ORDOVICIAN SUBMARINE DISTURBANCES IN THE GIRVAN DISTRICT

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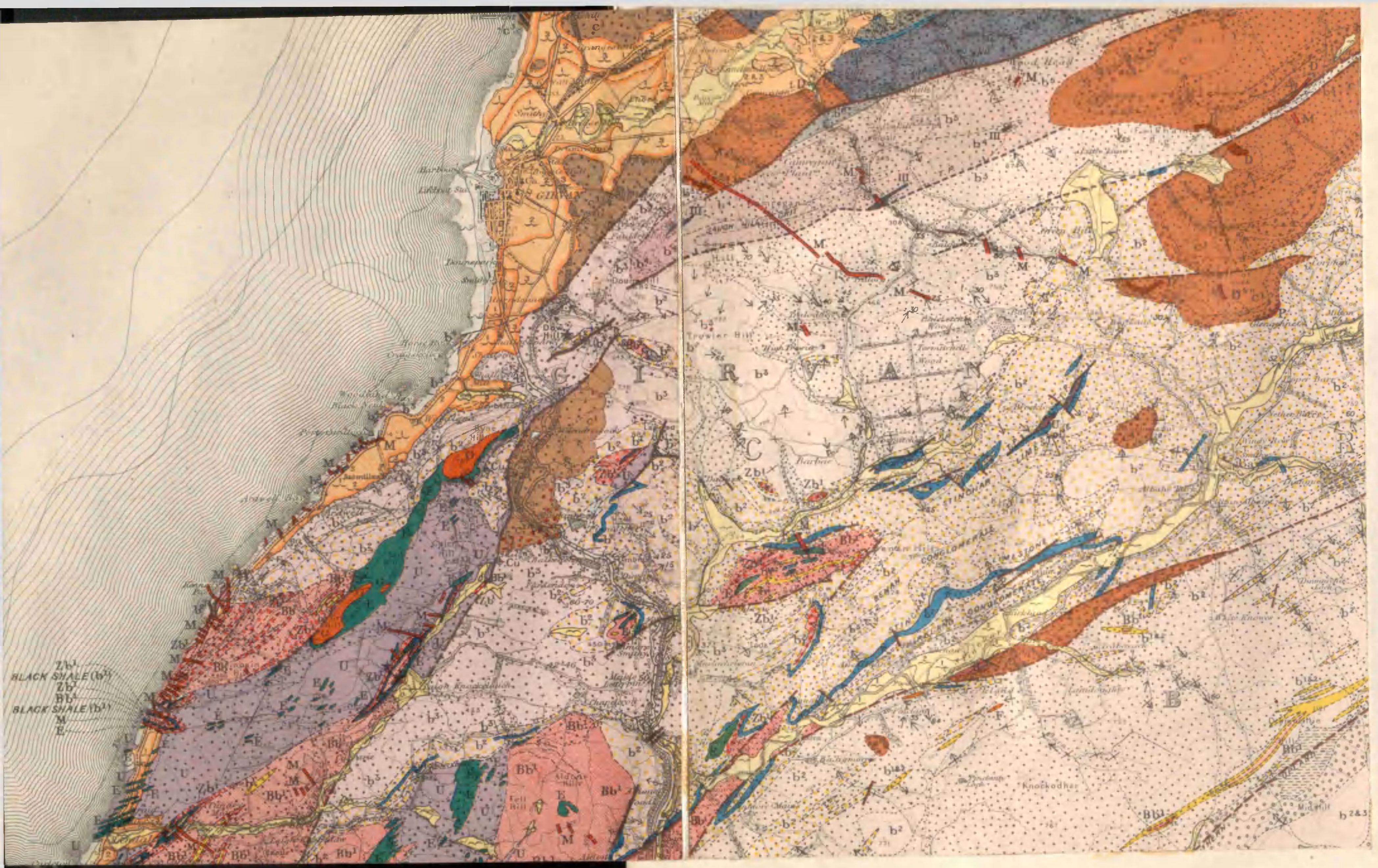

Portions of Sheets 7 & 8 - 1 inch=1 mile.
Geological Survey of Scotland.

ORDOVICIAN SUBMARINE DISTURBANCES IN THE GIRVAN DISTRICT

Introduction.

The study of the Lower Palaeozoic sediments of South Ayrshire has generally been devoted almost entirely to the palaeontological problems, and their relations to the stratigraphy rather than to the conditions of origin of the rocks. During investigations into the conditions of sedimentation of the Ordovician rocks of the Girvan District, special attention was attracted to a series of greywackes, the Ardwell Beds, owing to the frequent occurrence of intraformational disturbances and unconformities.

It is proposed here to follow the classification of Peach and Horne (1899) who, after careful consideration adopted Prof. Lapworth's (1882) succession, except for a few minor alterations. These authors pointed out in their classic Memoir that the Llandeilo rocks to the north of the River Stinchar, consisting of Kirkland Conglomerate, the Stinchar Limestone Group and the Benan Conglomerate at the top, were contemporaneous with the Tappins Greywackes and the Glen App Conglomerate south of the river. Both successions are underlain by the Arenig lavas and their associated sediments. The sediments of the northern area overlap on to a denuded and folded surface of the Arenig rocks. Recent work by the present author has shown that the massive Benan Conglomerate lies unconformably on various older members of the Girvan/

Girvan succession.

Peach and Horne placed the fossiliferous mudstones and grits of the Balclatchie Beds at the base of the Caradoc. These rocks are followed by a series of flagstones and shales, including the Ardwell Beds which form the object of this paper. It must be pointed out that the Caradoc of Peach and Horne includes the Ashgillian of later authors.

Throughout the district the Ardwell Beds rest unconformably, a point not previously discovered, either on the Balclatchie Beds or on the Benan Conglomerate. In the latter case the Balclatchie rocks are entirely absent. These Ardwell greywackes (flagstones and shales of Lapworth) are essentially a series of graded sandstones with greenish grey and black shales. At some horizons the shales are predominant over the sandstones giving the rocks a striped appearance. Throughout the series examples of intraformational breccias and folding have been discovered. Also several beds of conglomerate and coarse grit, and one perfect fossil landslip with the cliff from which it must have originated. Immediately it was realised that here was material with a close similarity, though on a smaller scale, to boulder beds and other phenomena described from the Kimmeridgian of East Sutherland, by Prof.E.B.Bailey and Dr.J.Weir (1932), and from the Lower Palaeozoic of Quebec by Profs. E.B.Bailey, L.W. Collet, and R.M.Field (1928). The boulder beds were attributed to submarine landslips caused by earthquakes originating along great faults, the debris being distributed by the resultant tunamis (tidal waves of common speech). In the Ardwells, the features/

features can only be attributed to submarine earthquakes resulting from the general movements of the Palaeozoic Geosyncline.

The Ardwell Beds are succeeded by the Whitehouse Beds,which consist of graptolitic shales, overlain by fossiliferous calcareous grits, followed in turn by purple and green mudstones. Throughout the whole of this series current bedding and more especially slip bedding of a complicated nature are characteristic features. The calcareous grits are apparently composed of sand and shell debris from other areas of the geosynclinal sea. Above the Whitehouse Group is a series of sandstones and shales showing similar characteristics in bedding, but almost entirely devoid of fossils, and thus known as the Barren Flagstones. The Ordovician succession closes with sandstones, mudstones, and grits belonging to the Drummuck Group at the top of the Caradoc Series.

The Ardwell Beds, over 1000' thick, form one of the largest outcrops of the Caradoc Series. The most important exposure as far as the present work is concerned, is on the sea shore 4 miles S.of Girvan (Fig.1). At the northern end of Kennedy's Pass below the road the Ardwell greywackes are seen resting unconformably on the Benan Conglomerate. These beds occupy the foreshore northwards for almost a mile until they are covered by the sand of Ardwell Bay. This large wavewashed exposure renders the series accessable to a very detailed study and likewise the shore lends itself readily to the method of mapping adopted by Prof.E.B.Bailey and Dr.J.Weir at Helmsdale. It may be as well, before proceeding further, to repeat the details of the technique of shore mapping, so that it may be readily/

ORDOVICIAN SUCCESSION

CARADOC					
DRUMMUCK GROUP	Sandstones, mudstones, grits.	200'			
BARREN FLAGS	Flagstones, and shales.	800'			
WHITEHOUSE BEDS	Shales, calc. grits, and mudstones.	300'			
ARDWELL BEDS	Greywackes, mudstones, & conglomerates.	1200'			
UNCONFORMITY					
BALCLATCHIE BEDS	Conglomerates, grits, & mudstones.	100'			
LLANDEILO					
N. of R. STINCHAR			S. of R. STINCHAR		
BENAN CONGL.	Congl. and sandstone.	500'	GLEN APP CONGL.	Congls. & sandstone.	500'
UNCONFORMITY					
GRAPTOLITIC SHALES	Grey shales (Didymog. superstes)	30'	TAPPINS GROUP	Greywackes & mudstones.	500'
STINCHAR LIMESTONE	Massive & flaggy Lst.	60'	GRAPTOLITIC MUDSTONES		6'
KIRKLAND CONGL.	Purple sdst. & congl.	240'	MUDSTONES AND RADIOLARIAN CHERTS		
UNCONFORMITY					
ARENIG					
Radiolarian cherts, spilite lavas, and tuffs, etc.		1570'			

Table I. Ordovician Succession after Peach and Horne (1899).

readily understood that the maps and sections of this paper have been drawn accurately to scale. First it must be pointed out that throughout most of the shore exposure the Ardwell Beds lie vertical or almost vertical. Thus maps of exposures automatically become sections. Important areas of the foreshore were measured out into squares with 100', 50', or 25' sides, according to requirements, and the corners marked off. The interior of each square was then mapped to scale on graph paper.

In the cliff of the Raised Beach and in the streams draining the Ardmillan Braes the evidence of the shore can be verified. The outcrop of the Ardwell Beds can thus be traced from Kennedy's Pass in a north easterly direction along the Ardmillan Braes and the slopes of Byne Hill to Dow Hill south-east of Girvan.

Fig.1.- MAP of GIRVAN DISTRICT showing outcrop of ARDWELL BEDS and LOCALITIES:- A= ARDWELL FARM; K.P.= KENNEDY'S PASS; P.M.= PINMORE; S.= SHALLOCH HILL; B.= BROCKLOCK; P.= PENWHAPPLE.

Owing to the repeated folding the Ardwell Group occupies a large area north of the River Assel. It can be traced over several miles, but the scanty nature of the exposures affords little chance of a detailed study. Following the general trend of the strike the outcrop is seen to narrow. In this eastern area an admirable section is exposed in the Penwhapple Burn, a tributary of the Girvan Water. A good starting point is Balclatchie Bridge on the road from Old Dailly to Barr where the massive Benan Conglomerate can be seen at the roadside and in the burn. Passing northwards down the Penwhapple Glen for about 250 yards the Balclatchie mudstones and fossiliferous conglomerates are found overlain unconformably by the Ardwell greywackes. The beds here are dipping steeply in a N.E.direction. For almost a mile the burn has cut its way through the Ardwell sandstones and shales, until it plunges over a waterfall formed by a series of grits and conglomerates, the Cascade Grits, at the top of the succession. The fact that the Cascade Beds are not to be found on the foreshore will be remarked on later.

Another large area of these greywackes forms the headwaters of the Water of Lendal, and spreads eastward past Pinmore on to the slopes of Daldowie between the Rivers Stinchar and Assel. The best locality is the quarry on the main road from Girvan to Pinwherry, ¼ mile S.of Pinmore Station.

Further details of the various exposures of the Ardwell Beds/

Beds may be obtained by reference to the paper by Prof.Lapworth (1882).

HISTORICAL

Up to the present the efforts of geologists working in the Girvan district have been directed almost entirely to the palaeontology of the Palaeozoic rocks. Thus the evidence described in this paper is entirely new and cannot be supported by any historical account of research beyond a general stratigraphical description.

Prof.Charles Lapworth (1882) was the first to unravel successfully the stratigraphy of the district. He devoted himself especially to the palaeontology and its value in relation to the succession. The detailed descriptions of the most important localities are illustrated by sections. Among these he gives descriptions and sections of the Ardwell Beds as displayed on the shore south of Girvan and in the Penwhapple Glen. Attention is drawn to the presence of the Cascade Grits in the Penwhapple and their absence from the shore is designated to a fault passing through Ardwell Bay. Prof.Lapworth mentions two outcrops of grit in the Penwhapple Glen separated by a series of shales and mudstones, with limy nodules often developing into limy bands. He points out that the fossil contents of these shales definitely places them on the same horizon as those on the shore at Ardwell Bay.

So excellent was the work of Lapworth that Peach and Horne (1899) decided that they could do no better than emphasise its important points. As was stated in the introduction, however, they/

they considered the Balclatchie Group should be placed at the base of the Caradoc rather than at the top of the Llandeilo as Lapworth had done.

During the Geologists' Association Summer Excursion in 1932 the present author pointed out the unconformity between the Benan Conglomerate and the Ardwell Beds as seen at Kennedy's Pass. The evidence was subsequently stated in the Excursion Report (1932).

ORDOVICIAN PALAEOGEOGRAPHY

It has long been recognised that the Lower Palaeozoic sediments were deposited in a broad geosyncline the shore line of which, in the area of the British Isles, had a N.E.-S.W. trend. Likewise, from the work of Prof.Lapworth especially, it has been realised that the Ordovician deposits of the Girvan District are neritic in origin, being laid down close to the shore of the continent of North Atlantis (Wills, 1929), while those of Moffat are bathyal, and accumulated in the depths of the geosyncline.

During geosynclinal sedimentation submarine ridges and accompanying troughs are formed, the ridges often developing into islands around which neritic deposits accumulate. The sea floor is continually being disturbed by earthquake shocks, and submarine erosion becomes an all important factor.

In a study of the palaeogeography the intensely folded and crushed nature of the rocks must be taken into account. It must be realised that the distance between the shore deposits and the bathyal sediments of the geosyncline was much greater at the time of deposition than at present.

Submarine Slipping in Arenig Times.

At the beginning of Ordovician times volcanic activity was predominant in the Girvan district. Great masses of lava welled forth below the sea to give rise to the well known pillow lavas of the Arenig. During periods of quiet, cherts and limestones were deposited. As would be expected displacements of the sea floor and resultant earthquakes accompanied the volcanic activity. The soft and unconsolidated sediments slid down the slopes, their bedding being generally disturbed.

An inlier of Arenig volcanic rocks with associated cherts and limestone forms Shalloch Hill (Fig.1) on the S.side of the valley of the Assel. One exposure, on the top of the hill, shows a pink crystalline limestone intermingled with the lavas, and often containing angular fragments of the underlying spilites. A narrow outcrop of brecciated chert can be traced right along the Arenig inlier, and forming the longitudinal axis. This chert owing to its brecciated nature and inclusions of igneous rock was believed by Lapworth to be the Kirkland Conglomerate, a pink much calcitised conglomerate at the base of the Llandeilo. Peach and Horne, however recognised it as Arenig cherts.

Fig.2.- BRECCIATED CHERTS,SHALLOCH HILL, with pillow lava boulders (above hammer) overlain by normal cherts (top right).

In a quarry above the farmhouse of Daldowie at the W.end of the area highly brecciated cherts containing large detached pillows of lava are seen overlain by normal radiolarian cherts (Fig.2). The junction is of a decidedly uneven nature, the overlying cherts filling in the hollows. Around each of these boulders of lava the cherts appear concentrically banded. There is apparently a considerable amount of serpentine or serpentinised lava among the brecciated material.

The probability is that the chert was being deposited in the lower parts of the sea floor and was at the time comparatively local. Submarine earthmovements disturbed the whole area, with the result that the already solidified cherts were brecciated. Pillows were dislodged from the surrounding lavas and rolled down and collected unsolidified chert gel as does a stone rolled in snow. The whole of the debris was distributed over the area by the resultant tunamis. After the disturbance, tranquillity again reigned and the cherts were deposited normally on the uneven surface of the brecciated chert debris.

EARLY LLANDEILO UPLIFT

At the close of the Arenig period a large uplift formed an island, or projection, from the northern continent, to the west and south west of the Girvan area. This land projected further to the N.E.on the northern side of the River Stinchar with the result that the Kirkland conglomerate was deposited near the shore line at the beginning of Llandeilo times. This conglomerate, as was pointed out by Peach and Horne and Lapworth, lying unconformably on/

on the Arenig rocks is composed mainly of debris from the lavas and cherts.

In the burns which drain the northern side of the Stinchar Valley W.of Barr the succession of the Llandeilo can be traced from the Kirkland Conglomerate at the base to the Benan Conglomerate at the top. The best succession is seen in the Benan Burn 2½ miles W.S.W. of Barr. Studying the sediments exposed, it is obvious that after the deposition of the Kirkland Conglomerate deeper water conditions prevailed. First, there is the Orthis Confinis Sandstone, which is current bedded, passing up into limy sandstone. Then impure limestone is followed by true Stinchar Limestone, and that again by the Didymograptus Shales. A new phase is introduced by the massive Benan Conglomerate with limestone pebbles at its base but composed mostly of Arenig debris.

