Chapter 8 Old Red Sandstone: Walls Formation

Introduction

The outcrop of the sedimentary rocks belonging to the Walls Formation (p. 9) is bounded in the north by the Sulma Water Fault, in the east by the Walls

Boundary Fault and in the south-east by the Sandsting Granite, which has intruded the sediments and produced a thermal aureole of variable width around its margin (pp. 229–233). As there are no stratigraphic marker horizons within the Walls Formation and as in some areas parts of the sequence may have been cut out or repeated by faults it is difficult to construct even an approximate succession or to make a realistic estimate of the thickness. Unless there are a number of major faults not recognized by the author which have repeated large parts of the sequence, the formation must be extremely thick, possibly attaining 30 000 ft (9150 m). In (Plate 12) a number of arbitrary horizons, taken to be 4000 to 5000 ft (1200–1500 m) apart, are marked 1 to 7, to give some idea of the possible stratigraphic relationships of the various outcrops within the area. If the structural interpretation shown on the diagram is correct, the oldest rocks within the formation crop out in the area around Clings Water [HU 310 560] and Loch of Vaara [HU 325 566] in the north-eastern part of the area, and the youngest preserved beds crop out along the axial region of the Walls Syncline near the head of Gruting Voe.

The enclaves of sediment within the Sandsting Plutonic Complex (p. 114, (Plate 25)) are part of the Walls Formation, and the small outcrop of sediments bounded to the west by the Sandsting Granite, between Rea Wick and Roe Ness ((Figure 10), p. 112) is probably also part of this formation, though its strati-graphical position cannot be determined.

Lithology

The salient features of the Walls Formation are its extreme thickness and the uniformity. of its lithology both throughout the sequence and along the strike within any given horizon. The succession is made up of rhythmic units, each composed of a sandy phase consisting of generally fine-grained grey to dark grey sandstone and a somewhat thinner phase of predominantly grey fine-grained thinly bedded sediment which consists of varying proportions of shale, siltstone and sandy siltstone, and in some cases limy shale and fine-grained limestone. The cyclic units range in thickness from 2.5 to 65 ft (0.75–20 m) and the thickness of the sandy phase within them varies from 2 to 60 ft (0.6–18 m).

Coarse-grained sandstones, pebbly sandstones and conglomerates are absent, as are sedimentary structures characteristic of deposition in very shallow water, such as sun cracks and fossil soils. Though planar and trough cross-bedded sets are present in the sandstone phases of the cycles, they are not usually developed throughout the coset. Individual cross-bedded sets do not often exceed 3 ft (1 m) in thickness. Strongly lenticular sandstones are absent. Some sandstones are laminated and dark laminae containing heavy mineral concentrates are common throughout the sequence.

The ratio of sandstone to shale and siltstone within the cycles varies in different parts of the sequence, and there appear to be roughly alternating groups of sand-rich and shale-rich cyclic units. The total thickness of a group of shale-rich cycles does not normally exceed 60 ft (18 m); the sand-rich groups are usually considerably thicker. The beds thought to belong to the lower part of the Walls Formation appear to contain a relatively high ratio of sandy rhythms in which the shale phase is either thin or absent. The sequences made up predominantly of sandstone form prominent hills and ridges with many rocky outcrops. Examples are the ridge extending from the Ward of Browland [HU 268 515] north-north-eastward towards Brindister Voe, the high ground forming North Houlan [HU 300 557] just west of Clings Water, and Brace Field [HU 256 524] just north-west of the Loch of Browland. The well-exposed areas of high ground between Walls and the Voe of Browland and just east of the Voe of Browland consist largely of sandstone, but it seems likely that in these areas the shale phases of the rhythmic sequences have been cut out by shear along the bedding planes.

Good continuous sequences are rarely exposed within the lower part of the Walls Formation (i.e. in groups 1 to 3 of (Plate 12)). All exposures are inland or along the sheltered shores of voes, where the fine-grained sediments are usually obscured, giving the impression that sandstone forms virtually the entire succession. In the upper part of the formation there are many good, easily accessible shore sections. These sections, however, lie to a large extent in areas which have been strongly folded and where the fine sediments in particular are deformed by small-scale folds, crinkles and cleavage. Small sedimentary structures have thus been partially obliterated, deformed or obscured, and in some cycles the junctions between beds of contrasting grain size are shear planes. Good examples of such shear planes, which have produced little or no shattering of adjacent strata, can be seen on the north shore of The Peak [HU 202 477] mile (1200 m) ESE of Braga Ness and along the coast between Ram's Head [HU 182 498] and The Hamar [HU 186 497] 1 mile (1610 m) ESE of Wats Ness.

Coast between Wats Ness and Wester Sound

The strata exposed along the shore between Wats Ness and Wester Sound consist of alternate groups of sand-rich and shale-rich cycles (Figure 9). The groups of shale-rich cycles are 50 to 60 ft (15–18 m) thick, and the thicknesses of individual cycles (i.e. the vertical distance between successive bases of sandstones) range from 2.5 to 17 ft (0.75–5 m). The groups of sand-rich cycles are 80 to 150 ft (24–45 m) thick and individual cycles range from 12 to 65 ft (3.6–20 m).

Shale-rich cycles

The rhythmic units containing relatively high proportions of fine-grained sediment have the following characteristics :

Sandstone phase

The sandstone phase of the cycle usually has a smooth, sharply defined base. Irregularities due to the channelling of the underlying fine-grained sediment are seen in only a few instances and the maximum recorded extent of vertical down-cutting is 2 ft 6 in (0.75 m) ((Figure 9)b at 23 to 25 ft (7–7.6 m) from top), though more often it does not exceed 3 in (7.6 cm). Fragments of siltstone incorporated in the basal part of the sandstone have been recorded in a few cycles at Gerdipaddle [HU 185 497], 0.75 mile (1200 m) E of Wats Ness. Some sandstone posts have a highly irregular base with lobate downward projections which resemble large pillow-like load casts. Most sandstones, however, have no recognizable bottom structures. In many cases this may be due to the obliteration of such structures by tectonic movement along the bedding. The sandstone cosets range in thickness from 2.5 to 12 ft (0.75–3.6 m). Most are fine grained throughout, but many are finer grained at the top than the base. Many are massive and non-laminated and some are at least partly planar-bedded, with dark laminae full of heavy mineral concentrates (p. 117). Quite a number contain plane- and trough-cross-bedded sets usually 1 to 2 ft (0.3–0.6 m) thick, and there are sets with ripple cross-lamination. Neither type of cross-bedding is very common and, where present, it is only found in a part of the coset. Slumped and contorted bedding are relatively common

In a number of the sandstone beds exposed in the area around the Voe of Footabrough there is a three-fold zonation of sedimentary structures within the sandstone coset. This consists of:

1. a lower planar-bedded zone up to 3 ft (0.9 m) thick;
2. a disturbed zone 3 ft to 3 ft 6 in (0.9–11 m) thick; and
3. a thin upper flaggy zone.

The sandstone in the disturbed zone is laminated and the structures within it are similar to, but on a larger scale than, the convolute lamination described on p. 107. Individual folds or 'flame structures' are up to 18 in (45 cm) high and the distances between crests reach 2 ft 6 in (75 cm). In some instances the direction of overturning of adjacent anticlinal crests is inconsistent. Near the top of the disturbed zone the convolutions are on a much smaller scale and the disturbed beds grade upward into the upper evenly bedded zone. The latter contains some thin sets (up to 4 in (10 cm) thick) with small-scale planar cross-bedding, characterized by a consistent low dip of foresets to the south-west.

Though this three-fold sequence of structures is not often well developed there is everywhere a tendency for disturbed bedding and convolute lamination to be confined to the fine-grained sandstone in the upper half of the coset. Troughcross-bedding with troughs up to 8 in (20 m) deep and 2 ft 6 in (75 cm) wide and an axial trend indicating movement from north-east to south-west has been noted in the lower, somewhat coarser-grained portions of some sandstones.

Though many sandstones become finer-grained upwards, graded bedding in unlaminated or evenly laminated sandstones has not been recorded. The tops of the sandstone cosets may either grade upwards into siltstone or may be sharply defined. There are even rare examples of eroded tops of sandstones, and in one section [HU 184 497] a sandstone set with disturbed bedding has been partially removed by erosion and is now overlain by silty shale containing small irregular clasts of sediment.

Shale and siltstone phase

The fine-grained sediments between successive sandstone posts which make up the shale and siltstone phase range in thickness from a few inches to 15 ft (4.5 m). There appears to be no consistent sequence of rock types in this part of the cycle and thin beds of shale, silt and fine-grained sandstone tend to alternate with each other. Calcareous bands or ribs may occur anywhere in this sequence. In a number of sections particularly in the area east of Braga Ness nearly all of the fine-grained sediment consists of homogeneous shale and silty shale, up to 12 ft (3.6 m) thick, which in some instances is red or reddish purple (e.g. Shore of Wester Sound [HU 218 473], 2 miles (3.2 km) SW of Walls), but is more commonly dark grey or black. As these shale bands are often either intensely microcrinkled or strongly cleaved, the original sedimentary structures are to some extent obliterated. Convolute lamination and ripple-cross-lamination are rarely found. Mixed sequences of mudstone, silty mudstone and siltstone with thin sandy ribs and, in some cases, thin ribs of limestone or limy shale are more common than homogeneous successions of shale or silty shale. A number of typical successions are illustrated in (Figure 9). In the fine-grained parts of the cycles exposed between The Flaes [HU 193 492] and Fidlar Stack [HU 191 493] (Figure 14), (Figure 9), the following four zones in descending order can be distinguished:

4	Silty mudstone with rare thin sandy ribs which in some cases passes up into grey or purple shale.
3	Sandy siltstone with sandstone ribs up to 3 in (7.5 cm) thick which become more closely spaced towards the top. The sandy ribs are cross-laminated. In some beds the lamination is convoluted into small regularly spaced cylindroidal folds (Plate 14A) and (Plate 14B). A bed with convolute bedding is 3 to 6 in (7.5–15 cm) thick and can be traced laterally for considerable distances.
2	Dark grey or purplish calcareous shale and silty shale with thin limestone ribs and with fish and/or plant remains on certain horizons.
1	Evenly bedded siltstone and shale with sandy ribs up to 3 in (7.5 cm) thick. The percentage of sandstone increases upward to nearly 50 per cent near the top of the unit, but individual sandstone ribs become progressively thinner upwards. Near the top of the unit they have sharply defined bases and contorted laminae within them.

