unleached areas, as found at Cushnie. Careful choice of geophysical technique and equipment therefore becomes more necessary, though the author will not pretend to have resolved this problem since none of the methods employed at Cushnie (SP and VLF) proved effective. The work of Leslie (pers. comm.) shows that deeply weathered zones produce areas of subdued geophysical properties which are limited in extent. Outwith this area, geophysical mapping is possible, and extrapolation into the weathered area gives satisfactory results. Correlation of geophysical anomalies from unleached structures through areas of deep weathering will, on this reasoning, be possible.

The type of glacial regime(s) which operated at Cushnie and resulted in the preservation of the mineralisation in its largely preglacial state and of the soils formed by deep Tertiary weathering, were operative over much of NE Scotland. Less aggressive glacial erosion was experienced by this part of Scotland than further west, so pre-glacial features will be better preserved as a result. This constitutes an additional reason to be aware of these effects on both mineralisation and the secondary dispersion of such, as described earlier, when prospecting this terrain. A large part of Buchan, just to the NE of the Cushnie prospect, is believed by some authors to have been ice-free during the last glaciation which affected much of the rest of Scotland, so the trend of decreasing degrees of glacial erosion and increasing degrees of preservation of the effects of Tertiary weathering will continue in this direction. Further west, as the degree of glacial erosion increases, Tertiary weathering effects will be less well preserved. At Cushnie the preservation of the almost full profile of leached, oxidised and unweathered zone allowed rapid understanding of the supergene alteration of the deposit. Increased glacial erosion would preserve this profile less completely and render the understanding of the pre-glacial effects more difficult. Near the west coast, the effects of Tertiary weathering will be only locally preserved and mineralisation will be fresh to slightly oxidised to only shallow depths The significance of the type of glacial regime is, then, that it affects the relative preservation of important characteristics of the deposit and can complicate or simplify their understanding. The distribution of oxidised or leached textures in a deposit affected by a later erosive glacial regime should be properly assessed with this in mind.

The geographic distribution of mineralised float on the Cushnie prospect can be seen to closely mirror the distribution of mineralisation exposed in bedrock during subsequent trenching. The operation of unaggressive glacial regimes has therefore resulted in only localised transportation of ripped bedrock. Thus, glacial redistribution by such a regime does not widen the exploration target substantially through the generation of an extensive float-train. On the other hand, the location of a mineralised float train implies proximity to bedrock mineralisation. Thus, float trains will be localised and proximal to source in areas affected by less aggressive glaciation.

Any newly found deposit has immediate implications for exploration in its host terrain. The Socach gold deposit possesses a diversity of geological characteristics which arose through a protracted and diverse geological history, and each of these has implications for the search for further such deposits. It is likely that further deposits exist in the poorly exposed northeastern part of Scotland, and the understanding of the Socach deposit may help in their future discovery.

CHAPTER 8

HIGH LEVEL CRUSTAL PROCESSES; EPITHERMAL GOLD MINERALISATION ON THE DALNESSIE ESTATE, CENTRAL SUTHERLAND.

Introduction

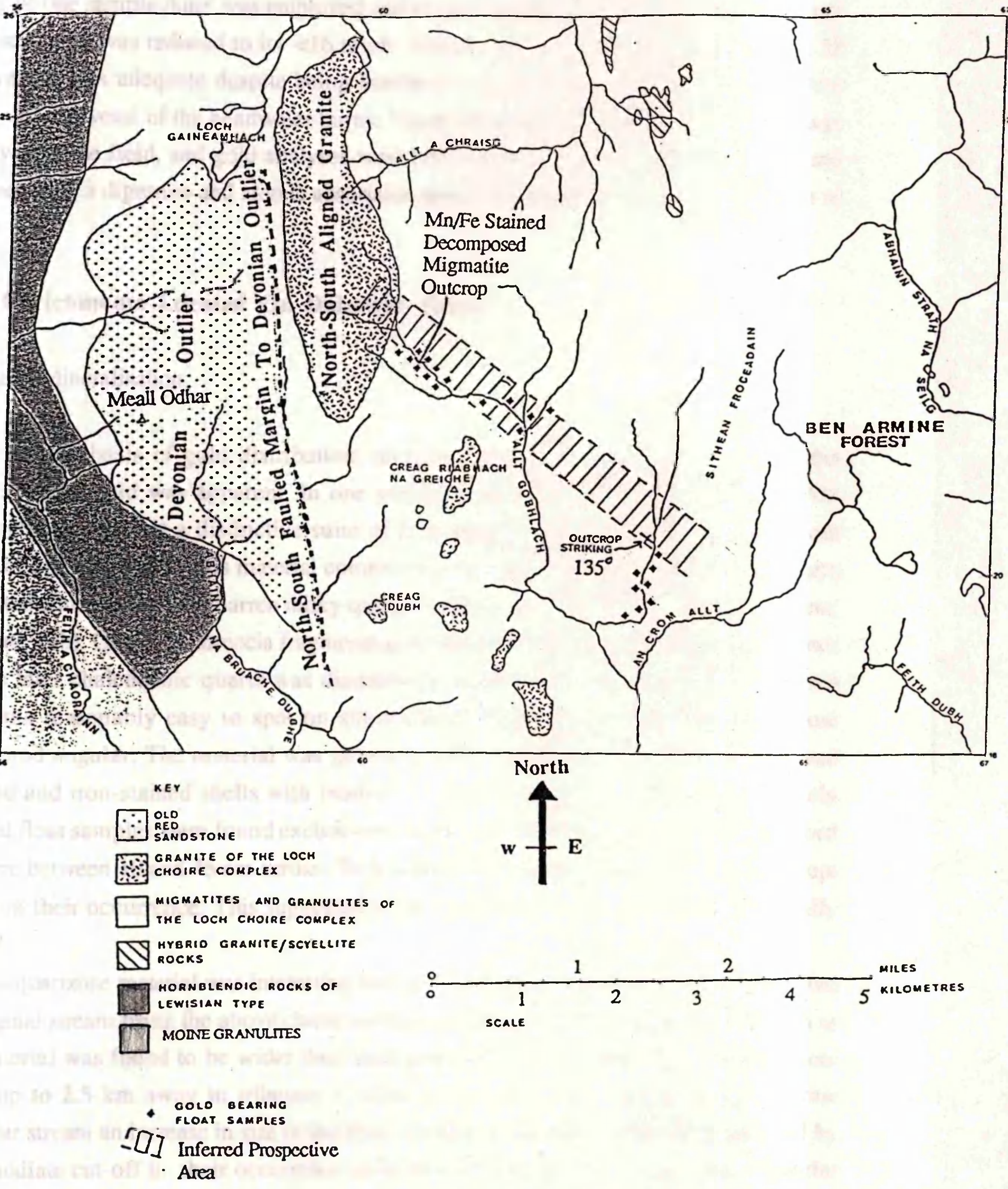
Eastern and central Sutherland is known for its abundance of alluvial gold showings, the most well known of which on the Suisgill and Kildonan burns, gave rise to a gold rush in 1868, and by the next year about 500 men were prospecting in the area, mainly encamped at the makeshift settlement Baille an Or (1 on Fig.33). Conclusive proof of the original source of the gold in these showings and several others in the district, eg. Clynemilton Burn near Brora, Blackwater (2 and 3 respectively on fig.33) remains enigmatic to this day but the gold is generally thought to have been derived by deep preglacial weathering of the granite and migmatite complexes which make up the geology of the area (Plant and Coleman 1973). Although deep weathering provides a mechanism for the final concentration of gold into these sometimes spectacularly rich placer deposits it still begs the question as to the original source of the gold. Such placer deposits, it is known, can form by deep regional weathering of a terrain only slightly enriched in gold and do not require anything approaching ore grades in bedrock to provide the quantity of gold found in these placers (Shilts and Smith 1988) Nonetheless, the presence of these placers implies that a terrain previously enriched in gold did exist. Such terrains merit exploration for any concentrated bedrock gold occurrences that they may contain.

The Exploration Target

Gold exploration in east and central Sutherland has concentrated, unsurprisingly, on the spectacular alluvial showings on the Suisgill and Kildonan burns (4 and 5 on Fig.33). At the time Navan Resources initiated an exploration program in Scotland, one very large licence existed in Sutherland centred on these showings, and some ground was covered by a company/landowner exploration agreement further to the east. Given that the enriched terrain was defined as the granite and migmatite complexes of the area this restricted further exploration.

Regional scale structures formed the basis of both commercial and academic interest in the area. The concept of localisation of orebodies on large scale lineaments is invoked in different geological contexts world-wide, and Russell and Haszeldine (Russell 1971, Haszeldine 1988 and Russell and Haszeldine 1992) have pointed to N-S geofractures in Britain and Ireland localising world-class Pb/Zn deposits, controlling sedimentary basin formation and subsequent hydrocarbon generation forming significant fields. Moreover, such lineaments explained several previously irreconcilable tectonic phenomena. These authors also point to the cryptic nature of such structures and the regional rather than local scale on which they are recognisable. On the Shiness and Dalnessie estates the surface expression of one such postulated lineament comprises a small north-south elongated granite intrusion, and a small north-south trending and north-south fault-bounded Devonian outlier, An analogue can be drawn with the Loch Doon granite in SW Scotland where the distinctive N-S alignment of the granite and the pronounced deflection of fabrics within the host

FIG 34 PROSPECT MAP OF THE DALNESSIE DISTRICT, CENTRAL SUTHERLAND, SCOTLAND.
Basic Geology after maps of the British Geological Survey



greywackes define the lineament (Haszeldine 1988) and where subeconomic gold mineralisation occurs in the greywackes at the southern margin of the granite (M.J.Gallagher, pers. comm.).

Fieldwork

The first stage in the exploration comprised regional panning coverage. An average sample density of one sample /km^2 was employed and at each sample site a 50 kg sample of <1cm steam sediment was reduced to its <16 mesh fraction which was then panned to about 35 g. Coverage was adequate despite being hindered by very dry weather and the complete drying up of several of the headwater burns. Visual inspection of the pan concentrates was employed in the field, and gold analyses were performed at OMAC Laboratories, Ireland using aqua regia digestion and atomic absorption spectrophotometry with a detection limit of 20ppb.

Gold Enrichments Located On Dalnessie Estate

Hypogene Mineralisation

On the basis of gold distribution, intensive prospecting was undertaken on the streams where gold was apparent. In one particular area, at the headwaters of the Allt Gobhlach (see Fig 34) a distinctive suite of float samples were found which gave gold grades of up to 12 g/ton. This material comprised a very finely pyritic bluish sugary quartz brecciated and cemented by barren milky quartz of cherty, chalcedonic and vuggy character (see Plate 14b). Quartzose breccia fragments gave the float samples a knobbled appearance and the later chalcedonic quartz was distinctively shiny in the wet, making mineralised fragments reasonably easy to spot on stream-beds. Some larger fragments were more blocky and angular. The material was generally very fresh but some larger samples had oxidised and iron-stained shells with fresh cores (Plate 14a). The slightly to moderately rounded float samples were found exclusively along a 250 m long zone on the stream-bed and were between 10 and 45 cm across. They increased in size upstream towards an abrupt cut-off in their occurrence. This suggested at the time that the float lithology was locally derived.

This quartzose material was interesting enough to prompt further prospecting away from the original stream using the above characteristics as a target. Suprisingly the distribution of this material was found to be wider than anticipated (Fig.34). Similar float samples were found up to 2.5 km away in tributary streams to the SE of the original stream. In one particular stream an increase in size of the float samples in an upstream direction followed by an immediate cut-off in their occurrence coincided with an outcrop 1.6 m wide of similar quartz-rich material poorly exposed on the stream-bank (Plate 14c). The structure trended, as far as can be discerned from the poor exposure, at 135° , parallel to the local foliation in

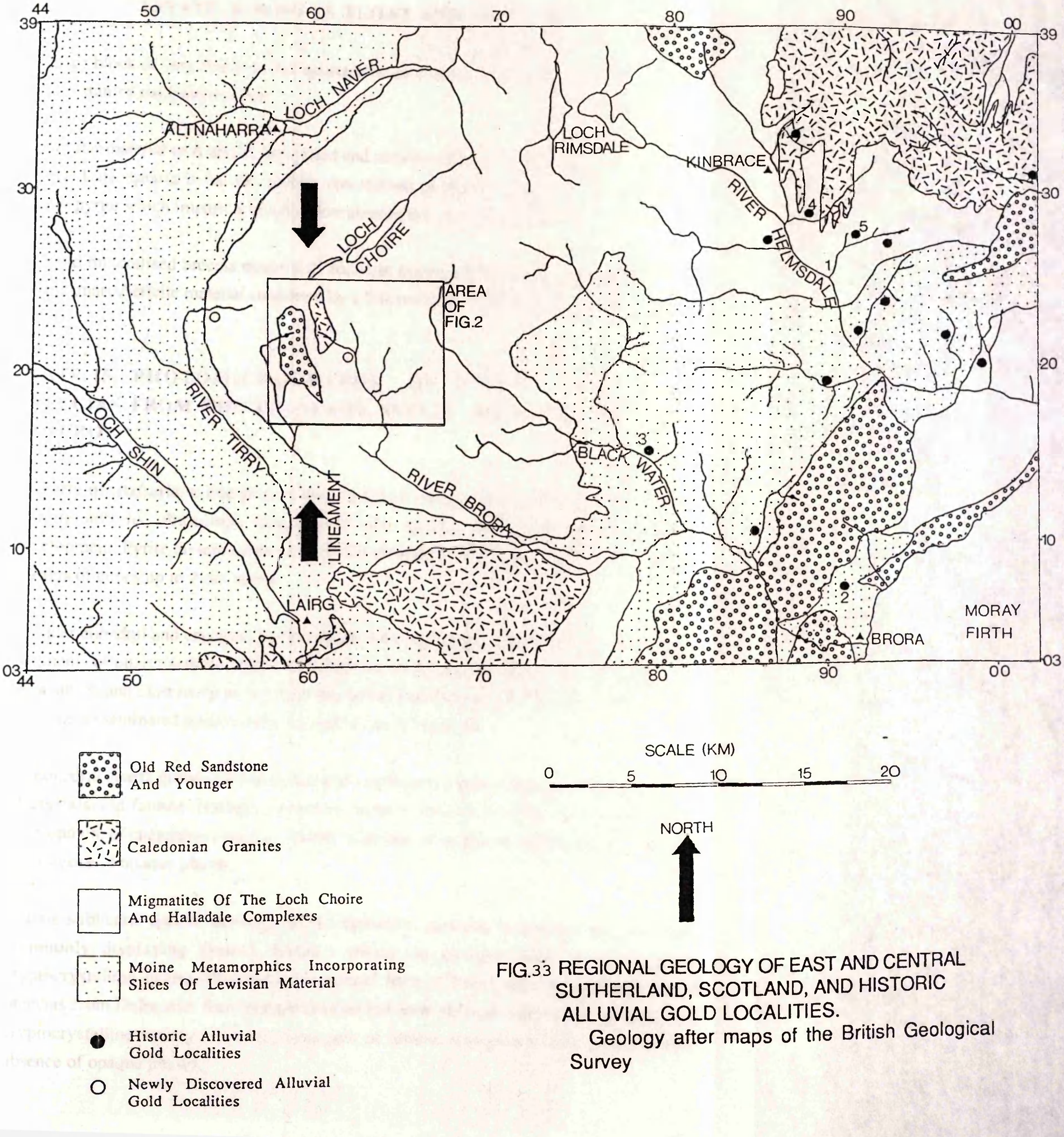


FIG.33 REGIONAL GEOLOGY OF EAST AND CENTRAL SUTHERLAND, SCOTLAND, AND HISTORIC ALLUVIAL GOLD LOCALITIES.

Geology after maps of the British Geological Survey

PLATE 14; GOLD MINERALISED BRECCIAS FROM THE DALNESSIE ESTATE, FOUND AS FLOAT AND OUTCROP

A)Large block of very finely pyritic quartz/sericite material showing a fresh bluish core and an iron stained oxidised exterior.

B) Similar material to A above, brecciated and cemented by later fine vuggy and chalcedonic quartz. Later quartz is barren, earlier iron-stained quartz/sericite material contains up to 5vol% pyrite which imparts a bluish colouration to the quartz in places.

C) Gold mineralised breccia material as found in outcrop. Rounded to sub-angular clasts of pyritic quartz/sericite material supported by a fine to chalcedonic, orange iron-stained, barren quartz.

PLATE 15; PHOTOMICROGRAPHS OF GOLD MINERALISED BRECCIAS FROM THE DALNESSIE ESTATE, FOUND AS FLOAT AND OUTCROP

A) Early quartz/sericite intergrowth hosting pyrite (opaque phase) Note lath-like habit of sericite and its ubiquitous intergrowth with quartz, indicating contemporaneous development. Pyrite disseminated through this material as fine cubes up to 1mm across and clusters of cubes up to 2mm across.

B) Later euhedral and cryptocrystalline quartz forming the matrix to a breccia composed of fragments of quartz/sericite material identical to A) above. Note early fine euhedral quartz growing around clast margins and later interstitial cryptocrystalline quartz. Note that clasts host fine disseminated pyrite, while the matrix quartz is barren.

C) Euhedral quartz growing around clast and displaying simple extinction pattern near roots of crystals and fanned, feathery extinction patterns towards the tips of crystals. Typical development of chalcedonic quartz textures. Note lack of sericite intergrown with quartz and the absence of opaque phases.

D)Late subhedral quartz showing simple extinction patterns in crystal cores with rims commonly displaying fanned, feathery extinction patterns. Note also interstitial cryptocrystalline quartz. Illustrates transitional form of late quartz in gold mineralised breccias from Dalnessie; from euhedral/subhedral form through chalcedonic textures to a cryptocrystalline variety of quartz. Note lack of sericite intergrowth with quartz and the absence of opaque phases.


PLATE 14a
scale bar 2cm long

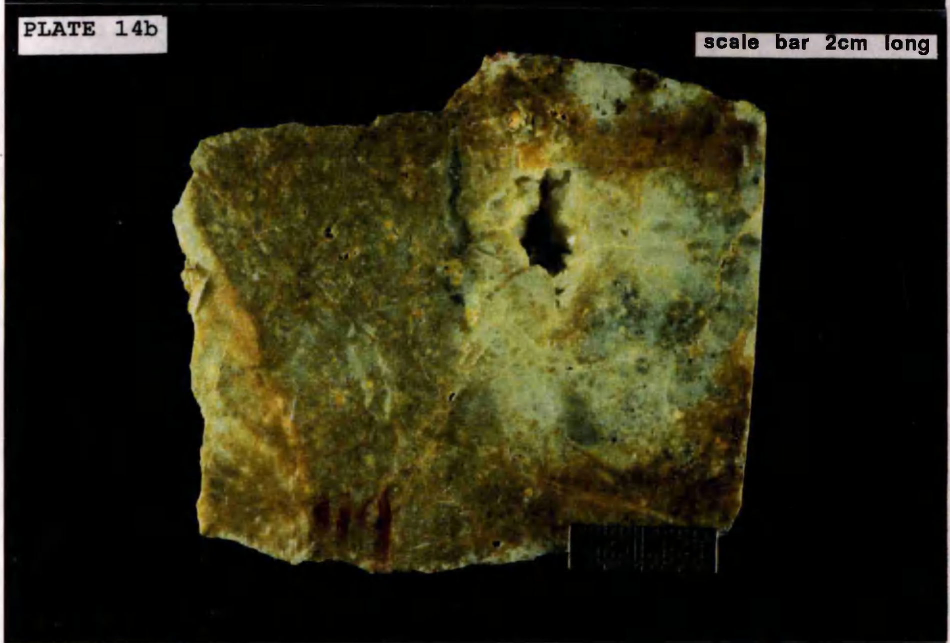


PLATE 14b
scale bar 2cm long

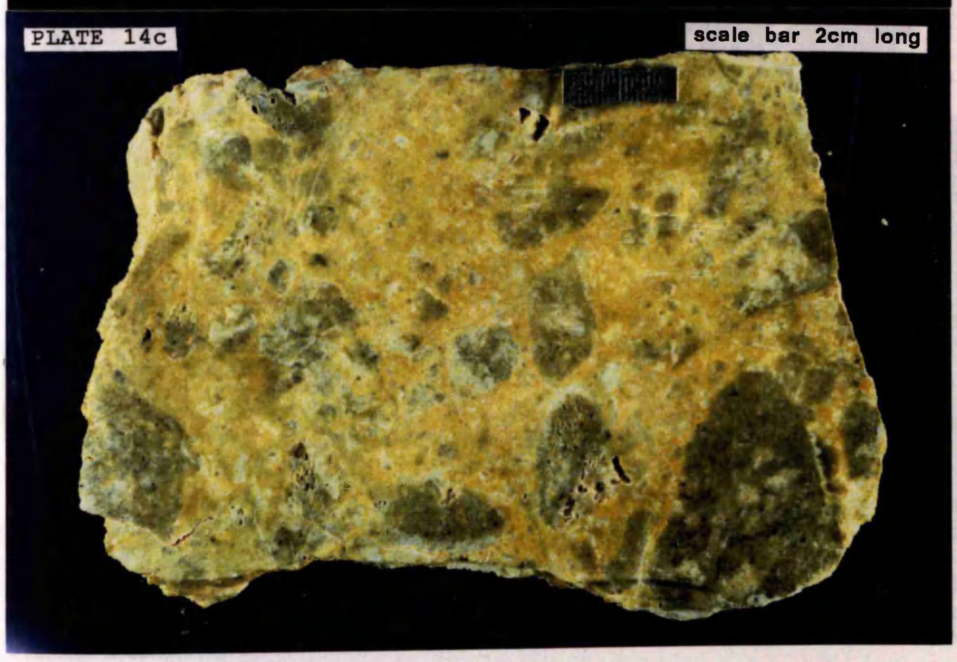


PLATE 14c
scale bar 2cm long

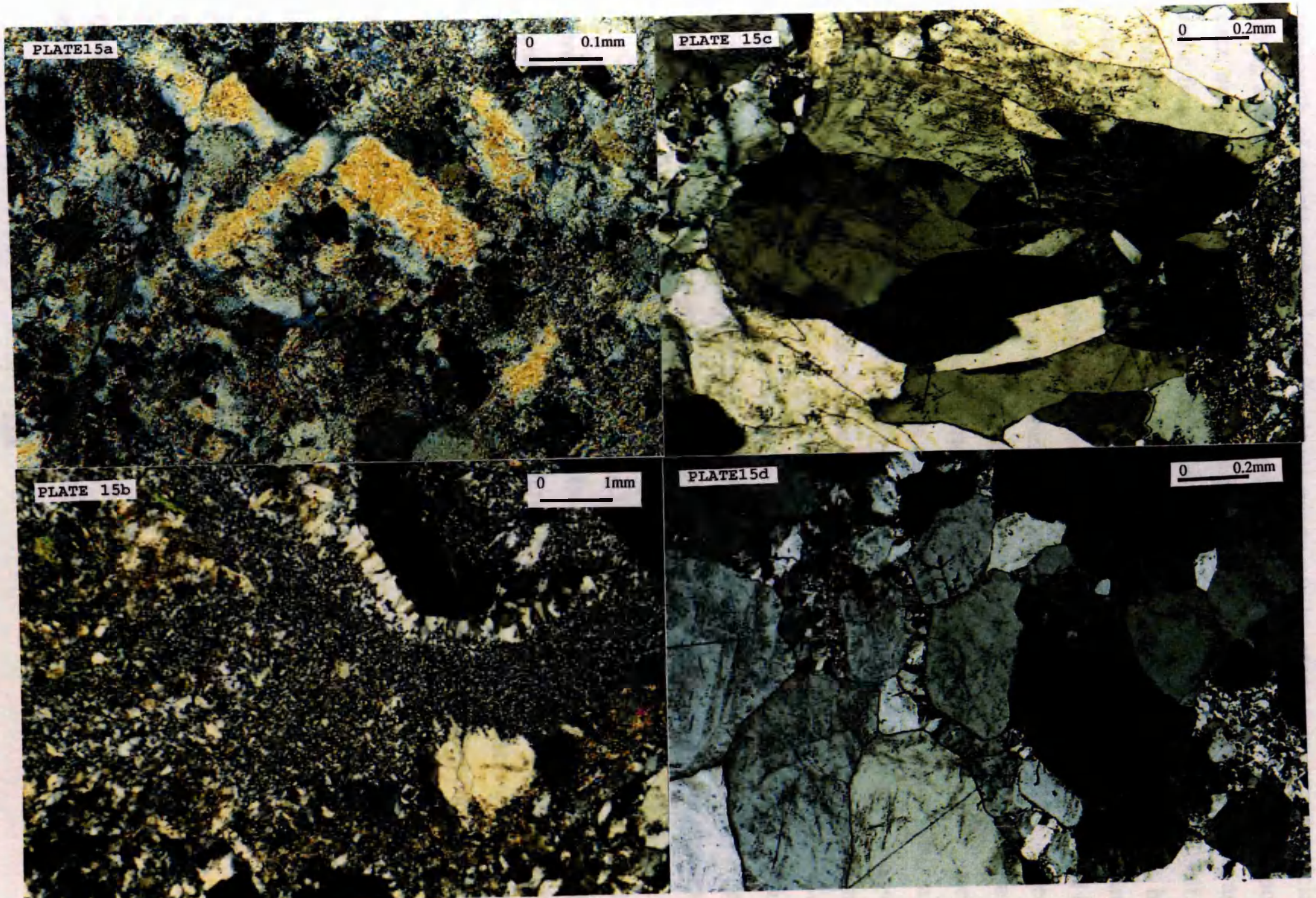


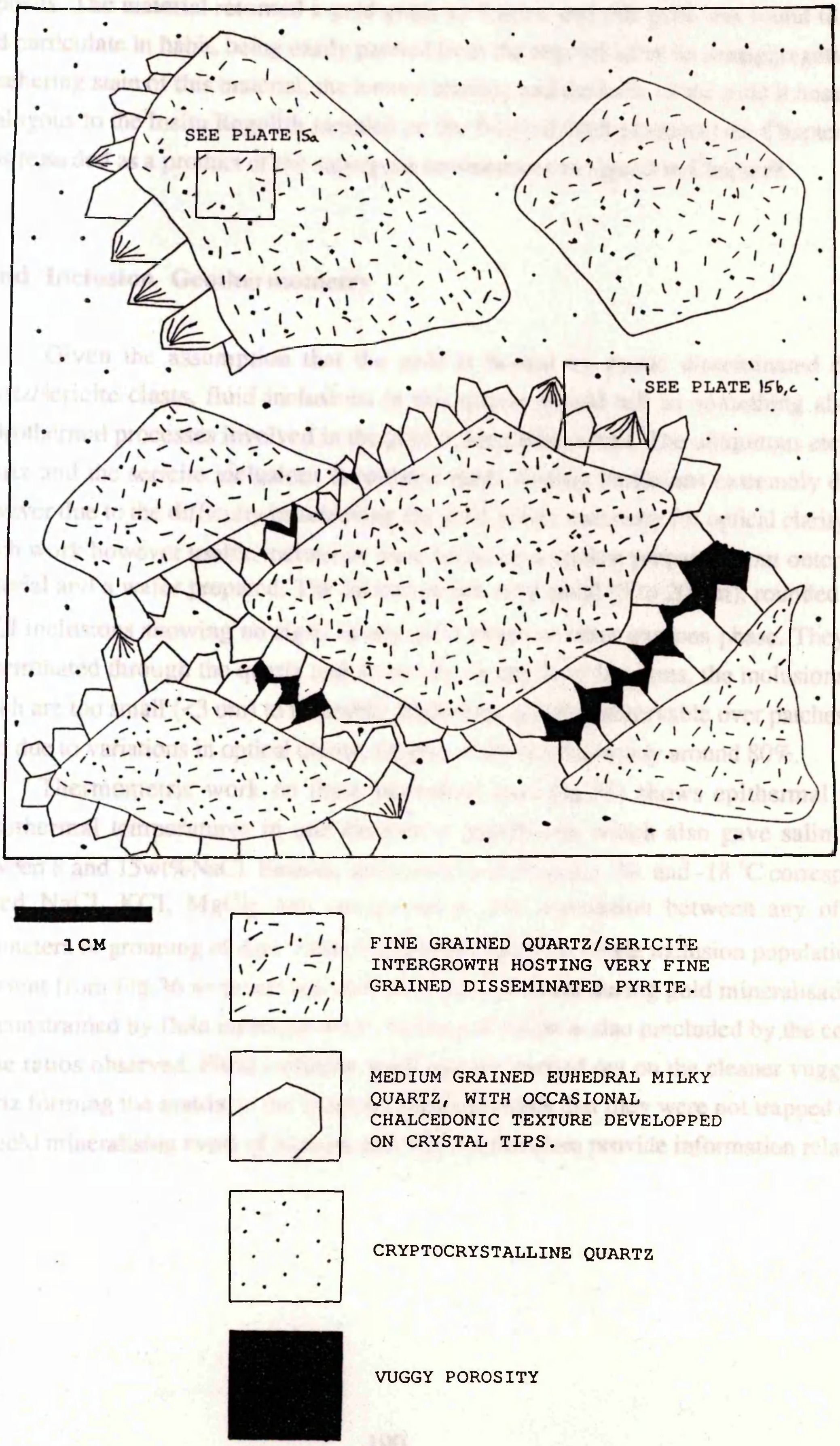
PLATE15a
0 0.1mm
PLATE 15c
0 0.2mm
PLATE 15b
0 1mm
PLATE15d
0 0.2mm

the migmatites, and no alteration halo is apparent. This mineralised outcrop proved the earlier supposition that the gold-enriched float samples were of local derivation and not the result of glacial dispersion from some distant source.

Petrographic work on mineralised material confirmed the field observation that there are two generations of hydrothermal material; a bluish pyritic quartz plus clay material forming the earlier clasts and a clean vuggy and chalcedonic quartz forming the matrix to the breccias (Plate 15). The former comprises a complex intergrowth of unstrained quartz and very finely lamellar sericite. The quartz appears heavily corroded, an effect caused by the intergrowth of quartz and sericite.. In places quartz can be seen to overgrow sericite, forming sericite inclusions in quartz. Thus sericite can be seen to be both pre and post quartz, and in all probability the intergrowth seen is a result of overlapping quartz and sericite formation. Thus quartz and sericite are roughly synchronous. The quartz itself is unstrained, anhedral to sub-hedral and generally equigranular within a single clast but crystals can range in size from 0.1mm to 1mm between clasts. The proportions of quartz and sericite are very variable also, with the latter making up anything between 15 and 60 vol% of any given clast.More sericite-rich samples also show subordinate pale green chlorite in a similar habit to sericite. Grain size of the sericite + chlorite does not increase in these samples, and nor do precursor mineralogies become any more discernible. Pyrite is disseminated through this quartz/sericite assemblage as sub- to euhedral crystals and occasional clusters of crystals. Oxidation on the weathered surface of outcrops or loose blocks converts pyrite to haematite, and causes dispersion of iron oxides through the matrix where it is adsorbed by sericite to give weathered samples their pale orangey brown colouration in hand specimen. The haematite is commonly amorphous but occasionally shows poorly developed botryoidal textures and occasional fresh pyrite cores. This pyrite is the most probable host to the gold detected by atomic absorption spectroscopy in samples of this material, but it has not been identified optically.