With regard to the Stinchar Limestone it has been noticed that going further west it becomes more impure and sandy and this probably indicates the proximity of the western shore line.

SUBMARINE DISTURBANCES AND EROSION IN STINCHAR LIMESTONE TIMES.

Proceeding S.W.from Benan Burn to Auchlewan, about 1 mile, it is found that the Didymograptus Shales are absent, and the Benan Conglomerate rests unconformably on the Stinchar Limestone (Fig.3).

Fig.3.- BENAN CONGLOMERATE resting unconformably on STINCHAR LIMESTONE at Auchlewan, R.Stinchar.

The quick disappearance of the shale was remarked upon by Lapworth. He admitted that the appearances suggest unconformity, but set this interpretation aside and concluded that "the visible phenomena are most unquestionably due" to a "powerful fault" (Lapworth,1882,p.563). After examination of the clearly exposed junction it is impossible to admit Lapworth's explanation. Further west, at Aldons, the shale is once more in its correct position between the limestone and conglomerate.

An examination of the Brocklock Quarries farther north at the head of the Water of Assel, and 1½ miles E.of Tormitchell proved invaluable. These sections were described by Lapworth who determined the succession to indicate a perfect transition from Limestone conditions through the Didymograptus Shales to the Benan Conglomerate.

At the present the base of limestone on the Orthis confinis beds/

beds below is nowhere exposed, and true limestone is never seen. All the limestone visible is breccia. Perfect limestone breccia, the angular fragments of which are enclosed in a very sparse shaly or sandy matrix, occurs at the base of the exposed succession, and was mistakenly described by Lapworth as compact Limestone (Lap.Ab^3).Where he found the Benan Conglomerate (AC) resting directly on this "compact limestone" (cf.Quarry IV) he claimed that "the line of contact is clearly a fault" and that "patches of lime in the conglomerate" that look at first like fragments are "merely nodular concretions" (Lapworth p.569 & fig.5). Where fragments occur in the Didymograptus shales (Ab^4) above the "compact limestone", he interprets them as "seams and patches of calcareous nodules". On account of the abundance of such "nodules" at the base of the Benan Conglomerate, he separated a basal transition zone under the title "yellow conglomerate with limestone nodules" (Abc). Although these beds have been termed "yellow conglomerates" they clearly contain a considerable percentage of angular fragments. These limestone fragments are enclosed in a matrix of shale (Fig.4).

In the most easterly of the Brocklock quarries, situated beside a small stream, the succession is as follows.

<u>Quarry I</u> (? Lapworth, fig.6).

(Lapworth's Ac)	-	Benan Conglomerate	
(Abc)	-	Lst.breccia + angular fragments of chert and lava.	8'
(Ab^4)	{	Shale passing W.into shale + Lst. boulders.	5' to 2'
		Shale and grit.	4'

Fig.4.- Limestone Breccia with shale matrix. Quarry II, Brooklock,Water of Assel. x ½

$Ab4'$ or Ab^3	-	Lst.breccia - few Arenig pebbles	8'

The basal bed of this exposure (Lap.$Ab^{4'}$ or Ab^3) is mainly a limestone rubble with sparse shaly matrix in which are included occasional quartz grains. There are a very few other fragments, including cherts and greywacke. Apparently this was the rock quarried for burning, and no true unbrecciated limestone is present. There are other disconnected exposures close at hand to the north. These include limestone breccia and conglomerate.

The junction between the Limestone Breccia and the band of Shale and grit is very irregular. It is noticeable that grit often penetrates in tongues downwards into shale below.

The thickness of the shale diminishes towards the west, giving the appearance of transgression by the overlying Limestone Breccia (Abc of Lapworth).

A feature of the next quarry to the S.W. is the clear and rapid thinning out of the shale dovetailing with the limestone Breccia. In the section the limestone breccias have a shaly matrix (fig.4).

QUARRY II

	EAST		WEST
(Lap.Ac)		Bennan Conglomerate	
(Abc)		Lst.Breccia	11'
($Ab4''$)	0'	Shale	12'
(Abc)	2'	Lst.Breccia	0'
($Ab4''$)	3'	Shale	3'
		Lst.Breccia (Fig.4)	1' 6"
(Ab^3 or $Ab4'$)	8'	Shale	3'

	Lst.Breccia	5'
(Ab$^{4''}$)	Shale	7'

To the north again are disconnected exposures seen in grassed quarries. They include a highly calcareous fine conglomerate, with igneous pebbles, reminiscent of the Kirkland Conglomerate.

Passing further to the S.W. to the third and largest quarry the evidence is very similar.

<u>QUARRY III</u> (Lapworth,fig.7)

(Lap.Ac)	(10)	Benan Conglomerate	
(Abc)	(9)	Lst.Breccia and shale	4'
(Ab$^{4''}$)	(8)	Shale	7'
(Abc)	(7)	Lst.Breccia	6'
(Ab$^{4''}$)	(6)	Shale + Lst.pebbles at base	12'
(Ab^{3})	(5)	Lst.Breccia	7'
Fault			Fault
(Ab$^{4''}$)	(4)	Shale and Lst.pebbles	3'
(Ab^{3})	(3)	Lst.Breccia	7'
Fault			Fault
(Ab$^{4''}$)	(2)	Shale + Lst.Boulders	4'
(Ab^{3})	(1)	Lst.Breccia	5'

In this succession of alternating Limestone Breccia and shale the junctions are very irregular. This is especially clear with the junctions between beds (1) and (2) and between (6) and (7). The faults recorded between (2) and (3), and (4) and (5) are probably minor features which have merely complicated the original irregular junctions rather than reduplicated the beds. Lapworth designated the/

the two lowest limestone breccias (1 & 3) as "compact limestone" repeated by faulting. Again to the N. are isolated calcareous conglomerate exposures.

The fourth and most westerly quarry shows the Benan Conglomerate resting unconformably on Limestone Breccia (figs. 5 & 6). The Didymograptus shales are entirely absent.

Fig.5.- BENAN CONGLOMERATE resting unconformably on LIMESTONE BRECCIA. Limestone pebbles in the conglomerate are ringed off with chalk. BROCKLOCK (Quarry IV).

QUARRY IV (Lapworth,fig.5).

(Lap.Ac) Benan Conglomerate + Lst. pebbles at base

U N C O N F O R M I T Y

(Ab3) Lst.Breccia.

The limestone breccia can be traced across the quarry

to/

Fig.6.- Specimen showing Benan Conglomerate (dark) resting on uneven surface of Limestone Breccia (light). Brocklock (Quarry IV). x $\frac{1}{2}$

to the N.W. corner where it apparently is in contact with typical Orthis confinis Sandstone. The position of this sandstone in the true succession is below the Stinchar Limestone which is absent at these Brocklock Quarries.

The limestone breccias of this range of quarries are comprised of fragments as a rule totally unrounded, the larger about 6" long, the smaller minute and not infrequently mere broken shells. Occasionally boulders 1 foot in length occur in the breccias. Neighbouring fragments may be of quite a different character, indicating some transport. This is supported by the slight rounding of some of the material especially in the higher beds of breccia. The matrix is generally shale similar to that with which the breccia beds are seen dovetailing.

It seems natural to connect the formation in some way with the uplifts responsible at a later stage for the production of the Benan Conglomerate. The general absence of rounding, and the relation to the matrix and the associated shale material suggests that the limestone was broken up by submarine disturbance. The breccia was formed by the slipping of the limestone down inclined surfaces to areas of mud, forming scree slopes, over the uneven surface of which succeeding shale was deposited. Possibly some of the debris was distributed by tunamis resultant on submarine disturbances. The unconformity of the Benan Conglomerate at Quarry IV, and the junctions of the breccias and shale in Quarry III indicate that the Limestone breccias presented an extremely uneven surface to the succeeding deposit.

A strong suggestion of submarine disturbance is indicated by/

by the presence of tongues of sand penetrating down through underlying shale, especially well seen in Quarry I. This sand was brought forward by the rush of water associated with the formation of a limestone breccia at a near locality, and was washed into the cracks and crevices of the broken sediments on the sea floor.

That the submarine erosion of this period was extensive is indicated in Quarry IV by the entire absence of the alternating limestone breccia and shale. The Benan Conglomerate rests unconformably on one of the lower beds of breccia.

Towards the close of the period the land to the west was spreading forth the Arenig debris to form the great Benan Conglomerate which was deposited unconformably over the whole area. It is to be seen resting on the Didymograptus Shales, limestone breccia, and the true Stinchar Limestone.

Gradually the sea again encroached upon the land to the west, with the result that the Benan Conglomerate is seen to overlap on to the Arenig rocks themselves. Near Millenderdale, Water of Lendal, the Conglomerate rests unconformably on Arenig Lavas.

Earthquake Records in South Stinchar Llandeilo.

Meanwhile in the area south of the River Stinchar deposition continued comparatively normally. Here a great series of greywackes known as the Tappins Group was deposited. Apart from occasional slip-bedding they show no signs of disturbance.

In 1930 Professor Bailey put forward a claim that graded beds in greywackes and sandstones are records of seaquakes, the unconsolidated/

unconsolidated coastal sediments providing the material. He pointed out that according to his experience graded bedding is not accompanied by current bedding probably due to the sediments being at a depth out of reach of currents. An examination of the Tappins Beds shows them to be perfectly graded but no current bedding is apparent anywhere. Again, the disturbances required to furnish the coarse material to be deposited on the muddy sea bottom to form graded beds, were undoubtedly very active to the N. and N.W., of the area of deposition.

This repetition of grading was brought to a gradual end by the uplift close at hand giving origin to the material of the Glen App Conglomerate. The conglomerate and the Tappins greywackes are seen interbedded,indicating perfect transition. This was most probably the same uplift which gave rise to the limestone conglomerate N.of River Stinchar and the subsequent Benan Conglomerate.

Thus towards the end of Llandeilo times the rise of land in the west and its subsequent erosion caused the deposition of a close shore deposit in the Benan and Glen App Conglomerates. The former conglomerate has already been fully described by Lapworth, Peach and Horne and others. The boulders and pebbles of granite and other igneous rocks range up to 2'-3' in diameter. Most, are well rounded and are included in a dark green matrix composed of basic igneous rock debris. It is noticeable that from east to west the Benan Conglomerate gradually gets thinner and laps up on to the Arenig rocks. There is a likewise increase from east to west in the average size of the boulders, and a corresponding decrease in the calcareous nature of the conglomerate matrix. This all appears to indicate a shore line of an island or projection from/

from the mainland S.W.of Girvan.

At Kennedy's Pass, 4 miles S.of Girvan, Lapworth maps the Benan conglomerate as brought down between two faults. Peach and Horne state that the base of the conglomerate comes against lavas by a fault, up which a dyke has penetrated, at the south end of the Pass. At the G.A.Summer Excursion in 1932, the author showed that the base of the Benan conglomerate lies unconformably on a compact greywacke which is faulted against the lavas. This greywacke has not been identified, but is possibly a representative of the Tappins Beds on which the Glen App Conglomerate rests. This discovery led to a close examination of the Pass resulting in a complete remapping of the area (fig.7). Thus the extensive folding of the conglomerate and its apparent thinness were brought to light.(fig.8). Likewise it was discovered that the Ardwell Flags lay unconformably on the Benan Conglomerate. This point will be dealt with later.

The Benan Conglomerate, entirely devoid of fossils, was followed by a deeper water phase in which the fossiliferous Balclatchie mudstones, fine conglomerate, and grits were deposited. The grits in Penwhapple Burn show a remarkable spheroidal weathering (fig.9). While there are examples of spheroidal structure in igneous rocks due to contraction on cooling there is no doubt that many rocks, both igneous and sedimentary show the same structure due to weathering. Greywackes and ferruginous sandstones weather in spheres as they oxidise and hydrate, expanding successive crusts from around the solid unweathered core. This has been well described by Prof.James Park (1914) in his Text Book of Geology (p.22). It is interesting to note that these spheroidal

grits/

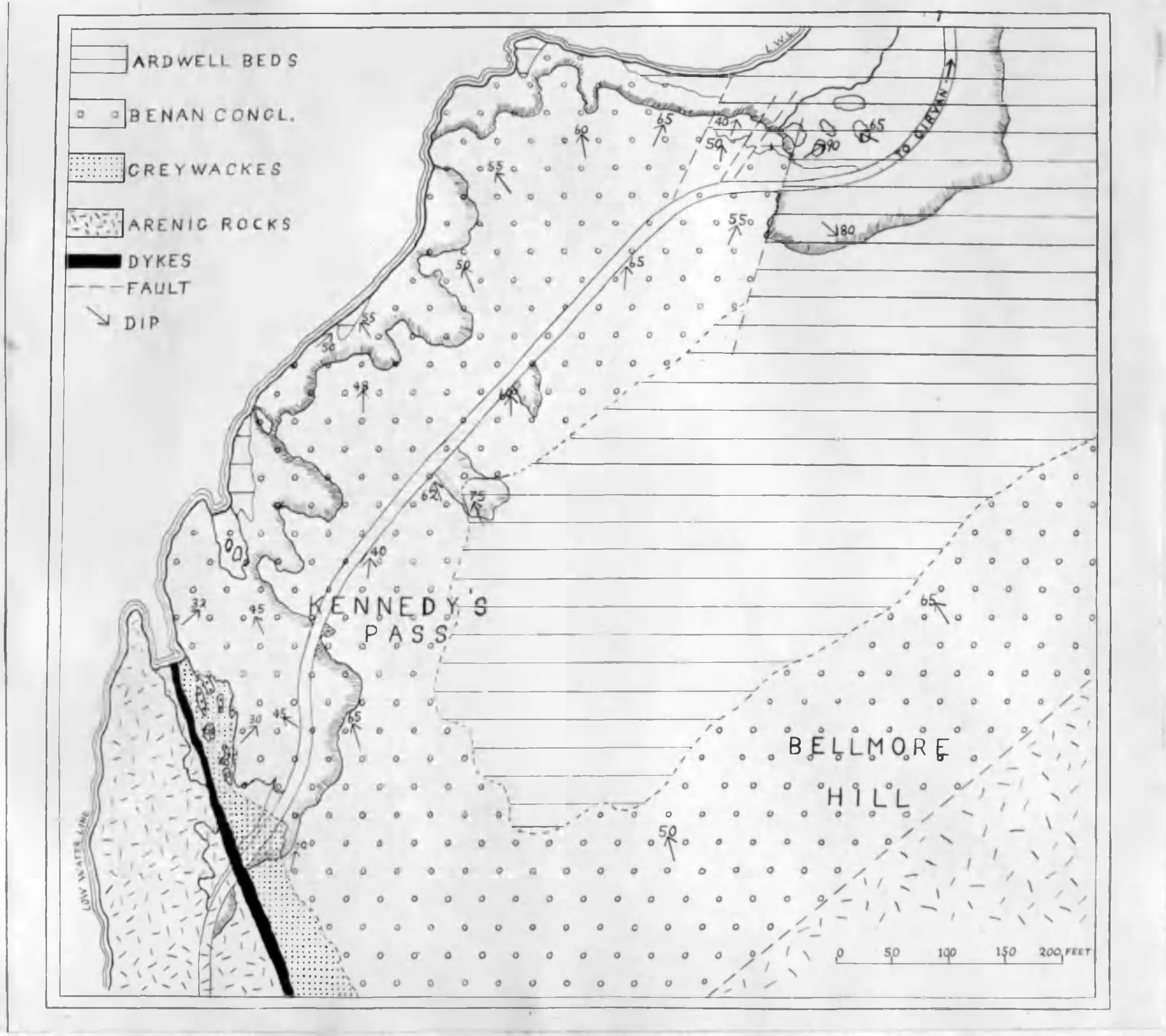

Fig. 7.- Geological Map of Kennedy's Pass Area.

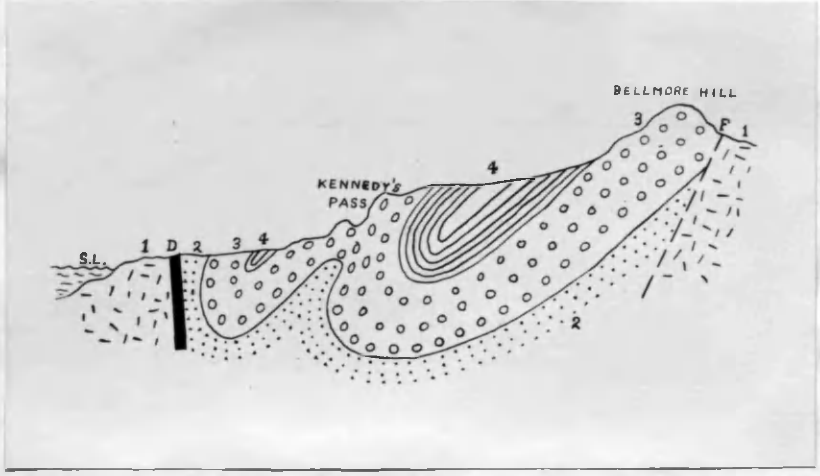

Fig.8.- Section across Kennedy's Pass Area.
1.Ballantrae lavas. 2.Greywacke below Benan Conglomerate. 3. Benan Conglomerate. 4.Ardwell Beds. D.Basalt Dyke.