Convolute structures aligned with tectonic fabric

The thin beds of sandy siltstone with regularly spaced 'convolute' folds (p. 131) are found in approximately the same position within the cycles at other localities in this area, particularly good examples being seen along the south shore of Braga Ness [HU 196 482]. Many 'convolute' folds have remarkably regular shapes. They have U-shaped troughs and pointed, flame-shaped crests. Their amplitude ranges from 1.5 to 6 in (4–15 cm) and their wavelength from 2.5 to 8 in (6.5–20 cm). Their shape and their relationship to the adjacent undeformed beds is very similar to that of the convolute bedding or convolute lamination described and figured from sediments deposited in turbidite, shallow water and fluviatile environments by Kuenen (1953), Sanders (1956), Ten Haaf (1956), Dott and Howard (1962), McKee and others (1962a, b), Dzulynski and Smith (1963), and many others. Convolute lamination is thought to be the result of either current drag (Sanders 1956), current turbulence (Dzulynski and Smith 1963) or inter-stratal laminar flow in unconsolidated water-logged sediment under load (Rich 1950, pp. 729–30; Williams 1960).

The 'convolute' folds in the Walls Formation, however, have certain geometrical features which are not typical of the convolute lamination described elsewhere. These are as follows:

1. The axes of most of the 'convolute' folds recorded in the strongly deformed strata of this area are straight and parallel not only to the axes of the adjacent 'convolute' folds but also to the regional lineation of the rocks and to the axes of the minor folds and wrinkles which are of undoubted tectonic origin (p. 131).
2. The axial planes of the 'convolute' folds are parallel to the cleavage planes of the sediments in which they are formed (Plate 14C). This is particularly striking on the steeply dipping limbs of the major folds, where bedding and cleavage are at an acute angle to each other. There is also a very consistent direction of overturning or 'recumbency' of the folds which is the same as the vergence of the minor drag folds (p. 128) found at various horizons in the same relative positions within the major folds.
3. Convolute lamination, as described by Ten Haaf (1956), is formed in bands of silt grade or of alternate laminae of fine sand and silt, which have been deformed into sharp-crested anticlines and rounded synclines, and whose deformation dies out gradually both upwards and downwards. Though many convolute structures in this area are of this type (Plate 14B) there are many instances in which adjacent folds have become detached from each other at the anticlinal crest, so that the U-shaped troughs now form almost complete oval cylinders. In some cases the convolute folds pass laterally along the bedding into normal small-scale asymmetric folds. There are several instances in calcareous beds where the convolute layer does not pass upward without break into the overlying undistorted laminae, but is sharply truncated, the junction between the two layers being tectonic, not erosional.

The convolute lamination within the strongly deformed beds of the Walls Formation thus shares its geometric parameters with the tectonic structures of these beds, and it is difficult to envisage such a complete parallelism if the convolute structures are of purely sedimentary origin. The style of the convolute folds, however, leaves no doubt that they were formed when the sediments were still in a plastic state. If their formation is ascribed to current drag shortly after deposition there must have been some link between the direction of the currents and the geometry of the later tectonic structures, the currents moving either normal or parallel to the later regional lineation, depending on whether the 'convolute' folds were formed by current drag acting at right angles to their axes (see Sanders 1956) or by current turbulence along them (see Dzulynski and Smith 1963). In either case such a coincidence would suggest a strong topographic control of the currents either by the actively forming major folds themselves or by the margins of the basin of deposition which must have been parallel to the fold axes. If such were the case one would expect evidence of contemporaneous movement within the sediments, such as angular unconformities, mudflow breccias and coarse elastic sediments, none of which are present. The evidence from dips of foresets and trends of trough-axes in the cross-bedded sandstones suggests a predominant current movement from the north-east to the south-west, whereas the trend of the axes of the convolute folds in the vicinity of the Voe of Footabrough ranges from west to W10°S. This divergence of current directions could be explained by the supposition that the structures in the fine sediments were formed by currents flowing parallel to the axes of the trough, whereas the coarser sediments were deposited by lateral currents flowing down the sides of a westward plunging basin (*see* Kelling *in* Bouma and Brouwer 1964, pp. 76–85).

Rich (1950, p. 729) has described intra-stratal distortions in siltstones in the Aberystwyth area, and has ascribed their origin to gravity sliding of the overlying sediments. Williams (1960, pp. 208–14) has suggested that most forms of convolute lamination may result from lateral interstratal laminar flow due to the liquefaction of certain laminae in a waterlogged unconsolidated sediment, the flow pattern being determined by the differential movements of adjoining layers which have remained solid. Within the Walls Formation the parallelism of the geometry of the 'convolute' folds with that of the later tectonic folds, the sharp tectonic upper contacts of some convolute horizons, and the observed transitions to asymmetric similar folds favour the mechanism of interstratal laminar flow, which was controlled either by the initial depositional slope or by pre-contemporaneous flexuring along the incipient fold axes. The latter mechanism presupposes either that the flexuring commenced very shortly after the affected strata were deposited or that the convolute folds were formed a considerable time after the deposition of the sediment under, possibly, a considerable thickness of overburden. In the latter case it must be assumed that certain thin beds in the sequence remained water-logged and in a state of loose packing, so that they would be liable to liquefaction by shearing stress, even at a considerable depth. As is shown in (Figure 9)a the layers with convolute lamination are both overlain and underlain by beds of fine-grained impervious sediment, which during the early stages of compaction could have acted as water seals, leaving the thin silty layers waterlogged and preventing their lithification. The relationship between the geometry of the convolute folds and the regional cleavage and lineation is discussed on pp. 128–134.

Disturbed bedding due to foundering of sandy laminae

Within the area under description there are many irregular small-scale structures which may have resulted from the foundering of thin sandy beds into the underlying mud. Good examples are seen near the Point of Hus [HU 197 482] where sandy laminae within a 1-ft (30-cm) thick bed of silty mudstone form closely packed rolled-up ovoids which average 6 in (15 cm) in length and breadth and 2 to 3 in (5–7.5 cm) in height. Structures of this type are termed 'ball and pillow structures' (Potter and Pettijohn 1963, p. 148) or 'pseudo-nodules' (Macar and Antun 1950). They are thought to have been formed during periods when the mud was temporarily liquefied, the actual break-up and foundering of the sandy laminae being due to differential loading resulting from slight variations in the thickness of the sandy beds. The foundering may have been initiated by earthquake shocks (*see* Kuenen 1958). The disturbed sediment is usually overlain by non-laminated medium-grained sandstone with a load-cast base, individual casts averaging 4 in (10 cm) in depth and 9 in (23 cm) in width, and underlain by up to 3 ft 6 in (1 m) of sandy shale which shows slight traces of penecontemporaneous disturbance. The latter rests in one case on a 2 ft 6 in (0.8 m) thick bed of silty mudstone with sandy laminae, which has several convolute horizons of the type described above (p. 106).

Limestones and calcareous argillites

The rhythmic units shown in (Figure 9) illustrate well-developed shaly phases within the cycles of the Walls Formation. In most cycles the shaly phase is considerably thinner than those shown in the diagram and may have one or more of the units missing. In many, both the calcareous and convolute units are absent. There are, however, a number of cycles in which the calcareous sediments are extremely thick and in some cycles almost the entire shaly phase consists of alternating layers of limestones and calcareous argillite. Details of a number of these are as follows:

1. North shore of Wick of Watsness [HU 176 503], 730 yd (670 m) S20°W of Suther House

In this section 30 ft (9 m) of calcareous sandy siltstone with pale and dark grey banding are intercalated with irregular ribs of clayey limestone. A number of the siltstone beds contain small-scale cross-lamination and some exhibit 'ball and pillow' structure (p. 108). The entire thickness is cut by an anastomosing network of calcite-filled fractures.

2. Headland and south-east shore of Gorsendi Geo [HU 177 503], 860 yd (790 m) S5°E of Suther House

This sequence is composed of 11 ft (3.4 m) of limestone and calcareous mudstone with several bands in which argillaceous limestone or calcareous mudstone is folded into asymmetric similar folds the axial planes of which are inclined at 64° to W30°N and the axes of which plunge at 39° to S30°W, which is parallel to the regional lineation.

The sequence is as follows :

	feet	metres
Ribs of argillaceous limestone up to 1 ft (30 cm) thick with similar folds interbanded with evenly bedded limestone	6.5	2
Shale, evenly laminated, unfolded	0.5 to 1	0.15–0.30
Limestone, massive, with shaly partings	4	1.2

The thick lower limestone is not folded, but the shale bands within it are either broken up into small fragments, or, near the base of the sequence, folded into very small asymmetrical folds with an alignment of fold axes and axial planes identical to that of the folds in the upper limestone.

This sequence is both overlain and underlain by sandstone.

3. South-west shore of Ram's Head [HU 182 498], 1050 yd (960 m) S16°E of Suther House

This is a relatively arenaceous sequence 10 to 11 ft (3–3.5 m) thick composed of intercalated bands of calcareous honeycomb-weathered sandstone and siltstone with one rib of massive limestone up to 10 in (25 cm) thick and several somewhat thinner ribs of clayey limestone. The limestone contains plant fragments preserved as a reddish film on the bedding planes.

4. Sterling Geo [HU 197 488], 900 yd (820 m) SW of head of Voe of Footabrough

The sediment exposed in Sterling Geo consists of calcareous shale with some ribs of calcareous siltstone, but no pure limestone. The entire thickness of sediment is deformed into plastic folds which plunge at 45° to S10°E thus making an angle of 60° with the trend of the regional lineation. The sequence is intensely veined by pink calcite.

5. South shore of Braga Ness [HU 203 477], 100 to 200 yd (90–180 m) WNW of The Peak

The calcareous sequence is here 25 to 30 ft (7.5–9 m) thick and composed of calcareous siltstone and shale. It contains a number of beds of sandstone up to 4 ft thick (12 m) with silty partings and small-scale ripple cross-lamination. There are several argillaceous limestones within the sequence, but no thick crystalline limestones. As in the limestone exposed on the east coast of Gorsendi Geo (p. 109) a number of the calcareous ribs show intense small-scale folding. Though individual folds are less regular than in the Gorsendi Geo section, their axes and axial planes are roughly parallel to the regional lineation and cleavage. There are several thin layers with 'convolute' folds the geometry of which is in accord with the geometry of the minor tectonic structures.

Sand-rich cycles

The sedimentary features of the cyclic units which contain a high proportion of sandstone and relatively little siltstone and shale are as follows :

Sandstone phase

Individual sandstone posts average 10 to 15 ft (3–4.6 m) in thickness but do, in rare cases, attain 60 ft (18 m). They are usually fine grained throughout. Most are planar-bedded and have flaggy partings and some dark bands with heavy mineral concentrates throughout the greater part of their thickness. Some sandstones, however, have well-developed trough-cross-bedding or, less commonly, planar-cross-bedding, usually but not always in the upper part of the posts. Trough-cross-bedded sets are in some cases 5 ft (1.5 m) thick, with individual troughs up to 25 ft (7.6 m) wide. Most are, however, less than 2 ft (60 cm) thick. Throughout the sequence there is a tendency for trough axes to have a south-west or west-south-west alignment and an inclination of cross-strata which indicates current movement from north-east or east-north-east. Sets with contorted (overturned) cross-bedding, in some cases up to 4 ft (1.2 m) thick, have been recorded in several of the sandstone posts.