Later quartz forming the matrix to the breccias is unstrained and uncorroded in contrast to that in the mineralised clasts it encloses. It is also monomineralic, without any sericite or sulphides, but in oxidised samples shows surficial to sub-pervasive iron staining. This later quartz has two main habits, a vuggy and a chalcedonic, approaching cherty one, the relationship between which is not discernible in hand specimen. In section, where the two are seen together it is always the case that vuggy quartz grows out from the surfaces of the mineralised clasts, forming euhedral crystals up to 5mm long which are abruptly followed by by equigranular cryptocrystalline quartz. A probable intermediate habit of quartz is seen where the tips of some vugs exibit a feathery, fanned undulose extinction pattern which fans around the end of the quartz crystal; this is interpretted as a typical chalcedonic texture and as such is considered an intermediate development between vuggy euhedral quartz and cryptocrystalline quartz. Sander and Black (1988) describe similar plumose textures in quartz and consider it to be the result of the recrystallisation of fine to cryptocrystalline quartz, and this interpretation is proposed for the textures observed in gold bearing breccias from Dalnessie..

FIG. 35 ; SCHEMATIC REPRESENTATION OF PETROGRAPHY OF GOLD MINERALISED FLOAT AND OUTCROP SAMPLES FROM THE DALNESSIE ESTATE.



Regolith Enrichments

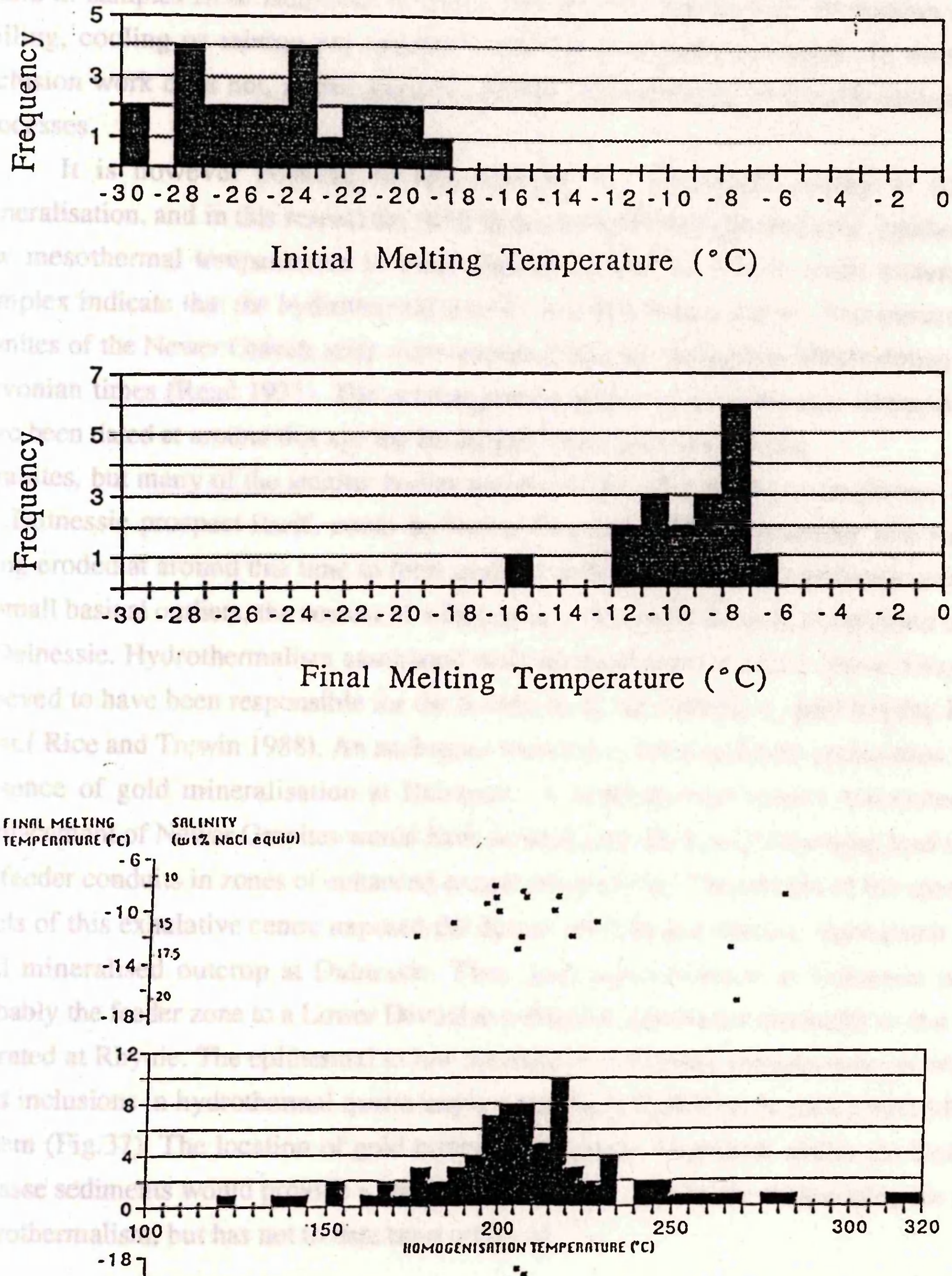
Also located during prospecting on the Dalnessie estate was a small outcrop of intensely weathered migmatite showing pervasive and intense iron and manganese staining (Fig.34) The outcrop occurred on a stream bank beneath thick glacial sand and gravel deposits. The material returned a gold grade of 3 ppm, and this gold was found to be free and particulate in habit, being easily panned from the regolith after its dissaggregation. The weathering state of this material, the intense staining and the habit of the gold it hosts are all analogous to the Insitu Regolith sampled on the Borland Glen prospect.(see Chapter 9) It is thus regarded as a product of the supergene environment as argued in Chapter9.

Fluid Inclusion Geothermometry

Given the assumption that the gold is hosted by pyrite disseminated through quartz/sericite clasts, fluid inclusions in this quartz should tell us something about the hydrothermal processes involved in the gold mineralising event. The ubiquitous etching of quartz and the sericite inclusions it contains made finding inclusions extremely difficult however due to the difficulty in achieving the good polish necessary for optical clarity. After much work however usable inclusions were found on a section prepared from outcropping material and a wafer prepared. The inclusions are very small (3 to 20 um), rounded H_20 + NaCl inclusions showing no signs of any solid phase or other gaseous phase. They occur disseminated through the quartz and do not lie on any later fractures, the inclusions along which are too small (<3 um) to be usable. Inclusions are only observable over patches of the slide due to variations in optical clarity. Degree of fill is consistently around 80%.

Thermometric work on these inclusions (see Fig.36) shows epithermal to low mesothermal temperatures in one distinctive population which also gave salinities of between 8 and 15wt%NaCl. Eutectic temperatures of between -30 and -18 °C correspond to mixed NaCl, KCl, $MgCl_2$ salt compositions. No correlation between any of these parameters or grouping of data (other than that defining the single inclusion population) are apparent from Fig.36 so processes such as mixing of fluids during gold mineralisation are not constrained by fluid inclusion work. Boiling of fluids is also precluded by the constant phase ratios observed. Fluid inclusion work was not carried out on the cleaner vuggy later quartz forming the matrix to the breccias, on the grounds that they were not trapped during the gold mineralising event of interest, and will not therefore provide information relating to it.

FIGS. 36 A-C; THERMOMETRIC CHARACTERISTICS OF GOLD MINERALISED BRECCIA FROM DALNESSIE ESTATE, CENTRAL SUTHERLAND.



Hypogene Mineralising Processes And The Geological Setting Of The Mineralisation

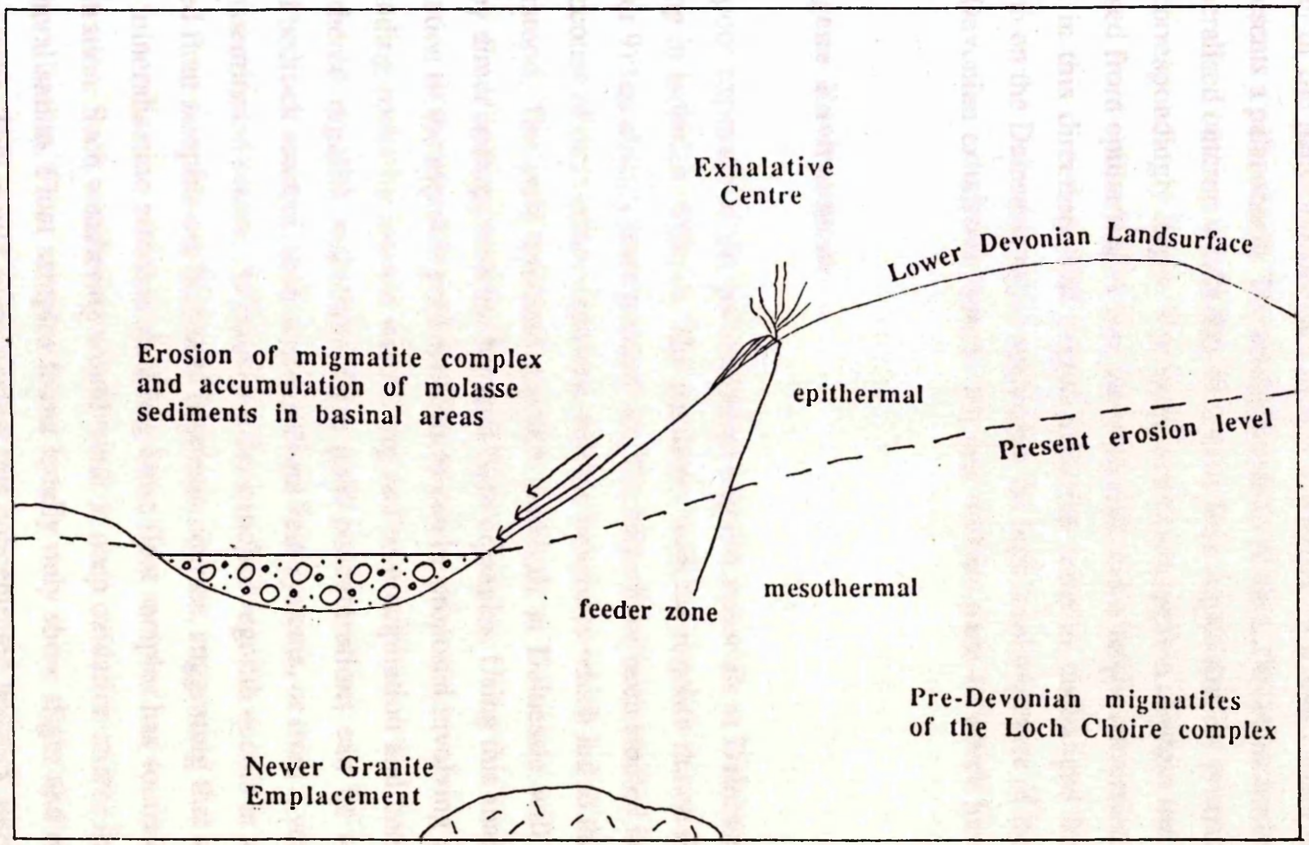
Given the limited information available from the fluid inclusion work it is difficult to constrain the mechanisms of hydrothermal gold transportation and deposition. Sulphur and chloride complexing are the modes of hydrothermal gold transportation most popularly cited in the literature (Seward 1990). No confirmatory evidence of the role of such complexing is found in samples from Dalnessie however. No obvious depositional mechanism such as boiling, cooling or mixing are apparent from the fluid inclusion study. In short, fluid inclusion work does not, in this instance, aid the understanding of specific hydrothermal processes.

It is however possible to speculate on the geological setting of the gold mineralisation, and in this respect the fluid inclusion work does prove useful. Epithermal to low mesothermal temperatures in mineralisation hosted by a high grade metamorphic complex indicate that the hydrothermal activity was post-metamorphic. Post-metamorphic granites of the Newer Granite suite were emplaced into the Sutherland Moine during Lower Devonian times (Read 1931). The nearest granite bodies to the Dalnessie prospect which have been dated at around this age are the Rogart, Helmsdale and Grudie Granites, but many of the smaller bodies mapped within the injection complexes, and on the Dalnessie prospect itself, could be Newer Granites. The metamorphic pile was also being eroded at around this time to form molasse sediments which are presently preserved as small basinal outliers, the nearest of which is only 2km from the gold mineralised outcrop at Dalnessie. Hydrothermalism associated with the emplacement of the Newer Granites is believed to have been responsible for the formation of the exhalative, gold bearing Rhynie chert.(Rice and Trewin 1988). An analogous situation is the most likely explanation for the presence of gold mineralisation at Dalnessie. A hydrothermal system associated with emplacement of Newer Granites would have exhaled onto the Lower Devonian land surface via feeder conduits in zones of enhanced crustal permeability. The erosion of the uppermost levels of this exhalative centre exposed the deeper level feeder zone(s), represented by the gold mineralised outcrop at Dalnessie. Thus, gold mineralisation at Dalnessie is most probably the feeder zone to a Lower Devonian exhalative system not dissimilar to that which operated at Rhynie. The epithermal to low mesothermal trapping temperatures recorded by fluid inclusions in hydrothermal quartz imply a relatively high level in such a hydrothermal system (Fig.37). The location of gold mineralised breccia fragments within the Devonian molasse sediments would provide a useful means of more accurately constraining the age of hydrothermalism, but has not to date been achieved.

Pressure Correction

Using the assumption that gold mineralisation at Dalnessie represents the feeder zone to an exhalative system debouching onto the now eroded Devonian land surface, a pressure

FIG; 37 PROPOSED PALAEOGEOGRAPHICAL SETTING OF GOLD MINERALISATION ON THE DALNESSIE ESTATE; THE FEEDER ZONE TO A LOWER DEVONIAN EXHALATIVE SYSTEM.



correction can be applied to the thermometric results. Using the present topographic difference in elevation of the exposed gold mineralised breccia and the Devonian outlier (130 m maximum) gives a palaeopressure of 35 bars if it is assumed to be pure lithostatic in origin, or 13 bars if the pressure is assumed to be purely hydrostatic as a consequence of unhindered hydraulic contact with the landsurface.This pressure correction when applied to homogenisation temperatures (Potter 1977), results in a small up-temperature shift, giving mean trapping temperatures of 170-240°C This method will provide a lower bound on the degree of correction to be made. The Lower Devonian outlier taken as representative of the regional level of the palaeolandsurface in fact is situated in a small basin and therefore actually represents a palaeobasin. The actual elevation of the L.Devonian landsurface above the gold mineralised outcrop would therefore have been higher and the pressure correction to be made correspondingly larger. The small correction applied changes the definition of the mineralised from epithermal to low mesothermal, and a larger correction will cause a further shift in this direction. The overall situation remains unchanged however; gold mineralisation on the Dalnessie estate represents the high level exposure of the feeder zone to a Lower Devonian exhalative system, the near surface parts of which have since been eroded.

The Supergene Environment

The poor exposure of the gold enriched regolith materials at Dalnessie make their understanding in isolation difficult. The similarity with the regolith materials in Borland Glen (Chapter 9) has already been pointed out. The latter have been studied in more detail, largely on account of their better exposure, and the processes which led to their formation better understood. The gold enriched regolith materials at Dalnessie will therefore be considered by direct analogy with the Borland Glen examples. Using this analogy, a model for the formation of the regolith gold enrichment can be proposed involving gold leaching from surrounding rocks by intense weathering and re-precipitation and concentration in deeply weathered regolith materials. Such gold concentrations can be sourced from concentrated bedrock sources, such as mineralised vein systems, or from a very large, very low grade disseminated source. At Dalnessie the enriched regolith occurs in an area where gold enriched float samples can be found in stream courses, suggesting that weathering of the bedrock mineralisation which is shedding these float samples has sourced the regolith gold concentration. Such weathering would result in deep oxidation and/or leaching of the bedrock mineralisation. Float samples found locally only show slight and non-pervasive oxidation however. This would argue against this concentrated bedrock source supplying the regolith and would point instead to a large, low grade source for this gold. However, the weathered regolith occurs beneath thick till materials, indicating that the weathering was pre-glacial in age, probably Tertiary by analogy with Borland Glen. Glacial erosion of the oxidised and leached part of the bedrock mineralisation could have occurred since then, whilst pockets of deeply weathered, gold enriched regolith could be preserved. Thus today the products of deep Tertiary weathering and Recent stream erosion of a concentrated bedrock gold source are found together. No definitive evidence is available to resolve which of the two possibilities forms the actual source of the regolith enrichment. It can only be concluded that the two possibilities are not mutually exclusive.

Exploration Significance; The Prospectivity Of The Dalnessie Estate And Of East And Central Sutherland.

1) Dalnessie

The field and petrographic work indicate a distinctive suite of gold bearing float samples of local origin and one outcrop of this material. The size and geographic distribution of these float samples around the outcrop indicate a minimum role played by glacial transport and the dominance of present day river transport as the dispersion mechanism. With this in mind it is interesting to examine the strikingly similar size and geographic distribution of the original similar suite found 2.5 km to the NW; this indicates the presence of local but unexposed outcrop of this material somewhere near the float cut-off point in the stream. Also, the persistence of this suite in the main stream and in tributary streams between these two localities is remarkable and indicates the presence of a zone prospective for gold mineralization at least 2.5 km long in this area (Fig 34).

What makes the persistence of the locally derived mineralised float even more remarkable is the terrain in which it has been identified. All the mineralised material has been found along stream courses. This is due to the absence of either outcrop or float beyond the streams. The area is characterised by a peat and glacial drift cover which each attain a thickness 10 to 12 metres. Only the highest ridges in the area where peat development has been hinderred by exposure to high winds is there any visible bedrock, and for much of their courses the headwater burns do not penetrate the thick superficial deposits. That a mineralised zone can develop a visible expression through this material is remarkable. This drift and peat cover however makes any further information on the nature of the mineralised zone extremely difficult to obtain. Soil geochemistry will not pick up any reliable expression through this type of cover, and the abundance of large blocks up to 3 m across in the till makes deep overburden sampling impractical. Geophysical methods would be unable to penetrate this extremely absorbent superficial material, and in any case it is difficult to see what, if any, geophysical contrast there would be between gold-rich but relatively sulphide poor quartz bodies and the migmatites and and gneisses characteristic of the local geology. Academically also it is extremely difficult to derive any further information on such a poorly exposed mineralised body. Fluid inclusion work is hinderred by the intense and largely pervasive etching of quartz which makes wafer preparation difficult and optics poor. Float and outcrop sample availability is limited and what is available cannot be guarantied to be representative. The Dalnessie prospect represents an awkward subject for economic or academic study on account of geographical remoteness, the poor exposure and thick superficial deposits, and this will apply equally well to most prospects in the geomorphologically similar east and central Sutherland district.

2)East and Central Sutherland

With the new information to hand it is interesting to speculate on the possibilities for bedrock gold sources to the alluvial gold showings further east in Sutherland. Lower Devonian sediments are found as small outliers scattered over a wide area of east and central Sutherland (Read 1931). It is therefore likely that much of the present land surface of this district lies at a level not far removed from the Lower Devonian palaeolandsurface. Thus it is currently exposed at a similar structural level to the Dalnessie prospect and the gold mineralisation therein. The presence of Newer Granites within the metamorphic pile together with the similarity in present exposure level renders this whole district prospective for gold mineralisation similar to that located on the Dalnessie prospect.

The other main metallogenic component in evidence at Dalnessie is the supergene environment. The effects of Tertiary weathering are only sporadically developed and/or preserved at Dalnessie, whereas they are extensively developed and/or preserved around the Helmsdale district where most of the rich placer deposits are located. As argued for Borland Glen (Chapter 9), these deposits can form by deep Tertiary weathering of a very large, very low grade disseminated source. The Helmsdale Granite is likely in this case to represent this source, in an analogous way to the Devonian volcanic succession at Borland Glen. However the Tertiary weathering model and the presence of a concentrated bedrock source are not mutually exclusive as demonstrated by the Dalnessie prospect. Deep Tertiary weathering of a very large, low grade source is therefore the most likely source of alluvial gold at Helmsdale, but the location of a concentrated bedrock gold occurrence in this terrain (at Dalnessie) implies that the possibility of further such occurrences cannot be completely dismissed.

Conclusions

Notwithstanding the difficulties of tracing the mineralisation under thick superficial deposits and in obtaining information on the origins of the mineralisation, the work has succeeded in outlining a new area of gold mineralisation using geological prediction as a first pointer and conventional prospecting to narrow the target further, and as such it qualifies as a technical success. Mineralisation on the Dalnessie estate represents a high level feeder zone to a Lower Devonian epithermal system. Within the context of the regional geology of east and central Sutherland its presence implies the prospectivity of the whole district for such mineralisation. Deep Tertiary weathering of a very large, very low grade disseminated source remains the most likely origin of the rich alluvial placers located inland of Helmsdale, but the presence of further concentrated bedrock sources in this terrain is a distinct possibility.

CHAPTER 9

DEEP PREGLACIAL WEATHERING AND RECENT ALLUVIAL REWORKING ON THE OCHILS/BORLAND GLEN GOLD PROSPECT, PERTH AND KINROSS

Introduction

Work on the Ochils/Borland Glen prospect was partly carried out in conjunction with other Navan Resources staff but the results are geologically important and so will be mentioned briefly here. The work was stimulated by the results of earlier reconnaissance and follow-up work by BGS in the area. Regional stream sampling across the extent of the Tay-Forth sheet indicated widespread alluvial gold occurrences mainly over the outcrop area of the Devonian volcanic sequence of Central Scotland (Fig 38), as well as several localised and extensive arsenic anomalies in stream sediments over a similar area. The most spectacular alluvial showing discovered was in Borland Glen, where rice-sized gold grains were found regularly in certain parts of the stream. The catchment area of the stream was subjected to soil geochemical and VLF/IP geophysical surveys by BGS as well as geological prospecting. A gossanous agglomerate outcrop at the head of the glen was found to be associated with distinctive IP anomalies and was subsequently drilled. Sulphide mineralization was intersected at depth but returned poor gold grades of up to 500 ppb.

Navan Resources took over the license once the BGS information had gone public. Blanket coverage by soil geochemistry located one coherent but low-order anomaly on the hillside above the stream, and geological prospecting showed up several variously pyritic, kaolinised, silicified, carbonated and generally altered looking float and outcrop samples from across the prospect. The soil anomaly was not followed up due to the small order of the anomaly, and none of the mineralised/altered float or outcrop samples returned anomalous gold grades. It was at this point, and with the BGS experience in mind, that it was decided to change the emphasis of the exploration effort to investigate the alluvial gold occurrences as alluvial deposits in their own right rather than trying to trace the gold back to a bedrock source.

Geomorphologically, Borland Glen appears as a typical Scottish upland valley, with steep sides for much of their height, a platform of glacial till materials near the base of the valley and a steep V-shaped valley cutting through this platform. The derivation of such features is through infill of a pre-existing valley with glacial deposits followed by renewed stream erosion through these till materials, forming a platform dissected by Recent streams. This till sequence was considered to be a potential source of the alluvial gold in the Recent stream and was therefore targeted for investigation. The till materials themselves were exposed in landslip scarps, in cuttings made by sheep and in erosive bends in the stream, and such localities were sampled and panned. Initial indications were that a layer of reddy-brown angular felsitic gravel exposed sporadically around stream level was highly enriched in gold whilst exposures higher up the till sequence were not appreciably enriched. Further exposure of the till sequence was required to verify this, and was achieved by a pitting program covering the area of greatest gold concentration in the stream. Pitting was undertaken using a JCB and revealed a consistent till stratigraphy typified by Fig 41.

Sampling and panning of the various till components showed the basal iron/manganese stained felsitic material, where present, to be highly enriched in gold, and

PLATE 16; THE GEOMORPHOLOGY OF BORLAND GLEN

A) General Geomorphology of Borland Glen; Note the overall V-shape of the valley with thick overburden deposits forming pronounced terraces near the base of the glen and incision of these terraces by Recent stream action to produce a steep V-shaped profile to the very base of the valley. Note also the abundant land-slip scarps on the steep faces of many of these incised overburden terraces. Figures 41a-c represent schematic profiles across the bottom of this valley.

B) Prominent bedrock high on floor of the upper reaches of Borland Glen. Bedrock ridge crosses valley floor and unusual thicknesses of Bouldery Alluvium are developed on its upstream side. Local alluvial environment on upstream side of bedrock high is strongly depositional with respect to gold, resulting in unusually high gold concentrations in the Bouldery Alluvium and immediately underlying regolith materials in this vicinity.

PLATE 17; THE GOLD ENRICHED SUPERFICIAL MATERIALS OF BORLAND GLEN

A) Excavated exposure of Bouldery Alluvium on the banks of the stream in Borland Glen. Notice large size and high degree of roundness of boulders, which are composed of both local and exotic lithologies, probably derived from the Boulder Clay through erosion and reworking by Recent alluvial activity. Note also the gritty, gravelly consistency of the matrix, which hosts the gold in this material, and is composed of dominantly angular local materials. Exposure lies just upstream of the bedrock high shown on Plate 16B above and is the most gold-rich locality found in Borland Glen.

B) Transported Regolith material exposed beneath topsoil in a ditch excavated in Borland Glen. Note very distinctive orange staining of angular gravel fragments and the lack of any discernible structure to the deposit. Exposure lies close to edge of till sheet, and regolith becomes buried by Boulder Clay towards the north. Insitu Regolith displays similar colouration but shows a clearly developed joint pattern. Both deposits are compact in consistency, with the latter becoming unrippable with depth.


PLATE16a


PLATE 17a


PLATE16b


PLATE 17b

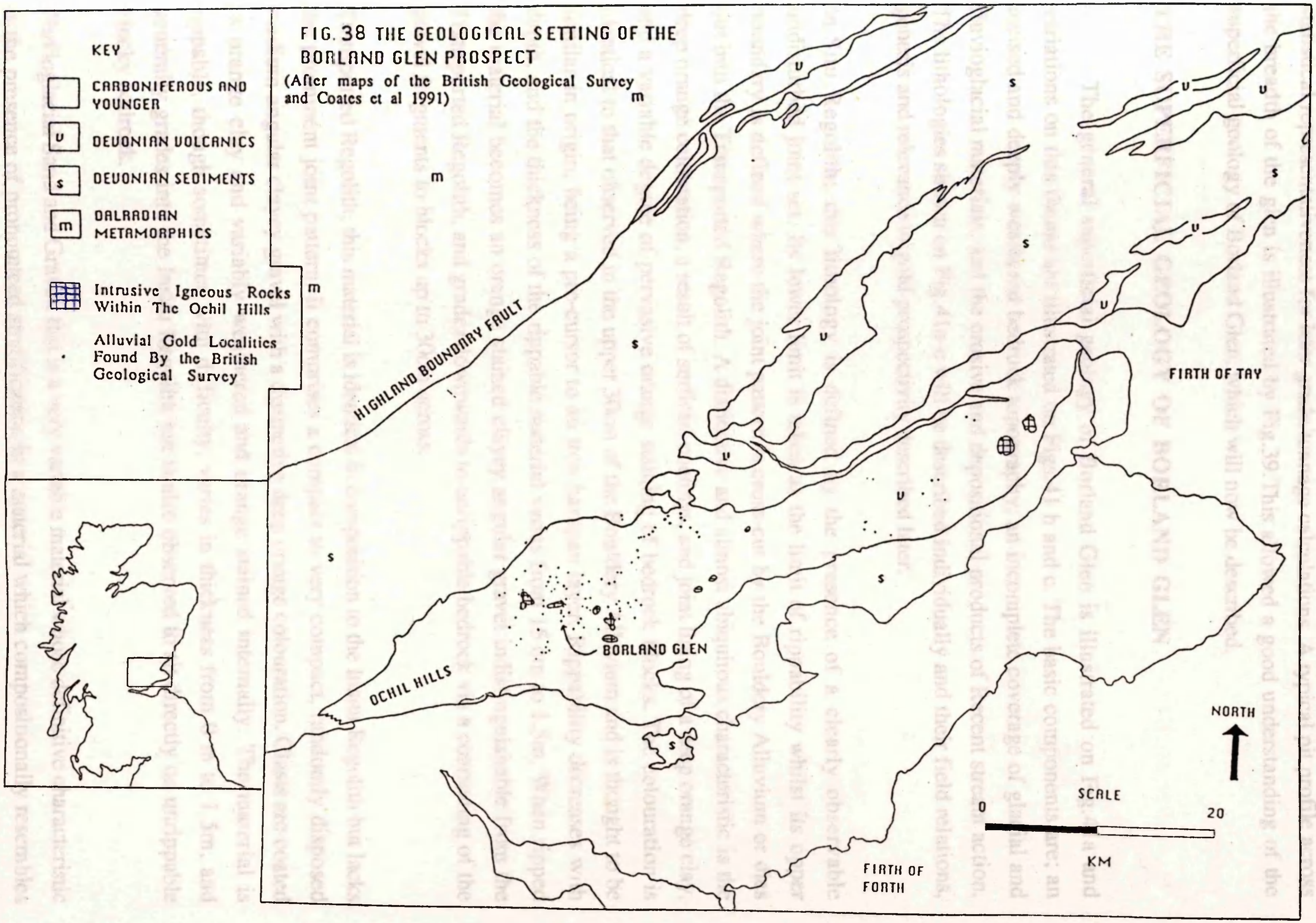


FIG. 38 THE GEOLOGICAL SETTING OF THE BORLAND GLEN PROSPECT
(After maps of the British Geological Survey and Coates et al 1991)

the underlying broken bedrock material was also enriched where it was exposed below this basal till layer.This initial pitting programme further stimulated interest in the prospect and so another more thorough pitting programme was undertaken. Pits were excavated along the length and across the breadth of Borland Glen in order to give good geological coverage and statistical representativeness for later grade/tonnage calculations. A typical pit profile across the breadth of the glen is illustrated by Fig.39.This allowed a good understanding of the superficial geology of Borland Glen, which will now be described.

THE SUPERFICIAL GEOLOGY OF BORLAND GLEN

The general superficial geology of Borland Glen is illustrated on Fig.41a and variations on this theme are illustrated on Figs.41 b and c. The basic components are; an incised and deeply weathered bedrock topography; an incomplete coverage of glacial and fluvioglacial materials; and the erosive and depositional products of Recent stream action. The lithologies shown on Fig.41a-c will be described individually and their field relations, genesis and relevance to gold prospectivity described later.

In-Situ Regolith; this lithology is defined by the presence of a clearly observable undisturbed joint set. Its lower limit is taken as the limit of rippability whilst its upper boundary is defined where the joint pattern is cross-cut by the Bouldery Alluvium or dies out into the Transported Regolith. A distinctive and almost ubiquitous characteristic is the deep orange colouration, a result of surficial coatings, and joint lining of a deep orange clay, and a variable degree of pervasive orange staining of bedrock blocks. The colouration is identical to that observed in the upper 30cm of the Bouldery Alluvium and is thought to be similar in origin, being a pre-cursor to an iron hardpan layer. Rippability decreases with depth, and the thickness of the rippable material varies from 15 cm to 1.5m. When ripped the material becomes an orange stained clayey angular gravel indistinguishable from the Transported Regolith, and grades downwards to unrippable bedrock via a coarsening of the gravel fragments to blocks up to 30cm across.

Transported Regolith; this material is identical in composition to the Insitu Regolith but lacks the prominent joint pattern. It comprises a compact to very compact, randomly disposed medium angular clayey gravel with a distinctive deep orange colouration. Clasts are coated in orange clay and variably weathered and orange stained internally. The material is rippable, though sometimes with difficulty, varies in thickness from 0 m to 1.5m, and generally grades into the Insitu Regolith but is also observed to sit directly on unrippable blocky bedrock.