Fig.9.- Balclatchie Grits showing spheroidal weathering. Penwhapple Burn.

grits of the Balclatchie Beds contain a high percentage of igneous rock debris. This fact points to the conclusion that spheroidal structure in many igneous rocks is due entirely to weathering, although in some cases contraction is undoubtedly the primary cause. The conglomerates at the top indicate the approach of the uplift which finally allowed these beds to be eroded away in places, especially in western areas.

This earthmovement caused a general tilting of the strata so that with the return of deeper water conditions the Ardwell Beds were laid down unconformably. The unconformity is best exposed on the shore at the northern end of Kennedy's Pass (fig.10).

Fig.10.- Ardwell Beds resting unconformably on Benan Conglomerate at Kennedy's Pass.

It can also be seen in the burns draining Ardmillan Braes. Again the Ardwell Beds may be seen unconformably on the Balclatchie conglomerate in Penwhapple Burn near Balclatchie Bridge.

The/

The close-shore deposits of the Ardwell Beds are to be seen in a newly mapped area of shore $\frac{1}{4}$ mile S.of Kennedy's Pass (fig.11). Here the sediments have been faulted down against the Arenig rocks. The greywackes of the Ardwell group lie unconformably on the Benan conglomerate at the S.end of the exposure. There follows a series of well graded greywackes in which are included two bands of conglomerate, having a matrix similar to the greywackes themselves.

During the beginning of Ardwell times an encroachment of sea upon land took place, but throughout the rest of the Ordovician the shore line apparently suffered little alteration. Sedimentation in the Girvan District went on in a fairly deep sea so that Bathyal and Neritic fossils are to be found interbedded. The red mudstones at the top of the Whitehouse beds apparently indicate deeper conditions, although shallower water returned for the deposition of the Barren Flags and the conglomerates of the Drummuck Group at the top of the Ordovician. Disturbances of the sea floor were continually upsetting the soft sediment, the results of which will be described later, but never were they of such magnitude as the great early Caradoc uplift.

Throughout the rest of the Ordovician rocks, slip bedding of a complicated nature and occasional beds of grit and conglomerate are to be found.

However the approach of shallower water conditions indicated at the top of the Ordovician were in preparation for the uplift which gave rise to the unconformity at the base of the Silurian.

It is apparent from the above general conditions of the sedimentation of the Ordovician that there were three cycles of uplift/

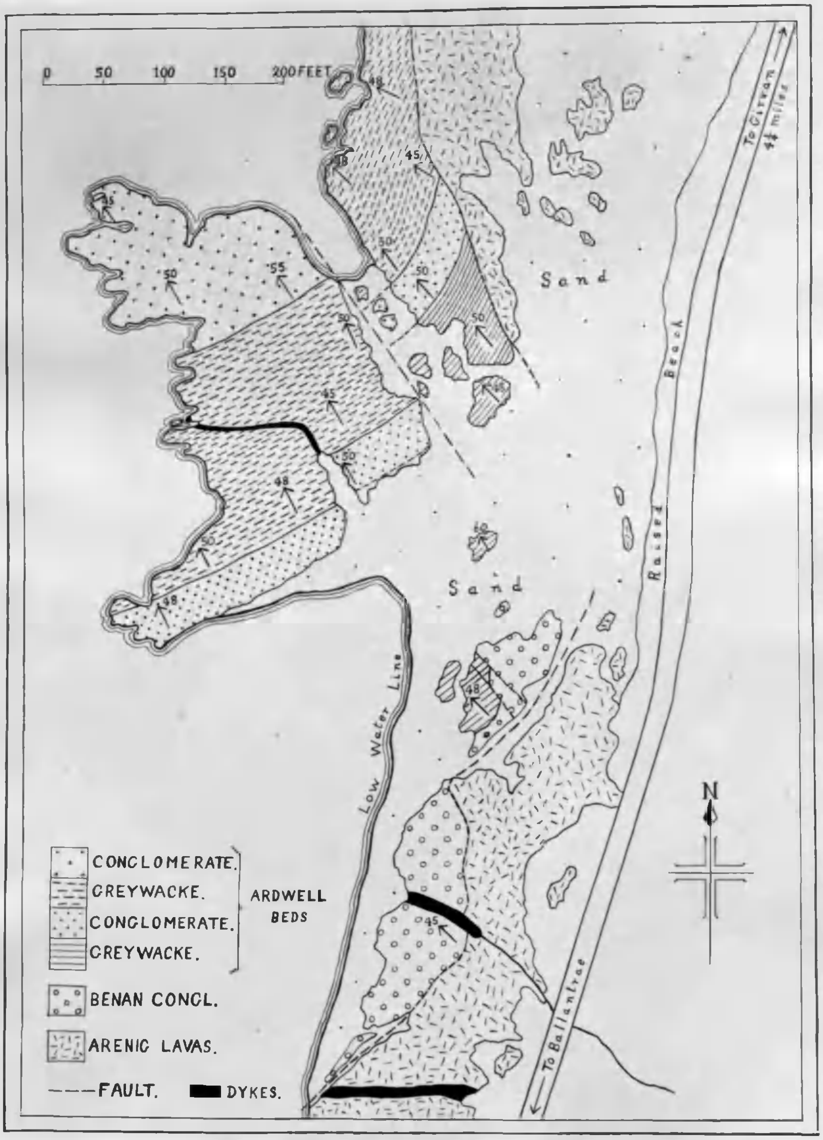

Fig.11.- Map of shore ¼ mile S.of Kennedy's Pass.

uplift and erosion followed by gradual subsidence with encroach of sea on land. These uplifts are responsible for unconformities at the base of the Kirkland Conglomerate, the Benan Conglomerate, and the Ardwell Beds.

Undoubtedly throughout the whole of the period the sea floor must have been disturbed by earthquake shocks dependent on these uplifts.

ARDWELL BEDS

An excellent opportunity for a detailed study of the Ardwell Beds is afforded by the foreshore exposures between Kennedy's Pass, 4¼ miles S.of Girvan, and Ardwell Farm. As has been stated already these rocks lie unconformably on the Benan Conglomerate at Kennedy's Pass while the topmost beds disappear under the sand of Ardwell Bay a mile to the northeast. Generally speaking the Ardwell Beds may be said to consist of a series of graded muddy sandstones of greywacke type with associated shales. As was shown by Professor Lapworth there are representatives of both a shelly and a graptolitic fauna. The latter occurs chiefly in thin black intercalated shales towards the top of the series.

After a very detailed study it has been found possible to divide this series of greywackes into lithological zones. The subdivisions are based upon the average ratio of the sand and mud in each individual graded bed, and are named according to the predominant member.

The accompanying table shows the zones with their thickness and named according to the evidence given in the second column headed "Individual Beds". Throughout the whole of the Ardwell/

ZONES			INDIVIDUAL GRADED BEDS			PRODUCTS OF DISTURBANCES		
No.	Type	Thickness	Average Thicknesses			No. of Occurrences	Individual Thickness	Type
			Mud	Sand	Total			
11	Shale	200'	3"	1"	4"	4	20' 50' 4' 2'	Landslips and Breccias
UNCONFORMITY								
10	Sandstone	120'	½"	2½"	3"	2	1' 1'	Breccias + Sand Injections
9	Shale	90'	2"	1"	3"	2	2' 1'	Breccias + Sand Injections
8	Sandstone	80'	½"	3"	3½"	2	14' 6'	Conglomerate & Breccia
7	Shale	70'	¾"	¼"	1"	-	-	-
6	Sandstone	60'	1"	3"	4"	-	-	-
5	Shale	30'	1'	6"	1'6"	4	5" 8" 7" 4"	Breccias
4	Sandstone	70'	1"	2"	3"	-	-	-
3	Shale	50'	2"	½"	2½"	-	-	-
2	Sandstone	80'	1"	4"	5"	2	4' 3'	Grits + Breccia
1	Shale	150'	2"	1"	3"	1	6'	Slipping + Sand Injections
		1000'				17	116'	

Table II. Subdivisions of the Ardwell Beds.

Ardwell series there is evidence of submarine disturbances in the presence of intraformational conglomerates, breccias, and slip bedding. The 3rd column of the table shows the number of Products of Major Disturbances with their individual thicknesses and the type of disturbance. The measurements of these Products of Major Disturbances are included in the total thickness of each zone. Omission of an entry in the third column does not signify that the zone is entirely devoid of disturbances, for throughout the Ardwells minor intraformational breccias and folding are present. This table is not put forward for the purpose of correlation by lithological zoning, but more to indicate the type of greywackes and their variations in the series. Methods of this type of study may lead to further and more intimate knowledge of submarine disturbances of the past.

When Professor E.B.Bailey (1930) wrote on graded bedding he had not met with associations of graded and current bedding. The study of the Ardwell Beds has furnished such association, but the current bedding is only on a very small scale. It is still possible to accept with slight reservation his conclusion that graded sandstones "mark the intermittent delivery of a mixture of grit, sand, and mud into the waters that overlie the mud floor of the sea beyond the reach of ordinary sand-pushing bottom currents". Professor Bailey has suggested that graded bedding is a record of sea quakes, the unconsolidated sand and mud of the coastal fringe providing the source of material. To support this theory he quoted Twenhofel (2nd Ed.1932-p.865 & p.739) concerning the slumping of sediments down the submarine slopes/

slopes around islands and continental margins, especially where the slopes are Seismic loci. He also mentioned the presence of slip bedding and the enclosure of angular fragments of the immediately underlying mudstone.

At the base of many of the graded beds of the Ardwell series, are angular fragments of the underlying shale, and slip bedding is by no means an uncommon feature. These facts, coupled with the numerous examples of intraformational breccias, submarine boulder beds and conglomerates, here interpreted as of earthquake origin, support the theories of Professor Bailey.

Assuming the Seismic origin of the Ardwell graded beds it is possible to calculate how many earthquakes are recorded. As explained already, the Ardwell Beds have been zoned according to the graded beds. Thus having the total thickness of the zone (from which must be subtracted the thickness of the products of the Major Disturbances) and the average thickness of the individual beds, the approximate number of graded beds (or seaquakes) per zone can be obtained. It can be estimated that there are 3,900 graded beds in approximately 1000' of Ardwell greywackes. Professor Bailey in a very rough estimate has suggested 30,000 graded beds in the Ordovician and Silurian as a whole, but this is probably an underestimate.

Petrography.

Some geologists have referred the term greywacke to the ferro-magnesian equivalent of arkose (Twenhofel - 1932,p.231). Scottish geologists however have always considered greywackes as muddy sandstones the chief constituents of which are quartz and felspar/

felspar (Bailey,1930). They are characterised by many of the Lower Palaeozoic sandstones of the Southern Uplands of Scotland. The Ardwell Beds are typical greywackes in the Scottish sense of the term. They are graded muddy sandstone composed chiefly of quartz and felspar, these minerals often forming at least 50% of the constituents. The other constituents include fragments of chert, basic igneous rocks, limestone and ferro-magnesian minerals. All are associated with a green silty matter.

Throughout the series there is naturally a range in the size of the fragments according to the coarseness of the grading. The quartz fragments vary from 0·50mm. in diameter down to a fine dust in the more muddy portions. In coarse beds the fragments reach a maximum of 1·8mm. The felspars are generally smaller and rarely exceed 0·30mm. in diameter. The other constituents average about 0·25mm.

The majority of the constituents are angular; quartz usually presents fragments with sharp points and often reentrant curves, while the felspars tend to retain their normal rectangular shape. The other fragments are generally angular to subangular.

Calcareous Concretions

The presence of fragments of limestone is at first rather misleading, but an examination of thin slices shows many horizons of the greywackes to have a more calcareous cement rather than the usual green silty material. In Zone 7 the graded beds are composed of limy greywacke passing up into black and grey shale. Again many of the intraformational conglomerates are seen to contain a considerable proportion of limy pebbles.

A/

A further examination of the series showed the presence of calcareous concretions at several horizons. These features are best developed towards the top of Zone 9. In this zone the calcareous concretions, which stand out yellow-white against the general dull grey of the greywackes, apparently occur along fairly definite horizons. They are orientated with their longer axis parallel to the bedding planes and in this direction they range from a few inches up to 1' 6" while the axis perpendicular to the bedding plane is shorter and ranges up to about 8". It is noticeable that often these concretions have apparently coalesced to form a band of limy greywacke. Concentrical lamination of the limy material is usually present, but radial structure and slickenside edges to the concretions are never apparent. The bedding planes of the enclosing greywacke pass almost undisturbed through these nodular concretions, and there is no deflection of stratification above or below. They are almost entirely independent of the bedding since a nodule of about 8" thick would pass across three or four normal graded beds. The more sandy portions stand out conspicuously from the lime saturated shale.

From the evidence stated above it is clear that these concretions are epigenetic, that is secondary or subsequent to the depositions of the enclosing greywackes. (Twenhofel 1932, pp.697-716). The possibility of their being syngenetic at first seems probable owing to the presence of short limy bands, and the concretions would then be due to a lack of material to form complete strata. This however is quickly eliminated when it is seen that the limy portion overlaps more than one stratum. These concretions must have originated/

originated by precipitation about nuclei. The sandstone and the fine silt, which now forms the shales, would readily permit migration of solutions from all directions, and, given the time and material, diffusion would produce these epigenetic concretions in any of the greywackes. The elongation of the axis parallel to the stratification is due to a slower and more difficult diffusion of the solutions across the bedding of the fine silty material compared with the horizontal move along the sandy portions. The concretions were developed before the solidification and compaction of the greywackes was complete, as is shown by the presence of numerous calcareous greywacke pebbles in the intraformational conglomerates derived from the underlying strata. These concretions of the Ardwell Beds might well be placed under the Penecontemporaneous Group of Richardson (1921).

SUBMARINE DISTURBANCES IN THE ARDWELL BEDS

Throughout the Ardwell Series there is evidence of submarine disturbances which broke up the soft and hard sediments, and caused landslips with resultant rushes of water. Examples can be examined almost at any horizon of the greywackes, but it is proposed here to describe only the most striking. They will be dealt with in order of occurrence on the shore from south to north. In the accompanying map (fig.12) of the shore from Kennedy's Pass to Ardwell Farm the exact positions of the localities are inserted with the numbers referring to the Text figures and photographs from each locality.

It is necessary to remind the reader that almost all the series lies in a vertical position so that a map of an area automatically gives a section.

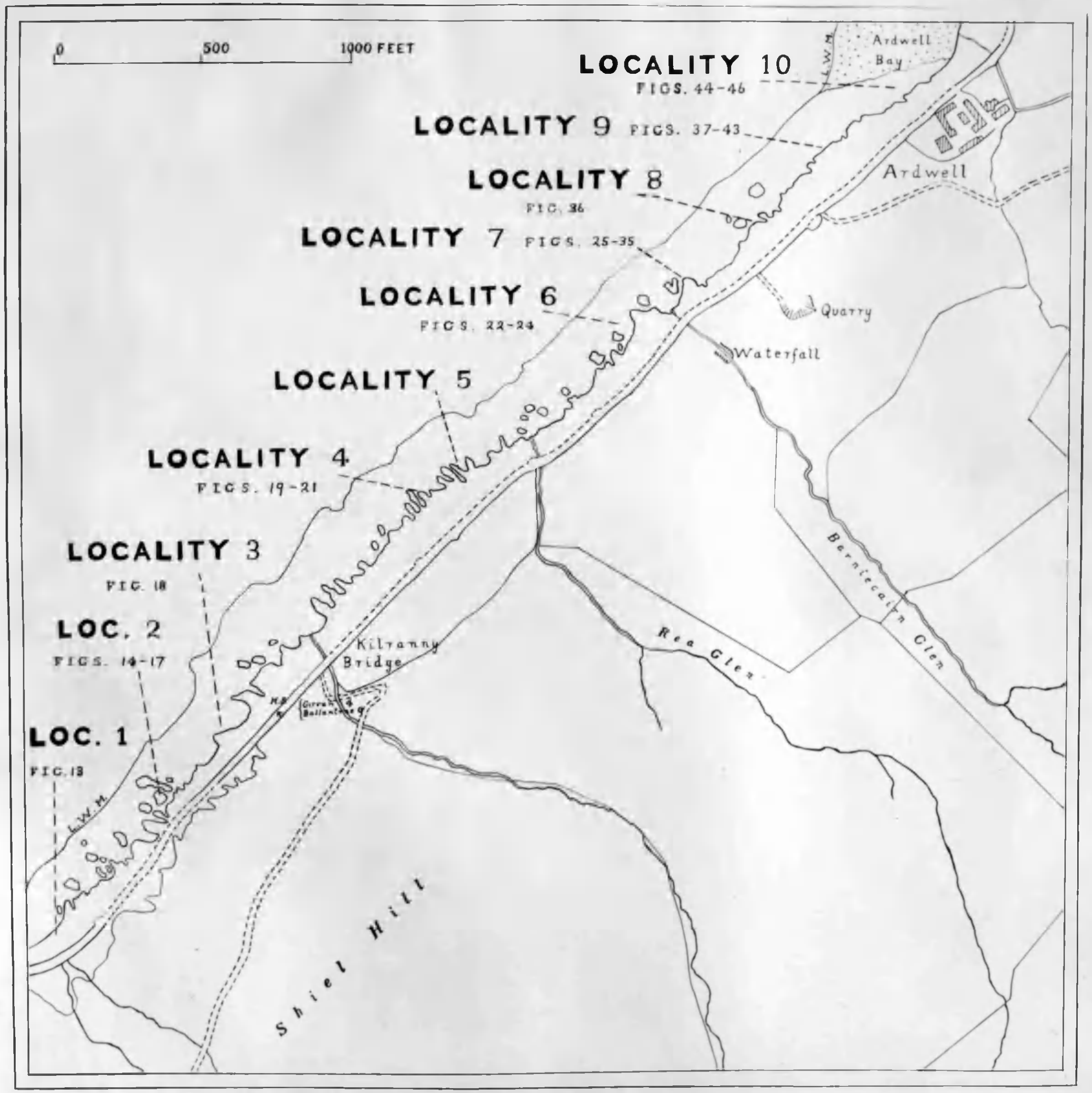

Fig.12.- Locality Index Map. Text-figures 13-46.