Shale-siltstone phase

The fine-grained sediments between the thick sandstone posts range in thickness from several inches to 4 ft (12 m). They consist of grey or purplish shale and silty shale, which may pass down into siltstone. Some have calcareous ribs, usually with plant remains, several inches thick, in their upper part. Small-scale cross-lamination is common in the siltstones but convolute lamination of the type described on pp. 106–7 is not usually developed. In many sections the fine-grained sediments between sandstone posts are intensely deformed by the shearing and small-scale folding and original sedimentary structures are largely obliterated.

Vaila Sound and Vaila

The strata exposed along the shores of Vaila Sound and Gruting Voe and on the Island of Vaila are partly within the belt of intense deformation and are affected in the north-eastern outcrops by two phases of folding (p. 133). They are also partly within the thermal aureole of the Sandsting Complex (Plate 25). The strata within the thermal aureole do not contain penetrative tectonic structures such as lineation, cleavage and tight minor folds (p. 134), but they are in some areas cut by a large number of irregular shear planes, which tend to obliterate the junctions between sediments of contrasting grain size.

The major lithologic features in this area are the same as those of the strata exposed between Watsness and Wester Sound (pp. 103–110). The fine-grained phases within the shale-rich cycles, however, appear to be more homogeneous than in the Wats Ness area, consisting almost entirely of shale and silty shale, which is locally calcareous. These shale bands appear to increase in thickness both as the sequence is ascended and eastward along the strike.

Along the south shore of Vaila the cosets of predominantly planar-bedded, fine-grained sandstone up to 25 ft (7.6 m) thick alternate with thin beds of dark grey or black evenly laminated shale. Somewhat higher in the sequence, along the west and north-west coasts of the island, the sandstones contain a higher proportion of sets with planar- and trough-cross-bedding as well as some sets with distorted or recumbently overfolded cross-bedding. Here the beds of fine-grained sediment are thicker, in one case reaching 12 ft (3.7 m). The latter are, again, composed almost entirely of shale and silty shale, with no trace of convolute lamination.

On the north-west shore of Wester Sound and Vaila Sound there are a fairly large number of cycles with thick units of fine-grained sediment, several of which are between 10 and 15 ft (3 and 4.6 m) thick. These consist predominantly of grey or purplish silty shale and shale with calcareous bands. Sandy laminae occur in only a small proportion of these beds, and convolute lamination has not been recorded. Most fine-grained sediments in this area are strongly cleaved, and some are affected by small-scale recumbent folding.

Along the east coast of Vaila and in the Whites Ness peninsula the shaly phases of rhythms are both thick and abundant. In most exposures they are made of black mudstone which has been hornfelsed so that the internal structures are largely obliterated. On Whites Ness, the peninsula between Vaila Sound and Gruting Voe, there are a large number of beds of black mudstone and silty mudstone between 6 and 15 ft (1.8 and 4.7 m) thick, but the details of their structure have been destroyed by thermal metamorphism and later shattering. On the east coast of Vaila, 850 yd (777 m) N of the southern end of Green Head (Vaila) there is an exceptionally thick development of 50 ft (15 m) of fine sediment with a thick limestone and calcareous mudstone near the middle. The sequence within this unit and the present mineral content of the component sediments is shown graphically in (Figure 25), p. 232. Both the thick mudstone and the limestone appear to thin out in a north-westerly direction and the probable horizon of this bed is represented on the north coast of Vaila by a 12-ft (3.7-m) thick bed of shale and siltstone.

Gruting Voe, Seli Voe, Scutta Voe and Voe of Browland

Along the coasts of Gruting Voe, Seli Voe, Scutta Voe and the Voe of Browland the fine-grained sediments are everywhere intensely puckered, cleaved and folded by two phases of deformation. On the shores of the Voe of Browland and in the northern part of Gruting Voe most junctions between fine sediments and sandstone are shear-planes.

The rhythmic units in this area are very similar to those of the upper part of the succession in Vaila Sound. The fine-grained sediment within these units is up to 11 ft (3.5 m) thick and consists mainly of thinly laminated shale and silty shale, but as all shaly units are tectonically distorted their true thickness cannot be established. It is therefore not possible to say whether the eastward thickening of the fine-grained beds continues into this area. Calcareous mudstone with limestone ribs is present in two localities:

1. On the north shore of Scutta Voe [HU 278 498], 140 yd (128 m) WSW of Lee of Houlland School, where calcareous ribs up to 6 in (15 cm) thick are present in 5 ft (1.5 m) of intensely folded and cleaved black shale.

2. On the east shore of Seli Voe [HU 293 484], 580 yd (590 m) NNE of Setter. Here almost the entire fine-grained phase of one cyclic unit appears to be made up of argillaceous limestone with thin partings of black shale. The limestone is affected by two phases of folding and has largely lost its original sedimentary characters.

Evidence for the presence of a very thick bed of black shale and silty shale with thin silty laminae is seen in a quarry cutting superficial deposits on the roadside [HU 294 482] just east of Seli Voe (Chapter 18, p. 271). The drift in this quarry contains many fragments of lineated and crinkled black shale and dark grey siltstone. Although no rock is exposed sediments of this type may well underlie the entire quarry area and the shale band may be over 40 ft (12 m) thick.

In the sandstone posts in the Gruting Voe area sets with both trough- and planar-cross-stratification, between 1 and 2 ft (30–60 cm) thick, are present. Most sandstones, however, are planar-bedded and have thin flaggy partings. The area immediately north and north-east of Scutta Voe has an exceptionally high proportion of exposed rock. All outcrops consist of hard grey fine- to medium-grained sandstone which is so intensely and regularly jointed that it is in places difficult to distinguish joint planes from bedding planes. As in most other inland areas the shaly horizons are not exposed.

Area between Lunga Water and Walls Boundary Fault

The ground immediately south of the Sulma Water Fault, between Lunga Water [HU 235 527] and the Walls Boundary Fault, has a fairly rugged topography with a large number of sandstone exposures but very few exposures in the fine-grained sediment. The sediments forming this area appear to be the oldest beds of the Walls Formation (p. 102, (Plate 12)) and they are folded and locally jointed and shattered by the north-east to north trending folds.

In the area south-west of Uni Firth [HU 288 562] some of the higher ground is formed by relatively thick cosets of medium- and very locally even coarse-grained sandstone with relatively thick cross-bedded sets and some horizons with distorted cross-bedding. There are very few exposures of the fine-grained sediments and nothing is known of their thickness or composition.

In the area east of Uni Firth exposures are more patchy and the rocks are nearly everywhere broken or crushed. Nearly all outcrops are in indurated fine-to medium-grained sandstone which is in some cases intruded by irregular squirts of felsite. Cross-bedded sets are common throughout.

The presence of a fairly large number of roughly concordant felsite intrusions, petrographically comparable with the felsites associated with Clousta Volcanic Rocks, suggests a tentative correlation of these sediments with the highest exposed strata of the Sandness Formation. As there are, however, no close lithological similarities between these beds and the higher beds of the Sandness Formation and as there are here no basic lavas or pyroclastic rocks, such a correlation seems unlikely.

The sediments exposed along the shores of and in the vicinity of Bixter Voe consist of thin cosets of fine-grained dark grey, generally evenly-bedded sandstone alternating with thin beds of siltstone and silty shale. The latter are indurated and partly converted into slate. The sequence has been intruded by numerous concordant sheets of fine-grained graphic granite, and is shattered within a zone extending for 250 yd (230 m) from the Walls Boundary Fault.

Rea Wick–Roe Ness peninsula

The one and a half mile (2.4 km) long outcrop of sedimentary rocks along the south-east coast of the Walls Peninsula between Rea Wick and Roe Ness (Figure 10) contains rhythmic alternations of fine-grained sandstone and relatively thin bands of siltstone and shale with thin calcareous ribs. There is again a rough alternation of sand-rich and shale-rich cycles and at Roe Ness at the southern end of the outcrop one bed of calcareous mudstone with thin siltstone ribs reaches a thickness of 8 ft (2.4 m). The probable structure of the area and the direction of younging of the sediments are shown in (Figure 10). These beds are strongly folded and the fine-grained sedimentary rocks in some exposures show rudimentary lineation, but no cleavage. The sediment is cut by a number of irregular mainly discordant veins of felsite and microgranite. Although the sediment west of the Roe Ness Fault appears to adjoin the granite without a tectonic junction, the extent of induration of the sediment is less than that of sediment in an equivalent position within the aureole farther west (p. 229).

Sedimentary enclaves within the Sandsting Complex

The Sandsting Complex contains large enclaves of sedimentary rock belonging to the Walls Formation as well as a number of smaller inclusions which are 10 yd (9 m) or less in diameter (Plate 25). The large enclaves are:

1. The Sand Water enclave [HU 265 446], an irregular mass of vertical and partly overturned sediment nearly 1000 yd (910 m) long and 550 yd (510 m) wide, interdigitated with diorite along its south-western margin. The strata within this enclave appear to young to the south-east.
2. The Loch of Sotersta enclave [HU 259 450], a narrow lenticular mass of sediment about 400 yd (370 m) long, which is bounded by diorite in the south and by granodiorite in the north.
3. The Swinsi Taing enclave [HU 263 442], a mass of steeply inclined sediment about 300 ft (91 m) thick, but apparently of no great lateral extent along the strike.
4. The Wester Skeld enclave [HU 293 443], a very poorly exposed mass of crushed sediment possibly 550 yd (500 m) long, which crops out on the hillside between Wester Skeld and Housa Water.

Small inclusions of sediment within the complex are most abundant along the shore of Keolki Field [HU 253 454] where they are enclosed mainly but not exclusively in diorite.

The sedimentary rock forming these inclusions and enclaves is thermally metamorphosed into hornfels of the hornblende-hornfels facies, but the major textural features and original structures of the rocks are everywhere preserved. The larger masses appear to be composed largely of fine-grained evenly bedded sandstone with relatively few thin cross-bedded sets. The beds of fine-grained sediment in the Swinsi Taing enclave are very thin. In the Sand Water and Loch of Sotersta enclaves only sandstone has been recorded but as neither outcrop has any coast exposures, it must be assumed that beds of fine sediment are present but not exposed.