Fluvioglacial Sand and Gravel; this is a very variable material whose definitive characteristic is the presence of pronounced stratification in a material which compositionally resembles the Bouldery Alluvium. Where subcropping beneath the topsoil it supports a bracken and

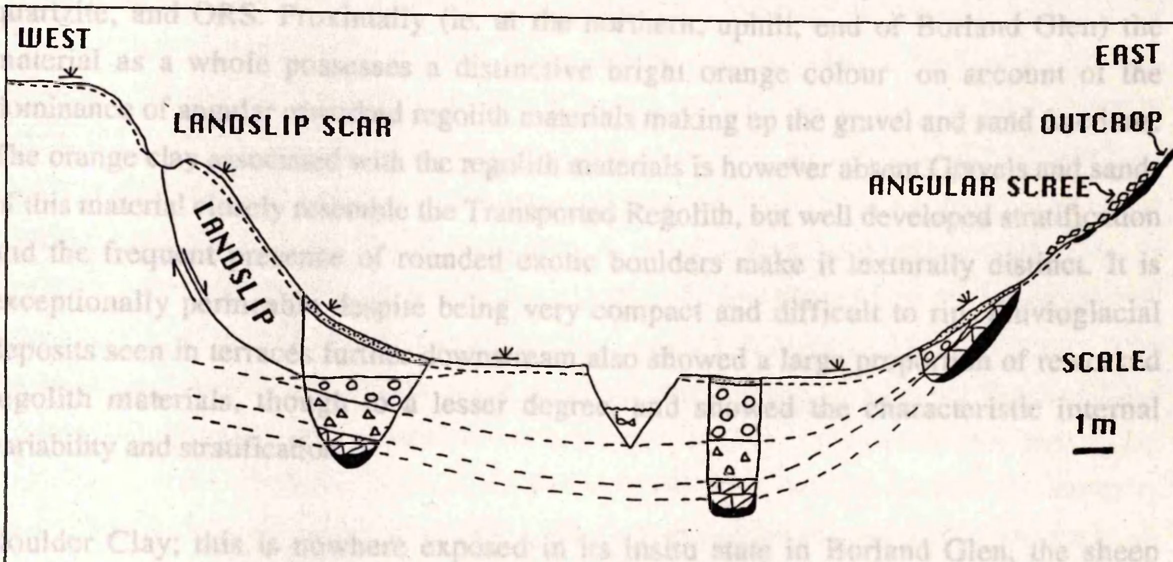


FIG.39 TYPICAL PIT PROFILE ACROSS THE FLOOR OF BORLAND GLEN, PERTH AND KINROSS, SCOTLAND (For Key see page 206)

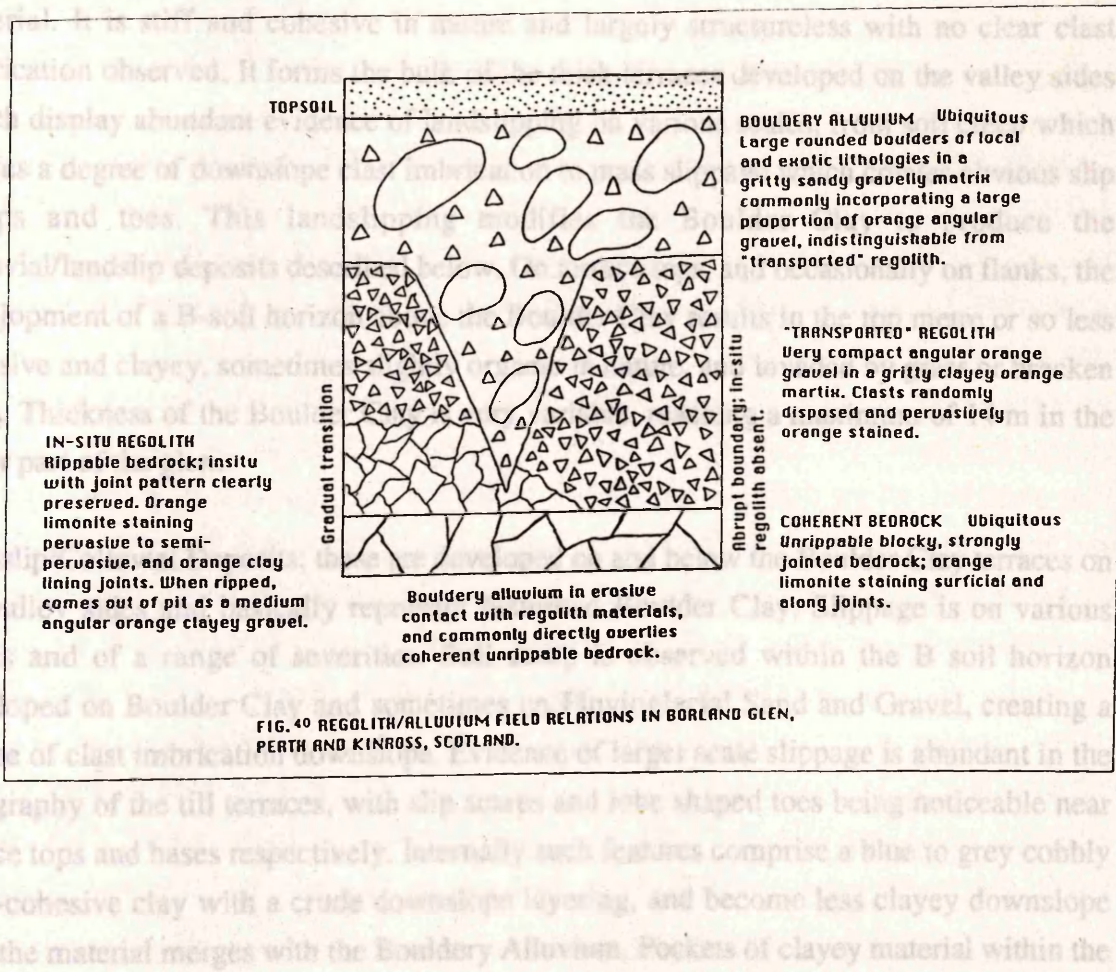


FIG. 40 REGOLITH/ALLUVIUM FIELD RELATIONS IN BORLAND GLEN, PERTH AND KINROSS, SCOTLAND.

heather flora on account of the good drainage it imparts to the ground, in contrast to the grass and reeds which grow above the Boulder Clay. The material comprises layered sands, gravels and pebbles of angular to well rounded shapes. Clast lithologies are variable but include both local volcanics and intrusives and exotic schists, epidiorite,vein quartz, quartzite, and ORS. Proximally (ie. at the northern, uphill, end of Borland Glen) the material as a whole possesses a distinctive bright orange colour on account of the dominance of angular reworked regolith materials making up the gravel and sand fractions. The orange clay associated with the regolith materials is however absent.Gravels and sands of this material closely resemble the Transported Regolith, but well developed stratification and the frequent presence of rounded exotic boulders make it texturally distinct. It is exceptionally permeable despite being very compact and difficult to rip. Fluvioglacial deposits seen in terraces further downstream also showed a large proportion of reworked regolith materials, though to a lesser degree, and showed the characteristic internal variability and stratification.

Boulder Clay; this is nowhere exposed in its insitu state in Borland Glen, the sheep scratchings and exposed landslips never penetrating through the B soil horizon developed over the till. In pits it was observed to be an overconsolidated grey to purple/grey clay incorporating large boulders of dominantly exotic lithologies (quartzite, vein quartz, ORS, epidiorite, schist) and a subordinate angular gravel fraction of local volcanic and intrusive material. It is stiff and cohesive in nature and largely structureless with no clear clast imbrication observed. It forms the bulk of the thick terraces developed on the valley sides which display abundant evidence of landslipping on various scales, from soil creep which creates a degree of downslope clast imbrication to mass slippage which creates obvious slip scarps and toes. This landslipping modifies the Boulder Clay to produce the colluvial/landslip deposits described below. On terrace tops, and occasionally on flanks, the development of a B-soil horizon above the Boulder Clay results in the top metre or so less cohesive and clayey, sometimes slightly organic in nature, and invaded by grass or bracken roots. Thickness of the Boulder Clay is very variable, reaching a maximum of 14 m in the upper part of the glen.

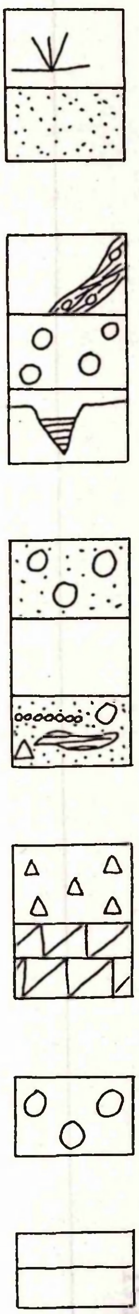
Landslip/Colluvial Deposits; these are developed on and below the Boulder Clay terraces on the valley sides and basically represent disturbed Boulder Clay. Slippage is on various scales and of a range of severities. Soil creep is observed within the B soil horizon developed on Boulder Clay and sometimes on Fluvioglacial Sand and Gravel, creating a degree of clast imbrication downslope. Evidence of larger scale slippage is abundant in the topography of the till terraces, with slip scarps and lobe shaped toes being noticeable near terrace tops and bases respectively. Internally such features comprise a blue to grey cobbly semi-cohesive clay with a crude downslope layering, and become less clayey downslope until the material merges with the Bouldery Alluvium. Pockets of clayey material within the Bouldery Alluvium are a result of this intermixing. Despite the clear topographic evidence for landslipping, discrete slip surfaces underground were enigmatic.

Recent Bouldery Alluvium; this lithology is commonly observable on erosive stream banks in Borland Glen. It comprises large, dominantly rounded boulders, anything up to a metre across, in a gritty, gravelly sand matrix, with the boulders commonly making up 20-30 vol% of the material.The boulder suite comprises both local and exotic lithologies. Local rock types are represented by rounded diorite boulders and angular-sub-rounded andesite, hornfels, tuff and felsite clasts. Exotic lithologies include quartzite, vein quartz, garnet schist, ORS sandstones and conglomerates and epidiorite, all rounded and probably of northern derivation.The matrix gravel comprises mainly local volcanics and intrusives as angular, generally well weathered fragments. A variably developed orange colouration to this matrix material reflects the proportion superficially and pervasively orange Fe-stained local regolith materials incorporated into the Bouldery Alluvium. An infrequently seen clayey consistency to the matrix is the result of landslipping of adjacent Boulder Clay terraces into the valley and incomplete washing by stream and groundwater after intermixing with the alluvium. The upper 30cm of the Bouldery Alluvium beneath the topsoil commonly shows the development of a bright orange oily clay, the probable precursor of an iron hard-pan layer. Thickness of the Bouldery Alluvium was very variable within the limits 30cm to 2.2m, being thickest along the axis of the valley and thinning out towards and beneath the till terraces. Variability along the axis of the valley was the result of localised topographic effects on the valley floor such as protruding bedrock mounds.

FIELD RELATIONS

The relationships between the various superficial lithologies in Borland Glen are illustrated schematically on Figs 41a-c. The lithologies can be categorised as pre-glacial, glacial and post-glacial by reference to their individual characteristics and their relationships with the other materials. The simplest to categorise are the Boulder Clay and Fluvioglacial Sand and Gravel which together constitute the glacial category. The regolith materials underly these glacial materials and are therefore pre-glacial in origin, or at least pre the glacial episode during which the materials in Borland Glen were deposited. Lithologies which formed by modification of the regolith and glacial materials are by definition post glacial; this category most obviously includes the Landslip/Colluvial Deposits and less obviously includes the Bouldery Alluvium. The latter shows a slightly more complex relationship to the Boulder Clay. In places it appears to form by a process of landslipping of Boulder Clay from the terraces followed by washing, and winnowing of the finer clays, by Recent stream action at the bottom of the valley. In places the Bouldery Alluvium is seen to underly the Boulder Clay as a wedge underneath the toe of the terrace, which thins into the terrace. Both relationships are compatible with the Bouldery Alluvium being a Recent deposit derived by stream action on, among other things, Boulder Clay, with periodic burial

KEY TO FIGS. 41 A-D (For Detailed Descriptions see Text)



Grass/Grass and Topsoil

Topsoil

Colluvium/Landslip Deposits

Bouldery Recent Alluvium

Clayey Alluvium

Bouldery Upper Till

Stiff Blue/Grey Boulder Clay

Fluvioglacial Sand and Gravel

Orange 'Transported' Regolith

Rippable Bedrock ('In-Situ' Regolith)

ORS Dominated Bouldery Valley Infill

Coherent Bedrock

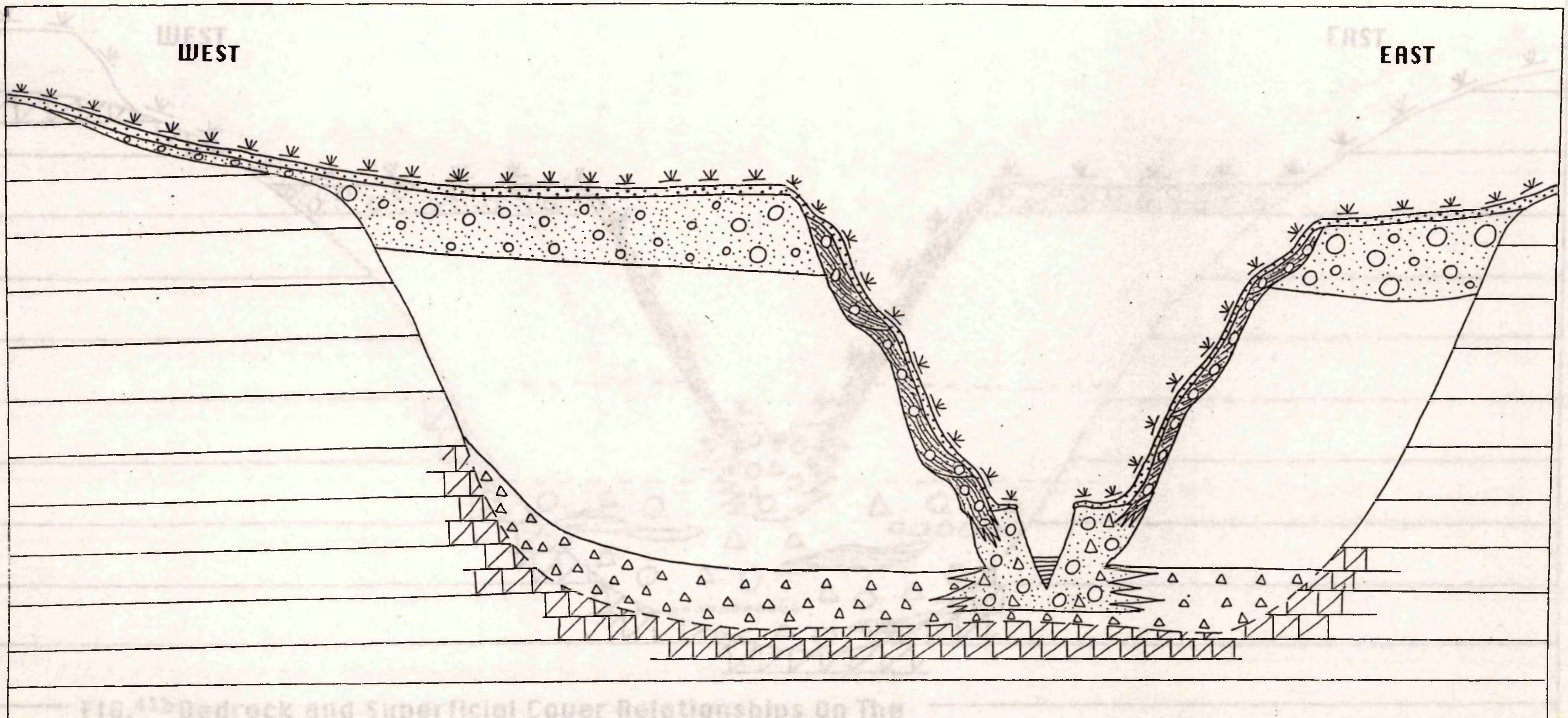


FIG. 41a Bedrock and Superficial Cover Relationships On The Borland Glen Gold Prospect, Perth and Kinross, Scotland.

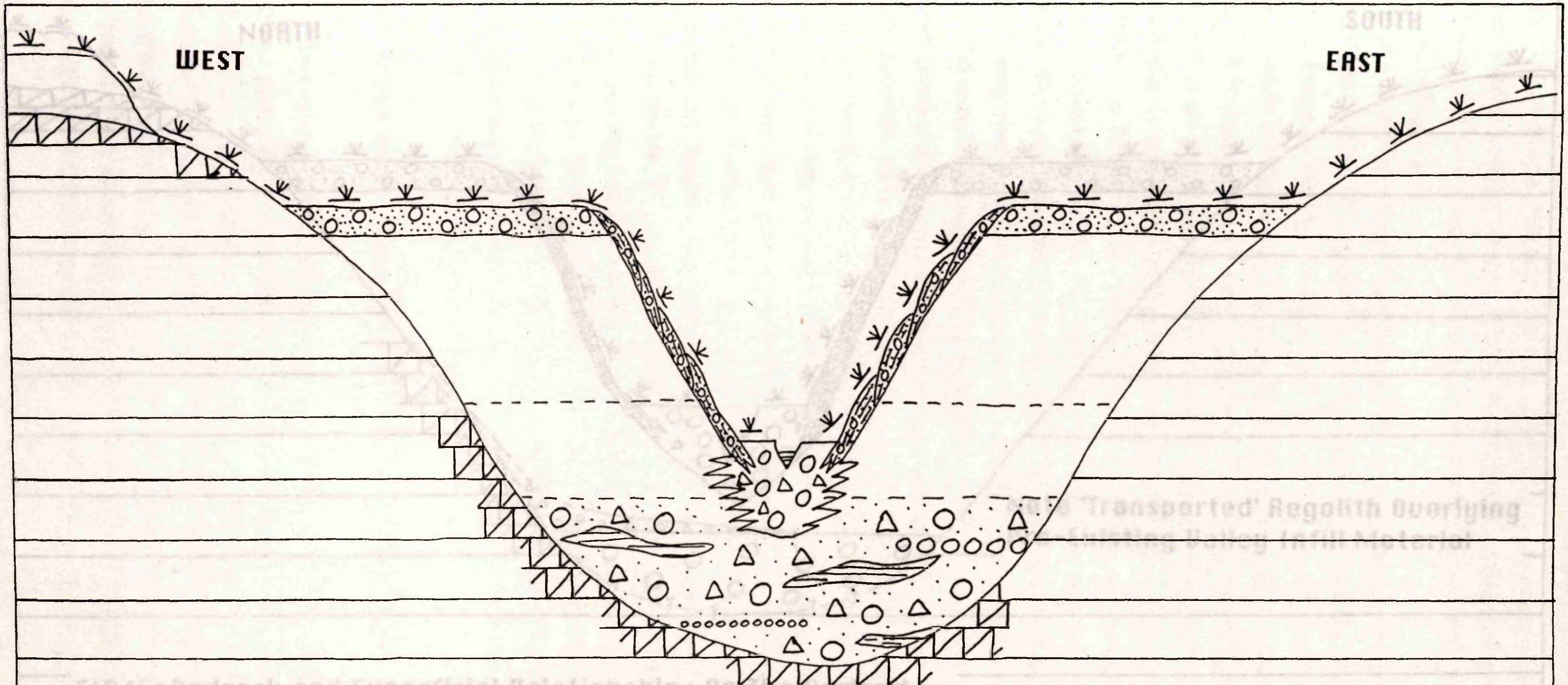


FIG. 41b Bedrock and Superficial Cover Relationships On The Borland Glen Gold Prospect, Perth and Kinross, Scotland; Variation on a Theme - Fluvioglacial Reworking Of Regolith Horizon.

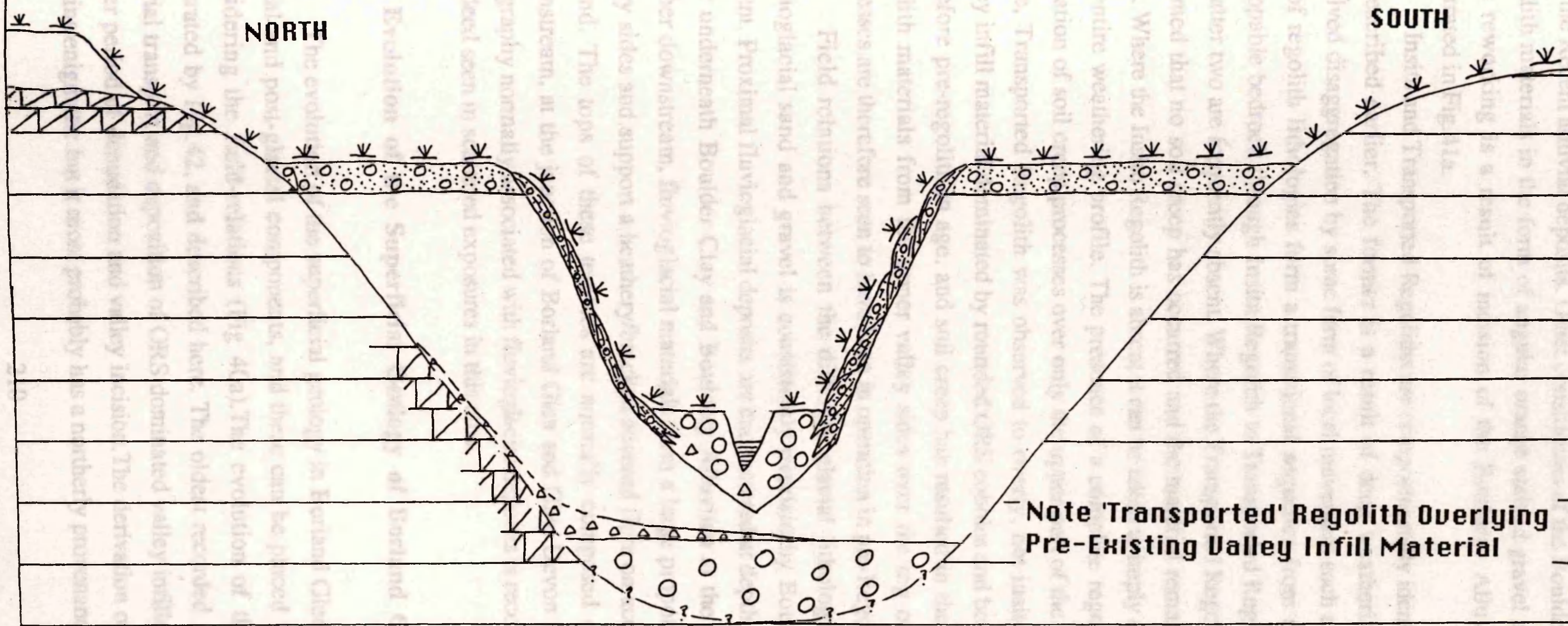


FIG 41c Bedrock and Superficial Relationships On The Borland Glen Gold Prospect, Perth and Kinross, Scotland; Variation on a Theme - Sequence Developped Over Pre-existing Valley Infill Materials.

underneath Till which has landslipped from the adjacent terrace, resulting in the latter overlying the former. The overlying Boulder Clay is eventually washed and incorporated into the Recent alluvial deposits. Other constituents of the Bouldery Alluvium are reworked regolith materials in the form of angular orange stained gravel and grit within the matrix. This reworking is a result of incision of the Bouldery Alluvium into the regolith as illustrated in Fig.41a.

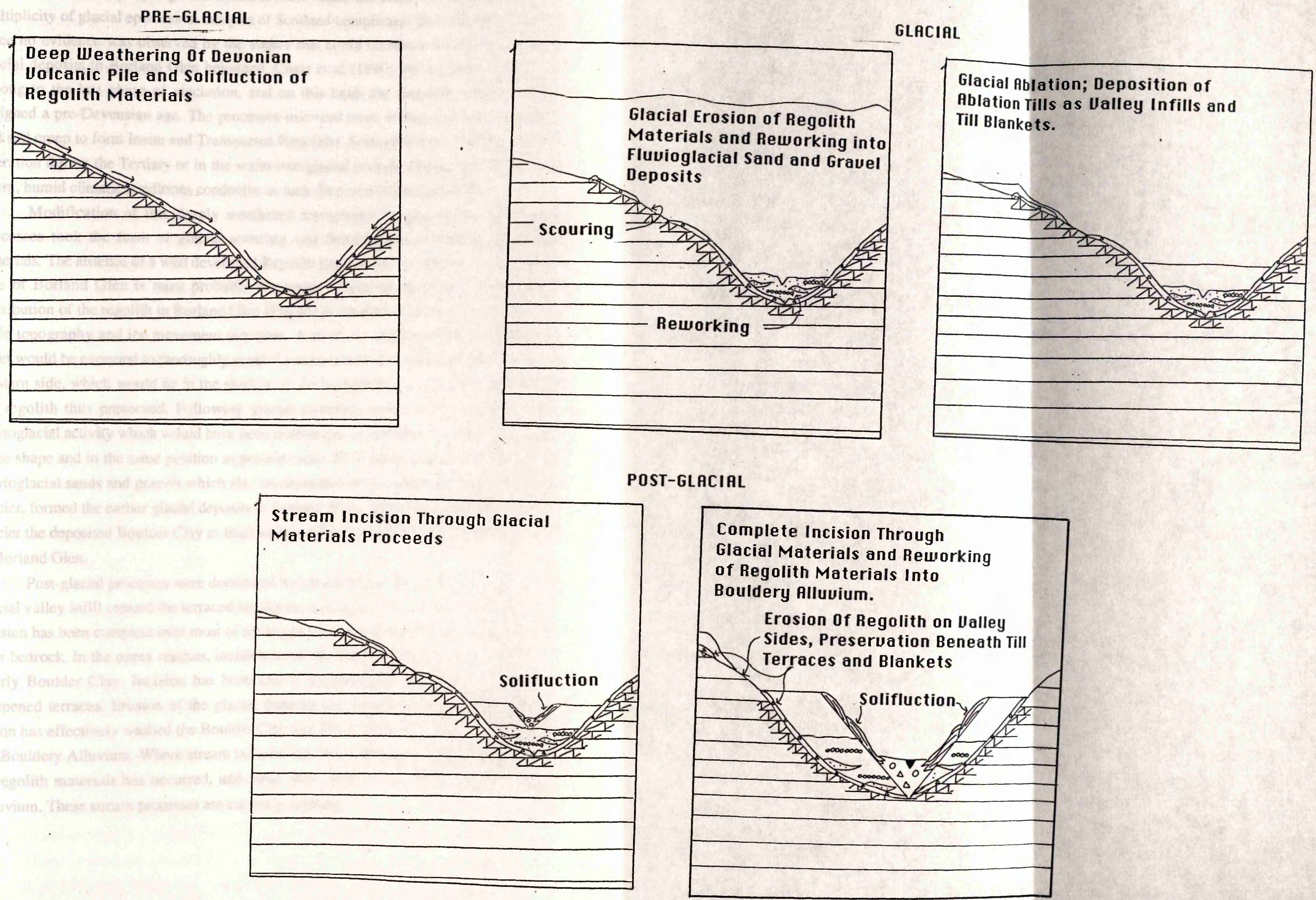
Insitu and Transported Regoliths are compositionally identical but texturally distinct, as described earlier. The former is a result of deep weathering alone whilst the latter involved disaggregation by some form of local movement such as soil creep. The complete set of regolith lithologies form a transitional sequence from (in an upwards sequence) unrippable bedrock through Insitu Regolith to Transported Regolith, but either or both of the latter two are frequently absent. Where the Transported Regolith is not present it can be assumed that no soil creep has occurred and the material remains in its insitu weathered state. Where the Insitu Regolith is absent it can be taken to imply that soil creep has involved the entire weathering profile. The presence of a complete regolith transition implies the operation of soil creep processes over only the upper part of the weathering profile. In one place, Transported Regolith was observed to overly, not insitu bedrock but a bouldery valley infill material dominated by rounded ORS cobbles and boulders. This valley infill is therefore pre-regolith in age, and soil creep has resulted in the downslope movement of regolith materials from the upper valley sides over the top of it. High energy alluvial processes are therefore seen to have been in operation in pre-Regolith times.

Field relations between the different glacial lithologies are relatively simple. Fluvioglacial sand and gravel is consistently overlain by Boulder Clay where both are present. Proximal fluvioglacial deposits are encountered at depth beneath the present valley floor underneath Boulder Clay and Bouldery Alluvium at the northern end of the glen. Further downstream, fluvioglacial materials form a large proportion of the terraces on the valley sides and support a heathery/bracken covered flora on account of the better drained ground. The tops of these terraces are normally composed of Boulder Clay. Further downstream, at the junction of Borland Glen and Glen Devon the characteristic moundy topography normally associated with fluvioglacial deposits is recognisable and such material is indeed seen in scattered exposures in this area.

The Evolution of the Superficial Geology of Borland Glen

The evolution of the superficial geology in Borland Glen has involved pre-glacial, glacial and post-glacial components, and these can be placed in chronological order by considering the field-relations (Fig 40a).The evolution of the superficial geology is illustrated by Fig.42, and described here. The oldest recorded superficial process is the alluvial transport and deposition of ORS dominated valley infills, and this implies an even earlier period of denudation and valley incision.The derivation of this valley infill material remains enigmatic but it most probably has a northerly provenance since extensive deposits

FIG. 42 EVOLUTION OF THE SUPERFICIAL GEOLOGY OF BORLAND GLEN, PERTH AND KINROSS, SCOTLAND



of ORS are to be found in Strathmore. The presence of other such deeply buried pre-existing valleys is indicated geophysically (C.Woodham 1991).

The development of a widespread deeply weathered Regolith on this dissected landscape was clearly a pre-glacial event, at least within the context of Borland Glen. The multiplicity of glacial episodes in this part of Scotland complicates this conclusion however since no evidence was observed by the author that could constrain to which episode the glacial deposits in Borland Glen belonged. Coats et al (1990) believe however that they belong to the last phase of glaciation, and on this basis the Regolith materials can be assigned a pre-Devensian age. The processes involved were widespread deep weathering and soil creep to form Insitu and Transported Regoliths. Such processes could have been in operation during the Tertiary or in the warm interglacial periods, during both of which the warm, humid climatic conditions conducive to such deep weathering prevailed.

Modification of this deeply weathered topography by glacial and fluvioglacial processes took the form of glacial scouring and fluvioglacial reworking of Regolith materials. The absence of a well developed Regolith sequence over large parts of the eastern side of Borland Glen is most probably the result of glacial scouring. The assymetric distribution of the regolith in Borland Glen (Fig 45) is considered to be a function of large-scale topography and ice movement direction. A south to southeastwards advancing ice sheet would be expected to thoroughly scour the eastern side of the valley whilst leaving the western side, which would be in the shadow of the topography, relatively untouched, and the regolith thus preserved. Following glacial scouring, retreat of the ice gave rise to fluvioglacial activity which would have been confined to contemporary valleys (roughly the same shape and in the same position as present ones). Reworking of regolith materials into fluvioglacial sands and gravels which also incorporated exotic materials transported by the glacier, formed the earlier glacial deposits in Borland Glen. Wholesale insitu ablation of the glacier the deposited Boulder Clay as thick valley infills and thin blankets covering hillsides in Borland Glen.

Post-glacial processes were dominated by stream action. Stream incision through the glacial valley infill created the terraced landforms seen at the base of the valley today. This incision has been complete over most of the length of the glen, with the stream now flowing over bedrock. In the upper reaches, incision is incomplete and the Recent alluvial deposits overly Boulder Clay. Incision has been and is accompanied by landslipping of over-steepened terraces. Erosion of the glacial deposits and subsequent reworking by stream action has effectively washed the Boulder Clay and Fluvioglacial Sand and Gravel to form the Bouldery Alluvium. Where stream incision has been complete, erosion and reworking of regolith materials has occurred, and these have been incorporated into the Bouldery Alluvium. These stream processes are currently ongoing.