Locality 1.

At the northern end of the small bay 200 yards north of Kennedy's Pass is an exposure almost covered by the shingle and sand. The area of disturbance exposed measures 8' in length, along the general strike of the surrounding greywackes, and 6' in thickness. It shows an irregular base on the normal bedded sediments, and is composed of a mass of rectangular fragments of the shaly greywackes below (fig.13). A rather coarse sandstone cements these fragments. It seems probable that a submarine shock broke up the sediments on the sea floor and the resultant rush of water distributed the debris. The angular shaly greywacke fragments are of local origin, but much of the cementing sand was brought from some distance as it is coarser than the normal material of the locality. If the greywacke fragments had travelled far they certainly could not have retained their angular shapes.

Locality 2.

At a point about 100 yards north of the last locality, and opposite the caves in the old sea cliff are several large stacks the tops of which are never below water. On the tops of these stacks, and also towards the north on the plain of marine erosion, is a coarse breccia overlain by coarse sandstone (fig.14). This

Fig.13.- Angular fragments of local shaly greywacke cemented by coarse sand. x 1.

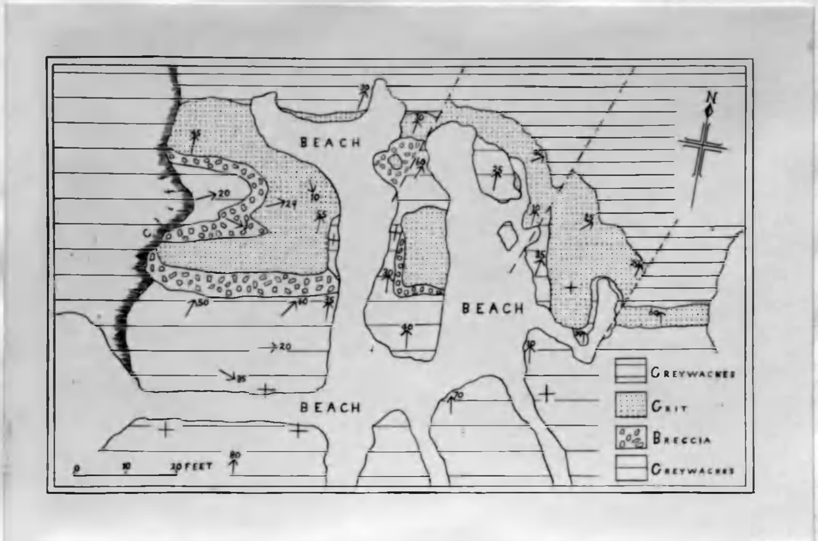

Fig.14.- Map showing outcrop of Breccia and associated Grit at Locality 2.

band is interbedded between the greywackes which here are much contorted, but as a whole dip towards the north-west at an average angle of 30°.

It is just over 100 feet in length, but is not all exposed owing to its abrupt finish in the West at the top of a 20 foot cliff, and a likewise sudden ending to the east against a patch of beach. All efforts to trace it further along the shore in the latter direction were fruitless, and it must be assumed that it is faulted out of sight.

The normally bedded greywackes are overlain by an 8" band of broken-up and contorted beds which show stringers of sandstone injected from above (figs.15 & 16).

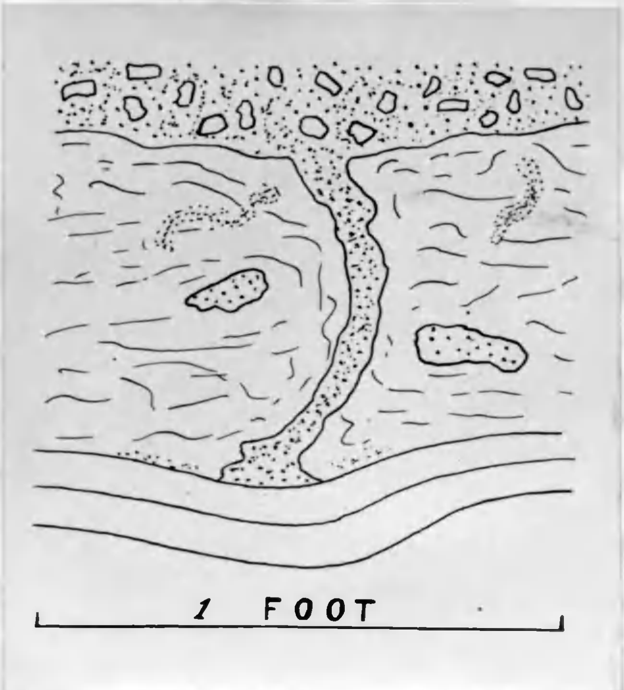

Fig.15.- Stringer of sand penetrating into fractured greywacke from overlying breccia.

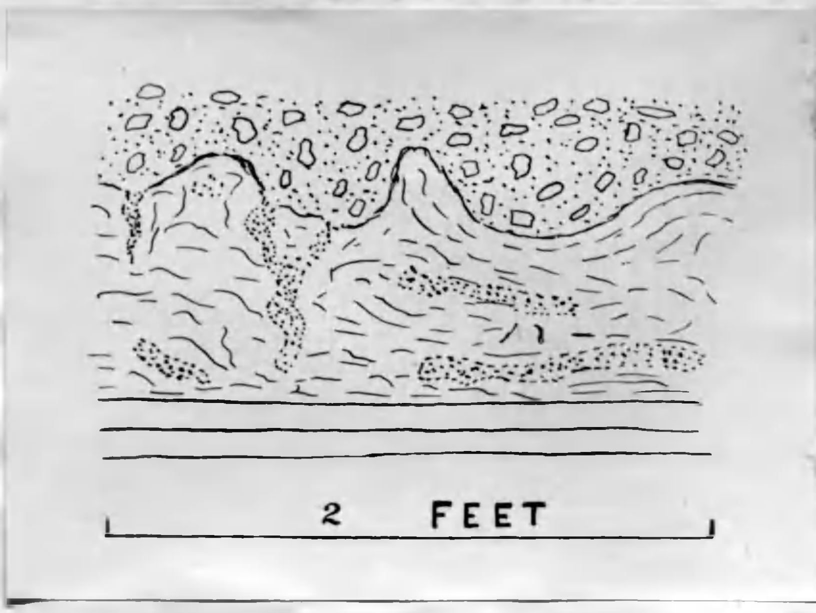

Fig.16.- Stringers of sand injected into fractured greywacke bed.

Resting on the uneven surface of this smashed greywacke is a bed of coarse breccia which is 2 feet thick at the S.W.end of the exposure, but is seen to thin out rapidly towards the N.E. to no more than 6 inches. This breccia is composed of angular fragments of shaly greywacke in a sandstone matrix (Fig.17). Some of the fragments are limy and tend to be more rounded which is explained by their origin from concretions. The greywacke fragments are of local origin, but much of the sand has been derived from elsewhere. It is obvious that the stringers of sand penetrating into the underlying broken sediments have come from the same source as the sandy matrix of the breccia. Again sand twines through masses of fragments of shaly greywacke forming stringers from the more sandy parts of the breccia.

Above this breccia, and forming the top of the zone of debris, is a coarse sandstone which gets finer upwards. This bed is about 2 feet thick at the S.W. end and increases to almost 4' in the N.E.

It is noticeable that the shelly fauna of the Ardwells are more abundant in this breccia and sandstone than in the surrounding greywackes. The fossils are often badly broken and occur in all directions among the sandstone. They are not to be seen in the angular shale fragments.

Apparently a submarine earthquake fractured and loosened the sediments, while the resultant tunamis broke up and distributed the material over the sea floor. The lower, more consolidated, beds were not swept away, but cracked and twisted by the disturbance. When the debris settled on this broken surface the sand, which was in a liquid condition, penetrated down into the cracks and crevices.

Similarly/

Fig.17.- Breccia of shaly fragments cemented by coarse sand.x 1.

Similarly it penetrated between the fragments, and into the cracks in the fragments forming the breccia. The shells included among the sand must have been brought by the tunamis. As conditions quietened down the bed of coarse sandstone was deposited on top of the breccia. Probably much of the sand was derived from the unconsolidated coastal sediments which were disturbed by the same shock.

Locality 3.

About 100 yards S.of Kilranny Bridge a bed of sandstone stands out prominently among the normal almost vertical greywackes (fig.18). It is exposed for almost 80' along the strike before

Fig.18.- Band of sandstone interbedded with normal Ardwell greywackes S.of Kilranny Bridge.

it disappears under the Raised Beach towards the N.E. At its thickest point it measures 3', but is seen to thin gradually to 1' at the S.W.end. This sandstone bed rests on an irregular surface of the greywackes, the latter having apparently been eroded extensively before deposition of the overlying sediment. For instance/

instance, in a water worn gully, it is possible to examine a vertical section, that is, a section along the bedding planes, and see the sandstone transgressive across the greywackes. Also on this water washed surface it is clear that the sand of the overlying bed is injected into the broken uneven surface of the lower sediments. The base of the bed is composed of coarse sandstone and contains angular shaly fragments. Gradually the sandstone becomes finer, and passes up into a 2"-3" thick limy greywacke. Above this, normal graded sediments lie transgressively on the whole bed.

The story of this sandstone is apparently very similar to that of Locality 2. Once again there are sand injections into the underlying sediments, fragments of local origin at the base of the bed, and a gradual grading up to finer material. The submarine quake, the centre of which was closer at hand than those for the formation of the graded beds, broke up the more consolidated sediments of the sea floor. The consequent tunamis whirled up the softer and finer sand, probably sweeping the sea bottom clear of soft sediment. All the debris gradually settled back through the water on to the uneven surface. The larger angular fragments came first and the ~~finer~~ sand followed. Some finer material penetrated into the fissures and cracks of the underlying rocks. After this the normal greywacke beds were deposited.

<u>Locality 4</u>

On the shore about midway between Kilranny Bridge and Rea Glen is another very interesting feature. In two of the rocky promontories extending from the Raised Beach interbedding or dovetailing/

dovetailing of breccia and sandstone is well seen. This alternating series rests upon an uneven surface of the greywackes, and this varies from 14' to a few feet in total thickness. The breccia is composed of angular greywacke fragments up to 3" along the longer axis, and a large quantity of nodular-shaped limy greywacke pebbles in a gritty matrix (fig.19). The limy pebbles are probably more rounded owing to their original shape as concretions. Along with fragments is a considerable quantity of Orthoceras, which are comparatively rare in the normal greywackes. These fossils are generally in a broken state and rarely found perfect. It is evident that some of the fragments were comparatively soft when deposited as debris, for some have obviously been forced into others without breaking (see right side of fig.19).

The sandstone into which the breccia dovetails is perfectly graded and shows slip bedding, the tops of the folds often being truncated by the overlying breccia. From the direction of the thickening of the dovetailing-sediments we can assume that the breccia was distributed from a S.or S.W.direction (figs.20 & 21). This dovetailing of breccia and sandstone records the distribution of successive tunamis related to a series of submarine shocks which broke up the sea floor to supply the material. Further along the strike breccias are seen interbedded with graded sandstones with a combined thickness of not more than 2' thick. The change of thickness is accompanied by less erosion of the underlying greywackes. The excessive quantity of Orthoceras points to their being killed by the submarine shock, or resultant tunamis, the latter washing them along with the other debris/.

Fig.19.- Breccia from Locality 4 showing angular shaly fragments and rounded limy greywacke pebbles. x 1.

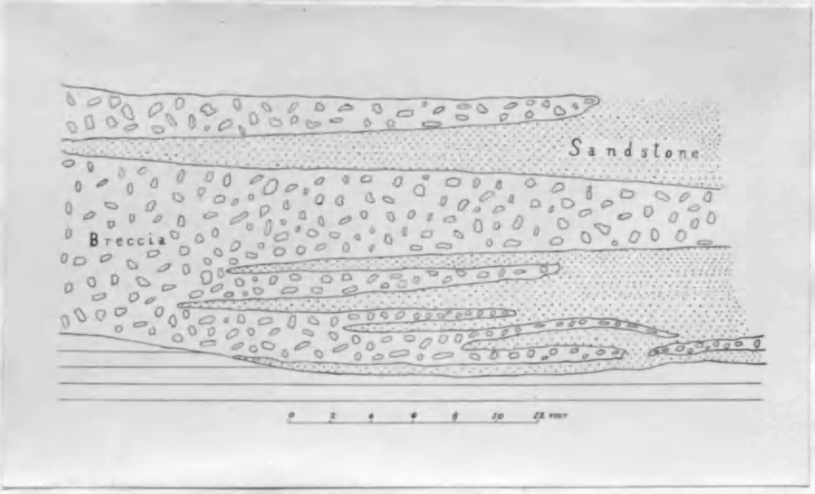

Fig.20.- Map showing dovetailing of breccia and sandstone.

Fig.21.- Dovetailing of breccia and sandstone,Locality 4.

Locality 5.

On a higher horizon and at a point about 50 yards further N. than locality 4 there is very similar evidence to be seen. Here the zone of disturbance is only 6 feet thick, and the dovetailing of the breccia and sandstone is not so apparent. Nevertheless, there are several bands of breccia, similar to those seen in the last locality, interbedded with graded sandstone. The sequence likewise rests on an uneven surface of normal greywackes resulting in the same local thickening of the breccias. Once again the quantity of shelly fauna present is striking. The material was apparently brought from the same south or S.W. direction.

The whole evidence of this exposure points to the same origin as in locality 4. The comparative thinness of the breccia bands and the less developed dovetailing seem to indicate that the centre of the disturbances was more remote so that only the remains of the debris reached that part of the sea floor.

Locality 6.

Between Rea Glen and Barniecairn Glen the greywackes furnish many excellent examples of the injections of liquid sand into the broken sediments beneath, a feature already mentioned in the descriptions of localities 1, 2 and 3. The beds of shattered greywacke and the accompanying sand range from a few inches up to 2' in thickness. The most striking example is to be seen near the Low Water Line about 100 yards south of Barniecairn Glen, where the raised beach is again extended seawards as a rocky platform. The/

The band of broken shaly sediment averages about 8" in thickness. Sand veins in and out among the fragments and sometimes is entirely enclosed. Above this, is a band in which sand and fragments are evenly distributed. It is obvious that it is from here that the lower sand veins have originated. This is followed by a levelling off of the broken surface by sand which continues as a normal graded bed.

In fig.22 the folded and broken green shaly sediment is injected with sand. The sand is seen veining down from the overlying breccia. Again fig.23 shows shaly fragments, in which the black shale is distorted, cemented together by the sand which after levelling the surface continues as a graded bed.

There seems no doubt that earth tremors folded and broke up the recently deposited sediments on the sea bottom. That folding of the sediments preceeded the brecciation is indicated by the contortion of the fine black shale in the fragments.

The older, more consolidated, sediments were fractured and folded while the resultant tunamis broke up the softer looser material, and deposited it in the form of a breccia. The sand accompanying the deposition of the larger debris being in a semi-liquid state owing to the high percentage of water was able to penetrate into the cracks and spaces in the underlying sediment, giving rise to stringers of sand passing down from the breccia. The coarser material was followed by the deposition of sand without fragments which continued in the normal manner to form a graded bed.

At the bottom of the third specimen from this locality (fig.24).

Fig.- 22. Injections and stringers of sand in broken shaly greywacke. Base of overlying breccia seen at top of figure. x 1.

Fig.23.- Breccia passing up into normal graded bed.
Note distortion of bedding in fragments. x 1.