In addition to the above-mentioned enclaves which are entirely enclosed in igneous rock there are a number of sedimentary masses, all intensely veined by granite and/or diorite, which are separated by faults from the igneous rocks of the complex. These include the narrow belt of shattered sandstone between Muckle Flaes [HU 249 451] and Burri Geo [HU 259 442] (Plate 25), and the sediment forming the headlands on either side of Vine Geo [HU 240 457], in the south-east corner of Vaila. It is not possible to assess if these masses were ever enclaves within the granite or if they are parts of the roof which collapsed during the final stage in the intrusive history of the complex (pp. 228–9).

Fauna and flora

The first find of fossil plants within the Walls Formation was that by Peach and Horne in the area just north and east of Walls and in the hills between Gruting Voe and Bixter Voe (p. 5). Unfortunately the records of the exact localities of these finds have not been preserved.

Finlay (1930, p. 675) recorded plant remains from 'a bed of sandy shale below the Watsness Limestone', but he did not give the locality of this limestone, and it is now not possible to ascertain which of the limestones in the Watsness district he referred to. Finlay stated that Professor Lang examined the district for plant remains and appears to have found plant fragments at various unspecified localities. Lang described these plant remains as hostimellid in type.

In the course of the geological mapping of the Walls Sandstone by the Geological Survey during the recent revision mapping by the author a number of localities yielding both plant and fish remains were recorded. These localities are shown in (Figure 11) and briefly described below. The search for fossils in the Walls Formation has not been exhaustive and there can be little doubt that much new material remains to be found. The numbers in the list below refer to localities shown in (Figure 11). Localities 1 and 2 are in the Sandness Formation and described on p. 92.

3	Trea Wick [HU 173 507], 600 to 615 yd (550–560 m) W15°S of Suther House. Plant and fish remains from three horizons in dark grey, ochre-weathering, mudstone and siltstone. Fish remains include scales of *Gyroptychius microlepidotus* type and two fragments of articulated acanthodians which can be determined as belonging to the Cheiracanthidae and might be close to the genus *Cheiracanthus.*
4	Loch of Watsness, south-west shore [HU 175 506], 450 yd (410 m) S45° W of Suther House. Dark shale with plant fragments including *Hostimella* sp.
5	Wick of Watsness [HU 175 501], west shore, 450 yd (410 m) S45° W of Suther House. Fine-grained grey sandstone with plant remains preserved as red film.
6	Gorsendi Geo [HU 179 510], 810 yd (740 m) S3°E of Suther House. Dark grey to purplish grey sandy siltstone with abundant plant debris. Plants occur above and within the limestone horizon. Only *Hostimella* sp.has been identified.
7	Ram's Head [HU 182 499], 1200 yd (1100 m) S21°E of Suther House. Dark grey siltstone interbedded with sandstone above the calcareous horizon. Rare fish scales of the *Gyroptychius microlepidotus* type.
8	Coast between Fidlar Stack and The Flaes [HU 192 492], 1 mile 420 yd (2 km) S40° E of Suther House.Fossils from two horizons ((Figure 9)a). Pale purplish grey to purplish green calcareous silty mudstone with fish bones, including a climatiiform spine and scales of the *Gyroptychius microlepidotus* type. Also ?eurypterid remains and plant remains.
9	Burn of Turdale [HU 197 509], 130 yd (120 m) E38°N of Turdale and 150 yd (140 m) E43°N of Turdale. Grey fine-grained sandstone with beds full of plant remains including Hostimella sp. and some trace fossils or roots. (This is the only locality in the Walls Formation where trace fossils or root remains have been recorded.) Also dark grey to black shale with fish scales preserved as carbonaceous films.
10	Voe of Littlure [HU 208 477], 620 yd (575 m) W23°N of outlet of Loch of Quinnigeo. Grey mudstone with poorly preserved plant remains
11	Bridge of Walls [HU 269 512], roadside 520 yd (475 m) S12°E of summit of Ward of Browland. Flaggy micaceous sandstone with plant debris.
12	Scutta Voe [HU 278 499), north shore, 110 yd (100 m) W20°S of School at Lee of Houlland. Grey silty mudstone with poorly preserved plant remains.
13	Bixter Voe [HU 334 514], north-east shore 650 and 850 yd (595 and 777 in) S of Bixter Post Office. Grey siltstone with plant remains. Plants have also been recorded from the south shore of Bixter Voe, 1350 yd (1235 m) SE of Bixter Post Office.

The fish remains have been examined by Dr. R. S. Miles, who has reported as follows :

"The major portion of the collection comprises indeterminable Crossopterygian remains. They are principally scales of an irregular cycloid form, but also include some plates provisionally determined as from the exocranium (opercular, gular and branchiostegal bones). The scales are broadly of the '*Gyroptychius microlepidotus*' type in their surface morphology; a fact of little stratigraphical or systematic significance. Two fragments have the cosmine layer of the bone preserved, clearly indicating a member of the Osteolepoidea.

Two articulated acanthodians can be determined as belonging to the Cheiracanthidae, and might be close to the Scottish Middle Old Red Sandstone genus *Cheiracanthus.* A small fragment has been tentatively identified as the base of a spine of climatiiform type.

The fragmentary fish remains indicate a Middle Old Red Sandstone age for the Walls Sandstone, but do not permit a more precise statement on the matter."

W. G. Chaloner has identified the plants, but none of them has proved to be of diagnostic value in determining the age of these strata. Specimens of carbonaceous mudstone from two localities were submitted to Dr. B. Owens for spore determination, but no material suitable for identification, even at generic level, was obtained.

Petrography

Sandstones

The characteristic features of the arenaceous sediments of the Walls Formation are the remarkable consistency in grain size within the 0.45 to 0.045 mm range, the absence of extraformational conglomerates, and the rarity of intraformational conglomerates. Individual grains in the sandstones are generally subangular to angular, poorly to very poorly graded, with corroded margins of quartz and feldspar grains due to partial replacement by the authigenic matrix minerals clay mica, chlorite and carbonate. The sandstones are very immature with the ratio of quartz to feldspar grains ranging from 55:45 to 80:20, and with up to 15 per cent of heavy minerals. Concentrations of heavy minerals also occur, as bands up to 3 mm thick, throughout the sandstone sequence ((Plate 13) fig. 5). The most common detrital heavy mineral grains are epidote, sphene, iron ores and apatite. Rarer mineral grains include tourmaline, zircon, allanite and garnet. Lithic clasts are virtually absent.

The percentage of matrix and mineral cement in relation to the total volume of rock of the great majority of specimens ranges from 15 to 35, but reaches 50 in some of the laminae with high concentrations of heavy minerals. The matrix is partly of secondary origin, being formed by the partial or complete replacement of detrital grains, particularly the feldspars, epidotes and garnets. In the least altered sandstones the matrix consists of a thin, more or less continuous film of chlorite mantling the grains, and interstitial patches of granular calcite and chlorite.

According to the classification adopted by Pettijohn (1957, p. 291) most of the sandstones are feldspathic greywackes. As in many samples the matrix and mineral cement were partly formed by the replacement of grains, a proportion of the sandstones may have originated as fine-grained arkose.

Within the tightly folded zones (p. 128) and in the entire eastern part of the area, muscovite, chalcedonic silica, ?albite and epidote are extensively developed, and over a large part of the area the composition of the matrix indicates a low-grade dislocation metamorphism with pressure-temperature conditions ranging from the zeolite facies to the lower grades of the greenschist facies (Turner 1968, pp. 265–70). The thermal alteration of the sandstones within the aureole of the Sandsting Granite is described in Chapter 15, pp. 229–233.

In the following description the sandstones are divided into arbitrary stratigraphic units based on the structural interpretation shown in (Plate 12). This brings out the slight petrographic differences within the sequence.

Lowest sediments (below band 3 on (Plate 12))

The sandstones are fine- to medium-grained, poorly graded with grain diameters ranging from 0.6 to 0.045 mm. Grains are angular to subangular, with the larger grains of some thin sections subrounded. Within the zone of tight north-north-east trending folds close to the Loch of Voxterby [HU 260 533] quartz grains in a number of specimens have an undulose extinction and serrate interlocking margins. Small quartz grains are partly replaced by matrix minerals. In some cases a high proportion of quartz grains shows extreme elongation parallel to the bedding.

The ratio of quartz to feldspar averages 70:30 and ranges from 60:40 to 80:20. The feldspar clasts consist, in order of abundance, of untwinned potash feldspar, oligoelase-andesine, microcline and microperthite, the ratio of potash feldspar to plagioclase varying greatly in different specimens.

Thin bands of heavy mineral concentrations, ranging from less than 1 to 2.5 mm in thickness, are developed throughout the sequence, and nearly all specimens of pale sandstone examined contain over 10 per cent and in one specimen 20 per cent of dark minerals evenly scattered throughout. In the dark bands up to 50 per cent of the clasts are heavy minerals. These are, in order of abundance, epidote, sphene, apatite, clusters of opaque iron ore, tourmaline and rare clusters of allanite. One specimen (S30975) [HU 277 551] from just south of the Sulma Water Fault 0.75 mile (1200 m) W of Brindister Voe contains a high proportion of large garnet grains, altered along the joints to a chloride aggregate. The garnets are present both in the dark bands and in the normal sandstone.

The amount of matrix and mineral cement in the specimens ranges from 10 to 15 per cent, rising to 20 per cent in the stratigraphically lowest specimens. The matrix is always somewhat more abundant in the dark bands and is variable in composition, depending on the extent of tectonic deformation. In the least altered sandstones it is composed of a green aggregate of chlorite and clay-mica coating the grains and interstitial patches of calcite. The specimens from the belts of intense folding (S2746) [NC 215 159], (S51494) [HU 266 516], have a fine-grained aggregate of green mica and a fine interstitial mosaic of silica and ?albite. In these specimens chlorite forms discrete irregular interstitial patches.

Sediments between bands (3) and (4) of (Plate 12)

The sandstones from this group are fine- to medium-grained and, with one exception, poorly graded. The grain diameters compare closely with those of the underlying sediments. They average 0.3 mm and range from 0.5 mm to 004 mm. Grains are subangular to subrounded but well rounded in one specimen (S30900) [HU 243 533]. The margins of the grains are either not corroded or only slightly corroded by the ingrowth of authigenic sericite. The ratio of quartz to feldspar grains in all but one specimen is close to 60:40 and the percentage of matrix ranges from 10 to 15 per cent in the normal sandstone, but is 30 to 40 per cent in the dark bands. The quartz grains are normally clear, but the samples from a locality 0.25 mile (400 m) N of Lunga Water have quartz grains full of needles of rutile. The composition of feldspar grains is the same as that in the underlying sediments, with untwinned potash feldspar, which in this group is slightly cloudy, most abundant in many specimens, though in some (S30872) [HU 233 533], (S30873) [HU 233 533] sodic plagioclase predominates. Dark, rounded, mineral grains are present in all specimens and form up to 15 per cent of the total detrital grains (S30900) [HU 243 533]. Epidote, though forming up to 60 per cent of the total heavy minerals in one specimen (S30900) [HU 243 533], is commonly less abundant than sphene and even apatite. Garnet forms abundant grains which are partially or completely broken down into chlorite in the dark bands of specimens from north of Lunga Water. The matrix consists of a thin, often discontinuous film of chlorite and clay-mica mantling most grains, together with interstitial patches of carbonate and chlorite and less commonly a mosaic of quartz and ?albite. Except in the heavy mineral bands, there is little evidence to suggest that a high proportion of the matrix was authigenically formed by the replacement of the detrital grains.