Gold Grade Distribution and Controls In Superficial Materials In Borland Glen

The consistently gold enriched materials in Borland Glen, in decreasing order of geological age, are the Regolith horizons and the Recent Bouldery Alluvium.There are reasons to believe that Borland Glen represents a closed system with respect to gold input, ie. that the gold is locally derived then recycled by one or more processes operative within the glen, rather than being brought in from an exotic source. The major primary accumulation of exotic materials is the Boulder Clay, which is not enriched in gold. The other units which contain exotic materials are the Bouldery Alluvium and the Fluvioglacial Sand and Gravel. The former is derived from erosion/reworking of a Boulder Clay/Regolith mixture; since the Boulder Clay is not enriched in gold it implies that the gold in the Bouldery Alluvium is derived from the regolith. The Fluvioglacial deposits contain a large proportion of regolith materials and it is considered that this reworking is the source of the sporadic and low order enrichments of gold in this material. Therefore the various gold enrichments in Borland Glen are explainable by citing processes operative within the immediate area rather than appealing to glacial processes. Glacial erosion of regolith materials and the associated gold, and the current stream transport of gold down and probably out of the glen make the system open with respect to gold loss from the immediate area.

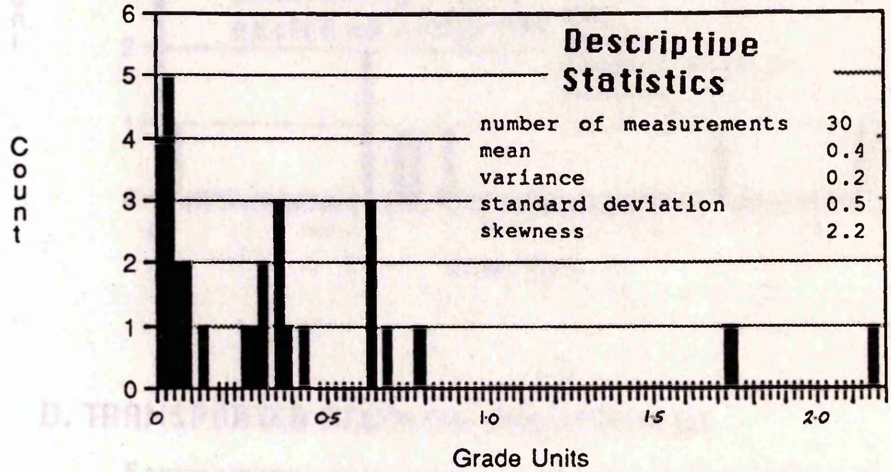
In order to protect commercially sensitive grade data the grades here are quoted in "Grade Units" which are linearly related to true grades. The weight of gold in each sample was divided by the number of units of a set volume represented by the original sample taken in the field. Thus each grade unit represents a weight divided by a volume and is related to true grade in grams/metre cubed by an undisclosed factor. This still allows the data to be treated statistically but protects its commercial sensitivity.

The grade data are tabulated by lithology in Appendix 8. The primary lithological descriptor is the nature of the material itself, and the lithology is further subdivided by a secondary descriptor, the nature of the overlying materials. The significance of this secondary descriptor will become apparent as discussion progresses. Graphical display and statistical analyses of these data are shown on Figs 43 A-G.

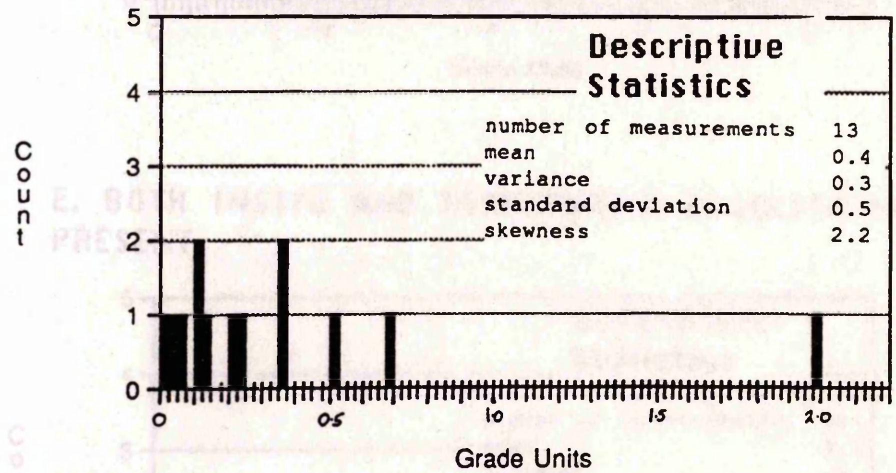
The main lithologies sampled were the Bouldery Alluvium and the Regolith materials, since they were found during earlier sampling to be the main gold enriched lithologies. The first conclusion that can be reached from graphical display of overall gold grades in these materials (Figs43 A,B) is that neither constitutes a totally reliable target as far as gold is concerned; a sizeable proportion of both have gold contents of less than 0.1 Grade Units. A wide spread of gold contents is apparent in both lithologies, with the bulk lying between 0 and 0.8 Grade Units. Rare highly enriched samples carrying up to 2.2 Grade Units of gold are present but are restricted to individual pits. Overall, the gold contents of both lithologies are statistically very similar. The reworking of a primary goldsource in the regolith by Recent alluvial processes cannot be concluded to be a grade

FIGS 43 A-G. GOLD GRADE DISTRIBUTIONS IN PROSPECTIVE GEOLOGICAL MATERIALS IN BORLAND GLEN, PERTH AND KINROSS, SCOTLAND.

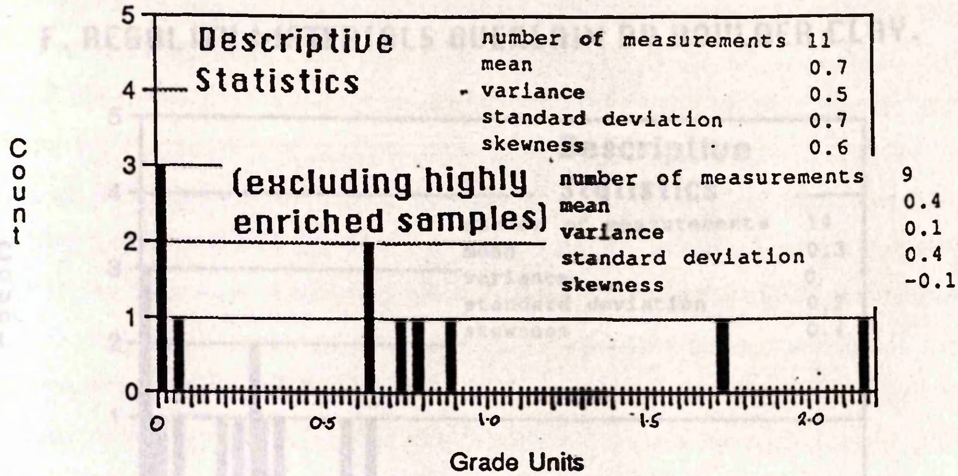
A. ALL REGOLITH MATERIALS



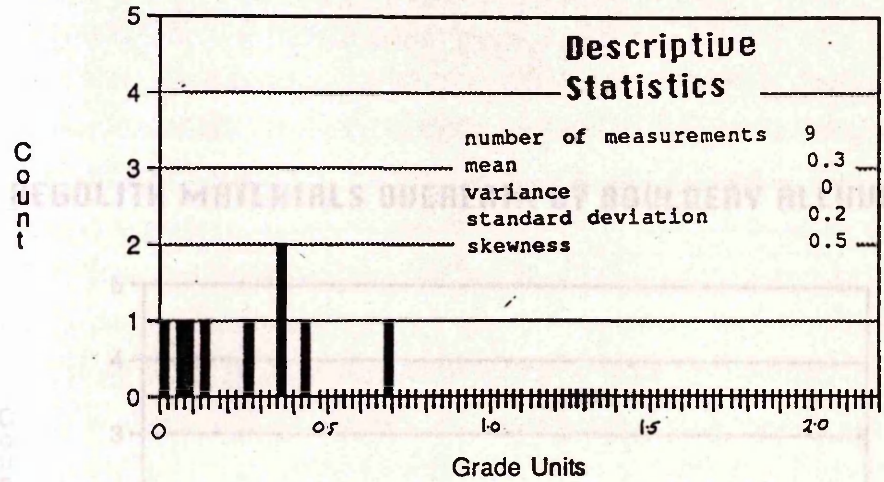
B. BOULDERY ALLUVIUM



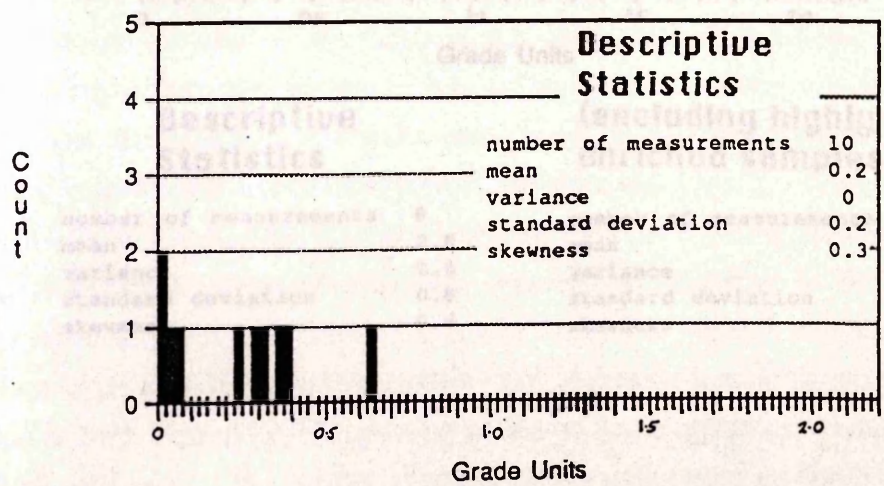
C. INSITU REGOLITH ONLY PRESENT



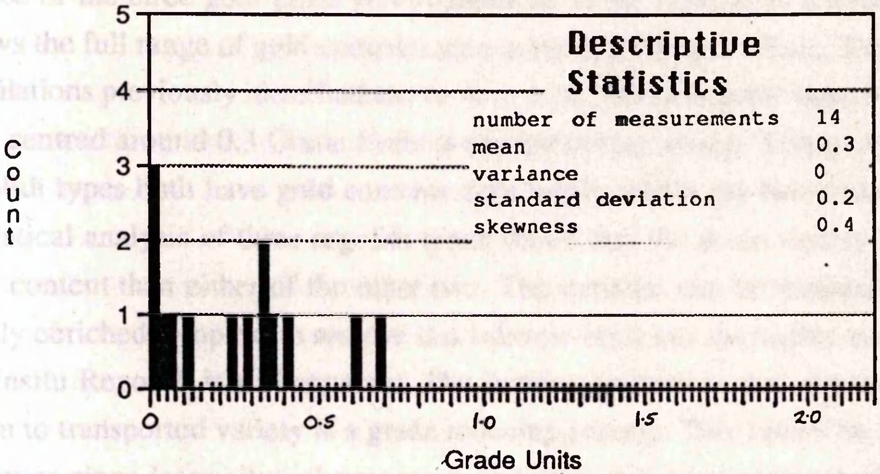
D. TRANSPORTED REGOLITH ONLY PRESENT



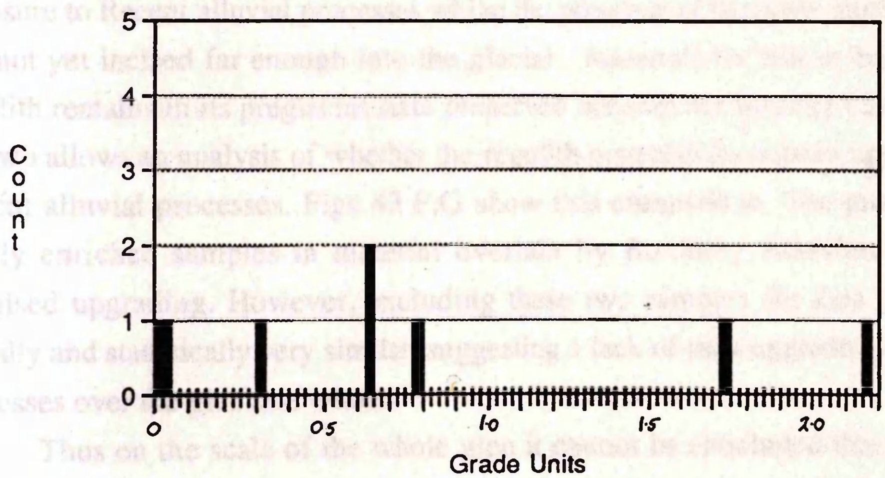
E. BOTH INSITU AND TRANSPORTED REGOLITH MATERIALS PRESENT.



F. REGOLITH MATERIALS OVERLAIN BY BOULDER CLAY.



G. REGOLITH MATERIALS OVERLAIN BY BOULDERY ALLUVIUM.



Descriptive Statistics		(excluding highly enriched samples)	
number of measurements	8	number of measurements	6
mean	0.8	mean	0.4
variance	0.6	variance	0.1
standard deviation	0.8	standard deviation	0.3
skewness	0.6	skewness	-0.1

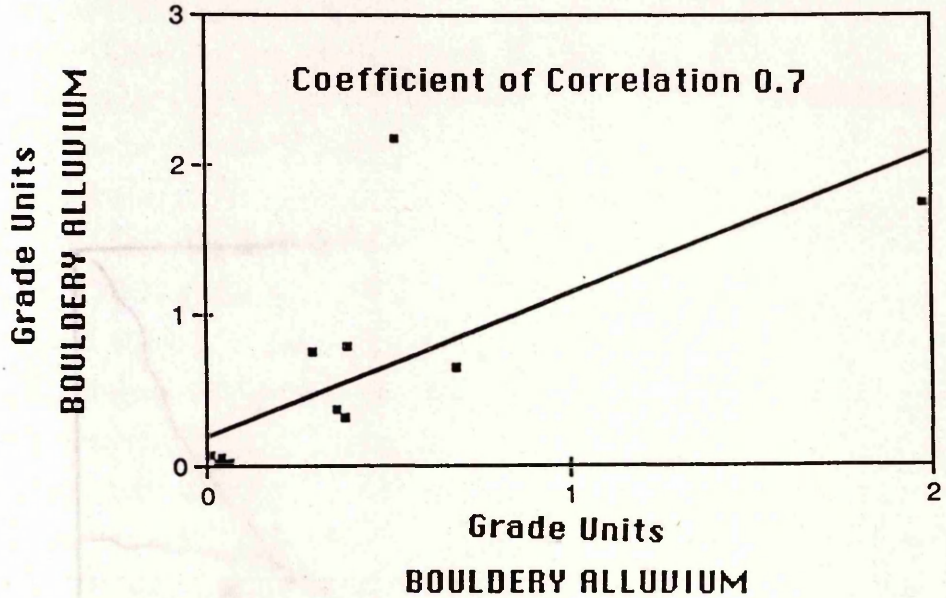
increasing or decreasing event on the scale of the whole glen therefore. No one lithology can be described as richer than the other in the overall sense.
Within the main data spreads, 3 sub-populations are discernible in the regolith materials and perhaps two in the Bouldery Alluvium.

Regolith materials can be subdivided by the specific type of regolith present; Insitu, Transported or Combined, and analysed statistically (Figs 43 C,D,E) to investigate the source of the three gold grade sub-populations in the regolith as a whole. Insitu Regolith shows the full range of gold contents seen in the regolith as a whole. Two of the three sub-populations previously identified can be seen in the Insitu Regolith data, but the intermediate one, centred around 0.3 Grade Units is conspicuously absent. Transported and Combined regolith types both have gold contents dominantly within the two lower sub-populations. Statistical analysis of three regolith types shows that the insitu variety has a higher mean gold content than either of the other two. The statistics can be recalculated excluding the highly enriched samples (to remove this inherent bias) and the higher mean gold content of the Insitu Regolith is still apparent. The implication here is that the transformation from insitu to transported variety is a grade reducing process. This cannot be said with certainty however since later alluvial processes and their upgrading/downgrading effect are not accounted for in this analysis. The available data-base is not sufficient to allow such affects to be investigated for individual regolith types.

Dividing the regolith materials according to the secondary descriptor, the nature of the overlying materials, serves to discriminate regolith that has been exposed to the Recent alluvial environment and material that has been preserved remote from it. The overlying materials are Bouldery Alluvium and Boulder Clay. The presence of the former implies exposure to Recent alluvial processes whilst the presence of the latter implies that the stream has not yet incised far enough into the glacial materials for this to be the case, and the regolith remains in its preglacial state preserved beneath the Boulder Clay. Comparison of the two allows an analysis of whether the regolith materials have been upgraded in place by Recent alluvial processes. Figs 43 F,G show this comparison. The presence of both the highly enriched samples in material overlain by Bouldery Alluvium is suggestive of localised upgrading. However, excluding these two samples the data for both cases are visually and statistically very similar, suggesting a lack of such upgrading by Recent alluvial processes over the glen as a whole.

Thus on the scale of the whole glen it cannot be concluded that any upgrading or downgrading of regolith materials has occurred on exposure to the Recent alluvial environment. Nor can it be concluded that reworking of regolith materials into Bouldery Alluvium is an overall upgrading process. The idea that physical disaggregation of Insitu Regolith to form Transported Regolith is an overall grade reducing process is suggested but downgrading of regolith materials has occurred on exposure to the Recent alluvial environment. Nor can it be concluded that reworking of regolith materials into Bouldery Alluvium is an overall upgrading process. The idea that physical disaggregation of Insitu Regolith to form Transported Regolith is an overall grade reducing process is suggested but cannot be concluded with certainty. Grade controlling processes are therefore not elucidated

FIG 44 CORRELATION GRAPH OF GOLD CONTENTS IN BOULDERY ALLUVIUM AND UNDERLYING REGOLITH MATERIALS, BORLAND GLEN, PERTH AND KINROSS, SCOTLAND.



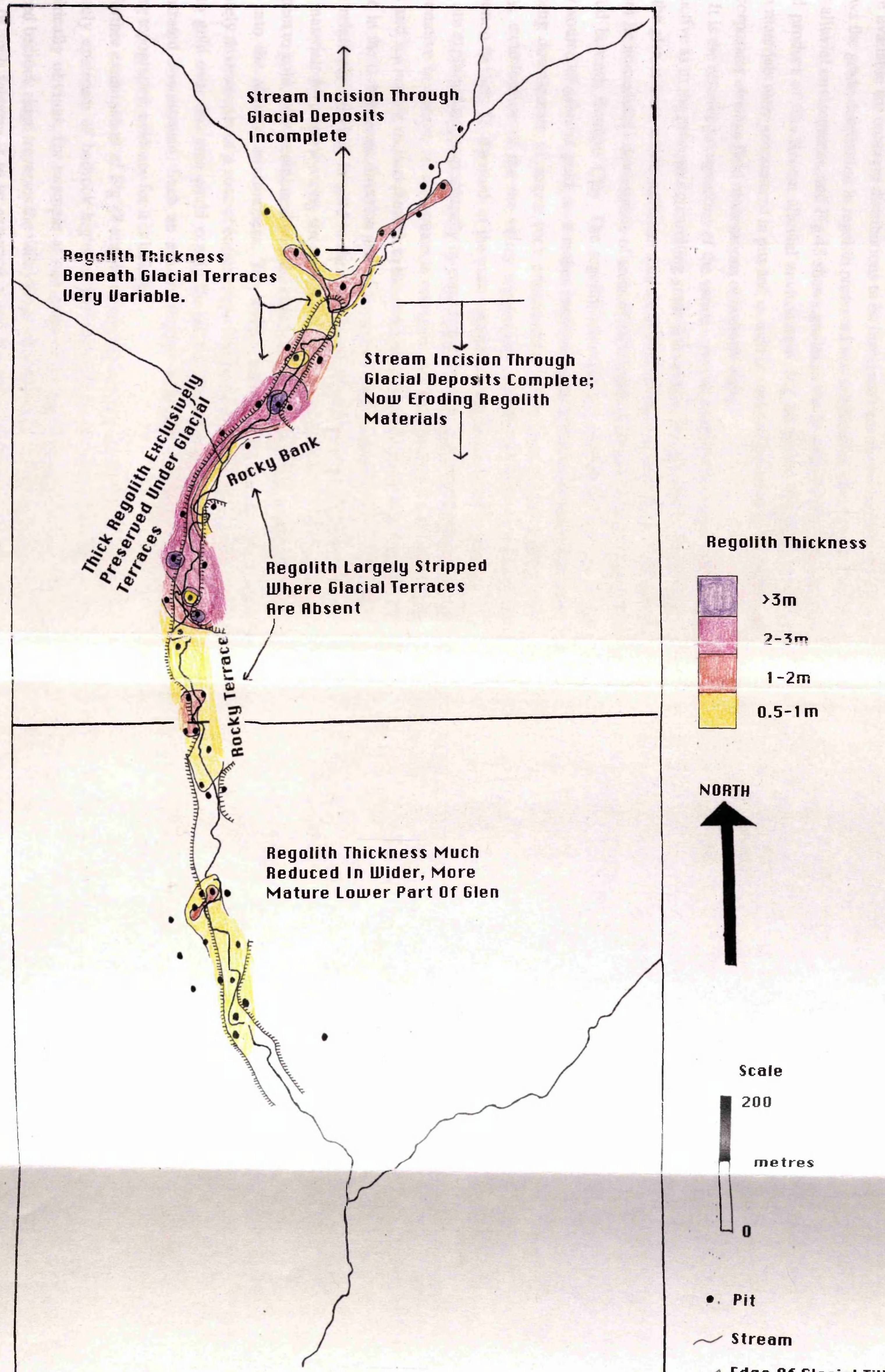


FIG. 45 SUPERFICIAL GEOLOGY OF BORLAND GLEN; REGOLITH THICKNESS AND LIMITS OF GLACIAL DEPOSITS

by examination of the data on the scale of the whole glen. The presence of three highly enriched samples within the data-set which come from isolated pits does however suggest some form of localised control. Perhaps this control can be elucidated by examining the data on either a more local scale or by taking the geographical distribution of the grades into account.

The geographical distribution of gold grades in different lithologies (where sufficient data are available for coherent distributions to be discerned) are shown on Figs 46-48. Fig 47 shows the grade distribution in regolith preserved beneath Boulder Clay remote from the Recent alluvial environment, and Fig 48 shows grades in the Bouldery Alluvium which is the end product of this Recent alluvial environment. Fig 46 shows the depth at which regolith materials were encountered in pits and as such is a map of the depth to bedrock, and also incorporates obvious field observations of bedrock highs.

It is the relative juxtaposition of the various anomalies shown on Figs 46-48 which is instructive as to the processes controlling grade distribution. It is notable (in the northern part of the glen at least, where sufficient data are available) that enriched areas of Bouldery Alluvium lie immediately downstream of areas of enrichment of primary regolith materials. preserved beneath Boulder Clay. The regolith materials are considered here to be the primary source of alluvial gold, so it makes intuitive sense to have alluvial enrichments developing downstream of source-rock enrichments. In the case of the northernmost anomaly, examination of the the valley topography and Fig 48 helps constrain this phenomenon further. To the north of the main upstream river junction the large depths to regolith are explainable topographically by considering this upper part of the stream system as rejuvenative in nature, ie. the stream is currently eroding through the Boulder Clay deposits and has not yet incised through to the underlying regolith. Incision becomes more complete in the downstream direction and where regolith materials are finally intersected they are relatively enriched in gold in their preserved preglacial state. Incision through regolith materials by a rejuvenating stream will constitute a regime which will be erosive with respect to gold, which combined with the enriched source will introduce large amounts of gold into the alluvial environment. The middle alluvial anomaly is also located immediately downstream of a zone of enriched preserved regolith. An erosive regime with respect to gold over this area could supply the gold to the alluvial environment, to be reconcentrated downstream. Such an erosive regime is implied by this analysis, but supporting topographic evidence for it is lacking.

Further examination of Fig 48 and 46 shows alluvial gold anomalies to be located immediately upstream of bedrock highs on the valley floor. In some cases these are topographically obvious, for example at one point in the upper reaches of the Glen a pronounced bedrock ridge traverses the valley floor. Alluvial gold enrichment immediately upstream of such features is to be expected, given the effective damming effect of the bedrock high; an overall slowing down of water flow on the upstream side will create a regime which is depositional with respect to gold, and alluvial concentrations will form. All three alluvial anomalies are located upstream of bedrock highs. The middle anomaly lies

FIG. 46 Thickness Distribution of Deposits Overlying Regolith Materials
Borland Glen, Perth and Kinross, Scotland.

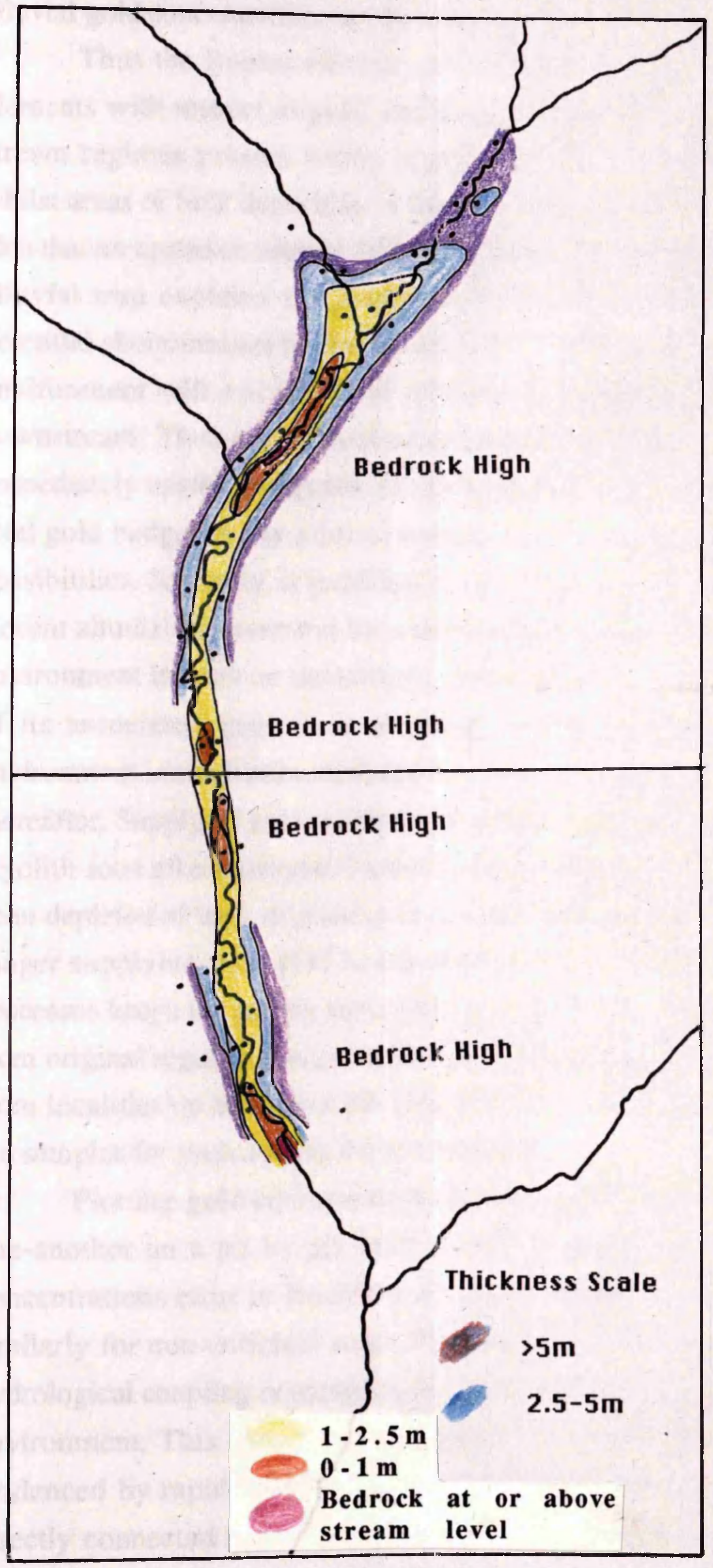


FIG. 47 Gold Grade Distribution In Regolith Materials Overlain By Boulder Clay
Borland Glen, Perth and Kinross, Scotland

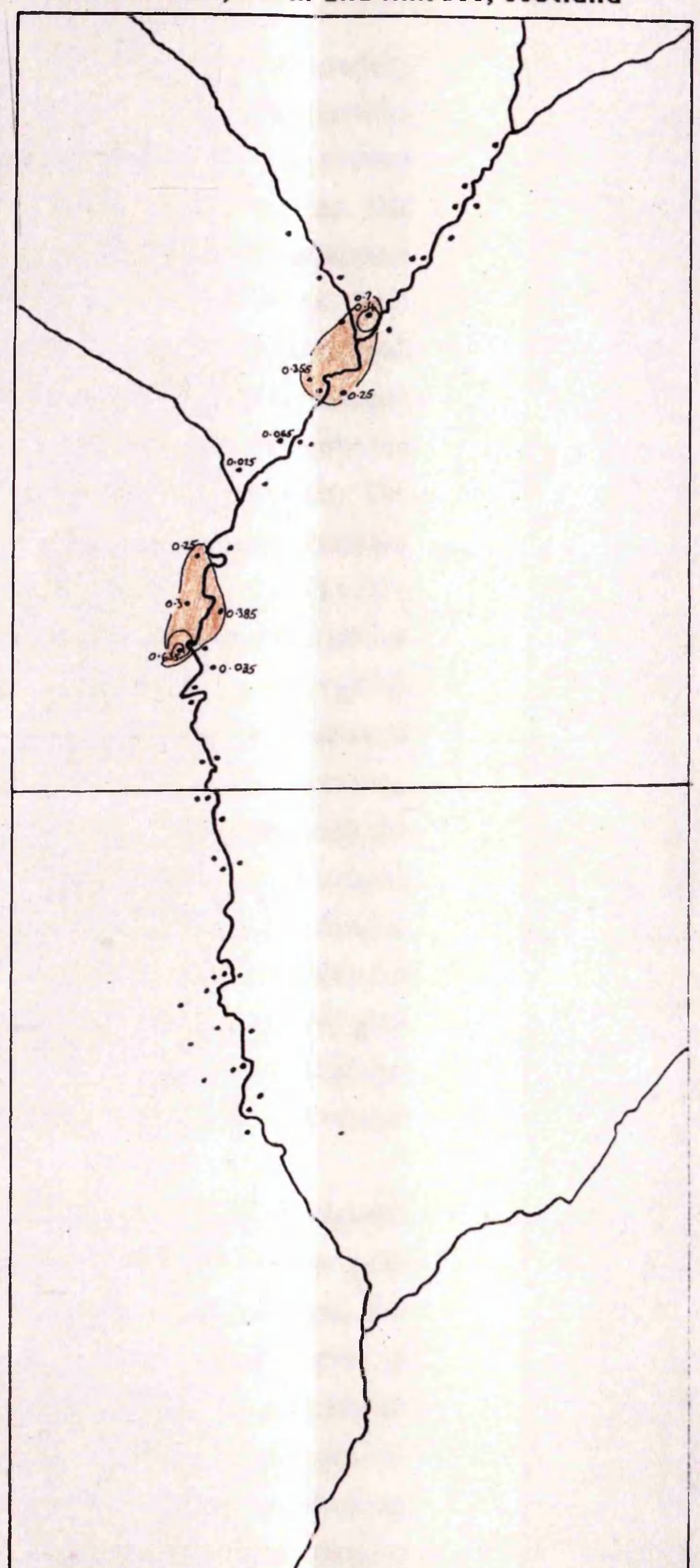
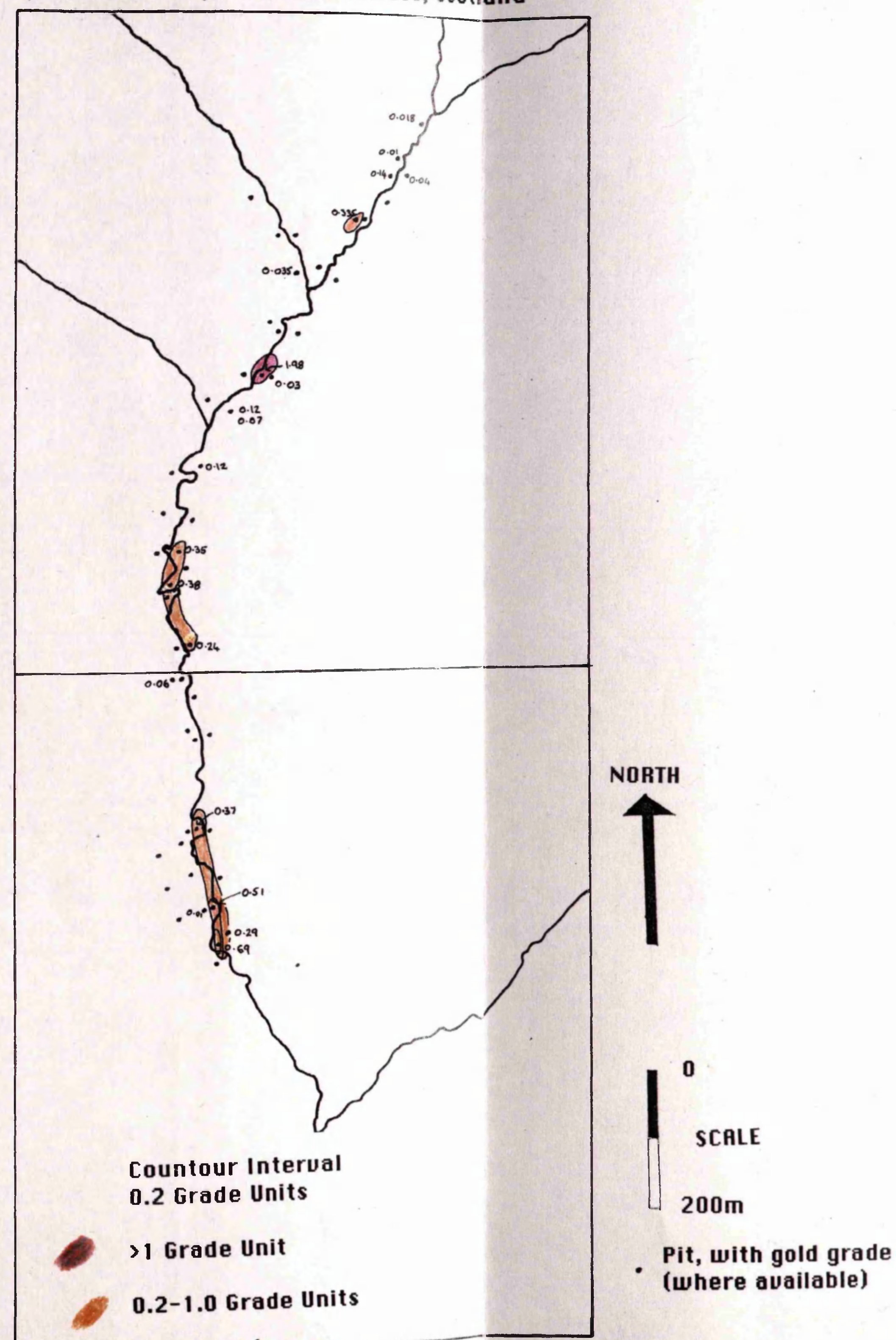


FIG. 48 Gold Grade Distribution in Bouldery Alluvium
Borland Glen, Perth and Kinross, Scotland



immediately upstream of the stretch of Creich Burn where it starts to flow hard against the fresh bedrock wall of the glen rather than incising through glacial materials. Incision was much more difficult through the bedrock, resulting in an effective high point on the valley floor and the resultant formation of alluvial gold concentrations on its upstream side. The southernmost alluvial anomaly is also upstream of a bedrock high. A gradual rise in bedrock level is seen in pits in the downstream direction, and bedrock outcrops are seen above stream level approximately 50 metres to the south of the furthest downstream pit. The alluvial gold concentrations on the upstream side are thus explainable on this basis.