Fig.24.- Injections of sand into broken sediments. In top right hand corner shale rucked by currents. x $\frac{3}{4}$

(fig.24) the band of broken sediment with injections of sand is seen followed by graded greywackes. In the top right hand corner the dark shale at the top of a graded bed is rucked up in the form of a crest of a wave. This feature, which is due to a wash of water disturbing the softer sediment on the sea floor will be discussed in the description of locality 7.

Besides the numerous examples of sand injection to indicate submarine disturbances there are, at this locality, beds of sandstone ranging from 6"-1' in thickness, which display complicated slip bedding. It is probable that these are indications of distant submarine shocks from which the locality received the sediment settling down on to the sea floor. Later, the weight of the sand aided by outside impulse caused horizontal movement of the sediment.

It is apparent that during a long period of sedimentation the floor of the geosyncline was being shaken by successive disturbance in this locality, the climax of which is registered by the unconformity seen at the foot of Barniecairn Glen.

Locality 7.

The rusty weathering of the greywackes forms a perfect landmark for locality 7.

In the prominent stack (1) on the S.W.side of the Barniecairn Burn an unconformity is well seen (fig.25). From here it can be traced across the wave-washed area to the N.E.(2), and on into the stack (3) to that side of the Barniecairn Burn. Here it is remarkably clear in the floor of a gully (4). On the/

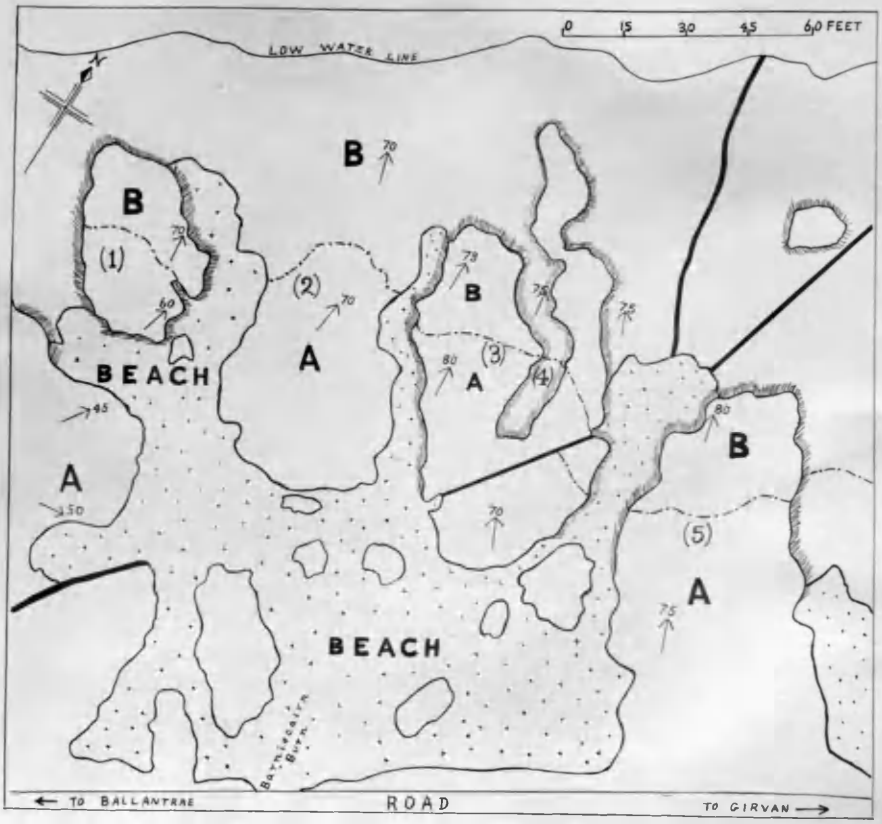

Fig.25.- Map of shore at the foot of Barniecairn Burn showing line of unconformity between the two types of greywacke (A) & (B). Unconformity -.-.-.-

the far side of the narrow sandy cut in these rusty greywackes, the unconformity is seen passing over the top of the most N. easterly stack (5). Next, it is faulted a few yards to the north but can be traced on across the wave washed shore in a N.E. direction.

A difference of the types of greywacke below and above the unconformity is immediately evident. The lower type is characterised by 2"-3" sandy bands with narrow black shales (A). Higher/

Higher up, and close to the erosion line, the black shale increases in thickness, the proportion sometimes being equal to the sand. Above the break the sediments are composed mainly of narrow green-grey and black shales with a small proportion of sandy material (B). Another distinguishing feature is the number of intraformational breccia bands seen above the unconformity, whereas the greywackes below are relatively undisturbed. All along the line of break, a greywacke breccia is resting on an eroded surface, and in fig.26 this breccia is seen passing across the successive beds of the underlying zone.

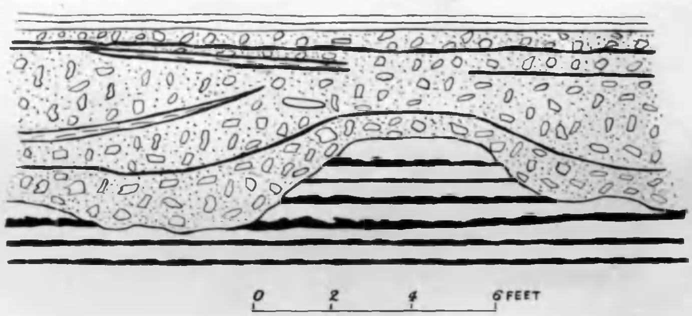

Fig.26.- Surface diagram of vertical strata showing breccia resting on eroded surface of greywacke.

The black shales of the lower zone furnish many examples of a disturbance of the normal bedding. This finer sediment shows an irregular upper surface often taking the shape of the crest of a wave with spray spreading out before it. It is noticeable that/

that the shale is always overlain by sand, resting on the broken surface of the underlying sediment and intermingling among the spread-out fine sediment at the crest.

A similar feature was observed by Sorby (1908) in the slates at Langdale, Cumberland. He assigned it to soft mud lying in a semi-liquid condition on the sea floor being washed up by a current of water which brought with it a fresh deposit of coarser ash, the origin of the whole being due to a volcanic disturbance with the consequent submarine wash.

In the Ardwell greywackes the mud was washed up in the form of wave crests some of which were completely carried away and others permanently preserved in the coarser greywacke sediment (figs.27 & 28). The latter was deposited on the uneven surface, and even mixed with the "spray" of mud from the wave crest. This current of water bringing forward fresh coarser greywacke was caused by a distant submarine disturbance, and gave rise to bedding which shows current deposition instead of grading. From the direction of the crest of these wave-like structures, it is clear that the current came from the N.or N.W., that is, from the margin of the geosyncline. This fact seems to lend support to the theory of Professor Bailey (1930) that graded bedding is due to submarine disturbances dislodging the unconsolidated sediments on the shore of the geosynclinal sea.

Above the unconformity is a remarkable series of intraformational breccias and intraformational folding, which indicates a rapid succession of submarine disturbances. In the enclosed gully (4), a few yards N.E.of the Barniecairn Burn, a measured/

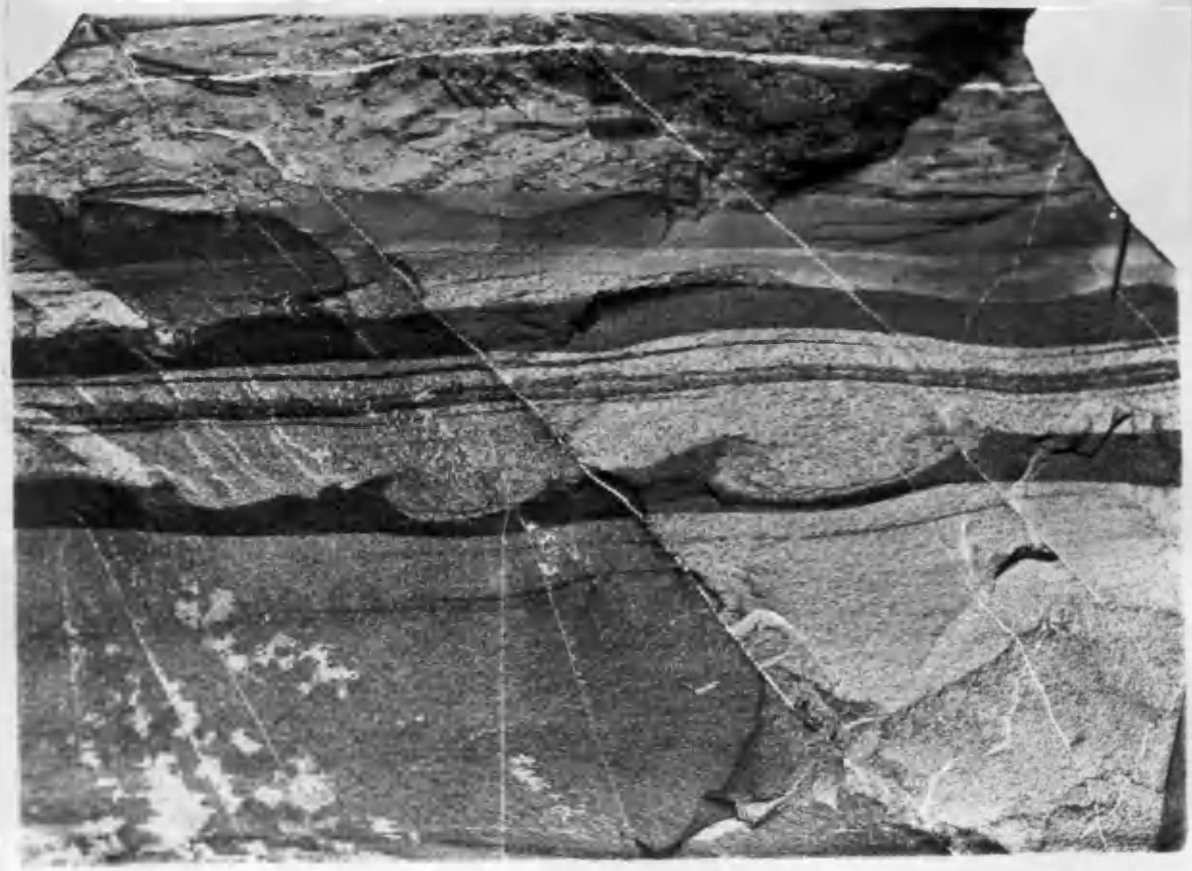

Fig.27.- Greywacke showing breaking up of semi-liquid mud by currents which brought forward overlying sand. x 1

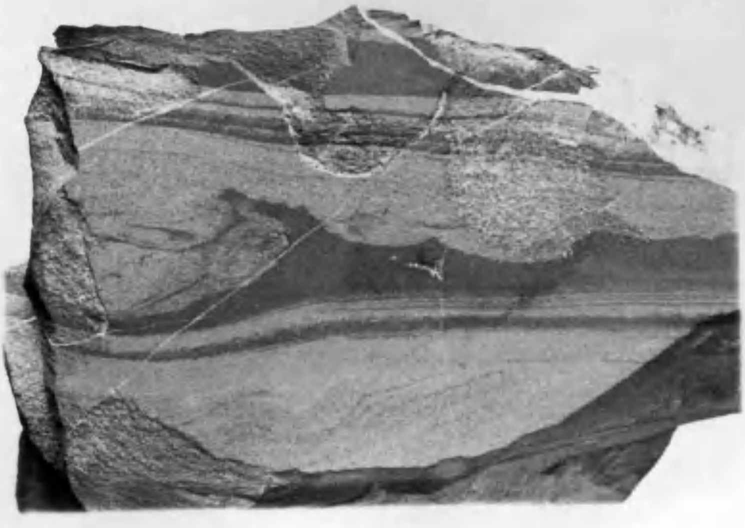

Fig.28.- Wave crest formed in semi-liquid mud by currents. x 1.

measured section of 14' from the unconformity upwards, shows 5' 9" of the total composed of intraformational breccia bands averaging 1"-1½" thick, and 2'1½" of folded beds of approximately the same average individual thickness. Thus, over half of the measured section is composed of brecciated and folded sediments, with perfectly normal thin bedded shales and sandstones, between the bands of disturbed material.

The lowest members of the series of intraformational breccias are the thickest, and range up to 1' thick immediately above the unconformity (fig.26). The bands of breccia tend to be replaced towards the top of the series by folded beds. After 9' 7½" of sediments folding and brecciation appear together in one bed, and higher up intraformational folding supplies the evidence of earth tremors.

In Fig.29, a specimen taken from a little above the unconformity, a coarse greywacke breccia is seen included between normal bedded greywacke. This band is about 1½" thick, and contains fragments ranging up to 1" across, which consist of both greywacke and black shale. Broken fossil fragments are also present. What little matrix there is, is composed of sand. At the top of the band, sand tends to level off the minor irregularities for the overlying grey shale; although the latter, and even the greywacke bed above, are deflected by the upstanding fragments.

After a series of normally bedded sediments there follows a band of intensely folded shale, which towards the right passes into breccia. The folding obviously involves more than one bed of/

Fig.29.- Intraformational breccia and folding. Note eroded tops of folds. x $\frac{2}{3}$

of shale. A striking feature is the erosion of the top, cutting off all the upper parts of the folds. Again, the uneven eroded surface is levelled by sand. The maximum thickness of this fold band is ½". Next, is a series of alternating grey and black shale, 2" thick in all, and followed by another band of breccia.

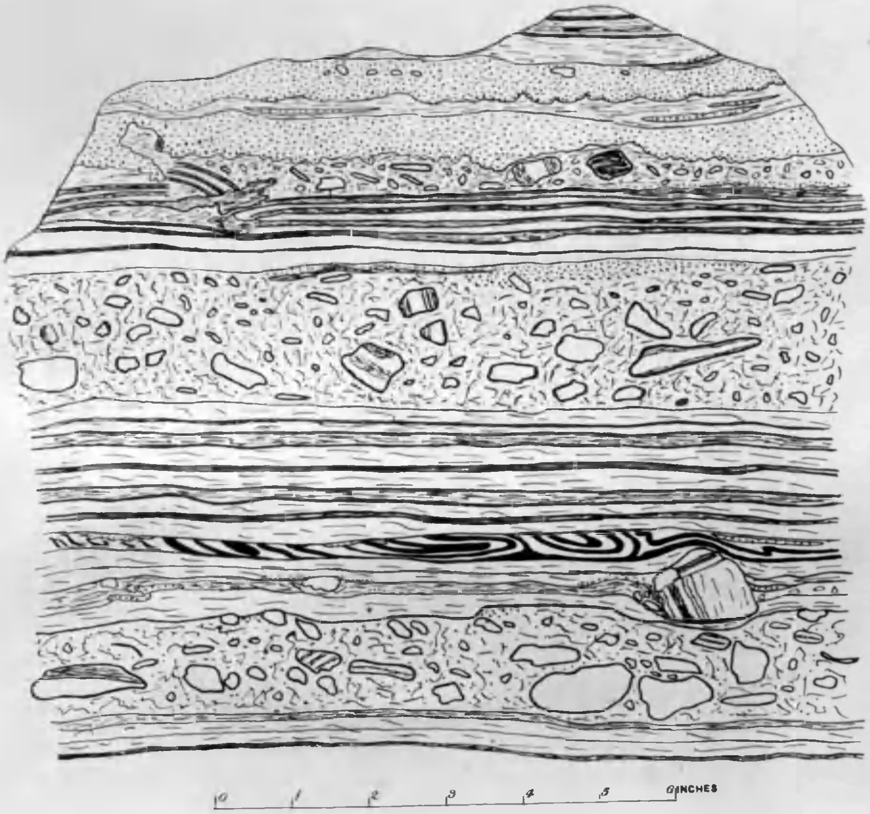

Fig.30.- Intraformational breccias and folding in greywackes at locality 7, Ardwell Shore.

The rapid alternation of the disturbed beds and the normal sediments is seen in fig.30. This drawing, constructed from a photograph of a specimen, displays the bands of breccia, and/

and folded shale with eroded tops. One noticeable point is the fragment towards the bottom right hand corner which has dented and broken the sediments below while the later deposits are deflected over it.

The intraformational folding of some of the sediment becomes highly complicated and gives excellent examples of Alpine structure on a small scale.