Strata between zones 4 and 5 of (Plate 12)

The sandstones in this group of strata are generally fine- to medium-grained with the average grain diameter slightly smaller than in the beds of the underlying groups, the maximum size ranging from 0.45 to 0.24 mm and minimum from 0.06 to 0.03 mm in different specimens. Some sandstones contain thin bands which are coarser and have grains exceptionally up to 0.8 mm in diameter. Grading is variable, most specimens are poorly graded but a number are moderately well to well graded. Grains are nearly always angular and within the strongly folded belt there are two cases with slightly serrate and interlocking margins. The grains of these sediments are, however, not as strongly deformed and serrated as the sandstones within the zone of the near-isoclinal north-east trending folds below band 3 (p. 119). There is a gradual increase in the serration and partial annealing of the grain margins as the aureole of the Sandsting Granite Complex is approached (p. 231).

The ratio of quartz to feldspar grains ranges from 60:40 to 80:20, with an average of 70:30. In only one specimen (S52547) [HU 179 493] is feldspar virtually absent. Quartz grains are almost invariably free from inclusions. Among the feldspar grains untwinned slightly cloudy and, in some instances, sericitized, potash-feldspar predominates over or is roughly equal in amount to plagioclase (oligoclase-andesine), which is always clear. In some specimens (e.g. (S29928) [HU 185 498]) potash feldspars form fresh angular cleavage fragments, suggesting a fairly local source. Muscovite occurs in scattered flakes or in clusters of stumpy plates and appears to be more abundant than in the lower sediments. Heavy mineral bands, up to 2 mm thick, appear to be less abundant than in the lower beds. Again, epidote, though still the most common heavy mineral in the dark bands, is rare or absent in many specimens of pale sandstone where sphene is by far the most abundant heavy mineral. Other minerals, in approximate order of abundance, are apatite, ilmenite-leucoxene, tourmaline, zircon and allanite. Clastic garnet has not been recorded in this group.

Matrix forms 5 to 30 per cent of the total rock volume and up to 40 per cent in the dark mineral bands. In nearly all specimens the matrix contains a high proportion (50 to 80 per cent) of carbonate which forms fairly large patches and has locally partially replaced quartz grains. The aggregate of chlorite and clay-mica forms a thin, often discontinuous rim around grains and has partly replaced some feldspars. Chalcedonic silica with chlorite forms irregular patches in several specimens. In some specimens in this group the matrix percentage is less than 10, and in others the matrix is almost entirely carbonate. Some of these rocks are thus not greywackes and it seems probable that the high proportion of matrix in the other specimens is largely of secondary origin.

Strata above band 5 of (Plate 12)

The beds above and just below band 5 appear to have a somewhat higher proportion of fine-grained sediments than the underlying groups, though the grain size of the sandstones is much the same. Average grain diameters range from 0.4 to 0.03 mm. Coarse-grained sandstones with a maximum grain diameter of 0.8 mm are very rare. Though most specimens are poorly sorted with sub-angular to angular grains there is a somewhat higher proportion with moderate to good sorting than in underlying sediments.

The composition of the clasts shows a quartz-feldspar ratio ranging from 60:40 to 80:20 with a possible slight westward increase in the proportion of feldspar. The feldspar clasts are in most cases predominantly untwinned potash feldspar with subordinate plagioclase (oligoclase-andesine) and rare microcline and microperthite. The latter is, however, fairly abundant in specimens from the Watsness district. Heavy minerals appear to be marginally less abundant than in underlying sediments, and epidote appears to be largely confined to the dark bands. Within the normal pale sandstones sphene is most abundant, in places forming 80 per cent of the total heavy mineral grains. Apatite is common throughout; tourmaline, iron ore and allanite are rare. Garnet has been recorded within this group only in a calcareous siltstone-from the Watsness district (S50821) [HU 172 501].

The percentage of matrix and mineral cement within this group is very variable, ranging from less than 5 to 40 per cent. In some specimens from the Watsness area it consists only of a thin discontinuous film of chlorite and small interstitial patches of carbonate. Further east within the highly deformed sandstones, muscovite is more abundant than chlorite and a quartz-albite aggregate as well as calcite forms interstitial patches.

Rea Wick–Roe Ness peninsula

The sandstones east of the Roeness Fault (pp. 00–00, (Figure 10)) are comparable with the non-hornfelsed sandstones with a relatively high percentage of calcareous cement from the main outcrop. The only sliced specimen (S51542) [HU 325 427] from this area is slightly better graded than most sandstones from the Walls Formation, the grain size being within the limited range of 0.25 to 0.08 mm. The grains are angular with serrate margins, and quartz grains are partially replaced by carbonate. The ratio of quartz to feldspar clasts is 70:30 and of the feldspar grains approximately 80 per cent are potash feldspar with irregular blotchy inclusions of albite and carbonate; the remainder is clear sodic plagioclase.

Muscovite forms abundant thin flakes and heavy minerals consist of abundant small rounded grains of apatite, scattered granules of iron ore, and rare olive-green tourmalines. Mineral cement forms over 20 per cent of the volume of the rock and consists essentially of finely granular calcite with scattered flakes of sericite.

Stratigraphic and regional variations within sandstones

The above petrographical descriptions deal with a thickness of possibly 30 000 ft (9000 m) of sediments which show remarkably little petrographic variation either strati-graphically or geographically. Nearly all specimens of sandstone are poorly graded, have subangular clasts, and contain a high proportion of readily altered minerals, which include up to 40 per cent of relatively fresh feldspar and varying proportions of epidote. Stratigraphic variations, which may not be statistically significant, are as follows:

1. There is a slight decrease in average grain size as the sequence is ascended, and a slightly higher proportion of subrounded to rounded grains near the top.
2. There is a fairly marked decrease in the amount of detrital epidote within the pale sandstones in the upper part of the sequence as well as a less marked decrease in the frequency of dark laminae of epidote-rich heavy mineral concentrates.
3. Garnet-bearing sandstones are confined to the lower part of the sequence and are found mainly near the northern margin of the area.
4. There is a slight but inconsistent upward decrease in the percentage of matrix. As a high proportion of the matrix was, however, formed by the partial or complete replacement of clasts by sericite, calcite and a quartz-albite aggregate during the intense folding of the beds the relationships of the original matrix content to the stratigraphy are largely obliterated.
5. There appears to be no obvious connection between the relative abundance of the various types of feldspar clasts (p. 120) and the stratigraphy. In the higher part of the sequence, however, there appears to be a marked westward increase in the percentage of perthite.

Siltstone and mudstone

Siltstones and mudstones make up between 10 and 20 per cent of the total sediment in the upper half of the Walls Formation. Only a limited number of thin sections are, however, available.

The siltstones (S29932) [HU 200 491], (S29937) [HU 208 476] consist of alternate quartz-rich and muscovite-rich laminae ranging, in thickness, from 0.5 to 1.5 mm. Feldspar grains are rare or absent in many of the specimens. Muscovite forms thin flakes normally up to 0.25 mm long, and in some specimens these are associated with flakes of chloritic material. There are also thin laminae of very fine-grained brownish aggregate of chlorite and mica. Heavy minerals are relatively rare in sediments of silt grain-size, but some bands with rounded epidote grains and rare sphenes (S29937) [HU 208 476] have been recorded. Minute grains and flecks of iron oxide are common throughout. The matrix of most specimens is a mixture of calcite, chlorite, and clay-mica, with the calcite content in the sandy laminae of certain specimens (S52550) [HU 179 493] reaching 40 per cent.

The fine-grained sediments have clearly recorded the effects of the two major episodes of folding. In the area where only the first fold phase is recognized, they have small-scale folds with wavelengths up to 0.3 mm and a strong axial-planar slaty cleavage. In the areas affected by the two periods of folding the early slaty cleavage, characterized by the development of greenish pleochroic micas, is re-folded into regular asymmetric folds with a newly developed strain-slip cleavage (p. 136).

Limestone and calcareous argillite

The limestones and calcareous mudstones and siltstones are generally finely banded and consist of alternate laminae of calcite-rich mudstone and calcite-rich siltstone, which contain varying proportions of grains of other minerals such as partially replaced quartz, feldspar, sphene and epidote, as well as fine flakes of muscovite and granules and films of carbonaceous material. Coarse-grained limestones, composed entirely of crystalline carbonate, are absent.

The calcareous deposits are very prone to mechanical deformation and many show intense small-scale folding or, in extreme cases (S50803) [HU 221 582], complete disruption of the fabric. In some thin sections (e.g. (S50821) [HU 172 501]) the laminae of mud-stone and shale within the folded calcilutite are broken up into discrete highly irregular fragments ranging up to 7 mm x 1 mm in size, which in many cases show evidence of some degree of initial folding. In the extremely deformed bands (S50803) [HU 221 582] the calcite-rich mudstone is discordantly folded and broken into irregular fragments. The latter are cemented by irregular branching veins of carbonate composed of parallel and, in many cases, slightly bent calcite fibres. These are in turn cut by a suite of often branching parallel veinlets of crystalline calcite, which shows no sign of deformation.

Tectonically undeformed calcareous mudstone is composed of laminae of calcite grains, which are elongated parallel to the bedding and enclosed in a thin film of carbonaceous material. Thin laminae of carbonaceous debris, which tend to split laterally, are interdigitated with laminae of pure carbonate rock, which are up to 0.4 mm thick. Most laminae contain scattered grains of quartz, and subhedral highly poikilitic crystals of authigenic pyrite up to 0.35 mm in diameter. The inclusions in the pyrite crystals are invariably calcite. Calcite also forms a narrow rim around these crystals, and in one case, the pyrite is completely enclosed by an euhedral crystal of calcite.

The limestone bands are particularly sensitive to the thermal alteration by the Sandsting Granite and the mineral assemblages developed in the limestones exposed on the east coast of Vaila are described in Chapter 15, pp. 232–3 and shown in (Figure 25), p. 232.

Environment of deposition

The sediments of the Walls Formation bear some resemblance to the higher members of the Sandness Formation exposed along the west coast of the Walls Peninsula (p. 80). The latter are believed to be river deposits laid down on alluvial plains, and they consist of fining-upward cycles in which channel sandstones are overlain by relatively thin overbank deposits. The fine-grained beds contain sun-cracks, asymmetrical ripple marks and local red beds, all of which are evidence for deposition on flood plains (p. 83). The beds of the Walls Formation also consist of rhythmic units composed of alternating sandy and shaly members, but they lack many of the features associated with river deposits.