Thus the Recent alluvial environment contains both upgrading and downgrading elements with respect to gold, and these are basically topographically controlled. Erosive stream regimes present within regolith materials constitute downgrading environments whilst areas of bulk deposition of alluvial materials constitute upgrading environments. The idea that an upstream zone of enriched regolith supplies gold to the immediately downstream alluvial trap explains the juxtaposition of the anomalies shown on Figs. 46-48. Two potential shortcomings of this model come to mind however. Firstly, any gold depositional environment will not be 100% efficient at trapping gold and a proportion will escape downstream. Thus any alluvial concentration will contain gold derived not only from the immediately upstream regolith but from enriched zones in the regolith further upstream. The total gold budget in any alluvial concentration will be sourced from all available upstream possibilities. Secondly, it is difficult to envisage the regolith materials supplying gold to the Recent alluvial environment for a substantial length of time given the aggressiveness of this environment in such an upland area. Such vigorous erosion would quickly rob the regolith of its associated gold. It is envisaged here that gold is introduced into the alluvial environment immediately on stream incision through to the regolith and for only a short time thereafter. Supply of gold to this environment is only as rapid as stream incision through the regolith soon after exposure. Further downstream, regolith materials are more likely to have been depleted of their original gold concentration by alluvial processes and are therefore no longer supplying new gold to this environment. Recycling of gold through later alluvial processes keeps the supply sustained in the downstream reaches, rather than erosion of gold from original regolith concentrations. A thorough examination of the textures of gold grains from localities up and down the glen would be necessary to further constrain this, however the samples for such a study are not available.

Plotting gold concentrations in regolith materials and Bouldery Alluvium against one-another on a pit by pit basis reveals a strong correlation, see Fig 44. Where gold concentrations exist in Bouldery Alluvium the underlying regolith is also enriched, and similarly for non-enriched areas. The strength of the correlation implies a high degree of hydrological coupling between the Bouldery Alluvium and the regolith in the Recent alluvial environment. This coupling is the result of the high permeability of both lithologies, as evidenced by rapid water flow into pits through both materials in wet weather, and the directly connected nature of the permeability between both deposits. Thus gold which is being moved in the Recent alluvial environment can move through both the Bouldery

Alluvium and the regolith. Once exposed to stream action then, the regolith materials become an integral part of the alluvial environment.

Alluvial reworking of gold bearing regolith materials thus causes localised gold erosion and deposition, of both the rock itself and the associated gold. Grade distributions in materials within the Recent alluvial environment are the result of variations in the gold content of the preserved pre-glacial regolith and alluvial reworking processes. These latter are controlled by the bedrock topography of the glen and the degree of alluvial incision through overlying glacial materials.

On this reasoning therefore the overall distribution of gold in Borland Glen is the result of pre-glacial weathering processes and Recent alluvial processes. The field relations shown between the regolith materials and the Bouldery Alluvium indicate that the former are being eroded and reworked in the recent alluvial environment. The reworked material is then incorporated into the Bouldery Alluvium where it makes up a large proportion of the matrix. The reworking of gold can be envisaged as following a parallel route. Thus, the primary source of the gold is the regolith and it is reworked and concentrated into the Bouldery Alluvium; the gold distribution in Borland Glen is the result of Recent alluvial reworking of a pre-glacial gold enriched regolith.

The nature of the gold reworking processes is therefore well understood, and it remains to explain the presence of gold in the primary gold source, the pre-glacial regolith. The correlation between the deep orange staining/alteration and gold enrichment is striking to the point of being predictive; a lack of this colouration in the regolith is associated with a less rippable consistency and a reduced gold grade. This is immediately suggestive of a direct link between the two, and co-precipitation of iron oxides and gold immediately springs to mind. This would require quite specific chemical conditions in the supergene environment at the time of co-precipitation; these conditions cannot be investigated directly today, but their effects can be examined to check for compatibility with the co-precipitation idea.

The morphologies of gold grains hosted by regolith materials are dominated overall by extremely thin platelets up to 5mm across. This dominance is geographically widespread, showing little or no noticeable variation either up or downstream in Borland Glen. The delicacy of these grains is such that they can be folded using a thin paintbrush. It is therefore improbable that such grains are the result of direct weathering of a vein source upstream and alluvial transport into their present position; such a delicate morphology would not survive long in the energetic alluvial environment prevalent in the glen. It is more likely that the morphology is developing or has developed locally. The jointed nature of the regolith before its colluvial disaggregation provides an opportunity for gold nucleation and growth within tight joints. Such growth would be restricted by the space available and would result in a platey morphology. Gold bearing solutions percolating along joints in bedrock would facilitate transport of gold to such restricted sites better than downward settling of particulate gold from the overlying alluvial environment, though the two modes of transport are not mutually exclusive. Platey gold growing insitu would result from the former whilst non-platey gold would result from alluvial destruction of the platey morphology followed by downward settling through alluvial and into regolith materials in Recent times. Thus the presence of a dominant platey morphology provides evidence for insitu precipitation of gold within the regolith, from supergene fluids.

The distinctive and almost ubiquitous orange colouration of the regolith materials and the clear association of this colouration with gold enrichment suggest a direct link between the two. Specifically, the suggestion is that gold and iron mobilities were closely linked during the period of deep weathering deemed responsible for regolith formation and and gold concentration.Iron oxides are known to be effective co-precipitants of gold in the supergene environment (Boyle 1979). Gold mobilised during deep weathering could therefore precipitate with iron oxides to produce the above association. The hydrogeochemical means of remobilising gold in the supergene environment and reconcentrating it within the soil profile are considered by Mann (1984) using examples from the Yilgarn block of western Australia. The weathering regime considered responsible for the development of laterites on the Yilgarn block is thought to be of the warm humid variety, of Mediterranean type. Thus it is probably drier than that prevalent during Tertiary times in Scotland. A further difference between the situations described by Mann and that in Borland Glen relates to the incomplete preservation of the soil profile in the latter. Regolith materials in Borland Glen comprise insitu and landslipped material alone, with no preservation of the upper soil horizons described by Mann. Despite these differences in the situations, the work of Mann provides a useful analogy which can be used to explain the features present in Borland Glen.

Mann invokes the presence of acidic conditions during lateritization, with Fe2+ and gold being mobile in supergene fluids under such conditions. Chloride complexing is deemed the most likely means of achieving this gold mobility in such acid conditions. The lack of intense weathering of sulphides in the soil profiles, evidenced in Borland Glen by the common presence of fresh pyrite in heavy mineral concentrates from trial pits, also mitigates against this complexing of gold, which is encouraged by the oxidation of sulphide minerals. The lack of organic matter in the laterites mitigates against humic or cyanide complexing in the examples studied by Mann, and this argument also holds for the Borland Glen situation. Gold precipitation is considered possible through dilution, raising pH or by reduction of the gold complex. In the present context the latter two mechanisms are considered likely.Hydrogeochemical work on soil profiles (Shanmugan 1990, Mann 1984) shows a drop in acidity and Eh with depth. This loss of acidity of supergene fluids results in the destabilisation of the gold chloride complexes, thus concentrating gold in regolith materials at the base of the soil profile. Dissolved Fe^{2+} will also be precipitated as iron oxides on loss of acidity (Krauskopf 1984). Reduction of the gold chloride complex can be achieved through reaction with Fe^{2+} by the following reaction;

$$AuCl^{+} + 3Fe^{2+} + 6H20 \text{ ---------->} \quad Au + 3FeOOH + 4Cl^{-} + 9H^{+}$$

causing co-precipitation of iron oxide and gold. Both mechanisms are consistent with the observation in Borland Glen of iron oxide enriched jointed regolith materials consistently enriched in gold. Additionally. the mechanism of Enzweiler and Joekes whereby gold is adsorbed onto colloidal iron oxides can be invoked to occur at the base of the lateritic soil profile where gold mobilised in the supergene environment encounters iron-stained regolith materials. One or a combination of the above mechanisms are capable of causing co-precipitation of gold and iron oxides to produce the observed correlation between gold enrichment and iron staining in regolith materials in Borland Glen. Precipitation of gold within regolith joint surfaces and subsequent growth within this confined space will result in the dominantly platey morphology of the gold in Borland Glen.

The hydrogeochemical conditions envisaged in Borland Glen during pre-glacial times are therefore considered capable of remobilising gold in the supergene environment and concentrating it in regolith materials at the base of the soil profile. Acid ground conditions and the presence of chloride enable mobilisation of gold in the supergene environment. Precipitation can result from loss of acidity, destablilising of the chloride complex through reduction with Fe^{2+}, and/or colloidal absorption on colloidal iron oxides. All three precipitation mechanisms can be invoked to occur at the base of the soil profile and in the underlying regolith, and can therefore concentrate gold at this level to produce the observed direct association of iron oxide and gold enrichments.

The regolith materials are demonstrably the products of a pre- or inter- glacial weathering process. It remains to investigate whether the climatic conditions prevalent during this period are indeed consistent with the evidence for widespread gold remobilisation and concentration in these regolith materials. The climate during Tertiary times in Scotland was characterised by warm, humid conditions (Anderton 1983), not dis-similar to those prevalent in tropical and sub-tropical latitudes today. As argued for the Cushnie prospect (Chapter 6) by analogy with gold prospects in these latitudes, such climatic conditions are capable of remobilising gold from bedrock sources and redistributing it within deeply weathered soil and regolith materials and within gold mineralised structures. In Borland Glen, hydrogeochemical processes associated with the formation of deep soils by this prolonged and intense weathering provide a plausible chemical means of concentrating gold in the regolith materials .The examples quoted in Chapter 6 related to the mobilisation of gold from concentrated bedrock sources. In Borland Glen, no such concentrated source is known, or believed, to exist, so the analogy with these examples is not exact. Remobilisation of gold from a large, low grade source is envisaged at Borland Glen. A more direct analogy can be drawn with the work of Shilts and Smith (1988) on gold placer deposits in Quebec. Tertiary weathering of an extensive area of land containing no known concentrated bedrock gold sources is believed by them to have resulted in the mobilisation of gold and its concentration in regolith materials that were subsequently reworked by glacial, fluvioglacial and fluvial processes to form rich placer deposits. This scenario is envisaged as the most likely explanation of the presence of rich placer deposits in the Ochil Hills.

It could also be argued that the regolith materials in Borland Glen represent a primary gold enriched regolith rather than simply a supergene enriched top of bedrock mantle. The definitive test of this idea would be a vertical gold grade profile through the regolith into fresh bedrock to some depth. The inherent unrippability of fresh bedrock precluded this test being carried out in the field, but boreholes drilled by the British Geological Survey showed no consistent gold enrichment over any depth. The dominantly platey nature of the gold contained in the regolith materials is strongly suggestive of enrichment along near-surface permeability. The strong association of gold enrichment with iron staining is also consistent with control by surface geochemical processes as described earlier. The characteristics of the regolith materials are all explainable by the operation of surface weathering and mass transport processes, and it is considered here that these materials and the gold enrichments contained therein are supergene in origin rather than the result of the weathering of a previously gold enriched protolith. The country-rocks of Borland Glen and the surroundings were *slightly* enriched in gold, and they constituted the large disseminated gold repository envisaged by the model, but the major gold concentrating event was supergene in origin.

It should be pointed out that the arguments put forward for the generation of highly auriferous pre-glacial regoliths without invoking a concentrated bedrock source are merely an explanation of what can be regarded as geological inconsistencies, ie. the presence of rich alluvial gold deposits but with no known bedrock source for this gold. No specific physical or chemical mechanism has been proven capable of performing the above task. Of the very large, low grade source of gold envisaged to be present, only that portion exposed to the supergene environment is available to provide gold to this remobilisation/ concentration process. Progressive weathering and erosion will extend the zone of influence of the supergene environment to progressively greater depths in this disseminated source, making a greater volume of rock available for leaching. This still constitutes a small proportion of the total volume of the disseminated source however. Further work is required to determine whether this portion of a given disseminated source is capable of providing the amounts of gold present in the associated placer deposits. This will require advances in analytical detection to the point that the infitesimally low grades in these disseminated sources can be measured accurately. In the mean-time, the 'best explanation of geological inconsistencies' approach is all that is available, and the arguments of the likes of Shilts and Smith (1988) hold.

DISCUSSION

If the conclusion is reached that the widespread occurrence of alluvial gold in the Central Ochils is the result of Tertiary weathering of a large disseminated low grade source then the distribution of these alluvial gold occurrences can be explained in two possible ways. The requirements of the model are the coincidence of a large low grade source AND a remobilising/reconcentration process, in this case Tertiary weathering. Where one or other of these ingredients is absent, the alluvial gold deposits will not form.

Fig.38 shows that alluvial gold occurrences are largely confined to an area of the central Ochils south and east of Auchterarder. Both the above ingredients were available over this area, but one or other was absent over the rest of the area. One possibility is that the Tertiary regolith which is currently supplying gold to the streams (eg. in Borland Glen) has been stripped from the rest of the Ochils by glacial scouring.The contained gold will now be dispersed through extensive thick boulder clay deposits in the down-ice direction.The presence of a Tertiary weathering surface preserved in one area but replaced by a glacially scoured surface in the surrounding area may produce detectable topographic differences between the two.Whether or not this is the case is worthy of further investigation, but is beyond the scope of this study.

Alternatively, the regional geology may hold clues to the presence of a disseminated source in the Central Ochils and its absence elsewhere. Fig.38 shows that the area of alluvial gold occurrences roughly coincides with a cluster of dioritic intrusions into the lava pile. The distribution of diorite outcrops is inconsistent with their representing this disseminated source on their own, simply on the basis of their limited aerial extent. However the possibility remains that they form the centres of large dispersed but semi-pervasive epithermal systems which could provide a suitable gold source. Their probable subcrop pattern within the lava pile could be very extensive, and the consequent aerial extent of this dispersed hydrothermal activity could be adequate to explain the distribution of alluvial gold occurrences.

Neither are the two competing theories for the source of the alluvial gold in Borland Glen , ie. a concentrated vein source vs. a large low grade source, mutually exclusive. It has been observed on the Cushnie prospect (this volume) that gold remobilised in the supergene environment from vein sources can find its way into the soil profile remote from the veins themselves during the deep weathering which both forms the thick soil and remobilises the gold. Thus a vein source in or around Borland Glen subjected to deep Tertiary weathering could supply gold to the regolith horizons, and subsequent erosion of these regoliths by Recent stream action could rework the gold into alluvial placers. The absence of gold-mineralised float samples on the prospect is then possibly explainable by this vein source being presently buried beneath thick glacial deposits. This latter point seems unlikely however in view of the findings on the Dalnessie prospect (this volume) where locally derived mineralised float samples were locateable over an extensive area of ground which was almost completely blanketed in till.

The presence of coarse cinnabar in the alluvial placers in Borland Glen adds further complication to the problem of the source of the gold. Cinnabar shows mineralogical associations with gold in several deposit types, notably the epithermal variety, but lacks the mobility in the supergene environment exhibited by gold. It is therefore more likely that cinnabar is currently being eroded, in particulate form, from a bedrock or a superficial source. A bedrock source is unlikely in view of of the lack of gold or mercury mineralised float samples (which would be generated by ongoing erosion of a bedrock source), leaving a superficial source as the only likely candidate. The glacial terrace materials are considered compatible with this idea, providing a source for the cinnabar and a small amount of the gold in the alluvial placers. The bulk of the gold is conclusively pre-glacial in origin however, for the reasons presented earlier. The original bedrock source of the cinnabar plus minor gold could be anywhere in the up-ice direction.

An almost exact analogy can be drawn between the Borland Glen situation and that described for the alluvial gold deposits of Quebec (Shilts and Smith 186, 1986 and 1988). Detailed and widespread stratigraphic work on the till sequences and records of sporadic gold production from the basal layers point to the conclusion that the prospective lithology was nearly always a locally derived pre-glacial regolith horizon . Lassale et al (1985) further constrains the possible age of such horizons by observing that the mineralogy of their fine fraction is dominated by kaolinite and gibbsite which he suggests can only develop through prolonged weathering under warm humid probably tropical conditions. Such criteria were only fully met during Tertiary times; interglacial periods being of inadequate duration to produce this mineralogy. XRD analysis shows that kaolinite is the dominant clay mineral in the prospective horizon in Borland Glen. Thus the basal till in Borland is considered to be a locally derived regolith developed during the Tertiary.

The behaviour of gold under the supergene conditions envisaged as being responsible for the formation of the pre-glacial regolith in Borland Glen can also be considered by analogy with the Quebec examples. A conclusion of Lassale et al (1985) is that such prolonged warm, humid conditions are capable of remobilising gold from a very large dispersed bedrock source and concentrating it in regolith or saprolite horizons. Preservation of these enriched horizons is by a fortuitous combination of local topography and ice-flow directions which protects them from glacial erosion, and their subsequent burying beneath thick glacial deposits which affords protection from later erosion. Incision of these glacial materials by later streams exposes the regolith as a palaeoplacer gold deposit and allows it to be reworked by Recent streams to form present-day placer deposits. This is entirely consistent with the situation in Borland Glen. Of great significance is the suggestion that a concentrated bedrock source is un-necessary for the generation of these placers. That no such source is present in Borland Glen is therefore not a problem. The large dispersed source deemed necessary under this model could be the local Devonian volcanic pile and perhaps the ORS sediments which regionally interdigitate with the lavas. The lavas, being of a similar age to and cogenetic with the Newer Granite suite of Scotland, which are known to be associated with gold mineralization as stockworks disseminations and breccia bodies, can be envisaged as possessing a relatively high background gold concentration. The interdigitating sediments are derived from erosion of the Caledonian metamorphic pile; this is known to host bedrock gold mineralization in several places which could supply, by erosion, Devonian palaeoplacer deposits. Thus the presence of a large dispersed source of gold in Borland Glen is a distinct possibility, and Tertiary supergene conditions would be capable of remobilising and concentrating this gold to form the palaeoplacers seen today.

Devonian volcanic and sedimentary activity followed by Tertiary weathering are thus responsible for the generation of a rich placer deposit at Borland Glen. The widespread occurrence of alluvial gold in the Ochils and the lack of concentrated bedrock sources discovered to date point to this model being applicable regionally over the whole outcrop area of the Devonian volcanic succession. Other alluvial gold localities in Perth and Kinross will be sourced by pre-glacial palaeoplacers which have recently been exposed by stream erosion. Other such palaeoplacers will be sporadically preserved beneath glacial till materials in this area but have not yet been exposed by stream incision through the overlying tills. The Ochils therefore constitutes an alluvial and palaeoplacer gold province, and further such deposits will be exposed or formed as erosion continues. Concentrated bedrock sources of gold in the Ochils are however likely to remain enigmatic.

CHAPTER 10

SCOTTISH GOLD METALLOGENY - KEY GEOLOGICAL PROCESSES

CHAPTER 10; SCOTTISH GOLD METALLOGENY - KEY GEOLOGICAL PROCESSES

Several important geological mechanisms of gold concentration and depletion have been identified as having been operative either within the crust or at the earth's surface through geological time in Scotland. These processes are summarised here in the order of decreasing crustal depth at which they operated, and the metallogenic implications discussed.

Formation Of Deep Crustal Gold Reservoirs

The Mid-Grampian Line (MGL) is considered of fundamental importance to metallogenesis in Scotland. (Russell 1985). The addition of a substantial proportion of basic and mafic material to both the deep and middle crust formed large reservoirs of rare metals, including gold. Large-scale tectonism in a collisional tectonic setting on the northern margins of the Iapetus Ocean resulted in a concentration of these gold reservoirs in the crust underlying the Southern Highlands of Scotland. Intrusion of magmas through this crust resulted in remobilisation of gold through crustal assimilation, and its transportation to higher crustal levels. This assimilation of crustal material is reflected in the sulphur isotopic compositions of sulphides hosted by appinites and in the regional provinciality shown by sulphur isotopic signatures. Appinites from north of the MGL show little or no contamination. Similarly, the only appinitic rocks sampled which show gold enrichment are located to the south of the MGL. This is consistent with Russell's model and adds weight to the idea that the area underlain by crust with a significant proportion of basic and mafic material will be prospective for rare metals, including gold. Recent extensions of the MGL towards the NE, largely on geochemical grounds, show it to extend across almost the entire outcrop width of the Scottish Dalradian. The discovery of the Socach gold deposit and the Sron Garbh Mo/W stockwork in NE Scotland, both to the south of the MGL, provides additional evidence for the existence and metallogenic significance of the line, and the prospectivity of the area between the MGL and the Highland Boundary Fault.Similarly, several significant metal deposits located during the gold boom years of the 1980s (Cononish, Calliachar, Glen Clova) lie to the south of the MGL Outwith the Grampian Highlands the effect of deep crustal composition and structure was not investigated in the course of this study, so the Dalnessie and Borland Glen prospects cannot be discussed in this context. Russell (1985) suggests that the presence of material of Lewisian affinity underlying large areas of the NW Highlands can be used to explain the distribution of metal enrichments in Caledonian rocks in these parts. This provides a possible ultimate source for gold enrichments on the Dalnessie prospect, but no additional collaboratory evidence for this idea was found during this work.

Devonian Magmatism and Hydrothermalism

Intrusion of Newer Granite and Appinite suite rocks into the crust involved assimilation of crustal material, causing geochemical contamination of the original magmatic compositions. This assimilation caused incorporation of rare metals, notably gold, into the magmas, and provided a means of remobilisation of the gold from the deep crust and its transportation to higher crustal levels within the uprising magmas. Subsequent hydrothermalism associated with this magmatic activity precipitated gold and other rare metals in breccia pipes, stockworks and zones of enhanced crustal permeability at middle to upper crustal levels. The magmas themselves, whether in the plutonic or associated volcanic (ie. ORS volcanics) form, constituted very large, low grade repositories for gold.

The final stages of gold emplacement into the upper crust involved hydrothermalism associated with the emplacement of the above magmas. Hydrothermal activity during the late stages of emplacement of Newer Granites resulted in the generation of stockworks and breccias hosting significant metal enrichments. In the case of the appinites the characteristic product of hydrothermalism are pyrite +/- gold mineralised breccia pipes. Rapid pressure release on explosive brecciation caused effervescence of hydrothermal fluids and consequent precipitation of gold in the breccia pipes. Migration of hydrothermal fluids away from their igneous source was facilitated by enhanced crustal permeability along faults and shear zones. These allowed further upward movement of gold bearing fluids to the point where exhalation occurred onto the contemporaneous Lower Devonian landsurface. Gold precipitation en route occurred in response to decreasing lithostatic/hydrostatic pressure and the presence of crustal porosity which encouraged effervescence, as well as cooling of fluids. The result is a spectrum of styles of gold mineralization at a range of palaeo-crustal levels. Exhalation produced gold bearing hot spring systems (eg. at Rhynie), whilst the structurally controlled feeder zones to these exhalative centres currently host gold mineralisation at palaeodepths of <1km (Dalnessie) and 1.2-1.8km (Cushnie). Greater crustal depths are associated with higher fluid temperatures (Rhynie-epithermal, Dalnessie-epithermal to low mesothermal, Cushnie-mesothermal), reflecting either conductive cooling during uprise or mixing with cooler meteoric water at higher crustal levels. The spectrum is completed by the products of deeper level magma-related hydrothermalism, the Newer Granite related stockworks and breccias and the breccia pipes associated with appinitic rocks. Gold grades within this spectrum are highest within the structurally controlled feeder zones to exhalative centres, and such features therefore represent the best exploration target. This structural level, at some distance beneath the Lower Devonian palaeolandsurface but above the level of exposure of the contemporaneous magmas, is highly prospective. Large parts of Scotland, particularly in the NE, are presently exposed at around this structural level and are worthy of further exploration.

Tertiary Weathering

Tertiary weathering has played a dual role in the development of gold mineralization in Scotland. Examples have been described in this volume of the remobilisation of gold from concentrated bedrock sources, and its redistribution within the mineralised structure. Other examples have been presented of laterally widespread enrichment of gold in soil and regolith materials formed by deep Tertiary weathering. Both phenomena are the direct results of pre-glacial weathering, and in

different places are found in direct or tenuous connection, or can be found individually. As an overall process, supergene gold remobilisation should involve some source of the gold and a final repository for the reprecipitated gold. Where the connection is direct a specific source and destination of the remobilised gold can be identified and a geological route between the two suggested, with, where possible, the most likely mechanisms of remobilisation and reprecipitation. The occurrence of any of the phenomena in isolation requires that the missing part of the overall process be elucidated within the context of the geology of the prospect.

The Socach deposit represents a concentrated bedrock source which has been subjected to supergene gold remobilisation and redistribution during pre-glacial times. The agent of this supergene alteration was the prolonged deep weathering which resulted from the long period of warm, humid climatic conditions prevalent during Tertiary times. Gold redistribution has occurred in three dimensions; within the mineralised structure itself vertical redistribution has occurred, whilst extensive lateral dispersion took place at the surface. Vertical redistribution has resulted in the development of leached and oxidised zones above primary sulphide mineralization on the Socach Structure and a gold grade distribution reflecting leaching above and reprecipitation below the water-table. Lateral migration of gold has produced enrichment in soils developed at a similar time but located some distance from the bedrock sources. The geochemical mechanism for the remobilisation is considered to be the generation of highly acidic, manganiferous fluids from the weathering of sulphides and manganiferous country-rocks, dissolution of gold therein and reprecipitation with manganese and iron oxides at the redox front represented by the water-table. The whole process has altered the deposit to produce internal characteristics such as ore textures and grade distribution and secondary dispersion patterns which can only be understood by consideration of the effects of deep Tertiary weathering.

On the Dalnessie prospect, gold enrichments in intensely weathered iron and manganese stained regolith materials are most probably the result of lateral gold migration in the supergene environment. The original source of this gold is more tenuous than at Cushnie, but the presence of significant quantities of highly gold enriched float in stream courses (and a small, low grade gold mineralised outcrop) is suggestive of the presence of a concentrated bedrock source on the prospect. The lack of leached or oxidised ore textures within these float samples makes the link more tenuous in so far as it provides no evidence for supergene leaching of gold from this postulated bedrock source. Leaching and formation of gold enriched regolith could have been followed by glacial scouring of the bedrock source. This could expose fresh sulphide mineralization but preserve small pockets of gold enriched regolith; current erosion would then be through both fresh sulphide mineralization and the products of earlier deep weathering.

Tertiary weathering on the Borland prospect has produced laterally extensive gold enrichments in regolith materials, but in this case no evidence is seen of any concentrated bedrock source for this gold. The dominantly flakey textures of gold grains hosted by the regolith and the intense iron staining of the regolith are both consistent with precipitation of gold from supergene fluids along tight joints in bedrock. A very large disseminated source is required for this gold, and the local Devonian volcanic succession is considered a likely contender for this in view of its genetic link with the Newer Granite suite which is associated with gold mineralization in several places in Scotland. Deep weathering in the warm, humid climatic conditions known to be prevalent during Tertiary times is known to be capable of remobilising gold from such a disseminated source and reconcentrating it in regolith materials. Thus the Borland occurrence represents an example of gold enrichments derived, not from a concentrated bedrock source but from a much larger disseminated source.