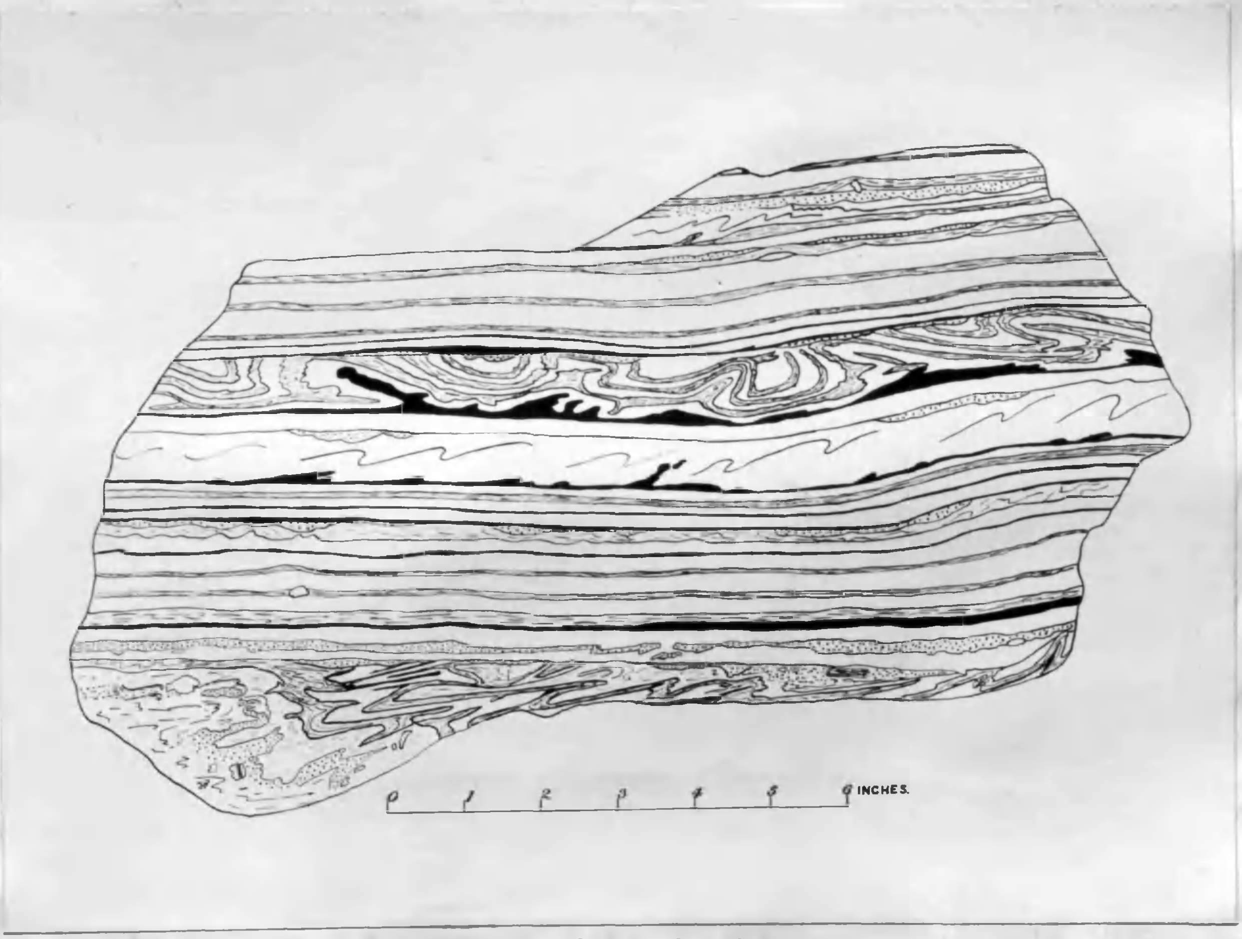

Fig.31.- Complicated Intraformational folding.

In fig.31 the intricacy of this folding is striking. It is evident that the sediment cannot have been greatly hardened, but was apparently rather plastic in nature. Here also, the top/

top of each fold band has been eroded, and the uneven surface has been levelled off by sand before the following shale and greywacke was deposited. The number of cases in which the black shale forms the base of the folded zone indicates the original slimy muddy nature of the sediment. The coefficient of friction would be low enough to allow slipping rather than brecciation under any stress.

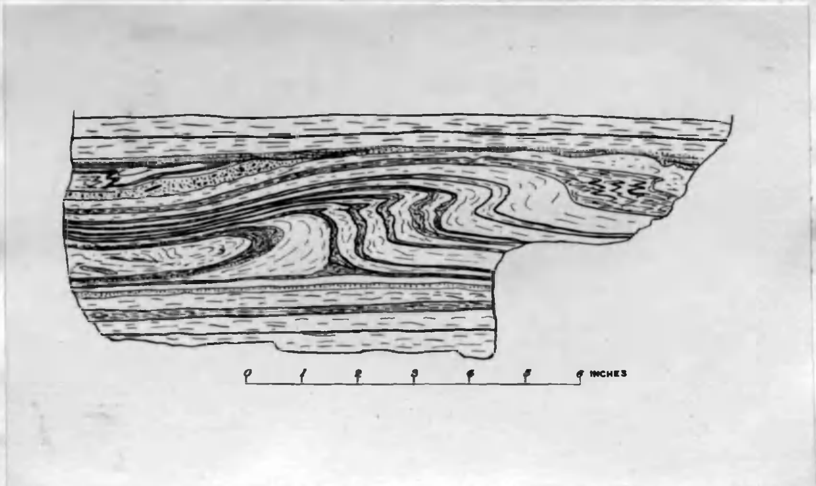

Fig.32 Intraformational folding in Ardwell greywackes.

A further example of intraformational folding is seen in fig.32. Again it is obvious that the underlying sediment is entirely unaffected. After the disturbance which caused the overfolding, erosion of the surface took place. This was followed by the deposition of sand probably from the debris of submarine tunamis erosion.

Another specimen (fig.33) from this locality, at the foot of/

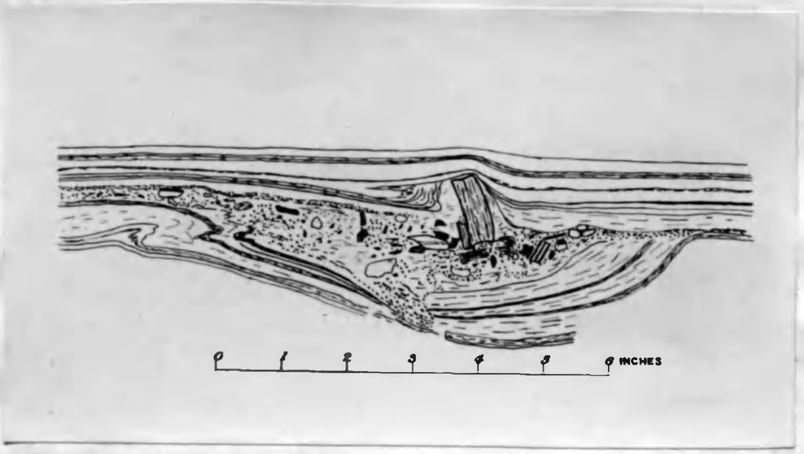

Fig.33.- Intraformational breccia showing catenary bedding against upstanding fragment.

of Barniecairn Glen, shows how the debris of sand and fragments derived from the submarine disturbance is washed into the hollows of erosion. In this case one fragment of greywacke has remained up on end so that the succeeding sediment has been banked up against it.

This feature of disturbed bedding, followed by erosion and deposition of the debris, is very clear in fig.34. The normal bedded greywacke and shale is overlain by extensive overfolding followed by more normal flexures, the tops of these folds being eroded. The uneven surface has been once again levelled off by the deposition of greywacke debris.

Summarising the evidence of this Barniecairn locality, it is apparent that here is a series of intraformational disturbances each of which is the result of a submarine earth tremor. First came the main shock which determined the surface of unconformity by slipping combined with submarine erosion. Then followed/

followed a series of minor disturbances. These tremors gradually became less severe and brecciation gave way to folding, and finally all disturbances of that nature ceased.

The bands of breccia indicate that the vibration was sufficient to break up the top layer of sediment, the lower parts of which were probably in a solidified state. The resultant marine disturbance would cause the debris to be distributed over the sea-floor, and at the same time cause contemporaneous erosion. Later, the sand, which was thrown higher from the floor, descended and was washed into the lower portions of the eroded surface. In the case of the highly folded bands, the vibration was probably less severe, while the nature of the black shale gave every facility for slipping and folding. Possibly minor unevenness of the sea floor aided in the slipping of the material. Here again, resultant contemporaneous erosion took place, and was followed by deposition of sand before normal sedimentary conditions again reigned. The breccias, which pass laterally into a folded zone, point to subaqueous-glide origin. In this case, the fragments of the breccia would be bent before breaking, and should show contorted laminae. Nevertheless the initial impetus is still attributable to earth tremors.

The unconformity, mentioned above as separating the distorted brecciated greywackes from the underlying comparatively normal sediments, can be traced along the shore in a N.E. direction (fig.35). At points, it is entirely lost/

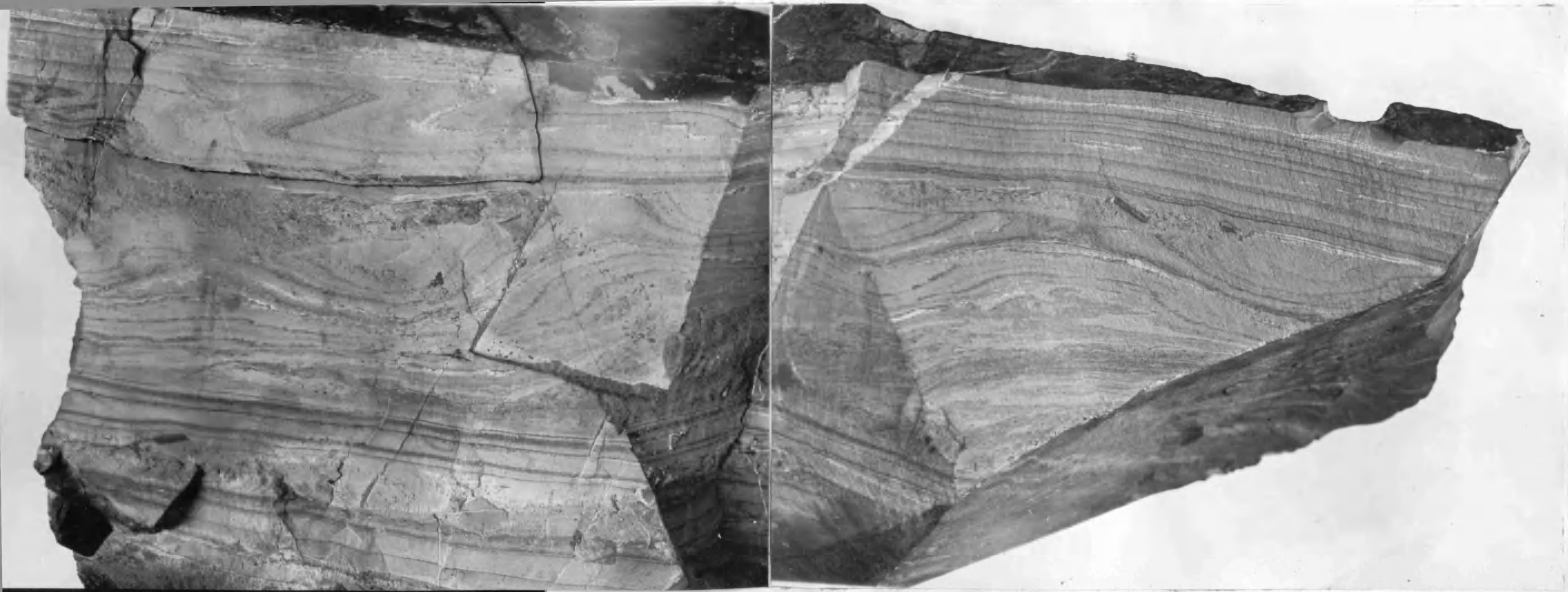

Fig.34.- Intraformational folding of highly complicated nature. Top of folds eroded, and uneven surface levelled off with greywacke debris. x ½.

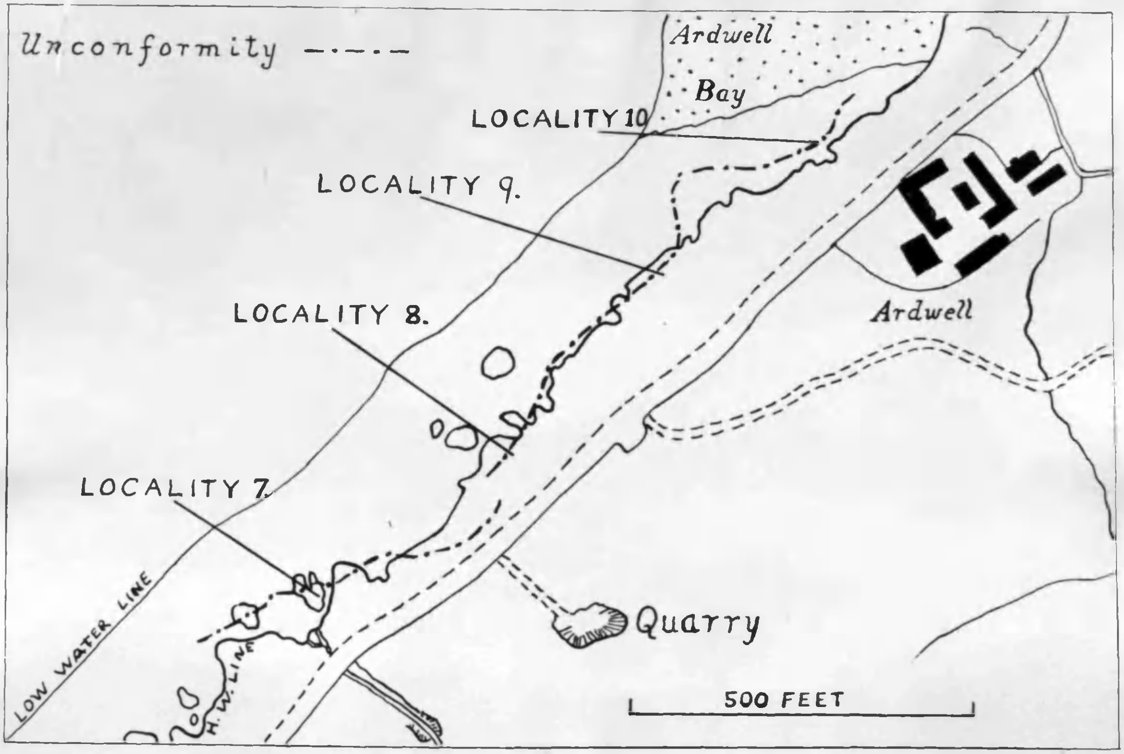

Fig.35.- Map of northern end of Ardwell Shore to show line of unconformity seperating the two types of greywacke A & B.

lost and can only be surmised by the different nature of the sediments. The lower series (A) is composed of sandy greywacke of 2", with narrow $\frac{1}{4}$" or less black shale bands between. Another noticeable feature is the presence of numerous large limy concretions. Above the unconformity (B) the shale is in greater proportion to the sandstone, and is mostly an alternation of black and grey shale or fine sand.

Locality 8.

With/

With the presence of the line of submarine erosion dividing the two types of sediment in mind, it is naturally expected that the ocean floor was of a very uneven nature. Thus, it is not surprising to find evidence of material having slipped down the steeper inclines forming submarine landslips. The resultant debris would subsequently be covered by the normal type of sediment being deposited at that period.

On the shore, almost opposite the quarry, on the Raised Beach cliff, a striking boulder bed is to be seen (fig.36). The bed which is transgressive across the sandstone type of sediment (A), seen below the unconformity, is composed of smashed crushed and twisted shaly sediment in which are enclosed numerous large boulders lying in all positions (C); limy nodules also form boulders in the bed. Across the uneven surface the more shaly type of sediment, of the character usually found above the unconformity (B), transgresses slowly, often showing catenary bedding against upstanding boulders. To the N.E., in a rather prominent stack, the transgression over the debris is clearly seen. Just above it, is a perfect boulder (C) which has fallen into softer sediment, and has gradually been covered over by the succeeding deposition.

The whole of this feature is undoubtedly due to soft sediment, and loose boulders of the underlying rocks, slipping down a submarine slope. The majority of the debris consisted of the soft shaly type of greywacke, which was in the process of being deposited, and would naturally be prone to slipping down the/

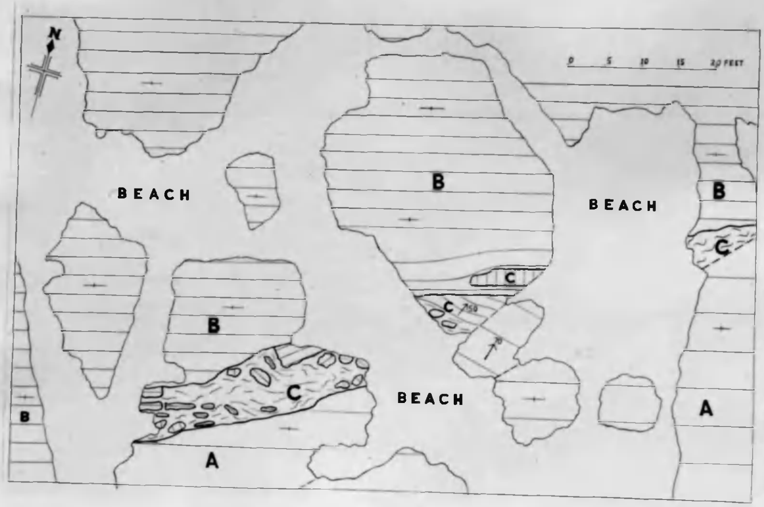

Fig.36.- Map of Boulder Bed at Locality 8.
B.= Shaly type of greywacke above the unconformity.
C.= Boulder Bed and separate boulders.
A.= Sandy greywacke below the unconformity

the eroded surface of the hardened sandy greywackes. The material would only require a comparatively slight tremor to start the downward motion.