The sandstones are almost uniformly fine-grained and contain no basal pebbly lenses or scattered pebbles throughout them. Though cross-bedded sets are present in many sandstones, they usually form only a part of the total coset, which also contains finely banded planar-bedded sets and massive unbedded sets. Channelling at the base of sandstones is rare, and some sandstones have lobate load-cast bases. All the sandstones contain a very high proportion of fine-grained matrix, and though some of this matrix was formed by the authigenic replacement of grains after lithification, the rocks do not have the character of typical 'clean' fluvial sandstones. Perhaps most significant of all is the remarkable uniformity of the sandstones throughout their entire outcrop and over a vertical distance of possibly 30 000 ft (9000 m). This uniformity is in marked contrast to the great vertical and lateral variation in the lithology of the predominantly fluvial Sandness and Melby formations.

The fine-grained phases of the rhythmic units in the Walls Formation show none of the characteristics of fluvial overbank deposits. Desiccation cracks are unknown and asymmetrical ripple marks are rare. The red beds are not of the type associated with topstratum beds. Many of the deposits are calcareous and some display certain of the characteristics found in the lacustrine flagstones of Orkney (Fannin 1970) and Caithness (Crampton and Carruthers 1914). The fine lamination of some bands and the presence of thin lime-rich and carbonaceous laminae associated with authigenic pyrite (p. 122) are obvious examples. The fish genera found in these beds are also of the type associated elsewhere with a lacustrine environment. In the flagstones of Orkney and Caithness, however, the laminated lacustrine beds are usually underlain and overlain by predominantly fine-grained sediment with sun-cracks and other structures which are diagnostic of a shallow water or mud-flat environment that was periodically exposed to sub-aerial conditions. As these features are completely absent in the Walls Formation, it is probable that it was deposited, not in shallow lakes of the Orkney–Caithness type, but in a rather deeper body of inland water. The great regularity in the direction of minor structures, such as the 'convolute' folds, could mean that the shape of the basin of deposition exercised a strong control over the directions of the currents within it (but see p. 132). If this hypothesis were to be accepted, it should be possible to use the alignment of sedimentary structures to get some idea of the approximate shape of the basin. The basin must have subsided fairly rapidly, as subsidence must at all times have kept pace with the deposition of a very considerable thickness of sediment.

The sandstones interbedded with the Middle Old Red Sandstone lacustrine flagstones of Orkney and Caithness are generally regarded as shallow-water deposits laid down either in the distributary channels of deltas which periodically invaded the shallow lakes, or in channels of rivers which traversed the dried up lake bed. The Walls Formation sandstones, however, bear a completely different relationship to the fine sediments, as they themselves appear to have been laid down in relatively deep water (but see below, p. 124). Though they are not marine sediments they can in some respects be compared with sandy flysch deposits which are generally believed to have been laid down in or on the slopes of marine basins. The Walls Formation has the following characteristics in common with flysch deposits:

1. The sandstones are 'muddy' and have a high proportion of clay grade material in the matrix.
2. The sequence displays the rhythmic repetition of sandstones and fine-grained sediments which is characteristic of most flysch successions.
3. The sandstones have sharply defined bottom surfaces on which sole markings are in some instances preserved. Sole markings are, however, less common than in typical flysch deposits.
4. Many sandstone cosets become finer-grained upwards. Good graded bedding of the type seen in many turbidites is, however, uncommon.
5. Fine-grained sandstones and sandy siltstones are generally well laminated and many beds show convolute lamination which is a characteristic, but not exclusive feature of flysch deposits. Slump bedding and other forms of contorted bedding are common in the sandstones.
6. There is no rapid variation in the overall composition of the sediments, either laterally or vertically.
7. The alignment of directional sedimentary structures, particularly in the fine-grained sediments, appears to be constant over considerable distances.
8. There is no evidence of sub-aerial or very shallow water conditions.

The sandstones of the Walls Formation, however, show a fair amount of large-scale cross-stratification which is only rarely found in flysch sandstones (Dzulynski and Walton 1965, p. 178) and which could not easily have been formed in deep water. There is also no evidence in the Walls Formation for the occurrence of large-scale slumping, nor are there any mudflow breccias or conglomerates of the type recorded in some flysch deposits. Most flysch sandstones are thought to be turbidites, which have been deposited by turbidity currents. The idealized complete turbidite unit should show the following four structural sub-units (Bouma 1962, pp. 49–51; Walker 1965): (1) lower unit with graded bedding and no cross-lamination; (2) unit with parallel lamination; (3) unit with ripple-cross-lamination, and (4) upper unit with current lamination. Some rhythmic units in the Walls Formation ((Figure 9) and pp. 104–6) have similar subdivisions, but it is doubtful if many of the sandstones in the formation can genuinely be classed as turbidites.

The origin and mode of deposition of the sediments of the Walls Formation is thus still open to speculation. Nor can anything be said at this stage about the size or shape of the original basin of deposition, which must have occupied a considerably larger area than the present outcrop of the Walls Formation.

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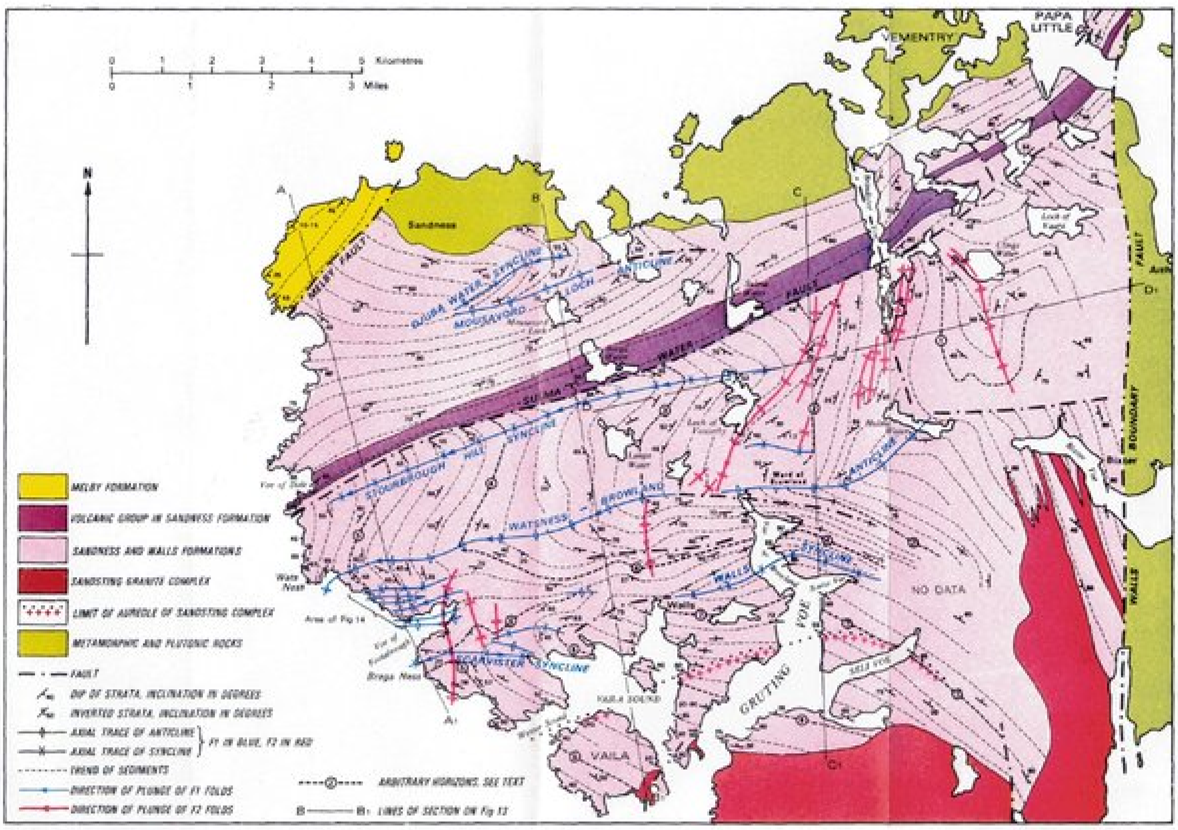
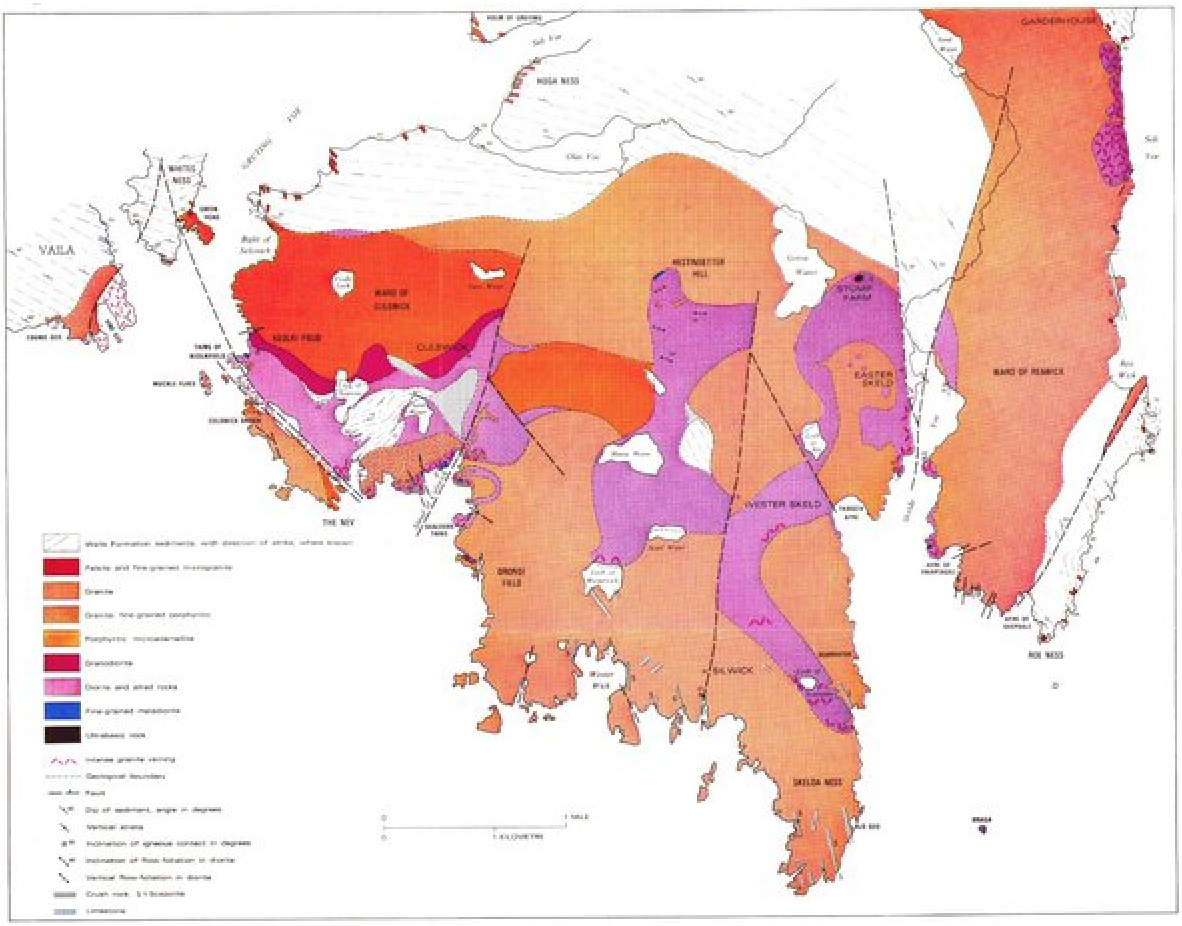
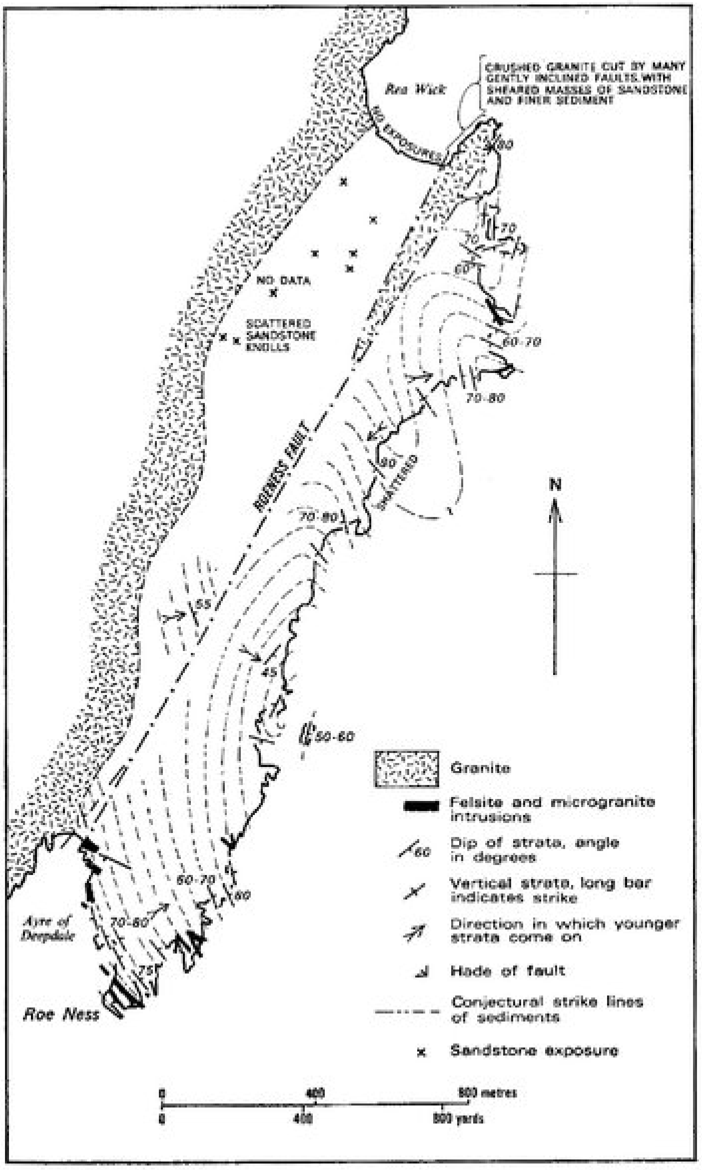