In exploration and evaluation terms the effects of Tertiary weathering can be seen to complicate the geological picture substantially. Vertical grade redistribution in mineralised bedrock makes evaluation of prospects using surface exposures difficult at best. Lateral redistribution of gold can widen the exploration target significantly, but poor preservation of the results of this secondary dispersion can make the results of, eg. soil surveys, difficult to interpret. Stream sampling as a regional reconnaissance tool for the location of bedrock mineralisation is complicated by the presence of Tertiary regolith sourced alluvial placers which may or may not be derived from concentrated bedrock sources. An appreciation of all the possible effects of supergene gold remobilisation is crucial to any exploration/evaluation programme in areas affected by Tertiary weathering. The geographical distribution of Tertiary weathering effects in Scotland and the origins of this distribution have been discussed in Chapter . They are predominantly developed and preserved in the eastern and northeastern part of the country. Supergene gold remobilisation will, then be a more significant process in these parts than towards the west. Leaching and deep oxidation of sulphide mineralization and the associated effects on gold grade distribution within concentrated bedrock sources, and the generation of Tertiary regolith sourced alluvial gold placers will be common features of the gold metallogenesis in the eastern half of Scotland. Towards the west, the more likely situation will be the presence of near surface fresh or only slightly oxidised, unleached mineralised bodies and a lack of rich derived placer deposits. The distinction is necessarily a generalization; pockets of preserved Tertiary weathering effects in the west or the localised operation of aggressively erosive glacial regimes in the east are are possibilities and could contradict the above. However the overall situation is likely to be as described and the effects of Tertiary weathering should be considered in any exploration/evaluation programme carried out in the east of Scotland.

Glacial Processes

That the effects of Tertiary weathering are deemed significant gold metallogenesis in Scotland is as much down to the preservation of these effects, ie. the lack of significant glacial erosion of the products of Tertiary weathering, as it is to the effects themselves. In the case of the Socach deposit, the preservation in its largely pre-glacial state was the result of a unaggressively erosive glacial regime. The preservation of the Tertiary regolith materials in Borland Glen was by a fortuitous combination of ice movement directions and valley topography. Less aggressively erosive glacial regimes were a characteristic of the glaciation of NE Scotland, and the Socach situation is therefore liable to be the norm in these parts. Elsewhere,more dynamic, erosive glaciation generally occurred, and the preservation of pre-glacial features will be largely unpredictable. In areas of aggressively erosive glaciation, eg. towards the west coast, little or no Tertiary weathering effects will be seen; regolith materials will be rarely and sporadically preserved and mineralised bodies will be exposed in a relatively fresh and unoxidised state. The depositional effects of glaciation serve to preserve Tertiary regolith materials, as at Borland Glen, until stream incision exposes them to alluvial reworking. Blanket coverage in glacial till also obscures bedrock gold occurrences, as at Dalnessie (and, possibly but unlikely, Borland Glen) and in so doing complicates the exploration effort.

Erosive processes of a fluvio-glacial nature also affected the Tertiary regolith materials in Borland Glen. Reworking of gold by such processes formed relatively gold enriched fluvioglacial sand and gravel deposits. The significance of this was not adequately evaluated in the Ochil Hills, but raises interesting possibilities. The hummocky topography present in Glen Devon at the mouth of Borland Glen is formed by thick sand and gravel . These have been investigated by Fife Sand and Gravel Ltd. as a potential aggregate resource. The fact that the fluvioglacial processes responsible for their deposition proximally reworked gold enriched regolith materials would suggest that this sand and gravel deposit could constitute a combined aggregate/gold resource. This is very speculative, but it does raise the possibility that sand and gravel workings in terrains known to have been affected by Tertiary weathering and where alluvial gold is known to be present, could produce by-product gold via a simple addition to the processing plant. This has not, to date, been attempted in Scotland.

Recent Alluvial Reworking

Alluvial processes are presently ubiquitous throughout Scotland, and their effects are nowhere unique. However, where a suitable, easily eroded gold source is available, alluvial action results in significant gold redistribution and the development of significant placer deposits. Gold enriched Tertiary regolith materials form the most suitable such source due to the concentrated and free particulate nature of the gold and the relative incoherence of the materials which makes for easy erosion. Preservation of Tertiary regolith materials beneath glacial deposits largely obscures their presence in the majority of cases. Alluvial action erodes these glacial deposits, exposing regolith materials to alluvial reworking. Within the alluvial environment, upgrading and downgrading processes are operative which are largely controlled by valley topography, in particular the presence of bedrock highs. Significant localised gold concentrations can be found upstream of bedrock highs and are sourced by the erosion of recently exposed regolith materials further upstream. Such processes were responsible for the generation of the significant placers in the Ochil Hills, and are probably ultimately responsible for the development of the similar Helmsdale and Leadhills occurrences, as well as others which are awaiting discovery or awaiting formation on exposure of Tertiary regolith materials to alluvial processes.

CONCLUSIONS

Several key geological processes of relevance to Scottish gold metallogenesis have thus been identified. The generation of a mineral deposit is in all cases a result of several coincidental geological circumstances, each of which is necessary to the formation of the deposit but none of which are capable of generating the deposit individually. The coincidence that this thesis indicates as implying prospectivity of a Scottish terrain for gold is; 1) the presence of a deep to middle crustal gold reservoir intruded by uprising magmas, and 2) the operation of magma-related hydrothermal processes at a specific crustal level and concentrated within zones of enhanced crustal permeability. From what has gone before it can be proposed that criterion 1 is met by the area between the MGL and the Highland Boundary Fault, especially near where plutonic rocks are presently exposed or can be inferred to be present at depth. Criterion 2 requires that a current erosion level not far beneath the Lower Devonian palaeolandsurface. The necessary erosional level is to be found over much of NE Scotland, and the crustal permeability required to concentrate the gold mineralising effects of hydrothermalism is available in the form of shear-zones and faults of a pre-Devonian age. It will be the coincidence of these factors which will render a terrain worthy of exploration.

The failure of crustal processes to generate a mineral deposit can be partly offset by the operation of surface concentrating processes. Where a large, low grade repository for gold exists in the form of plutonic bodies or eruptive masses, deep weathering under the warm, humid conditions typical of Tertiary times can remobilise this gold and reconcentrate it in weathered regolith materials. Subsequent reworking by alluvial activity can result in further concentration of gold. Thus, the large areas of Scotland where the products of Devonian magmatism have been affected by Tertiary weathering will be prospective for alluvial deposits, particularly where less aggressive glacial regimes have operated and the regolith materials are therefore well preserved. Such conducive weathering conditions were a characteristic of the geological history of large parts of the eastern half of Scotland.

The operation of both crustal and surface processes in one area results in intense supergene alteration of mineral deposits. Leaching and deep oxidation of sulphides and the redistribution of gold grades will be a characteristic of deposits found towards the east of Scotland, whilst towards the west the poor preservation of any such effects will make unoxidised, unleached mineralisation exposed in its primary hydrothermal form the norm.

Scotland remains an under-explored terrain for gold, despite the work done during the boom years of the 1980s. The information collected during that period has however proven the prospectivity of the country for gold and other rare metal deposits. Enhanced metal prices are however required before economic significance can be attributed to any of the discoveries made to date and, in the author's judgement before the terrain can be regarded as worthy of further exploration of the intensity of that carried out during the 80s.

REFERENCES

Alderton, D.H.M. (1988) Ag-Au-Te Mineralization In The Ratagain Complex, Northwest Scotland. *Trans. Instn. Min. Metall.*, **97**, 10.

Ashcroft, W.A., Kneller, B.C., Leslie, A.G. & Munro, M. (1984) Major Shear Zones And Autochtonous Dalradian In The North East Scottish Caledonides. *Nature*, **310**, 3.

Baker, Kirwin and Taylor (1986); Hydrothermal Breccia Pipes, EGRU Contribution 12, Geology Department, James Cook University of North Queensland.

Blackbourn, G.A. (1981) Correlation Of Old Red Sandstone (Devonian) Outliers In The Northern Highlands Of Scotland *Geol. Mag*, **118**, 6.

Bluck, B.J., Haughton, P.D.W., House, M.R., Sellwood, E.B. & Tunbridge, I.P. Devonian Of England, Wales and Scotland 305-323.in Devonian of the World (McMillan et al (eds) 1988

Boast, A.M., Harris, M. & Steffe, D. (1990) Intrusive-Hosted Gold Mineralisation At Hare Hill, Southern Uplands, Scotland. *Trans. Instn. Min. Metall.*, **99**, 7.

Bowell, R.J. (1992) Supergene Gold Mineralogy At Ashanti, Ghana: Implications For The Supergene Behaviour Of Gold. *Mineralogical Magazine*, **56**, 545-560.

Bowes, D.R.(ed) (1989) The Encyclopaedia of Igneous and Metamorphic Petrology *published by Van Nostrand Reinhold, New York.*

Bowes, D.R. & McArthur, A.C. (1976) Nature And Genesis Of The Appinite Suite. *Krystalinikum*, **12**, 18.

Bowes, D.R. and Wright, A.E. (1967), The Explosion Breccia Pipes Near Kentallen, Scotland and their Geological Setting. Trans. Roy.Soc. Edinburgh, 67, 109-143

Boyle, R.W. (1979) The Geochemistry of Gold and its Deposits *Geological Survey of Canada Bulletin*, **280**,

Chaussidon, M., Albarede, F. & Sheppard, S.M.F. (1987) Sulphur Isotope Heterogeneity In The Mantle From Ion Microprobe Measurements Of Sulphide Inclusions In Diamonds. *Nature*, **330**, 3.

Cloke, P.L. & Kelly, W.C. (1964) Solubility of Gold Under Inorganic Supergene Conditions Econ. Geol. **69**, 259-270.

Coleman, T.B. (1990) Exploration For Metalliferous and Related Minerals In Britain: A Guide. BGS Keyworth, 52pp.

Corry, C.E. (1985) Spontaneous Polarization Associated With Porphyry Sulphide Mineralisation. *Geophysics*, **50**, 15.

Craw, D. (1990) Regional Fluid And Metal Mobility In The Dalradian Metamorphic Belt, Southern Grampian Highlands, Scotland. *Mineralium Deposita*, **25**, 8.

Craw, D., Johnstone, R.D. & Rattenbury, M.S. (1989) Tectonic-Hydrothermal Au-C Mineralisation In A Metamorphic-Meteoric Fluid Mixing Zone, Westland, New Zealand. *Proceedings, WRI-6; Water-Rock Interaction Symposium*, 167-170.

Craw, D. & Koons, P.O. (1989) Tectonically Induced Hydrothermal Activity and Gold Mineralisation Adjacent to Major Fault Zones. *Econ. Geol. Monograph*, **6**, 471-478.

Curtis, S.F. , Pattrick, R.A.D. , Jenkin, G.R.T., Fallick, A.E., Boyce, A.J., and Treagus, J.E. Fluid Inclusion and Stable Isotope Study of Fault-Related Mineralization in The Tyndrum Area, Scotland. Trans. Instn. Min. Metall. (sect. B), 102, 1993, B39-47

Dempster, T.J. (1985) Uplift Patterns And Orogenic Evolution In The Scottish Dalradian *J. Geol. Soc. London*, **142**, 111-128.

Edwards, R. & Atkinson, K. (1986) Ore Deposit Geology , published by Chapman and Hall.

Emmons, W.H. (1917) The Enrichment Of Ore Deposits *U. S. G. S.*, **625**, 535.

Enzweiler J. and Joekes I. (1991) Adsorption of Colloidal Gold On Colloidal Iron Oxides; Journal of Geochemical Exploration, 40 pp. 133-142

Foster, R.P. (1991) Gold Metallogeny and Exploration, Published by Allen and Unwin

Freeze , R.A. and Cherry, J.A.(1979) Groundwater: Englewood Cliffs, New Jersey, Prentice Hall, Inc.,604p

Gallagher, M.J. (1992); Metalliferous Mineralisation, in the Grampian Highlands Regional Guide (in press)

Geonics Limited; EM16 VLF Electromagnetic Unit Operating Instructions and Interpretation Techniques; Geonics Ltd., 2 Thorncliffe Park Drive, Toronto 17, Ontario, Canada.

Gould (1989); Geology of the Rhynie Area, in "The Rhynie Chert; Workshop and Fieldtrip" 1989.

Groen, J.C., Craig, J.R. & RimStidt, J.D. (1990) Gold-Rich Rim Formation on Electrum Grains In Placers *Canadian Mineralogist*, **28**, 207-228.

Hall, A.J., A.J.Boyce & A.E.Fallick (1988) A Sulphur Isotope Study of Iron Sulphides in the Late Precambrian Easdale Slate Formation, Argyll, Scotland *Mineralogical Magazine*, **52**, 483-490.

Hall, A.J., Boyce, A.J. & A.E.Fallick (1987) Iron Sulphides in Metasediments: Isotopic Support For A Retrogressive Pyrrhotite to Pyrite Reaction. *Chemical Geology (Isotope Geoscience Section)*, **65**, 305-310.

Hall, A.M. (1991) Pre-Quaternary Landscape Evolution In The Scottish Highlands. *Transactions Of The Royal Society Of Edinburgh; Earth Sciences.*, **82**, 26.

Hall, J. (1985) Geophysical Constraints on Crustal Structure in the Dalradian Region of Scotland *Journ. Geol. Soc. London*, **142**, 149-155.

Hallbauer, D.K. & Utter, T. (1977) Geochemical and Morphological Characteristics of Gold Particles from Recent River Deposits and the Fossil Placers of the Witwatersrand. *Mineral. Deposita*, **12**, 293-306.

Halliday, A.N. (1984) Coupled Sm-Nd and U-Pb Systematics in Late Caledonian Granites and the Basement Under Northern Britain. *Nature*, **307**, 229-233.

Hamidullah, S. & Bowes, D.R. (1987) Petrogenesis Of The Appinite Suite, Appin District, Western Scotland. *Acta Universitatis Carolinae-Geologica*, **4**, 100.

Harris, L.B. & Cobbold, P.R. (1984) Development Of Conjugate Shear Bands During Bulk Simple Shearing. *Journal Of Structural Geology*, **7**, 8.

Harris, M., Kay, E.A., Widnall, M.A., Jones, E.M. & Steele, G.B. (1988) Geology And Mineralisation Of The Lagalochan Intrusive Complex, Western Argyll, Scotland. *Trans. Instn. Min. Metall.*, **97**, 6.

Hazseldine, R.S.. (1988) Crustal Lineaments In The British Isles; Their Relationship To Carboniferous Basins. *in; Besley B.M. and Kelling G. (eds) Sedimentation In a Synorogenic Basin Complex. The Upper Carboniferous of Northwest Europe.*,

Krauskopf, K.B.(1979) An Introduction to Geochemistry, *; McGraw Hill International series in the earth and planetary sciences.*

Krauskopf, K.B. The Solubility Of Gold *Econ. Geol.* 858-870.

Laouar, R., Boyce, A.J., Fallick, A.E. & Leake, B.E. (1990) A Sulphur Isotope Study On Selected Caledonian Granites Of Britain And Ireland. *Geological Journal*, **25**, 11.

LaSalle, P., Kimpe, C.R.D. & Laverdiere, M.R. (1985) Sub-Till Saprolites In Southeastern Quebec And Adjacent New England: Erosional, Stratigraphic, and Climatic Significance. *Geological Society Of America, Special Paper 197*, 13-20.

Lister, G.S. & Snoke, A.W. (1984) S-C Mylonites *Journal Of Structural Geology*, **6**, 22.

Lister, G.S. & Williams, P.F. (1979) Fabric Development In Shear Zones: Theoretical Controls And Observed Phenomena. *Journal Of Structural Geology*, **1**, 15.

Lowry, D. Boyce, A.J.,Fallick ,A.E.& Stephens,W.E. (1992) Terrane Characterisation in the British Isles using Sulphur Isotopes*; Trans. Instn. Min. Met. Part Applied Earth Sciences.*

Mackay, R.A. The Purity of Native Gold As A Criterion in Secondary Enrichment *; Econ . Geol.39; 56-67*

Mann, A.W. (1984) Mobility of Gold and Silver in Lateritic Weathering Profiles; Some Observations from Western Australia. Econ. Geol., 79. 38-49

Nicholson, K. Contrasting Mineralogical-Geochemical Signatures Of Manganese Oxides: Guides To Metallogenesis. *Econ. Geol.*,(in press)

Nicholson, K. (1897) Ironston-Gossan Discrimination: Pitfalls of a Simple Geochemical Approach-A Case Study From Northeast Scotland. *Journal Of Geochemical Exploration*, **27**, 18.

Nicholson, K. (1988) Geothermal Deposits In Ancient Terrain As A Tool In Epithermal Gold Exploration: Examples From Scotland. *Proc. 10th New Zealand Geothermal Workshop 1988.*, 3.

Ohmoto, H. & Rye, R.O. Isotopes of Sulphur and Carbon in M.L. Barnes (ed.) (1979) .Geochemistry of Hydrothermal Ore Deposits; John Wiley and Sons, New York.

Osborne, M. and Haszeldine, S. (1993) Evidence For Resetting Of Fluid Inclusion Temperatures From Quartz Cements In Oilfields. Marine and Petroleum Geology, 1993, Vol. 10, June

Pattrick, R.A.D. and Polya, D.A. (eds); Mineralisation In The British Isles, published by Chapman and Hall

Pattrick, R.A.D.(1992) Trans. Instn. Min. Met.101,3 Part B Applied Earth Sciences

Pitcher, W.S. & A.R.Berger (1972) The Geology Of Donegal; A Study of Granite Emplacement and Unroofing, published by Wiley Interscience, New York.

Plant, J.A. & Coleman, R.F. (1973) Application of Neutron Activation Analysis To The Placer Gold Concentrations *James M.J. (ed) Geochemical Exploration IMM*, 373-381.

Platten I.M. and Money M.S.(1987) Formation of Late CAledonian Subvolcanic Breccia Pipes at Cruachan Cruinn, Grampian Highlands, Scotland. Trans. Roy. Soc. Edin. 78, pp85-105

Poulson, S.R. & Ohmoto, H. (1989) Devolatisation Equilibria In Graphite-Pyrite-Pyrrhotote Bearing Pelites with Application to Magma-Pelite Interaction *Contrib. Mineral. Petrol.*, **101**, 418-425.

Potter, R.W.II. & Brown, D.L. (1977) Volumetric Properties Of Aqueous Sodium Chloride Solutions From 0 C to 500 C At Pressures up to 2000bars Based on a Regression of Available Data in the Literature. *U.S. Geol. Surv. Bull.*, **1421-C**, 1-6.

Ramsay, D.M. & Sturt, B.A. (1979) The Status of the Banff Nappe *in; A.L. Harris, C.M. Holland and B.E. Leake (eds.) The Caledonides of the British Isles-reviewed, Geol. Soc. London Special Publication No.8 pages* 145-150.

Read, H.H. (1931) The Geology of Central Sutherland *Mem. Geol. Surv. Sheets 108,109*,

Rice, C.M. and Davies, B. (1979) Copper Mineralisation Associated With An Appinite Pipe in Argyll, Scotland. Trans. Instn. Min. Metall. (Sect. B.: Appl. Earth Sci.) 88, B154-60

Rice, C.M. & Trewin, N.H. (1988) A Lower Devonian Gold Bearing Hot-Spring System, Rhynie, Scotland. *Trans. Instn. Min. Metall.*, **97**, 4.

Rock, N.M.S., Duller, P.R., Haszeldine, R.S. and Groves, D.I. (1987); Lamprophyres as Potential Gold Exploration Targets; Some Preliminary Observations and Speculations. In Groves, D.I. and Ho, S.E. (1987) Recent Advances in Understanding Archean Gold Deposits. University of Western Australia, Geology Department and University Ectension Publication No.11.

Rock, N.M.S. & Groves, D.I. (1988) Do Lamprophyres Carry Gold As Well As Diamonds? *Nature*, **332**, 253-255.

Roedder, E. (1984) Fluid Inclusions *Reviews In Mineralogy*, **12**, 645.

Rogers, G. and Dunning, G.R. (1991) Geochronology of Appinitic and Related Granitic Magmatism in the W. Highlands of Scotland; Constraints on the Timing of Transcurrent Fault Movement. J. Geol Soc. London, 148, 17-27

Russell, M.J. North-South Geofractures In Scotland And Ireland. *Scott. J. Geol.*, **8**, 10.
Russell, M.J. (1985) The Evolution of the Scottish Mineral Sub-Province *Scott. J. Geol.*, **21**, 513-545.

Russell, M.J. & Haszeldine, R.S. (1990) Accounting For Geofractures *The Irish Minerals Industry-A Review Of The Decade*, 1.

Sasaki, A. & Inshihara, S. (1979) Sulfur Isotopic Composition of the Magnetite-Series and Ilmenite-Series Granitoids in Japan. *Contrib. Mineral. Petrol.*, **68**, 107-115.

Scott, R.A., Pattrick, R.A.D. & Polya, D.A. (1991) Origin Of Sulphur In Metamorphosed Stratabound Mineralisation From The Argyll Group Dalradian Of Scotland. *Transactions Of The Royal Society Of Edinburgh; Earth Sciences.*, **82**, 8.

Shanmugan, G., 1990, Porosity Prediction Using Erosional Unconformities. In; Prediction of Reservoir Quality Using Chemical Modelloing, Eds. I.D. Meshri and P.J. Ortoleva, AAPG memoir 49, pp. 1-23

Shepherd, T., Rankin, A.H. & Alderton, D.H.M. (1985) A Practical Guide to Fluid Inclusion Studies; *published by Blackie and Son Ltd., Glasgow*

Shilts, W.W. & Smith, S.L. (1986a) Stratigraphic Setting of Buried Gold-Bearing Sediments, Beauceville Area, Quebec *Current Research, Part B, Geological Survey of Canada*, **Paper 86-1B**, 271-278.

Shilts, W.W. & Smith, S.L. (1986b) Stratigraphy of Placer Gold Deposits; Overburden Drilling in Chaudiere Valley, Quebec *Current Research, Part A, Geological Survey of Canada*, **Paper 86-1A**, 703-712.

Shilts, W.W. & Smith, S.L. (1988) Glacial Geology and Overburden Drilling in Prospecting for Buried Placer Deposits, Southeastern Quebec. *Prospecting in Areas Of Glaciated Terrain*, 141-169.

Simpson, C. (1983) Strain And Shape-Fabric Variations Associated With Ductile Shear Zones. *Journal Of Structural Geology*, **5**, 12.

Stephens, W.E. & Halliday, A.N. (1984) Geochemical Contrasts Between Late Caledonian Granitoid Plutons of Northern, Central and Southern Scotland *Transactions of the Royal Society of Edinburgh; Earth Sciences*, **75**, 259-273.

Tindle, A.G. & P.C.Webb (1989) Niobian Wolframite From Glen Gairn, Eastern Highlands of Scotland: a Microprobe Investigation *Geochim. Cosmochim. Acta.*, **53**, 1921-1935.

Vlassopoulos D. and Wood S.A. (1990) Gold Speciation in Natural Waters: I Solubility and Hydrolysis of Gold in Aqueous Solution. Geochim. Cosmochim. Acta, 54, 3-12

Webb, P.C., Tindle, A.G. & Ixer, R.A. (1991) W-Sn-Bi-Ag Mineralization Associated With Zinnwaldite-Bearing Granite From Glen Gairn, Scotland *Trans. Instn. Min. Metall. (Sect B: Appl. earth sci.)*, **101**, 59-72.

Webster, J.G. & Mann, A.W. (1984) The Influence Of Climate, Geomorphology And Primary Geology On The Supergene Migration Of Gold And Silver.; J.Geochem. Explor., 22, pp 21-42.

White, S.H., Burrows, S.E., Carreras, J., Shaw, N.D. & Humphreys, F.J. (1980) On Mylonites In Ductile Shear Zones. *Journal Of Structural Geology.*, **2**, 13.

Willan, R.C.R. & Coleman, M.L. (1983) Sulphur Isotope Study of the Aberfeldy Barite, Zinc, Lead Deposit and Minor Sulphide Mineralization in the Dalradian Metamorphic Terrain, Scotland *Economic Geology*, **78**, 1619-1656.

Wilkins, R.W.T. (1989) The Relative Chronology Of Fluid Inclusions In Minerals.*in Proceedings of the Conference on Stable Isotopes and Fluid Processes in Mineralisation. Herbert, H.K. and Ho, E.S. (eds) Geology Department and University Extension, The University of Western Australia Publication No. 23.*

Wright, A.E. & D.R.Bowes (1968) Formation of Explosion Breccias ; *Bull. Volcanol. 32, pp. 15-32* .

Wyman, D & Kerrich, R. (1988) Alkaline Magmatism, Major Structures and Gold Deposits: Implications For Greenstone Belt Gold Metallogeny *Economic Geology*, **93**, 0216-0223.

Zheng, Y.F. (1990) The Effect Of Rayleigh Degassing Of Magma On Sulphur Isotope Composition: A Quantitative Evaluation. *Terra-Nova*, **2**, 5.

Zhou, J. (1988) A Gold and Silver-Bearing Subvolcanic Centre in the Scottish Caledonides near Lagalochan, Argyllshire. *Journal of the Geological Society, London.*, **145**, 225-234.

Zhou, J.-x. (1987) Lithogeochemical Exploration for Copper and Gold in Kilmelford District, Argyllshire, Scotland *Trans. Instn. Min. Metall.*, **96**, B187-B193.

APPENDIX 1; STOCKWORK MOLYBDENUM/TUNGSTEN MINERALIZATION IN THE GRAMPIAN HIGHLANDS

Note; in the interests of protecting commercially sensitive information the present chapter has been deliberately re-written to omit certain relevant place-names, but the text does concern a factual mineral locality.

Exploration

Exploration for molybdenum and tungsten in the Grampian Highlands was prompted by discussions with Mike Gallagher of the British Geological Survey who pointed to the prospectivity of the region for Mo/W skarn mineralization. The region was considered prospective on the grounds of the existence of known Mo/W mineralisation such as at Glen Gairn (Tindle et al) where Mo and W occur in veins and greisens hosted by the lithium-rich Glen Gairn Granite, and the presence of calcareous and calc-silicate lithologies within the regionally developed metamorphic pile. The presence of both a metal source and potentially reactive lithologies was considered conducive to the formation of metalliferous calc-silicate skarn mineralization. In addition, BGS stream sediment geochemical data showed several pronounced anomalies on streams draining parts of the Grampian Highlands.

Exploration started with the collection of stream-sediment samples a part of the Grampian Highlands, to confirm the existence of a localised geochemical anomaly found by BGS, and to locate others that could have been missed during the original survey. The original anomally was confirmed, and two further anomalies located in nearby drainage courses. Prospecting was carried out both during and after the stream-sediment sampling, partially guided by the geochemical results. Any form of mineralization formed the target at this stage; the prospecting was not confined to the search for skarns.

A substantial area of the catchment areas of the streams showing anomalous geochemistry was prospected in some detail, but not as intensively as on the Cushnie Prospect (see Chapter 3) due to lack of available time. Exposure was very poor, fairly typical of this part of Scotland. A tungsten and molybdenum bearing stockwork was quickly located on a prominent ridge, where it occurred in a bouldery scree with a few insitu blocks, occupying an area of about 200 m by 250 m. on the east side of the ridge. Mineralised blocks range from 10 cm-1m across and can be found over the whole area occupied by the boulder-field, with the detectable limit of the stockwork being defined by the edge of the boulder field where the slope decreases and scree gives way to undulating peat and heather covered moorland. Within the boulder field the incidence of molybdenite mineralisation is high, with most blocks containing molybdenite or tabular porosity thereafter. The distribution of wolframite mineralisation is less certain, due to the difficulty in recognising fine grained wolframite in the field, but it does appear to be more common towards the SE part of the mineralised area. Hand samples taken from the stockwork for chemical analysis (carried out by OMAC plc) returned molybdenum and tungsten grades of up to 1% each. A noticeable feature of the analytical results was that samples which were anomalous in Mo returned W grades of below the 20ppb detection limit, and similarly samples showing anomalous W grades showed no Mo enrichment. This suggests a spatial and/or temporal gap between two mineralising events.

Host Rocks

The stockwork is hosted by a variety of lithologies, including metasedimentary, meta-igneous and intrusive rocks. The relationships between these lithologies are not discernible in the field and neither are the lithologies mappable, due to their occurrence in a boulder-scree which though very locally derived has suffered enough transport, mixing and dissaggregation to obscure these important details. The dominant metasedimentary lithology is a variable fine-grained to gritty quartz mica schist. In places this lithology becomes sub-quartzitic in character with a gradual loss of the striped appearance. Meta-igneous rocks are dark, basic, medium-grained and highly sheared and would fit the description 'meta-dolerite'. They are only locally present, suggesting an occurrence in bedrock as small sheared pods in the metasedimentary country-rocks, and are not dissimilar to the sheared margins of the basic plutons of the Grampian Highlands. Intrusive lithologies, again only found locally, are a pale microgranite found close to the centre of the exposed stockwork, and feldspar porphyries, as fresh, unsheared angular blocks.

Mineralization

Mineralization within the stockwork is also variable in character (see Plate 18), and no correlation is apparent between the type and style of mineralisation and the nature of the host-rock. The dominant style of the mineralization is as thin (5 mm-2cm wide), randomly disposed quartz veinlets. Several cross-cutting vein sets are commonly seen on individual blocks, with the veins making up to 10-15 vol% of the rock mass. Multiple vein sets and close spacing produces textures akin to crackle breccia in places. Alteration of host rocks adjacent to veinlets is characteristically slight, with only slight bleaching occasionally seen, though one float block showed development of severe bleaching, sericitic alteration and a very friable consistency.

Vein fillings are of quartz, quartz + K feldspar, and lithium mica +/- quartz +/- feldspar, with molybdenite and wolframite the only ore minerals found. Molybdenite is hosted by orange stained milky to sub-glassy quartz veins, almost exclusively 5 mm-2cm across, though a limited number of float samples were located which showed veins up to 25 cm across. Orange staining is frequently not apparent on the weathered surfaces of the blocks, and in such cases veins appear milky unless fresh surfaces are exposed. In thin-section the orange staining is seen to be a result of thin translucent intergranular hematite films on quartz crystals. The fact that this staining is less apparent on weathered surfaces suggests it is a hydrothermal rather than a supergene effect. Molybdenite is characteristically medium to coarse grained and occurs as individual flakes up to 7 mm across and aggregates of flakes. It occurs either as disseminations through the full width of the quartz veins or, more usually is concentrated towards the margins of the veinlets, and constitutes 0-10 vol% of the veinlets at the hand-specimen scale. Wider veins show molybdenite aggregates up to 3 cm across in the orange stained vein margin, and a barren, unstained milky quartz centre. These veinlets cross-cut one-another in a complex fashion. Tabular porosity after molybdenite is a common feature in these quartz veins, with in certain cases up to 20 vol% of the rock mass comprising such porosity. Molybdenite also occurs as very thin, almost oily films along late open fractures which intersect mineralised quartz veinlets. On close examination this material is seen to comprise an accumulation of very fine grained molybdenite platelets. Given the extremely friable nature of the molybdenite (breaking of blocks is seen to disaggregate the molybdenite which falls out leaving behind tabular porosity), the presence of both porosity and these joint coatings can be reasonably attributed to disaggregation and transport by rainwater in the near surface region.

Wolframite is present as brown sub-metallic crystals interstitial to fine vuggy milky quartz which is easily distinguished from the massive orange stained milky quartz hosting molybdenite. Veinlets of this material are up to 3 cm across, with the wolframite characteristically concentrated near the vuggy centre of the veinlets. These veinlets are less common than the molybdenite bearing ones. Quartz/K-feldspar veinlets are relatively common, are up to 2 cm across and are internally medium to fine grained. On the margins of these veinlets, and less commonly on the margins of Mo and W bearing veinlets, a fine grey/brown mica is frequently developed, with the platelets lying perpendicular to the vein margin and the mica appearing to grow out from the wall-rock. Such micas are also occasionally found interstitial to and disseminated within quartz in the Mo and W bearing veins. They are also developed independently, where they fill thin, mm scale, anastomosing partings in the host-rocks. Occasionally these partings are developed to greater widths (up to 2 cm) with fillings of massive fine grained mica. The partings are found in float samples within the area of the stockwork and also some distance outwith this area, and may provide a means of widening the exploration target for the unexposed extension to the stockwork. The micas are found by the common flame test to be lithium bearing.