Between Localities 8 and 9 the line of unconformity is hidden by faulting.

<u>Locality 9</u>.

Approximately 200 yards N.E. along this line of junction, a larger boulder bed is seen. This locality is on the foreshore almost directly opposite the road which, passing behind Ardwell Farm, ascends the Ardmillan Braes. The area was mapped carefully to scale by the method indicated earlier in this paper, and owing to the vertical position of the strata a/

a section was thus constructed.

This boulder bed has a maximum thickness of 50' and is 200' long, tapering towards the N.E. and S.W. (fig.37). The boulders of greywacke lie in all directions and it is noticeable that they are never rounded, some not even having the corners smoothed off. The average size is 3' by 4', but occasionally reaches 6' in one direction. Between the boulders, and forming what might be termed the matrix, is distorted and smashed shaly greywacke.

The base of this mass of debris is seen to be transgressive across a surface of the sandy type of greywacke (A) containing numerous limy nodules. Gradually, the boulder bed thins out, and finally the shaly sediment (B), which overlies the debris, is seen resting unconformably on the lower type. This unconformity can be traced along the shore, and turning in a more northerly direction finally passes out to sea. The upper greywackes are transgressive across the boulders, and towards the S.W.end of the locality they form catenary bedding against upstanding parts of the debris.

The whole evidence points to slipping of soft muddy sediment deposited on the steeply sloping plane of the unconformity. This type of sediment resting on a steep slope would require little vibration to set the mass in motion. It slid down to the lower area dragging with it numerous boulders of the underlying hardened and semi-hardened material, all becoming mixed up in a muddy slush at the base of the slope. This landslip caused a steepening of the gradient of the sea floor/

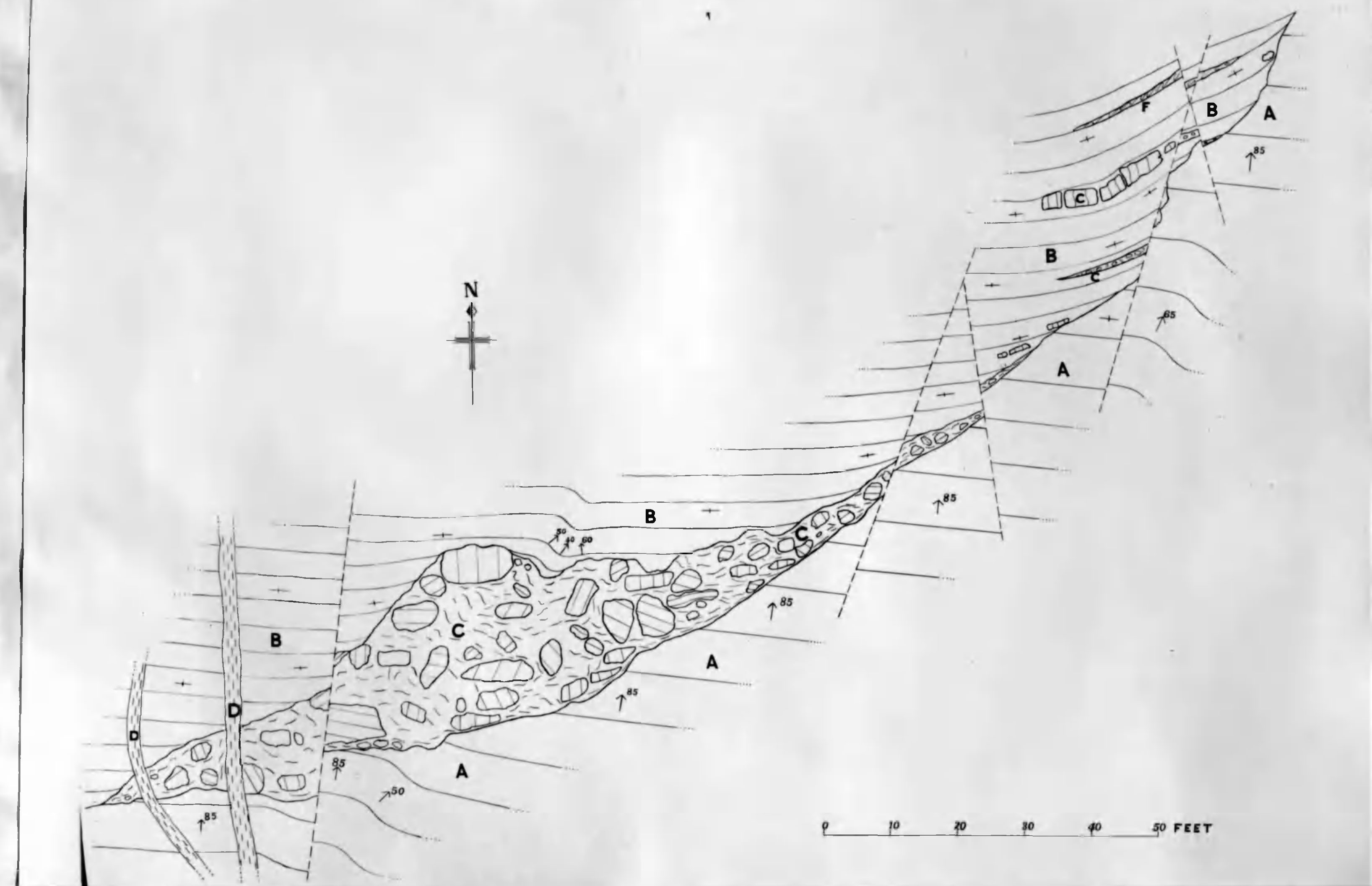

Fig.37.- Map of shore at locality 8 showing Boulder Bed (C) passing to the N.W.into an unconformity between the sandy (A), and the shaly (B) types of greywacke. Note large boulder (C) included in upper greywackes in N.W.corner of map (see fig. 41). F= Bands of complicated large scale slip-bedding (see fig.43). D.= Dyke.

floor to an angle almost severe enough to be termed a submarine cliff. Succeeding sediment was banked up over the mass of debris, and against the submarine cliff.

The wash of water subsequently detached debris from the cliff, so that throughout the series of sediments above the unconformity are fragments and boulders of greywacke lying at all angles in the enclosing material. Figs.38, 39 and 40 show examples of these fragments, which being dropped into the soft mud, dented and squashed it. The succeeding deposits had to pass over these angular obstructions and became banked up against them until they were finally covered. The fragments were often deposited 'en masse' forming beds of intraformational breccia, and in this case the distribution was due to submarine quakes, the resultant tunamis distributing the debris.

Towards the upper end of the unconformity a large boulder (c), 20' long, lies among the shale sediments (B) (fig.41). Its bedding is approximately at right angles to the enclosing lines of stratification. The shale below is squashed and crumpled while that above is banked up over the boulder. It is obvious that this boulder has fallen in the form of a stack from the adjacent submarine cliff. It fell outwards, and toppled over into the soft mud below (fig.42). At the same time the smaller debris became spread out to form a band of breccia. Gradually the normal sediments covered over the fallen stack and its associated debris.

Another/

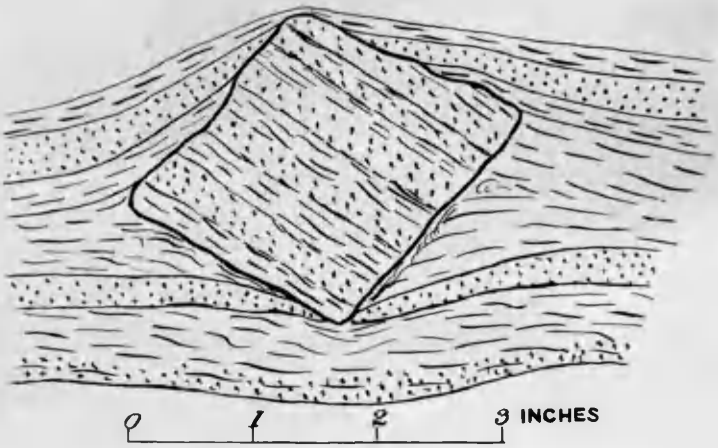

Fig.38.- Greywacke fragment in sediment type B, depressing beds below, and arching up those above.

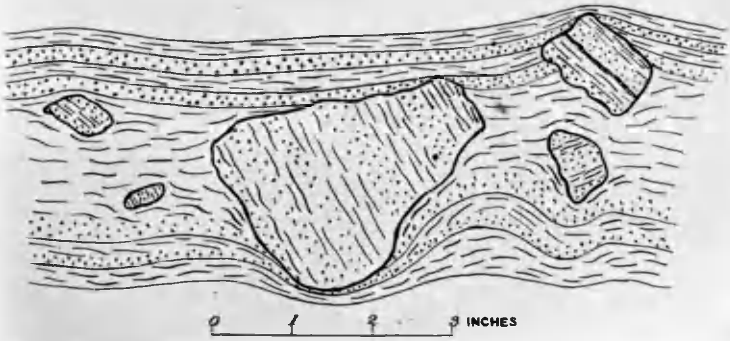

Fig.39.- Greywacke fragments included in shaly type B.

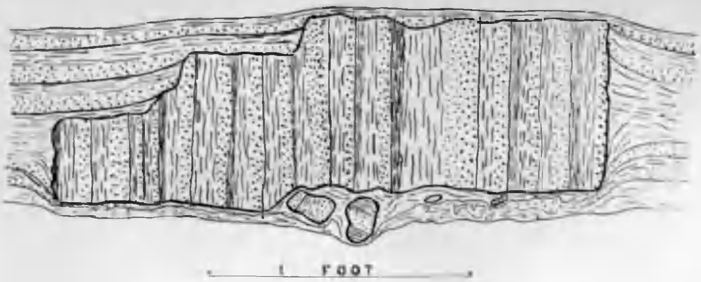

Fig.40.- Boulder of greywacke with depressed sediment below & catenary bedding above.

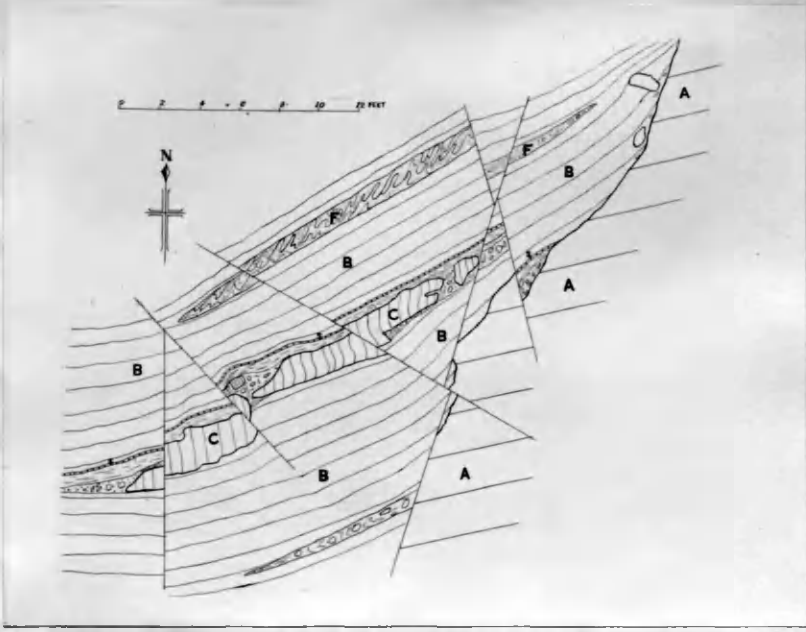

Fig.41.- Map of stack (C) lying in Shaly type of greywacke (B) which is unconformable to sandy type (A) F.= Band of slip-bedding (see fig.43).

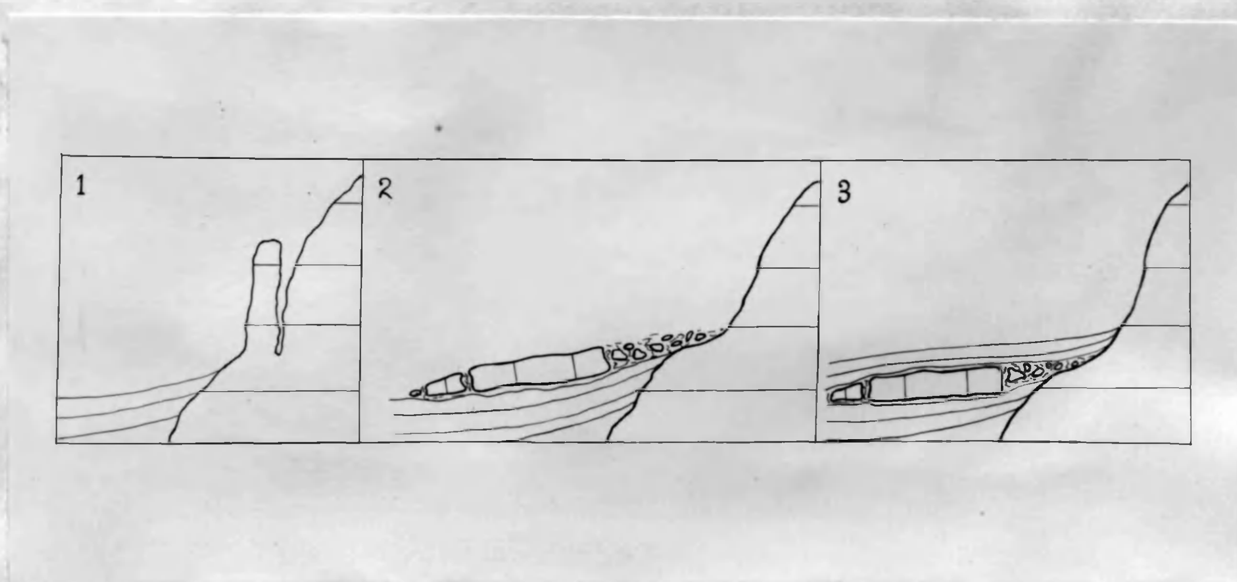

Fig.42.- Reconstruction of Fallen Stack. 1. Stack in original position. 2. Stack fallen into soft mud. 3. Stack covered by succeeding sediment.

Another striking feature is the numerous examples of slip bedding which is most complicated near to the unconformity along the submarine cliff. These bands often reach a thickness of 8". Passing out into the shaly sediments, folding is less complicated and even fades out. One very noticeable folded bed was mapped along with the stack (fig.41), and it is from this point that the accompanying example was taken (fig.43). The direction of folding and thrusting in the disturbed bed, indicates slipping of the sediment away from the cliff down the consequent submarine slope. The underlying and overlying beds are perfectly normal.

Summarising the evidence it is clear that this locality furnishes a perfect fossil landslip. A submarine cliff almost 100' high, at the foot of which is a mass of landslip debris. The later sediments covered over the boulder-bed and lapped up against the cliff giving rise to a marked unconformity. During the deposition of these sediments, stacks, boulders, and finer debris from the cliff, sank into the soft mud below. The movement of the landslip was due to the slippery muddy nature of the deposits set in motion by a submarine earthquake, a happening by no means uncommon throughout the Ardwell period.

Locality 10.