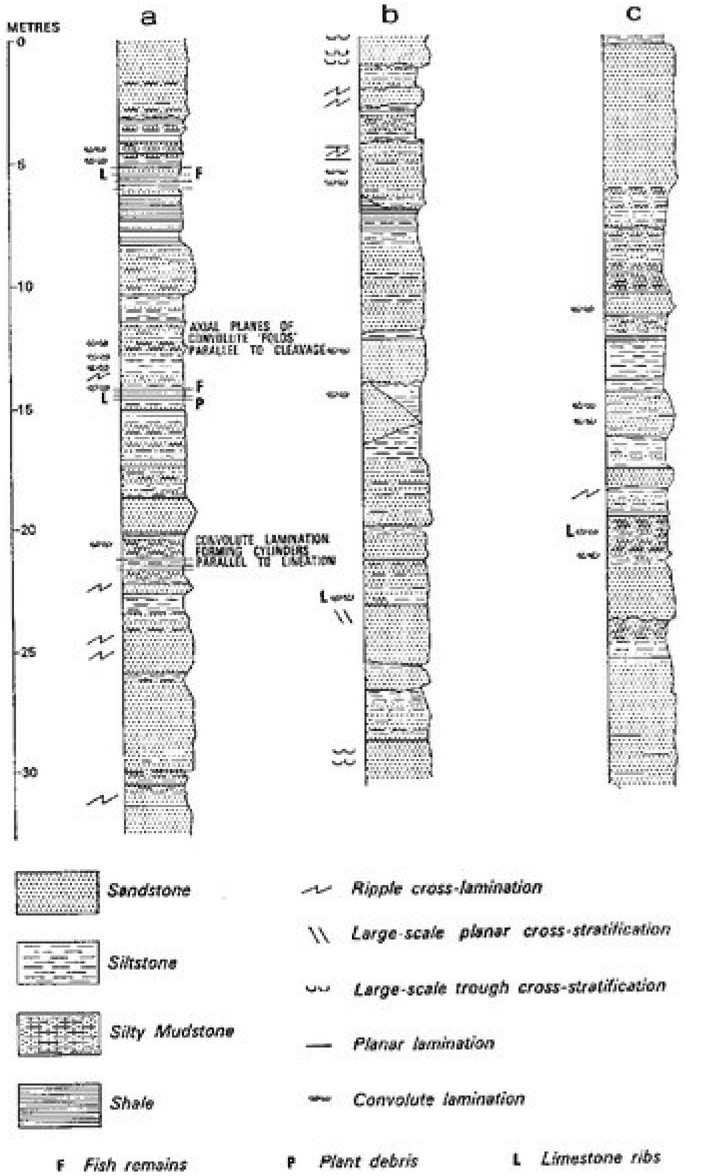
(Plate 12) Major stratigraphic and structural features of the Old Red Sandstone sediments and volcanic rocks of the Walls Peninsula.



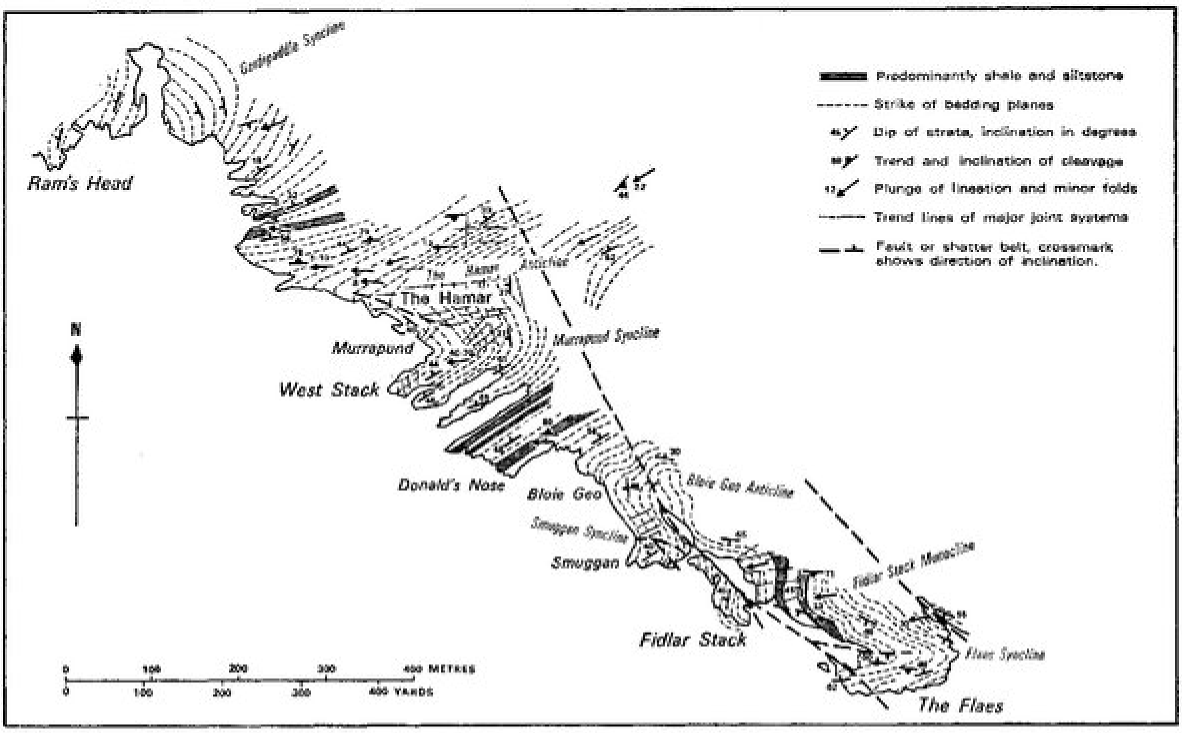
(Plate 25) Geological Sketch map of the Sandsting Granite–Diorite Complex.



(Figure 10) Geological sketch-map of the Roe Ness–Rea Wick area.