Rarer vein types include a fine, barren, sugary quartz variety and a coarse vuggy quartz variety, the latter being associated with intensely bleached, sericitically altered host-rock. A milky variety similar to that hosting molybdenite but without the orange staining is often mistaken for Mo bearing quartz, and may well be a barren variety of the same vein set.

Relative Timing of Mo, W and Li-mica Mineralisation

Relative timing of the various vein sets is extremely difficult to ascertain in the field due to the poor exposure, occurrence of much of the mineralization as an incoherent boulder scree and the usual occurrence of only one vein set in individual boulders. Three ages of similar looking thin molybdenite bearing veinlets are seen on one sample (Plate 18), and it is also apparent that the development of white Mo-poor quartz in the centres of the wider veins is later than the orangey Mo-rich quartz on the outside of these veins. Wolframite bearing veinlets are observed in places to cross-cut molybdenite veinlets, but nowhere is the opposite relationship seen. The development of lithium micas is a sporadically recorded early phase in the formation of all the vein types seen on Sron Garbh. The relative timing of the quartz/feldspar veins has not been discerned.

Comparison With Mo/W Mineralisation At Gairnshiel

The best studied occurence of Mo/W mineralisation in the Grampian Highlands occurs at Gairnshiel (Tindle et al 1989 and Webb et al 1992), and it is relevant to compare the two localities.The author's observations on the current prospect can be compared with the descriptions given by the above authors for the Gairnshiel locality. Overall geochemical and mineralogical similarities are obvious; the presence of Mo, W and Li enrichments are apparent at both localities and the dominant ore mineralogy constitutes molybdenite and wolframite, with lithium micas in both cases. The style of the mineralisation differs markedly, with greisen and vein hosted and disseminated mineralisation at Gairnshiel and a stockwork on the current prospect. As far as can be discerned from mineralised blocks on the current prospect, the relative timing of the molybdenite and wolframite mineralisation is similar to that at Gairnshiel, with Mo preceding W. Host rocks to the mineralisation differ between the localities; at Gairnshiel mineralisation is developed entirely within varieties of the Glen Gairn granite whilst on the current prospect the stockwork is seen to cut mainly Dalradian metamorphic lithologies plus subordinate meta-igneous and intrusive materials.

Metalliferous mineralisation is more substantially developed on the current prospect, covering a wider area and showing a much greater incidence and richer concentrations than at Gairnshiel (Mike Gallagher, pers. comm.)

The Genesis Of The Deposit

The details of all the possible modes of genesis of the deposit will not be described here; the work of Webb et al (1992) on the Gairnsheil mineralisation presents the various options. The recently located stockwork can however be considered within the context of the various metallogenic ideas developed in the main body of this thesis. The main gold metallogenic processes were argued to be the formation of deep crustal gold reservoirs by large scale tectonic processes, the tapping of these reservoirs by uprising magmas whose emplacement provided a means of transportation of gold to higher crustal levels where it was concentrated by magma-related hydrothermal processes, and the later supergene alteration of the mineralisation produced.

In geographical terms the recently located stockwork lies to the south of the Mid Grampian Line, the geological and metallogenic implications of this being that it lies above and within a deep and middle crust enriched in rare metals (Russell 1985). This crust could provide the ultimate source of the metal enrichments on the current prospect. The association of the mineralisation with micrograniti c and felsite porphyry lithologies is suggestive of a magmatic component to their genesis. Such magmatism could provide a means of tapping the crustal reservoirs and remobilising metals within the crust. The age of this igneous emplacement is not known but the mineralisation itself could be dated by isotopic age-dating of the lithium micas. By analogy with mineralisation at Gairnsheil which is hosted by granites of the Newer Granite suite, it is suspected that magmatism on the current prospect will be Lower Devonian in age. The presence of a microgranitic lithology close to the centre of the exposed stockwork is suggestive of an overall form to the mineralisation as a stockwork developed around and within an igneous boss. Thus the mineralisation has strong similarities with porphyry molybdenum deposits (Edwards and Atkinson 1986). In such deposits hydrothermal activity associated with igneous emplacement produces the stockwork and provides a mechanism for metal precipitation and concentration. The recently located stockwork can be considered as the product of magmatic/hydrothermal processes and has strong porphyry molybdenum affinities.

The magmatic/hydrothermal processes would have occurred at some depth in the crust, necessitating substantial erosion of the overlying rocks to expose the mineralisation at the surface. Once exposed the deposit would be subjected to supergene processes. In light of the effect that deep weathering during Tertiary times has been shown to have had on several other prospects described in this thesis, it is appropriate to attempt to determine whether the newly located stockwork has been subjected to such weathering. The identification of supergene effects is problematic on the current prospect however. The most visible ore mineral, molybdenite, is comparatively immobile in the supergene environment and is not therefore prone to leaching and oxidation. Any supergene mobility recognised on the current prospect is attributable to physical disaggregation and transport by rainwater in the near surface. The relative freshness of intrusive lithologies, which elsewhere are seen to be very prone to disintegration by deep weathering (eg. Chapter 3 and 6), argues against the operation of such weathering, but this could simply be a function of the poor exposure on the prospect; such weathered materials are unlikely to be exposed in such situations. In short, Tertiary weathering effects are not discernible on the current prospect, but their presence is not discounted.

The similarities with the Gairnsheil mineralisation suggest a genetic link between the two. The magmatic association in both cases but with better exposure of the granitic body at Gairnshiel suggests that they are both products of similar magmatic/hydrothermal systems. The recently located stockwork could simply represent a higher structural level in such a system. Comparison would also suggest that certain crucial metallogenic processes operated more efficiently on the current prospect; the presence of a stockwork and the implications this has for metal precipitation by hydrothermal processes in the typical porphyry Cu/Mo situation (Edwards and Atkinson 1986) would suggest that the final process of metal precipitation was more efficient.

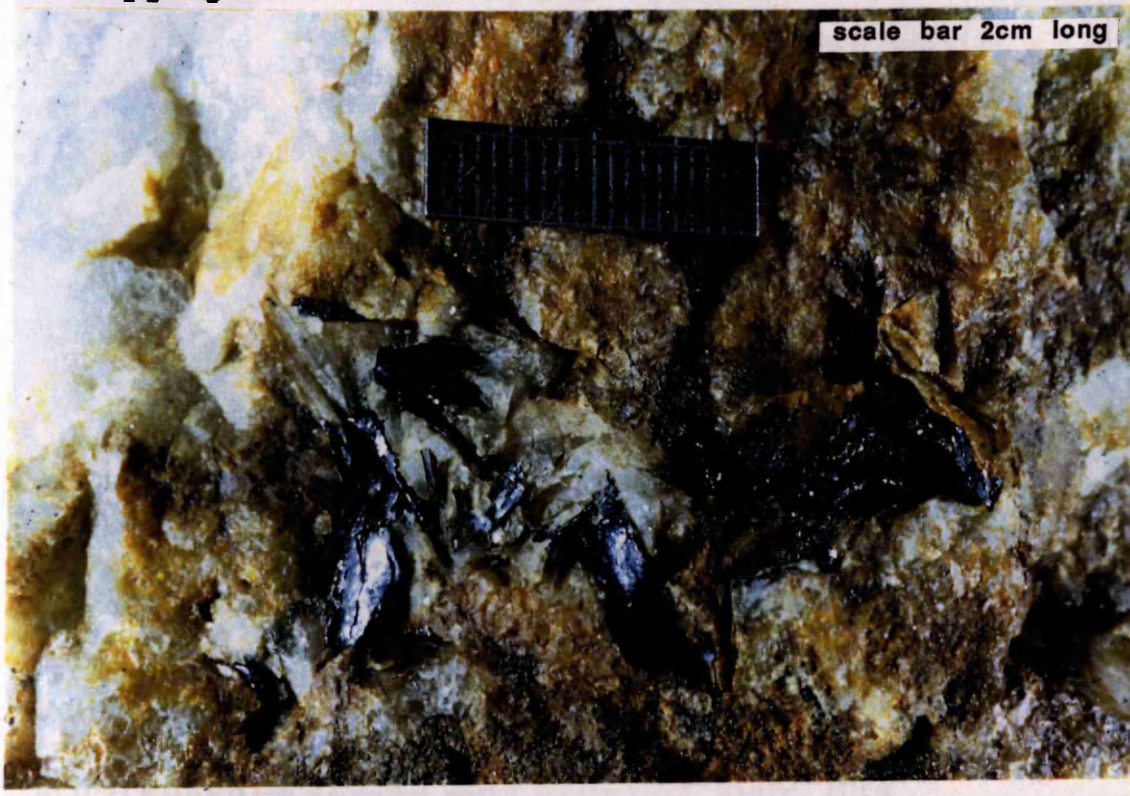
The similarities between the mineralisation on the current prospect and the typical porphyry molybdenum situation, and the presence of calc-silicate lithologies amongst the local metamorphic country-rocks enhances the prospectivity of the immediate area for W/Mo skarn type mineralisation. The stockwork, where it occurs as a boulder-scree, is situated within 5 km of the nearest mapped calc-silicates, but the extension of the stockwork in a direction towards these lithologies and/or the presence of other calc-silicate lithologies in the unexposed intervening ground could bring these two crucial metallogenic elements into closer association. A metalliferous hydrothermal system similar to that responsible for the formation of the recently located stockwork could generate skarn mineralisation in this instance.

Suggested Further Work

Time permitting, the mineralisation on the current prospect was to be subjected to a detailed field, mineralogical, fluid inclusion and isotopic study in order to understand the processes involved in the genesis of the mineralisation and their timing. Mineralogical and fluid inclusion work were to be placed in a spatial and temporal context derived from the field relations between the different vein sets observed in the field, and isotopic work was to provide the age of the mineralising event through dating of the micas and also possibly the origin of the fluids via sulphur isotopic analysis of molybdenite. The field study was to be based largely on the trenching programme being planned by Navan Resources plc on the prospect, but the onset of winter before the necessary access agreements had been negotiated with Morven estate resulted in the postponement of this work. Additional constraints on the timing of thesis submission necessitated curtailment of the detailed field study and also therefore the lab based work. Nevertheless, the recently located Mo/W stockwork represents an important mineralogical locality in the academic sense and a commercially promising prospect (though, arguably,not at present Mo and W prices). Future academic work could be along the lines of that described above or could follow the methodology of Webb et al (1992). Follow-up exploration should include a closely spaced stream sediment sampling programme; this will delineate upstream cut-off points in the geochemical anomalies and thus reveal the probable extent of the unexposed stockwork. Soil geochemistry should be used to extend this information into the areas between the stream-courses, and should be effective given the relatively thin peat cover and the known efficiency of secondary dispersion of molybdenum in such soils (Mike Gallagher, pers. comm.) Evaluation of geochemical anomalies may be achievable by mechanical trenching in view of the thin soil cover, though the steep, bouldery topography on the prospect may prove hazardous to most types of excavation plant. Further evaluation of the potential for skarn type mineralisation should involve further prospecting of the area towards the outcrop of the calc-silicate lithologies . The poor exposure in this area (recently worsened by a new drainage scheme on the estate which has caused the streams to become overgrown) may mean that effective ground coverage can only be achieved through soil or deep overburden sampling of this area.

PLATE 18; HOST ROCKS AND MINERALIZATION FROM MOLYBDENUM/TUNGSTEN STOCKWORK MINERALISATION IN THE GRAMPIAN HIGHLANDS

A. Massive, orange stained milky sugary quartz hosting coarse molybdenite. Occurs in veins up to 12cm wide. Rare. Note frequent porosity after molybdenite caused by physical dissaggregation.



B. 1cm wide orange stained quartz vein lined with abundant medium grained molybdenite. Molybdenite typically occupies either the margins or the middle of the veinlet, but never both. This represents the typical moly bearing veinlet [redacted]

C. Milky quartz fragment displaying abundant tabular porosity after coarse molybdenite similar to A. A common feature of float samples on Sron Garbh.

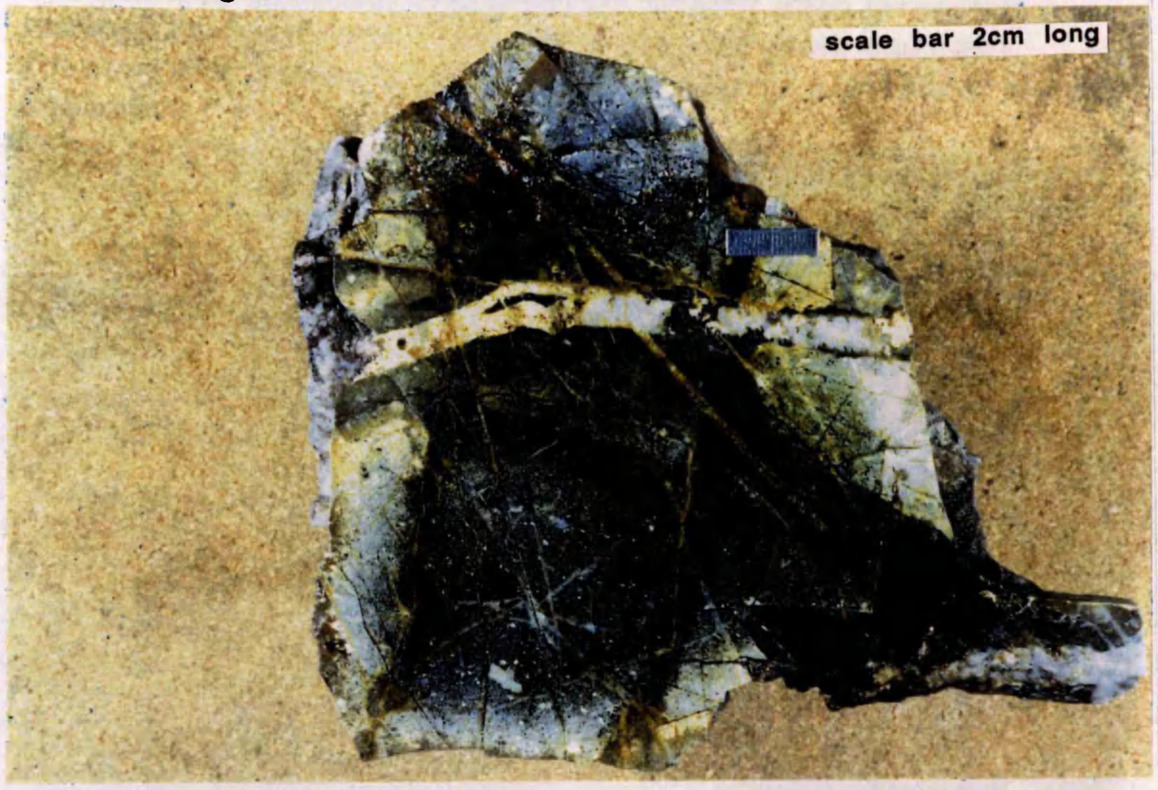
F. Thin multiple cross-cutting molybdenite bearing quartz veinlets in porphyritic felsic intrusive. Note late empty fractures cross-cutting mineralised veinlets, the walls of which are frequently coated with very fine 'moly-slick'.

D/E. Molybdenite bearing crackle breccia developed in Culchavie Striped Schist. Breccia infilled with orange stained quartz carrying molybdenite. Note overall freshness of host rock.

G. Cross-cutting molybdenite bearing orange quartz veinlets developed in Culchavie Striped Scist, and wider, finely vuggy, milky quartz vein sharply cross-cutting them. Note brown sub-metallic mineral interstitial to quartz vugs in the latter, indentified as wolframite.

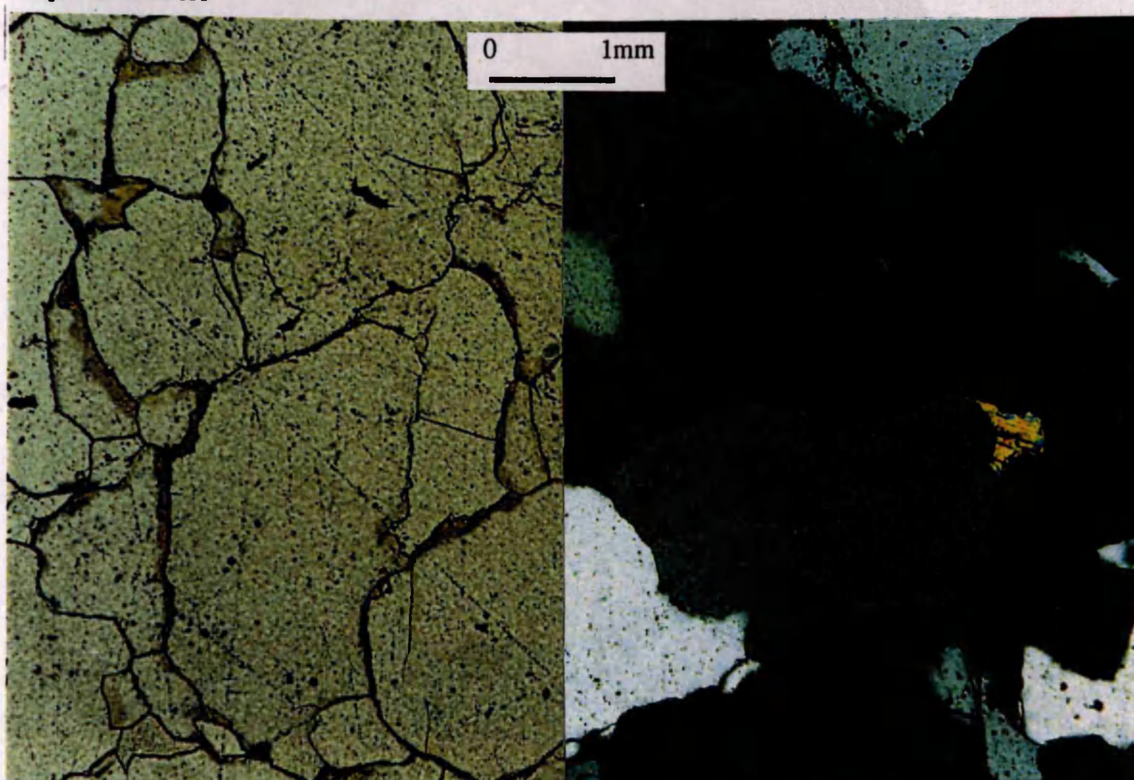
H. Thin cross-cutting molybdenite bearing orange quartz veinlets cut by finely vuggy, milky quartz vein carrying a fine sub-metallic mineral interstitial to quartz vugs (identified as wolframite) and streaks of white feldspar. Lithium bearing micas and feldspar developed within the latter. All hosted by sheared, altered metabasic lithology

I. Multiple cross-cutting orange quartz stringers, some hosting molybdenite, cut by granitic veinlet, all developed within porphyritic felsic intrusive material.

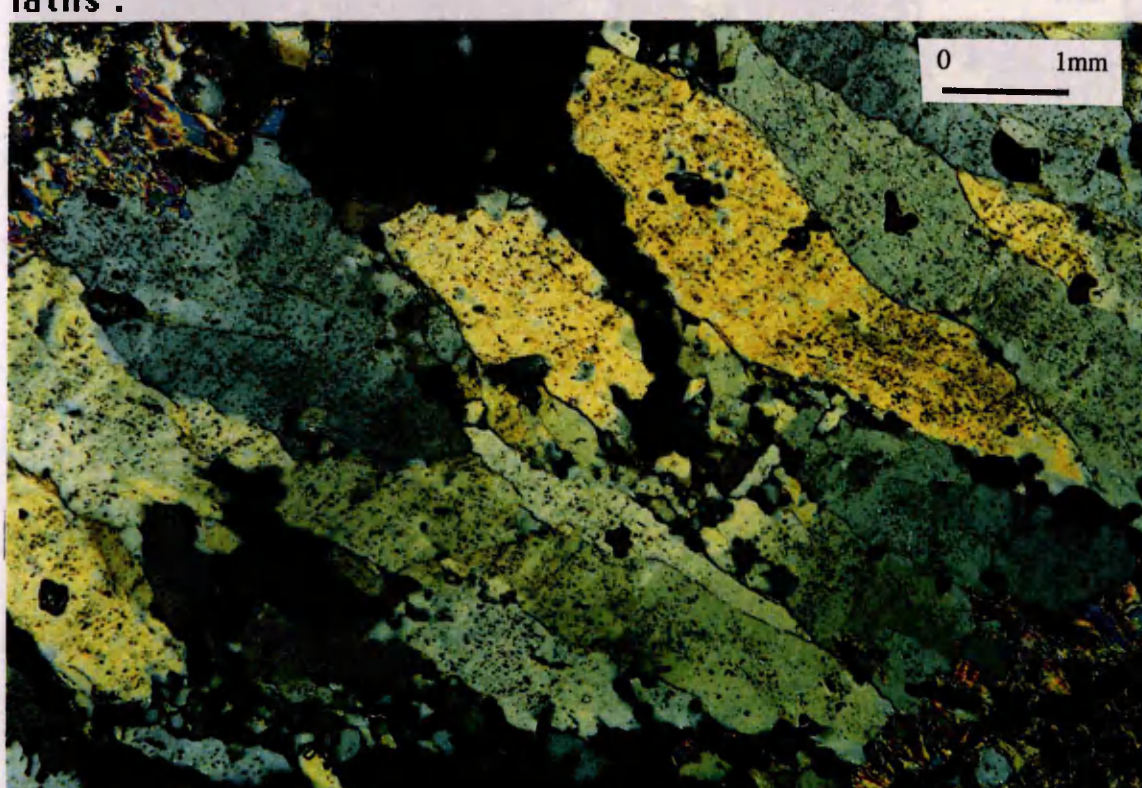


K. Multiple veined microgranite. Orangey quartz throughout, massive and finely vuggy varieties , the former hosting fine molybdenite. Note late empty fractures cross-cutting mineralised veinlets, the walls of which are commonly coated with very fine metallic blue 'moly-slick'.

K. Typical Quartz texture of the Sron Garbh stockwork; unstrained, anhedral equigranular quartz with interstitial muscovite. Note intergranular iron oxide grain coatings, responsible for the orange colour of quartz veinlets in hand specimen.

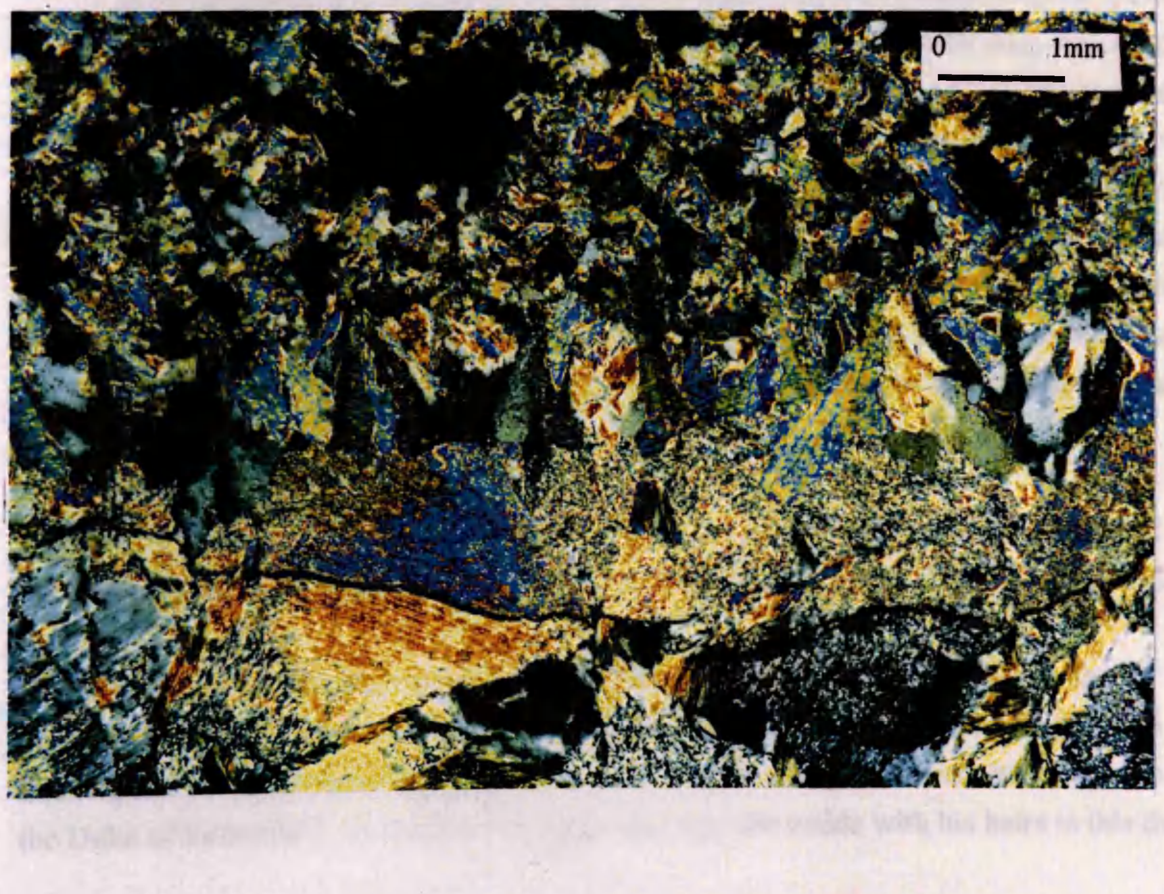


L. Less common quartz texture of the Sron Garbh stockwork; finely vuggy veinlet of subhedral quartz lined by muscovite laths .



M. Medium grained micas lining a granitic veinlet.

N. Fine grained muscovite, lining a fine parting in micaceous schist, hosting massive sericitised muscovite and feldspar.



APPENDIX2; LOGISTICAL IDIOSYNCRASIES OF GOLD EXPLORATION IN SCOTLAND

Introduction

Britain has been referred to by captains of the mineral exploration industry as having some of the worst laws regarding mineral resource exploration and development in the world, to the point that these laws constitute a substantial disincentive to exploration in Britain. This brief note intends to introduce the idiosyncrasies of the system that has created this opinion and in places offers suggestions from the author's own experience of how the system can be worked to advantage. The author, and Navan Resources plc. had by necessity to unravel the workings of the British system largely from scratch when they started exploring in Scotland, and this proved to be a time-consuming and frustrating exercise. The existence of the Crown Licence system was known about beforehand and the overall structure of land ownership in Scotland was known, but the ways in which these affected ownership of mineral rights and other aspects relevant to exploration were not. No brief written introduction to the system is known to exist and it is to be hoped that this note will fill this gap and save other interested parties the initial time wasting that its elucidation from scratch entails. The chapter deals mainly with the situation as regards the precious metals, silver and gold, but considers also how this situation differs from that concerning the other metals.

The Crown Licence System

Precious metal exploration can proceed in Britain once two prerequisites have been met, namely the obtaining of a Crown Licence and an access agreement with the current landowner(s). The former relates to the fact that precious metals rights in Britain are almost exclusively held by the Crown, and exploration for them is as such under their jurisdiction. The Crown is free to issue exploration licences to interested parties on application for such. The licensing round system used for North Sea hydrocarbon acreage whereby the government puts its own choice of licenses out to tender at a time dictated by itself, does not apply to precious metals licenses. An interested party applies for a Crown precious metals licence when and for what area specifically interests them. The operators of this scheme are the Crown Mineral Agents who presently are; Wardell Armstrong,

This address and the company charged with the job do change however, and did in fact change during the course of this research. A direct enquiry to the Crown Estates Office at

would reveal the most recent agents should they be different from the above. It should be pointed out here that certain areas of the UK are not under the jurisdiction of the Crown in this respect. Precious metals rights to the entire county of Sutherland were handed down to the Duke of Sutherland, the landowner, some time ago and reside with his heirs to this day.

This is the only specific exception to the Crown licence arrangement known to the author, but others are liable to exist elsewhere in Britain. In such a case, negotiation for the precious metals rights to a prospect will be with the landowner himself and the situation will be similar in all respects to that for the non precious metals as described later.

Application for a licence requires that the interested party be a registered business, be it personal, corporate, public or private. This information and a map of the area for which the application applies are sent to the Crown Mineral Agents who then process the application and subsequently inform the applicant of the success or failure of their request. The holder of the Crown licence effectively leases the precious minerals rights from the Crown. All other things being favourable, the licensee is then free to explore for, produce and sell gold and silver from within the licensed area(s). On production a royalty comprising a fixed percentage of the value of precious metals produced is payable to the Crown by the licensee. This represents the Crown's jurisdiction over precious metals in Britain. Other bodies such as the landowner and local and regional council planning boards also have a say in any production or advanced exploration/evaluation situation. This chapter deals solely with exploration scenarios and will not discuss the negotiations with planning boards required once the programme moves on to the evaluation stage.

The above represents the Crown licence system as it explicitly presents itself, and things would be relatively simple were this the whole story. Several complicating idiosyncrasies are found to be present however once an attempt is made to use this system, and these will now be described from the author's own experience.

The first idiosyncrasy is the inconsistency in the strength of enforcement of the system. Situations arose during the course of this research where exploration was found to be underway by a rival company on a prospect of independent interest to the author and Navan Resources plc., without that rival company holding the exploration licence for the ground. The company was operating with an access agreement from the landowner and in total disregard for the Crown Licence arrangement. The fact that such a strategy can be used undermines the authority of the Crown Licence system to the point of rendering it an irrelevance. On questioning over this matter once it had become apparent the Crown Mineral Agents let it be known that should a second party become interested in the ground their licence application would be refused and the licence offered to the original party. It is interesting to speculate on what would happen in the event that the licence application was delayed whilst exploration was pursued to the evaluation stage. Without the Crown Licence, production would be technically illegal, but without an access agreement, exploration by a second party which managed to wrestle the Crown Licence in its favour through the courts would also be illegal. This situation could lead to the sterilization of the resource as the two companies , the Crown Mineral Agents and the landowner were locked in legal stalemate. A situation similar to that prevailing over the northern part of the Navan Zn/Pb deposit could arise whereby rival claims become legally deadlocked and the resource is sterilised to nobody's benefit.

The above stalemate could easily arise, but a more likely situation is where the Crown Mineral Agents offer the licence to the original interested party and refuse the application from the other party. It would then be an audacious junior exploration company that would take the Crown Mineral Agents to court; they would in effect be up against the Crown's own lawyers and financial clout. The bottom line to all this is that the access agreement is much more important than the Crown Licence as far as initiating an exploration programme is concerned. Once the former is obtained, exploration can be started and the exploration licence will be offered to the company by default should a second party become interested in the ground. In the author's opinion this is a wholly unsatisfactory situation and effectively penalises those parties who play by the official rules. The situation has no basis in the Crown Mineral Agent's official policy but is a manifestation of the weakness of enforcement of the Crown licence system. The solution would be to either strengthen the powers of enforcement of the system or discontinue the Crown licence arrangement altogether. Strengthening the system would force interested parties to take the licence before starting exploration and everyone would know where they stood. Discontinuing the arrangement would remove the initial complication, and an a royalty agreement could be made with the Crown should production be anticipated. While the present limbo prevails things will be confused but in balance the access agreement with the landowner overwhelms the exploration licence in terms of both urgency and ultimate legal weight.