On the shore opposite Ardwell Farm the unconformity seen at the last three localities is visible once more. At one point, the upper series of sediments is broken and injected/

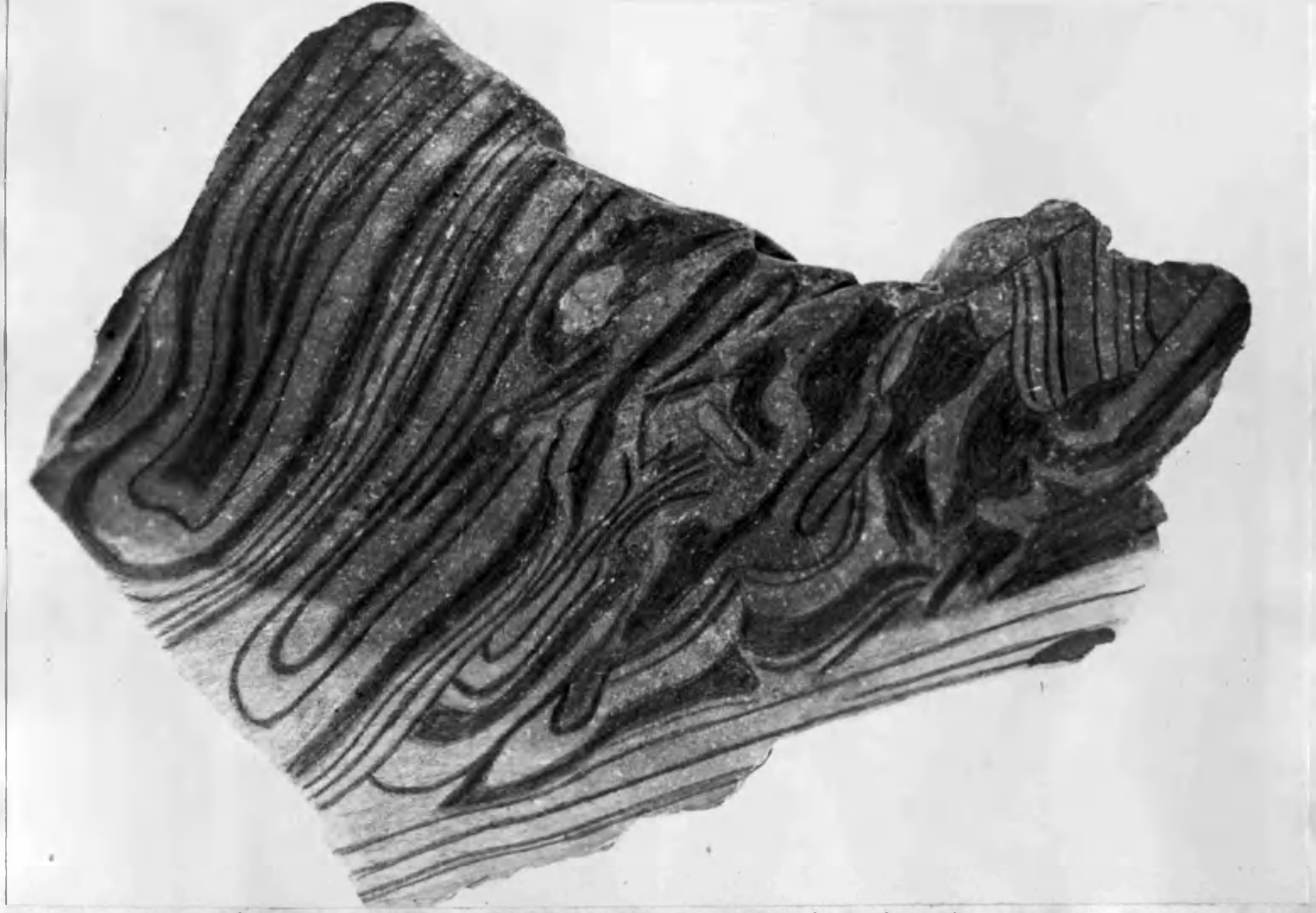

Fig.43.- Complicated slip bedding, or slumping of sediment close to the unconformity. Specimen taken from band marked F. in fig.41. x $\frac{1}{2}$

injected with sand, while a little north the shaly greywacke (B) shows remarkably complicated slip bedding. The material below the hiatus is still the sandy type of greywacke (A) with numerous limy nodules and bands.

The whole area of disturbance visible has a maximum thickness of 4', and can be traced over 50' along the strike. The disturbed sediments transgress in a N.E. direction across the eroded surface of the sandy greywackes. Like the base of the landslip (locality 9) the unconformity here tends to turn in a northerly direction, showing the original slope of this part of the sea floor to have been from the N.E. to the S.W. The softer muddy sediments are again seen above the break, and the folding is due to their nature and the slope on which they were deposited. As at locality 9, the sediments were banked up against the inclined plane of the unconformity. Sedimentation went on normally until the weight of these soft muds, aided by their slippery nature, overcame the resistance of friction, and slid down the slope. It is very probable that the motion was inaugurated by an earthquake shock. The disturbance of the sediment was followed by a rush of water which eroded away the top of the folds (fig.44). It is doubtful whether the slipping of the mud would cause sufficient wash to carry out the amount of erosion present; this points rather to minor tunamis resultant on a larger disturbance, the centre of which was at a distance. The same vibration caused the initial slipping of the sediments.

After the eroded surface was levelled off with the sand/

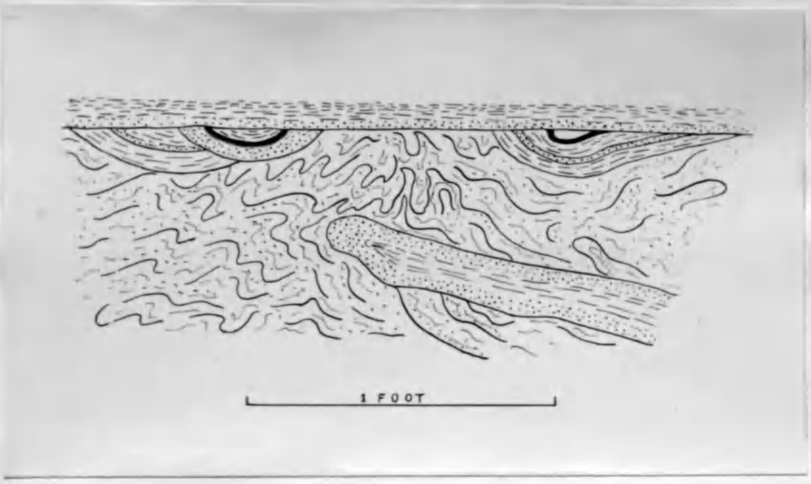

Fig.44.- Slumping of sediment with contemporaneous erosion.

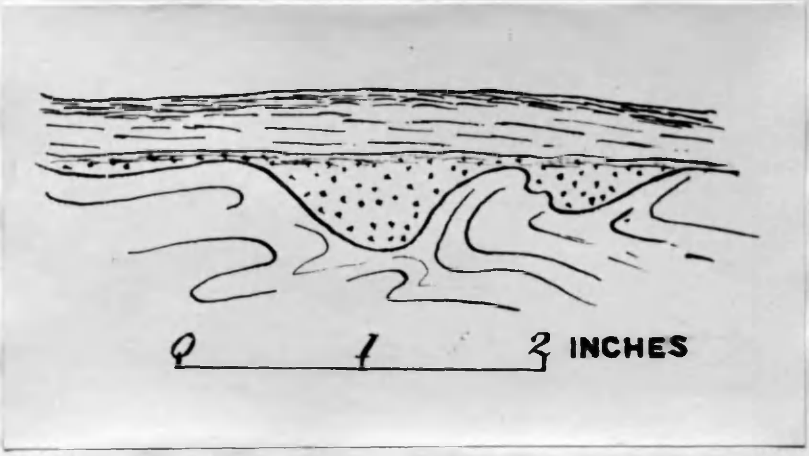

Fig.45.- Eroded surface of slumped sediment levelled off with sand brought along by eroding water.

sand brought by the eroding rush of water (fig.45), normal black and grey mud was deposited. This sediment became increased in thickness until the process of slipping described above was repeated. Thus, above the unconformity is a series of beds of highly contorted shale between which are narrow bands of perfectly normal sediment, which were evidently too hardened to be affected by the following disturbance.

A few feet above the zone of folding, and separated from it by normal sediments, is a local erosion line. The depressions of the eroded surface are either filled, or partially filled, with sand among which is a quantity of Orthoceras and some Brachiopods. The Orthoceras may have been killed near at hand by the submarine shock, while the erosion and the transport of sand and brachiopods can be attributed to the resultant tunamis. Most of the debris was swept clear, but, the sand and shells descended on to the eroded surface and were washed into the depressions (fig.46). This was followed by the

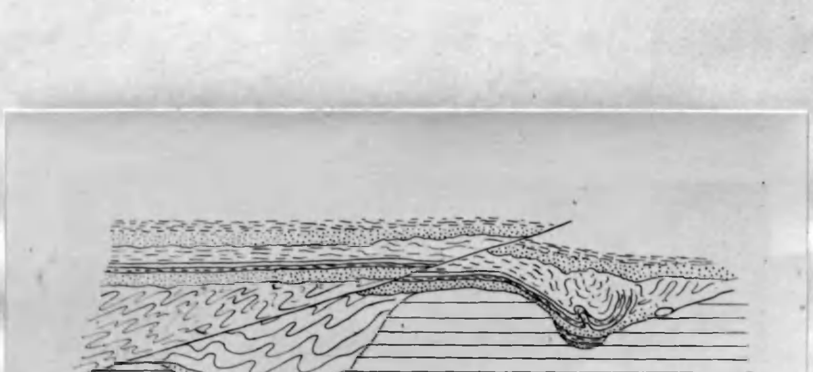

Fig.46.- Map of local erosion line at Locality 10. Depressions in eroded surface contain sand and fossils. Muddier sediment slumped down slopes.

deposition of the normal muddy sediment which in time accumulated sufficient weight, with the aid of earth tremors, to slide down the sloping surface. Then after deposition of further sand on the uneven surface, muddy conditions again returned, and later the same process of slipping was repeated.

Inland Exposures.

Generally the inland exposures do not facilitate the study of such material as is required here. The ordinary hill exposures are of little import and the search for evidence has to be confined to quarries and burns where better rock surfaces are available.

In the cliffs of the Raised Beach between Kennedy's Pass and Ardwell Farm many examples of intraformational breccias and folding are to be seen. Again, in the burns draining the Ardmillan Braes the same evidence exists.

A very good section of a portion of the Ardwell Beds is seen in the quarry on the roadside S.of Pinmore Station (fig.1). In this comparatively small outcrop of the greywackes there is no sign of intraformational breccias. Nevertheless on the north side of the quarry there are repeated examples of slip bedding.

The most important of the inland sections is that exposed in Penwhapple Burn (fig.1). Throughout the Ardwell greywackes, the same evidence as on the shore is obtainable. At one point, a breccia passing up into a grit, and totalling 6' in thickness, transgresses across the eroded surface of the underlying greywackes. The whole feature is analogous to the evidence seen in the foreshore/

foreshore exposures.

Lapworth (1882), in his description of the Ardwells of Penwhapple Glen, pointed out the perfect similarity of the greywackes to those on the shore, except for the presence of coarse green grits and conglomerate, the Cascade Beds, at the top of the succession. The beds are analagous to the beds of debris described from the shore section. They contain boulders of greywacke, ranging up to about 5' across, included in a grit of quartz and greywacke fragments. Lapworth pointed out that these grits are associated with a series of greywackes containing limy nodules, which often develop into limy bands. He also remarks that mineralogically these associated beds are similar to those on the margin of Ardwell Bay.

Thus, all the evidence points to these grits and conglomerates being on approximately the same horizon as the unconformity, at the top of the Ardwell beds described in the shore section. From this, it seems highly probable that the debris was distributed by tunamis resultant on the same disturbance. No doubt much of the material was derived from other areas as that along the Ardwell shore.

OTHER RESEARCHES.

The Ordovician Boulder Beds of Quebec have been claimed as of landslip origin (Bailey, Collet and Field - 1928), the slipping taking place down a growing fault scarp. Professor E.B.Bailey and Dr.J.Weir (1932) claimed that the Kimmeridgian Boulder Beds of Helmsdale substantiated the theory for the Quebec deposits. They pointed out, however, that apart from time/

time, there were differences between the two districts. One of these was the penecontemporanity of the boulders in the Quebec Beds, contrasted with the Old Red Sandstone boulders included in Jurassic rocks at Helmsdale. The boulders of the Quebec exposures are mainly limestone which consolidates almost as soon as deposited. In the Ardwell Beds, the boulders are penecontemporaneous, and the number of limestone pebbles at one locality especially are very noticeable.

Comparing the evidence of the Helmsdale beds with material in the Ardwell greywackes at Girvan many points are analagous.

(1) Boulder Beds have a matrix of shelly sand. The fossils are broken and undoubtedly transported.

(2) Eroded or uneven surfaces of disturbed strata are levelled off by sand, furnishing a smooth base for the beds above. This feature is apparent at the top of all intraformational breccias.

(3) Erosion and levelling of the top of contorted shale beds.

(4) Boulder beds sometimes end abruptly and in irregular fashion. They are involved in folding and faulting which affects all the surrounding strata.

(5) Injections of sand into underlying broken shale.

(6) Dovetailing of boulder beds with the normal deposits.

As did the authors of the Quebec paper and the Helmsdale paper insist on the boulder beds being due to contemporaneous faulting, so did Dixon and Hudson (1931) insist on a Carboniferous Boulder Bed at Craven, Yorkshire, being of the same origin. In fact/

fact, most material of this type has been attributed to contemporaneous faulting, but in the Girvan District local submarine faulting is not in evidence, and the disturbances must be attributed to geosynclinal movements. These movements undoubtedly took the form of faulting in certain areas.

Twenhofel (1932,p.739) under the heading "Contemporaneous Deformation of Unconsolidated Sediments" mentions the slipping of sediments down general submarine slopes. He points out that the friction of the surface on which the movement takes place causes over-folding in the sliding mass. Also, this slipping will naturally give rise to local unconformities.

Among the examples of subaqueous slipping in the geologic column, Twenhofel refers to a paper by S.H.Knight (1929) on the Casper Sandstone of Wyoming, Pennsylvania. Here, fine grained limestones are crumpled into folds ranging from minute wrinkles up to 25'. Another point of interest in the paper, is the reference to erosion planes at the top of the folded zones proving contemporaneous deformation. Likewise Twenhofel (p.216) gives examples of intraformational conglomerates, the material of which is contemporaneous with the surrounding strata. He says "Such (intraformational conglomerates) are known to be developed under marine conditions, where partially consolidated sediments are torn up by strong waves and redeposited. Laminae and bedding planes are arched downwards between fragments and these lie in all directions".

W.J.Miller (1922) writing on "Intraformational Corrugated Rocks" contended that many, if not most cases of intraformational corrugations/

corrugations, are due to differential movement, and he opposed Hahn's (1913) theory of subaqueous slumping. Nevertheless, he states that differential movement does not preclude subaqueous slumping, for it is possible that material may slip down a delta-front, the action of gravity alone or gravity aided by earthquakes being the initial cause of movement. In his paper Miller quotes a private communication from John M.Clarke on the Devonian Cape Bon Ami limestone of the Gaspe Peninsula. It reads "Generally the corrugated strata is softer than non-corrugated but this is not the case in the Gaspe rocks. Here the deformed beds are thin limestones like those next to them. They are greatly crumpled and broken. The only explanation is sliding on a soft sea bottom, or sloping surface, under gravity, helped forward, perhaps, if on a large scale, by earthquake shocks or some other jolt like impulse. It follows that the deformation was contemporaneous and preceeded the deposition of the overlying beds".

W.H.Norton (1917) in "A Classification of Breccias" subdivided subaqueous gliding into three types. 1. Overload Glides. 2. Earthquake Glides. and 3. Deformation Glides. Under the second group he states that earthquakes occur in the same area for long periods, ~~and that earthquakes occur in the same area for long periods~~ and that earthquake glide breccias may recur at successive horizons in a formation. In this paper Norton also mentions that subaqueous glide breccias may zone into folded structures, and in that case the fragments of the breccias have contorted laminae. (Horizontal transition seen in fig.29).

Assar/

Assar Hadding (1931) gives more evidence "On Subaqueous Slides". He points out that the primary cause of slipping is the insufficiency of cohesion or friction between sediments to resist the force of gravitation. At the same time gravity may be aided by changes in slope, removal of support, and lastly by external impulses. Changes in sedimentation are, according to Hadding, conducive to slipping. Alternate sand and clay beds are frequently found in slipped masses. Discussing "Edgewise Conglomerates" he considers that the fragments cannot have been freed from the matrix by waves. If they had they would have turned their flat surfaces towards the deposition plane. This, however, does not seem correct for the examples in the Ardwell greywackes. Most of the breccias and one case in particular, (fig.33) the overlying sediment is seen banked up against the outstanding fragments in the form of catenary bedding.

J.G.Goodchild (1901) in a paper on "Canty Bay and the Bass", referred to contemporaneous contortions of strata as a characteristic feature of the sandstones of the Oil Shale Series of Fife and Lothians. He regarded them as due to earthquake shocks proceeding the volcanic activities of that time.

Finally, as has already been stated, Professor Bailey (1930) suggested that grading in sandstones is recordance of seaquakes. It may be pointed out for emphasis, that throughout the Ardwell greywackes grading is ever present.

SUMMARY

1. From Arenig times earth movements, with accompanying earthquakes, occurred repeatedly in the Girvan District.

2./

2. A Palaeozoic island, or projection from the Northern Continent, to the W. and S.W. of the district supplied the close shore deposits of the Kirkland and Benan Conglomerates.
3. The main unconformities occur at the base of the Kirkland and Benan Conglomerates, and the Ardwell Beds.
4. Earthquakes and resultant tunamis were very evident during Ardwell times. These disturbances gave rise to subaqueous Intraformational breccias and corrugations, boulder beds, unconformities, and submarine landslips. Submarine erosion was an all important factor.
5. Intraformational Breccias - Submarine earthquakes loosened and broke the sediments of the sea floor; the resultant tunamis tore up and spread out the debris in the form of breccias. Contemporaneous erosion of the debris was followed by the deposition of sand, levelling off the uneven surface. The sand was the final product of the disturbance.
6. Intraformational Folding - The corrugation took place in sediment more plastic than that forming the breccias. Probably there was less initial vibration to start gliding. Folding often preceeded brecciation. Contemporaneous erosion removed the tops of the folds, and was followed by the deposition of sand. Noticeable that the base, or friction surface, of folding was invariably black mud.

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