A major problem encountered during this research related to the Crown Mineral Agent's unwillingness to disclose information on which ground was under licence and which wasn't. This unwillingness was again completely inconsistent in that maps containing such information sporadically appeared during conference talks given by the Crown Mineral Agent himself. The normal lack of this information is highly problematic to exploration in that valuable field time is lost trying to obtain the information from scratch. One field season of author's work, and Navan Resources' exploration time, were completely wasted over this. The solution is for such information to be made available on request by the Crown Mineral Agents through the production of regularly updated maps, as is the case for exploration licences in Eire. Within the present system it seems sensible in hindsight to not waste field time over this problem. Rather, speculative licence applications should be made for areas of interest prior to payment for the licence; the pattern of success and failure of these applications will produce a picture of which overall areas are unavailable for exploration. This is far from satisfactory however since licence applications are rarely completely speculative; the normal situation being that brief initial reconnaissance has produced encouraging results which prompt the application. This initial reconnaissance work therefore runs the risk of being wasted. The problem is most acute for a company new to exploration in Scotland; established companies already have the information, new ones waste time obtaining it. A significant disincentive to exploration by incoming companies results, again to nobody's benefit. The problem remains insurmountable to a significant degree until regularly updated information is available on request from the Crown Mineral Agent.

The holding of exploration licences can be taken as evidence that a company intends to explore on the prospects. Another level of commitment is available to companies however, but its existence is not explicitly acknowledged by the Crown Mineral Agents. It is unofficially referred to as the "Statement of Interest". It normally comes into operation after a company has worked on a prospect but does not intend to do any more work in the near future whilst on the other hand wishes to maintain its stake in the prospect. The exploration licence is renewable annually given that an adequate amount of work has been done on the prospect and a report describing this work has been submitted to the Crown Mineral Agent. The Statement of Interest does not include a commitment to spend money on the prospect annually. It allows a company to keep exclusive rights to the licence for the foreseeable future. In the event that a second party becomes interested in the prospect, the original party is informed and asked whether they want to renew the licence. The licence is thus offered to the first party by default prior to processing of the second party's application. The situation is compounded by the fact that whether or not ground is covered by statements of interest is even more difficult to ascertain than for exploration licences, mainly due to the fact that the scheme's existence is not explicitly acknowledged by its managers, the Crown Mineral Agent. The only way round this is the same as that described for Crown Licences, but is equally unsatisfactory.

Land Ownership and Access Agreements

The Crown licence system simplifies matters for the mining industry in so far as it removes the complicating factor of who owns the precious metal rights to a patch of ground; it is reliably known that the Crown owns them over the vast bulk of the UK landmass. Land ownership details are therefore not relevant to the obtaining of precious metals rights. If any use is to made of these rights however, through exploration for or extraction of a resource then legal, agreed access to the land covered by the licence is required. Any field work requires land access, except for the various types of aerial or satellite based remote sensing. If groundwork is intended an access agreement with the relevant landowner(s) is required. The problem here is two-fold; firstly the pattern of land ownership over a prospect must be ascertained and secondly once this is done a mutually acceptable access/payment deal must be negotiated between the landowner and the interested party.

Various means of ascertaining land ownership exist. A few publications do exist on the subject, notably "Heading for the Scottish Hills" (compiled by the Mountaineering Council of Scotland and the Scottish Landowner's Federation) and "Who owns Scotland" by . The information they contain is helpful at the initial stages of research into land ownership, but neither covers the whole Scottish landmass nor represents a definitive and continually updated statement of the situation. Both are useful for obtaining initial contacts with keepers and local landowners prior to researching the subject by enquiring of local keepers and farmers as described later. The Register of Sasigne, presently housed in Meadowbank House in Edinburgh, is a register of abstracts from title deeds covering all or nearly all of the land surface of Scotland. The specific details registered relate to land transactions rather than land ownership. The latter must be elucidated by careful scrutiny of all transactions that, through history, have affected the plot of land of interest. Given an area of ground of interest, details of all land ownership transactions within a given period can be obtained. If further details are required the full title deeds can be consulted in using the reference provided by the Register of Sasigne. The library system used by the register needs much practice, but staff from Meadowbank house can be hired at an hourly rate to assist. This can prove very costly however, and the resultant documents, being written in complex legal language, are extremely difficult to decipher. Legal advice is required to make sense of the documentation, incurring further expense. It is at this point that the exploration geologist would conclude that this avenue of research was not an effective one; the Register of Sasigne is of limited use to a company trying to initiate an exploration programme.

Asking local farmers in the area of interest about land ownership can be quite an effective strategy. The method works well in areas where the previous large estates have been broken up into smaller farming units owned by the farmers themselves. The average Scottish hill or dairy farmer does not object to an unheralded personal approach from a geologist on this matter, and most offer a positive response, being keen to maximise their returns from the land by allowing exploration to start. Their curiosity is often to the geologist's benefit and as long as it can be maintained by keeping them informed about progress (without giving away sensitive information) the arrangement becomes self-perpetuating. The end result of this strategy is usually a patchwork of areas about which the land ownership details are known, with gaps that need filled in by one or other means. The method is less effective where the land is held by large estates; the average estate owner does not welcome an unheralded personal approach and his answer is liable to be negative as a direct consequence, though his factor or (more so) his keeper can be more approachable.

A highly effective method of ascertaining land ownership patterns is to consult Regional Council files from the Ratings and Valuations Office. These files are kept as a record of the rateable values of people's homes and their land holdings, and therefore contains details of the latter. They are not, to the author's knowledge, available for public scrutiny, but if the relevant officer can be found he can usually be negotiated with. An exploration geologist at this stage of a programme effectively represents an enterprise wishing to set up within the area governed by that Regional Council. Subtle emphasis of this point will usually win Co-operation from its officials. The ratings system in Britain has changed form twice during the period of this work, with the introduction of the Poll Tax and then the Council Tax. The relevant information has remained in the same place, under Regional Council jurisdiction, but may have changed names. Planned political changes involving the disbanding of large Regional Councils may in future cause a shift of this information to the Local Council domain. The Local Council office serving the area of interest will point you to the correct current source of this information.

Significant simplification of the land ownership and access situation was found where state-owned land was concerned. The Forestry Commission is the dominant public-sector landowner in upland Scotland and were found to be very welcoming of any exploration activity on their land. This may partly be due to the planned privatisation of the

Commission at the time of the negotiations and their desire to get the maximum financial return from their land in the run up and immediate aftermath of privatisation. In any case, where the Forestry Commission owned significant parts of a prospect, for example at Cushnie, the research and subsequent negotiations necessary to ensure land access were much simpler and less drawn out. The unfortunate aspect of this is that Forestry Commission ground is typically not conducive to effective conventional exploration due to dense forestry cover. Judicious use of better exposed areas and possible follow-up using biogeochemistry are potential ways around this disadvantage. Exploration on Forestry Commission ground is therefore to be encouraged; areas possibly under their jurisdiction can be pinpointed quickly on 1:50,000 Ordnance Survey maps and the relevant regional Forestry Commission office contacted to confirm this and initiate negotiations over access.

It is appropriate here to point out a fundamental difference between Scottish law and other UK law as regards land access. Where in the rest of Britain a formal, explicit law of trespass exists, no such law exists in Scotland. In the rest of the UK, one's presence on private property uninvited constitutes grounds for prosecution, whilst in Scotland actual witnessed damage to that property or its contents must be proven before prosecution can proceed. Thus in Scotland any member of the public can wander at will over any part of the country so long as damage is not perpetrated en route. The significance of this is that it makes possible reconnaissance work over large areas (eg. stream sediment sampling) without detailed preparation as regards land ownership research. It is possible to carry out such a survey discreetly without previous access arrangements being made; the legal risks inherent in this strategy are much less in Scotland than in the rest of the UK. However, other risks do remain and should be appreciated before any such strategy is adopted. One's presence on land uninvited constitutes bad manners personally and bad ethics professionally, and both aspects can be used by local farmers/landowners to the geologist and his company's discredit. It is to be remembered also that should reconnaissance work indicate areas meriting detailed follow-up work, a history of the above practise in an area will be disadvantageous to the company in negotiations with farmers, landowners and local authorities. Therefore whilst the Scottish laws present an opportunity for advantage in this respect, in the author's opinion, partly borne out by experience, opportunism of this type is unethical and in any case is not worth the risk. An informal approach to local tenant or owner farmers is usually all that is required to carry out brief sampling on their land, and removes this risk. This becomes more necessary in more densely populated areas where the opportunity for discreet, uninvited sampling is obviously lessened. Reconnaissance work eg. regional stream sampling, can be carried out using this informal approach, and meanwhile land ownership information can be obtained from local farmers which will be helpful to any follow-up programme.

The Non-Precious Metals

The situation as regards the non-precious metals differs from the above mainly in that the Crown does not own the mineral rights , except in cases where they also own the land as part of the Crown Estates. This is a significant complicating factor and is compounded by the fact that mineral rights and land ownership do not necessarily go hand in hand. Originally the two did go hand in hand, but subsequent sales of plots of land did not necessarily involve handover of the mineral rights. The result is that the mineral rights can be held by the landowner, his descendants, his close or distant, recent or historic relatives, or by any unrelated person or institution who has purchased them sometime in the past. Such sales can take place several times through history. The elucidation of mineral rights holdings thus involves very detailed search through past and present title deeds relating to the land of interest, and is a time-consuming, legally specialised and therefore very expensive process. Mineral rights can be leased on a temporary or permanent basis to second parties, or 'held under their care', the exact legal meaning and practical implications of such arrangements being unclear to the author. In dealing with non-precious metal exploration, the two prerequisites are the purchase or lease of the mineral rights from the present holder and a land access agreement with the present landowner. This is at least as complex as the situation for the precious metals, though the author has little experience of it. Land ownership details are obtainable by the means described above for precious metals exploration; an access agreement allows exploration to proceed at a reconnaissance level but if interest in a prospect is sustained beyond this, mineral rights have to be researched and obtained. It is the complexity of both land ownership and mineral rights laws that creates the disincentive towards exploration for and development of non precious metal resources in Britain.

The relationship between crofting rights and mineral rights was not fully researched by the author. Crofting rights date back to the Crofting Tenure Act of 1888 which gave crofters security of tenure on their lease from the landlord. Mineral rights are, in the author's experience on Shetland, retained by the landlord and negotiations for such should be conducted through the landlord. This does not apply to the precious metals, which as explained earlier are owned by the Crown. Land access arrangements are jointly under the jurisdiction of the landlord and his tenants. Crofting communities on an estate generally arrange themselves into management committees of one sort or another; the relevant person to contact (probably under a title such as "Crofters' Convener") can be ascertained by enquiring of the crofters themselves or by contacting the local council who will have the relevant details.

The above represents the author's present state of knowledge of the rules controlling mineral exploration in Scotland. They were elucidated largely from scratch during fieldwork for this thesis, mainly on a trial and error basis due to the lack of any written description of these rules. It is to be hoped that the above chapter goes some way towards filling this gap and will save someone else the frustration and time-wasting involved in working them out from scratch.

APPENDIX 3 ; SELF POTENTIAL VOLTAGE DATA ACROSS THE SOCACH STRUCTURE.

WIDE, LEACHED PART OF THE SOCACH STRUCTURE

SPline1

distance (m)	SP(mV)	Repeat1	Repeat2
0.0	-0.40		
2.5	-9.30		
5.0	-9.10		-8.6
7.5	-20.10		
10.0	-5.60		-6.8
12.5	-20.00		
14.0	-26.00	-23.90	
15.0	-29.50	-29.30	-29.7
16.0	-24.00	-23.00	
17.0	-21.10	-23.40	
18.0	-26.00	-26.90	
19.0	-22.10	-24.40	
20.0	-28.70	-32.40	-32.5
21.0	-27.30	-26.20	
22.0	-6.60	-12.30	
23.0	-5.50	-7.70	
24.0	-5.10	-4.70	
25.0	-2.50	-2.80	-5.0
26.0	-5.80	-7.10	
27.0	-3.90	-5.30	
28.0	-9.90	-9.60	
29.0	-6.70	-11.00	
30.0	-7.50	-6.60	-6.3
31.0	-10.90	-10.40	
32.0	-5.10	-4.60	
33.0	-0.30	-0.03	
34.0	-4.30	-12.70	
35.0	-0.02	-2.30	-3.1
36.0	-5.40	-3.50	
37.0	-1.30	-1.20	
40.0	-10.60		-11.5
42.5	-6.00		
45.0	-5.30		-7.0
47.5	-8.50		
50.0	-6.80		-8.9
52.5	-6.80		
55.0	-11.40		-13.9
57.5	-11.30		
60.0	-20.30		-21.3
62.5	-31.90		
65.0	-11.50		-10.3
67.5	-24.50		
70.0	-14.40		-13.7
72.5	-12.50		
75.0	-14.70		-11.7
77.5	-14.60		
80.0	-7.70		-6.9
82.5	-9.30		
85.0	-15.00		-16.1
87.5	-14.80		
90.0	-12.80		-12.3
92.5	-9.20		
95.0	-9.50		-11.9
97.5	-9.30		
100.0	-11.50		

SPline3

distance	SP(mV)
0.0	-1.60
2.5	-20.50
5.0	-5.80
7.5	-0.30
10.0	-2.70
12.5	-2.30
15.0	-0.50
17.5	-7.10
20.0	-3.40
22.5	-1.30
25.0	-3.20
27.5	-2.50
30.0	-1.70
32.5	-2.60
35.0	-0.90
37.5	-5.40
40.0	-2.60
42.5	-4.30
45.0	-1.20
47.5	-8.00
50.0	-11.40
52.5	-6.50
55.0	-4.50
57.5	-8.40
60.0	-17.80
62.5	-6.50
65.0	-3.30
67.5	-2.20
70.0	-1.50
72.5	-8.20
75.0	-9.60
77.5	-27.20
80.0	-8.70
82.5	-2.90
85.0	-5.00
87.5	-2.70
90.0	3.40
92.5	3.10
95.0	-2.40
97.5	4.00
100.0	-6.70
102.5	-8.70
105.0	-6.90
107.5	-10.90
110.0	-7.00
112.5	-1.20
115.0	-1.20
117.5	4.80
120.0	9.60
122.5	-13.60
125.0	0.07
127.5	-6.80
130.0	-5.50
132.5	2.70
135.0	-3.50
137.5	-3.20
140.0	-4.70
142.5	-3.10
145.0	-5.20
147.5	-1.50
150.0	4.10
152.5	0.00
155.0	-2.20

SPLINE4

DISTANCE(m)	SP(MV)	REPEAT
0.0	0.0	0.0
2.5	-2.9	-9.9
5.0	-13.8	-15.7
7.5	-29.2	-27.5
10.0	-28.9	-26.7
12.5	-15.2	-21.1
15.0	-14.5	-20.5
17.5	-14.1	-19.9
20.0	-9.2	-14.5
22.5	-15.8	-19.0
25.0	-9.1	-13.4
27.5	-11.2	-15.5
30.0	-21.2	-23.5
32.5	-21.8	-23.2
35.0	-31.5	-21.5
37.5	-26.6	-26.8
40.0	-18.4	-17.1
42.5	-13.5	-14.5
45.0	-23.5	-23.9
55.0	-26.7	-28.3
57.5	-21.3	-20.5
60.0	-10.2	-12.3
62.5	-21.5	-22.3
65.0	-9.7	-11.4
67.5	-14.2	-16.9
70.0	-25.6	-26.5
72.5	-20.9	-19.9
75.0	-20.4	-22.9
77.5	-18.4	-20.5
80.0	-27.8	-29.7
82.5	-26.3	-26.2
85.0	-22.8	-24.5
87.5	-18.8	-12.5
90.0	-17.2	-16.8
92.5	-24.5	-21.6
95.0	-18.6	-17.0
97.5	-15.0	-13.2
100.0	-14.1	-12.9

NARROW, OXIDISED PART OF THE SOCACH STRUCTURE

SPline2

distance (m)	SP(mV)
1	-7.30
2	-6.80
3	-3.90
4	-1.50
5	2.20
6	-4.40
7	-4.60
8	-2.70
9	-6.00
10	-2.90
11	-2.00
12	2.00
13	0.50
14	-2.30
15	-1.80
16	0.40
17	-14.40
18	0.14
19	-1.90
20	1.10
21	-11.50
22	-2.30
23	-9.00
24	-11.30
25	-6.10
26	-2.20
27	-7.50
28	-1.30
29	-3.70
30	-1.50
31	-9.30
32	-7.50
33	-10.50
34	-7.20
35	-10.70
36	-8.90
37	-2.10
38	-2.30
39	-4.70
40	-2.90
41	-2.40

APPENDIX 4 ; VERY LOW FREQUENCY ELECTROMAGNETIC TRAVERSE DATA ACROSS THE SOCACH STRUCTURE.

NARROW, OXIDISED PART OF THE SOCACH STRUCTURE

VLFline2

Dist (paces)	In Phase (%)	Quadrature(%)
0	-2	3.5
5	-3	4
10	0	3.75
15	-1	5
20	-2	3
25	-1	4.5
30	0	4
35	1	5
40	0	4.25
45	2	7
50	2	6
55	2	5.5
60	2	3
65	3	6
70	4	7

VLFline2rpt

Dist (paces)	In Phase (%)	Quadrature (%)
0	-3	4
5	-2	6
10	-3	6
15	-2.5	7.5
20	-1	9
25	2	10
30	2	11
35	3	6.5
40	5	8
45	2	10.5
50	4	7
55	7	11.5
60	6	12
65	4	13
70	4	13
75	2	15
-5	-5	7.5
-10	-6	4
-15	-4	5
-20	-6	4.5
-25	-5	4

VLFline3

Dist (paces)	In Phase (%)	Quadrature (%)
-20	-15	-1
-15	-14	-1
-10	-15	-0.5
-5	-15	-1
0	-13	-2
5	-17	-2
10	-10	-2.5
15	-14	-2
20	-14	-0.5
25	-15	-3
30	-15	-1
35	-16	-1
40	-13	1
45	-16	2
50	-14	1
55	-17	2
60	-19	-1
65	-17	0.5
70	-19	1
75	-21	-5
80	-23	-5
85	-24	-5
90	-20	-3

WIDE, LEACHED PART OF THE SOCACH STRUCTURE

VLFline1

Dist (paces)	In Phase (%)	Quadrature(%)
0	-20	-11.5
5	-17	-11
10	-17	-9.5
15	-16.5	-12
20	-16	-12
25	-16	-11
30	-17	-10
35	-15	-10
40	-16	-12.25
45	-16	-8
50	-14	-9
55	-17	-10.25
60	-17	-11
65	-15	-10
70	-18	-9.5
75	-16	-10.25
80	-19	-11
85	-18	-11
90	-16	-11
95	-15	-10
100	-17	-14
105	-14	-13
110	-14	-10
115	-12	-11
120	-14	-11
125	-14	-12
130	-15	-11
135	-14	-12
140	-14	-12
145	-14	-11
150	-14	-12.5
155	-15	-11.75
160	-16	-10
165	-14	-11

VLFline4

Dist (Paces)	In Phase (%)	Quadrature(%)
-10	-14	-7
-20	-15	-11
-30	-13	-9
-40	-16	-7
-50	-13	-8
0	-16	-9.5
5	-17	-11
10	-17	-8
15	-14	-10
20	-15	-11
25	-14	-10
30	-13	-10
35	-16	-9.5
40	-13	-12
45	-12	-9
50	-12	-10
55	-16	-11
60	-15	-9.5
65	-14	-10.5
70	-13	-9
75	-10	-10.5
80	-14	-11
85	-14	-11
90	-13	-12
95	-15	-11
100	-13	-10
105	-15	-10
110	-11.5	-13
110	-13	-11
115	-14	-12
120	-14	-12

DISTANCE SCALE 5 paces = 4.5m

APPENDIX 5 THERMOMETRIC DATA FROM FLUID INCLUSIONS IN HYDROTHERMAL QUARTZ GANGUE TO CRUACHAN CRUINN BRECCIA-PIPE.

Homogenisation Temperature C	Carbon Dioxide Homogenisation Temperature C	Final Melting Temperature C	Initial Melting Temperature C	Volume % Carbon Dioxide
235		-6	-22	0
290			-19	0
273		-7	-20	0
219			-17	0
237		-10	-13	
193			-30	0
197			-27	0
	30	-9	-22	
	17	-14	-39	
203			-36	
305				55
	30			30
290				0
275	30	-15	-33	80
190		-11	-27	0
170		-6		0
267		-15	-26	0
200	18			45
205		-14	-37	0
	23			80
204		-11		0
233		-14	-28	
304		-8	-18	80
230		-8.5	-15	0
268				0
220	30	-13	-26	20
	21			50
	28			90
273			-21	0
225		-7		0
289	32			45
272				0
228				0
278				0
275				
	30	-8	-29	45
		-7	-20	0
		-12	-30	0
		-6	-20	
310	28			
218	11			60
	9			70
	20			70
	13			
	18			
	34			
	28			80
200	31			
	30			80
280	28			30
	32			100
271	12			40
301	33			25
310				0
311				0
	13			100
310	31			85
214		-8.5	-21	0
232				0
235		-12	-25	0
222				0

Homogenisation Temperature C	Carbon Dioxide Homogenisation Temperature C	Final Melting Temperature C	Initial Melting Temperature C	Volume % Carbon Dioxide
236		-15	-25	0
308		-14	-26	0
230		-8.5	-26	0
184				0
156		-8		0
175			-39	0
192				0
234		-6	-14	0
163		-9	-24	0
298		-12	-19	
273		-11	-23	
234		-8.5	-16	
215		-10	-21	60
280	28			45
303	25			35
295				0
299	29			80
	25			40
	25			50
326				80
225				0
289				0
314				0
239		-6	-18	0
297				0
227	28	-12	-28	70
237	27	-4.5		70
300	28			55
299				0
210	28	-8	-24	40
208				0

Homogenisation Temperature C	Final Melting Temperature C	Initial Melting Temperature C
295		
290		
255		
257		
183		
170		
205		
186		
266		
270	-6	-22
303	-9	-21
238	-9	-25
189		
190		
300	-7.5	
296		
180		
317		
300		
284		
212		
236		
335		
280		
301	-14	
219	-5	
222	-10	
147		
178		
152		
190		
137		
224		
223		
315		
218		
257		
227		
235		
279		
225		
275		
306		
245		
275		
281		
235		
206		
212		
283		
293		
214		
220		
301		
289		
278		
327		
210		
287		
295		

APPENDIX 6 FLUID INCLUSION DATA FROM HYDROTHERMAL QUARTZ FROM THE SOCACH STRUCTURE, CUSHNIE GOLD PROSPECT, ABERDEENSHIRE SCOTLAND.

TmCO2	Tim	Tfm	TmClath	ThCO2	ThTOT	Vol%CO2	Tdec	
				31				
				31				
	-24			30.5	305	60		same crystal
	-28	-11			123	0		
					221			
					225			
			3	28	275	80		
	-22	-10			345			same crystal
-55.5	-26		2	32		40	278	
	-24	-9			295	0		
-56	-22	-9	4	31		50	330	
-55.5	-28	-11	4	31			335	
	-21	-10	2	31.5	375	35		
-56	-31	-9	1.5	30.5			335	
-56	-29	-10	3	31	297	50		same crystal
	-35	-4			146	0		
		-9			169	0		
	-31	-10			285	0		
-56	-21		4	31			305	
-55	-28	-14	2	29			286	
-55	-24	-14	3	30.5	375	40		same crysta
-56	-21		2.5	30		75		
-56	-28		2	31	375	50		
-56	-21	-7	3	31	375	50		
-55	-19	-10	2.5	30	232	25		
-56	-20		3	32		70		
-56	-32	-10	3		265	60		
-56				32		35	288	
-56	-30	-11	3.5	31	335	40		
	-22	-9			341	0		
-55	-32	-13	2	32	311	40		
-56			4	31	331	60		
	-27		3	30	224	15		
	-26	-11			174	0		
	-33	-14			297			
-50				29	305			
					245			
					265			
	-26	-14			258			
	-27	-13			225			
					280			
					250			
	-35			30	302	15		
	-22	-7			310	30		
	-20	-13			303			
	-20	-6			292			
				32	298	50		
		-16			259			
	-18	-11			290			
	-20	-9			307			
				30	320	40		
				30		90		
				32		90		
				31	325	90		in a cluster
				31		90		close to one-ano
					230	0		
					275	0		
					225			
					232			
					239			
					250			
					251			in a cluster
					235			
					240			
					234			
					296			
					305			
-58	-26	-12			233	0		
	-30	-14	4	30	315	60		
					221			
					330			
					341			
					196			
					181			
					201			
					245			
					225			
					282			
					287			
					270			
					280			
					230			
					189			same crystal
					221			
					250			
					313			
					315			centre of cryst

TmCO2	Tim	Tfm	TmClath	ThCO2	ThTOT	Vol%CO2	Tdec	
					345			same crystal
					330			
				33		100		
					256			
				34		100		on fracture
					233	0		
					189	0		
					234	0		
					225	0		
					220	0		
					205	0		
					209	0		
					228	0		
					128	0		
-57			3	30	307	50		
			5	32	313			
-59			3	31	315			
-55	-35		4	31	310	40		
					295	10		same crystal
	-23	-6			245	0		
				31.5		100		
					230	0		
					225	0		
					218	0		
					229	0		
				30		100		
					278			
					189			
					202			
					220	0		
					228	0		
					295	0		
					255	0		
					152	0		same crystal
					179	0		
					270	0		
					287	0		
				32		100		
				31	273			
					272	0		
					289	0		
					291	0		
					345	0		
					257	0		
					234	0		
					228	0		
					290	0		
					235	0		
					259	0		
					176			
				33		100		
					283	0		
					351	0		
-55	-32	-14	3	32	340	45		
	-21				275	0		same crystal
	-21				298	0		
			3	32	335	50		
					219	0		same crystal
	-33	-10		31	310			
					204	0		
					250	0		
	-18			31	321	40		
					300	0		
					335	50		
	-25		3		270	25		same cluster
				33	306	30		
					251	0		
	-30	-14			245	0		in quartz near interstitial haematite
	-35	-15			228	0		
	-38	-14			252	0		
					259	0		
	-28				241	0		
					258	0		
-57	-28	-10			295	50		in quartz distant from interstitial haematite
					344	50		
-58		-7	4	32	324			
-57			3	29	274	40		
					260	0		
					255	0		
					265	0		
	-26	-13		30	317	25		
					237	0		
	-23	-8	3	32	276			
	-26	-16			311			
				31		100		
					224			
					262			
					222	0		

APPENDIX 7 ; FLUID INCLUSION DATA FROM GOLD MINERALISED BRECCIA FROM DALNESSIE ESTATE, CENTRAL SUTHERLAND.

Homogenisation Temp (C)	Initial Melting Temp (C)	Final Melting Temp (C)	Size (um)
175			10
192			6.5
223			17
139			14
215			
245			10
123			8
142			6
218			6
318			6
210			15
215			14
200			12
203			10
197			12
247			18
283			18
310			18
185			20
250			8
259			15
169			16
199			12
219			15
209			14
207			12
217			10
232			18
224			14
231			
210			
240			
150			5
197			10
150			
190			
214			15
160			
181			7
178			10
215			8
215	-28	-8	
231			
214	-22	-9	6.5
205		-7.5	
193	-25		
208	-19		
196	-23.5	-7	
210	-19.5		
203			
206	-21	-8	
205	-20	-11	
242			3.5
	-23	-8	10
197	-25	-8	8
198	-24	-9	8
173	-28		15
202			
226		-10	
197	-26		10
215	-27		10

Th	Tim	Tfm	size
187	-28		5.5
201			3.5
204	-28	-12	5.5
175		-11	9
219	-30	-11	10
209			5
185	-24	-10	8
265	-30	-16	8
232			10
263	-26	-12	6
194	-22	-8.5	12
203			10
218	-24		12
200	-27		6
278	-21	-8	7
180			6
206			4
228			12
221			10
167			8

APPENDIX 8 ; LITHOLOGICAL, GRADE AND THICKNESS DATA FOR BORLAND GLEN TRIAL PITS.

	LITHOLOGY			
PIT NUMBER	PRIMARY DESCRIPTOR	SECONDARY DESCRIPTOR	GRADE UNITS	DEPTH TO REGOLITH (metres)
2A	TIR	BC	0.035	3.1
3	IR	BC	0.635	6.8
4	TIR	BA	0.64	2.9
5	BA		0.12	1.4
5rpt	BA		0.07	
6	IR	BC	0.025	3.45
7	BA		0.12	1.8
8	TR	BC	0.25	4.1
9	TIR	BC	0.385	3.5
11	TIR	BC	0.25	2.9
12	TR	BC	0.355	3.5
12rpt	TR	BC	0.36	3.5
13	TIR	BC	0.305	2.8
14	TIR	BC	0.065	2.3
15	IR	BC/BA	0.025	2.5
15rptA	BA/BC		0.03	2.5
15rptB	IR	BA/BC	0.015	2.5
16A	BA		1.98	1.0
16B	IR	BA	1.745	1.0
17A	TR	BC	0.075	>5m
17B	BVI	BC		>5m
17C	BVI	BC	0	>5m
18	BA+IR		0.31	1.2
19A	BA	BC	0.035	3.2
19B	TR	BA+BC	0.05	3.2
20	BC		0.007	>6m
21a	TR	BC	0.695	2.3
21b	TR	BC	0.44	2.3
22	FGSG	BA	0.07	>2.5
23	BA+FGSG		0.07	>4.5
24	TR	BC	0.125	2.75
25A	BA/BC		0.035	2.25
25B	TIR	BA/BC	0.02	2.25
27	BC+BA	BC	0.01	>6m
28A	BA		0.04	3.6
28B	TR	BA	0.01	3.6
29A	BA		0.14	>5.4
29B	FGSG	BA		>5.4
30	FGSG	BA	0.01	>4.8
31	BA		0.0118	>5.5
32	BA		0.24	1.6
33	IR+BA		0.06	0.9
34A	BA	BC	0.06	2.4
34B	TIR	BA+BC	0.02	2.4

35A	BA	BC	0.3512	2.5
35B	TIR	BA+BC	0.3628	2.5
36A	BA		0.3805	1.9
36B	IR	BA	0.7868	1.9
37	IR+BA		0.501	1.1
38A	BA		0.3731	1.95
39	IR	BA/BC	0.2788	2.5
40A	BA		0.6898	1.2
40B	IR	BA	0.6456	1.2
41A	topsoil		0.02	2.15
41B	IR+BA		0.1388	2.15
42A	BA	BC	0.01	2.9
42B	IR	BA+BC	0.076	2.9
43A	BA		0.5141	2.0
43B	IR	BA	2.165	2.0
44	BA			1.75
44dup	BA		0.2246	1.75
45	IR+BA	BC	0.5327	2.4
47	IR+BA		0.6046	1.4
48A	FGSG		1.359	3.4
48B	BA	FGSG	0.2886	3.4
48C	IR	BA+FGSG	0.753	3.4
49	IR		0.8865	0.9
50	BA+IR		0.6631	2.4
51A	Topsoil		0.01405	>2.1
51B	FGSG		0.0071	>2.1
54	BC		0.0275	>5m
55A	FGSG		0.01305	>5m
55B	FGSG+IR		0.0407	>5m
51A2			0.0105	>2.1
38B	TIR	BA	0.3105	1.95
26	BA+IR		0.025	3.1

LITHOLOGICAL KEY

BA Bouldery Alluvium
IR Insitu Regolith
TR Transported Regolith
TIR Transported and Insitu Regolith
FGSG Fluvioglacial Sand and Gravel
BC Boulder Clay
BC/BA hybrid lithology; boulder clay/bouldery alluvium
BC+BA boulder clay plus bouldery alluvium