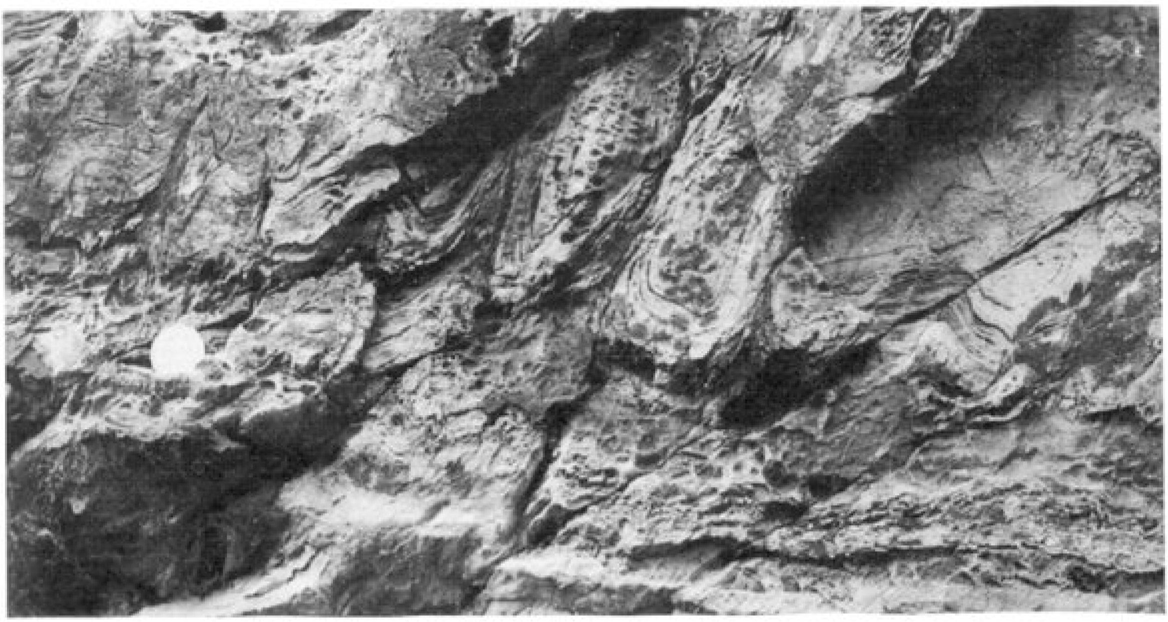


(Figure 9) Some characteristic sequences in the Walls Formation.

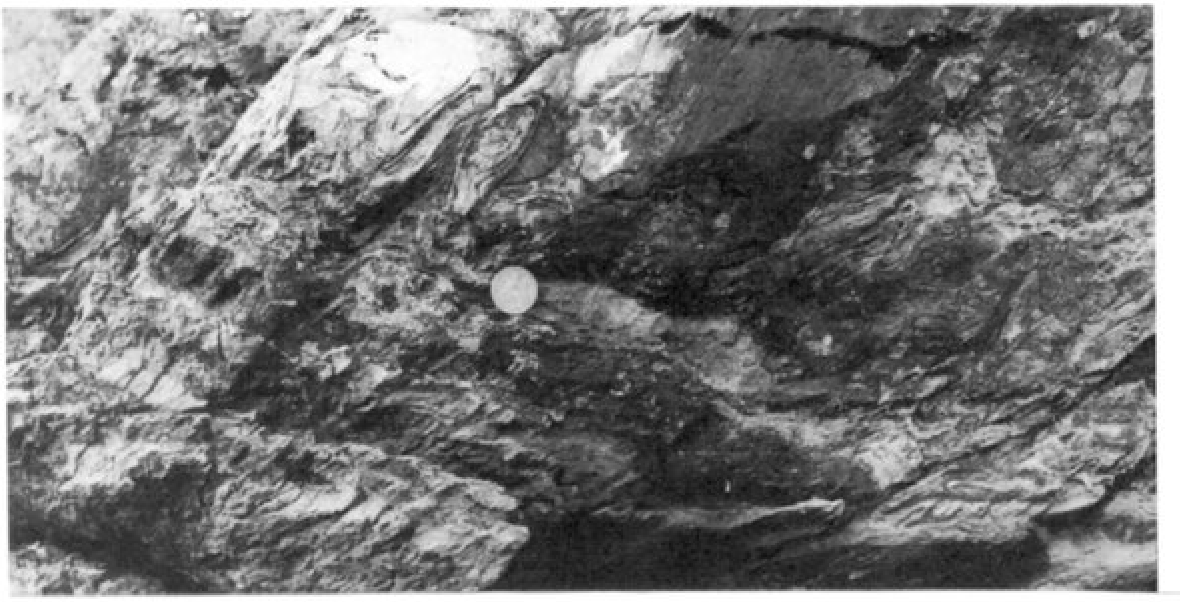


(Figure 14) Sketch-map showing the structure of the sediments of the Walls Formation exposed on the coast between Ram's Head and The Floes.

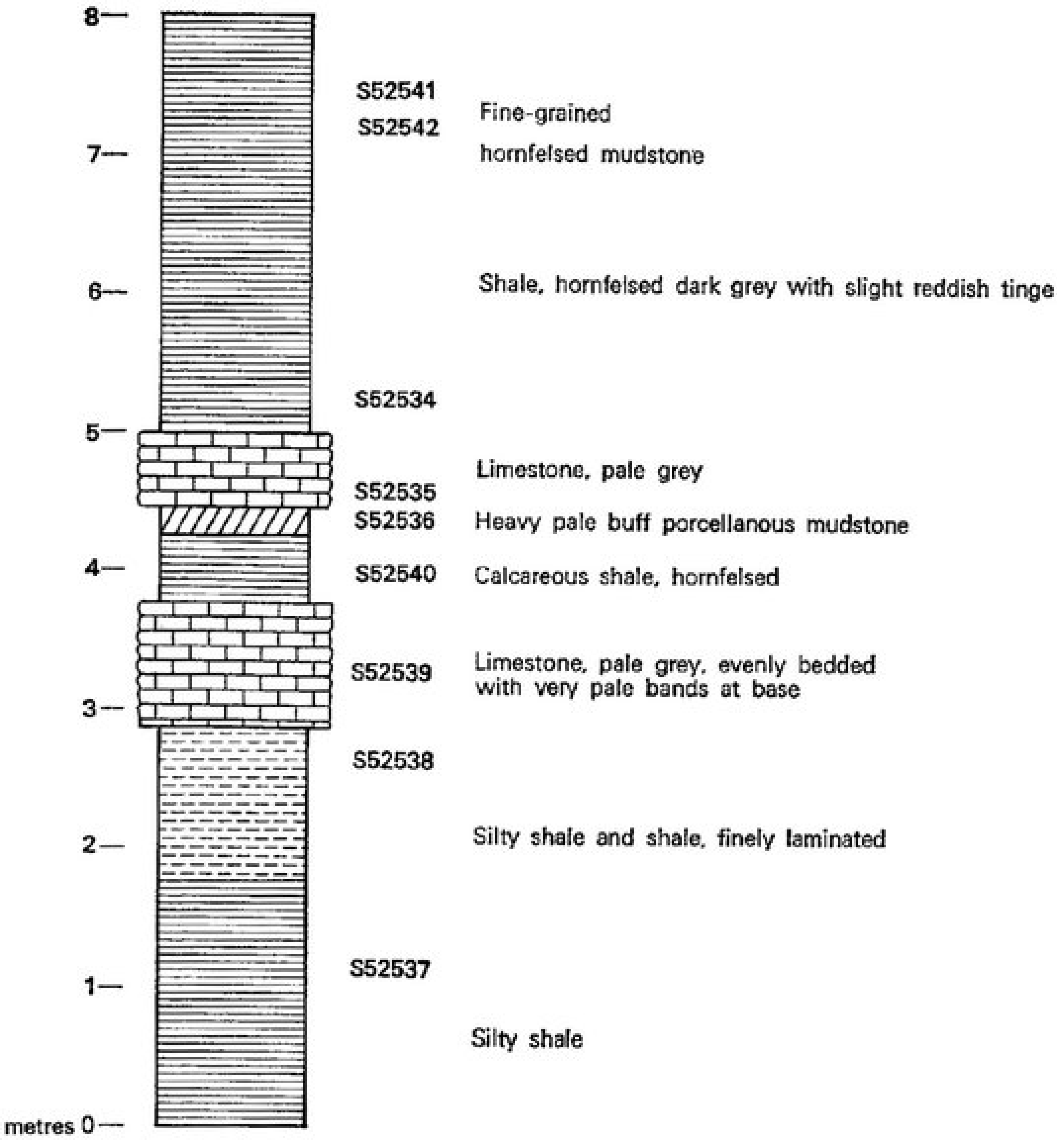
(Plate 14A) Fidlar Geo, south-west shore of Walls Peninsula [HU 190 494]. Thinly bedded siltstone and mudstone of Walls Formation, showing relationship of convolute lamination to cleavage. (D956).



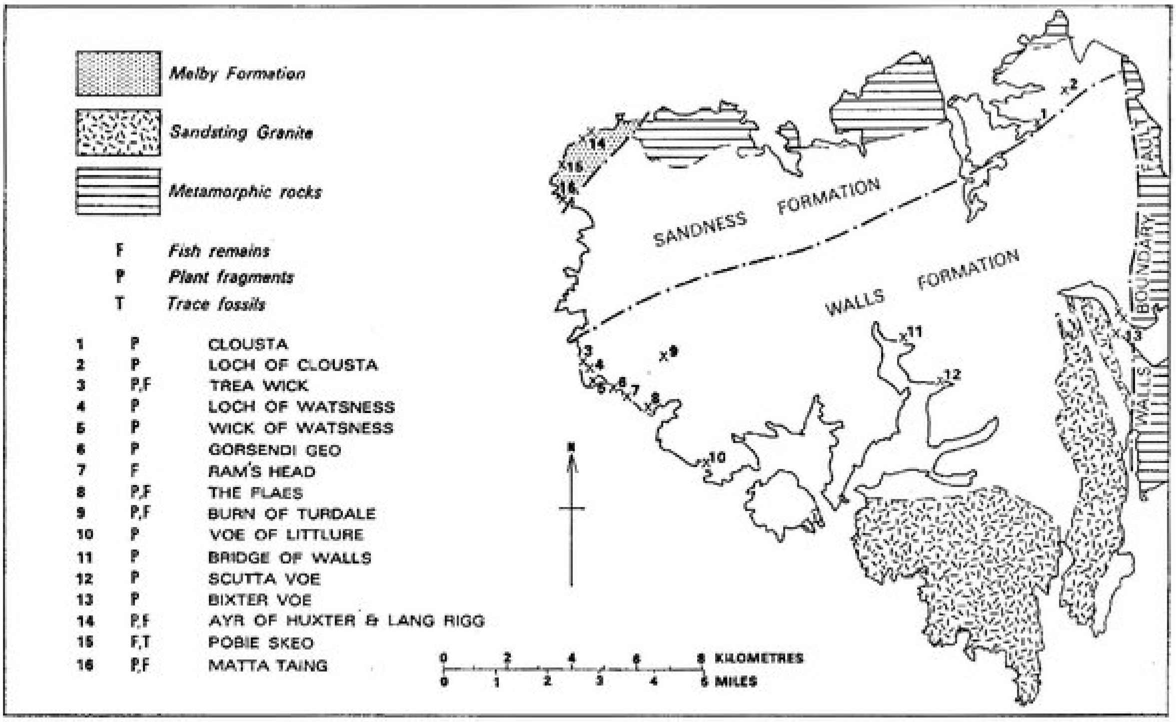
(Plate 14B) Fidlar Geo, south-west shore of Walls Peninsula [HU 190 494]. Thinly bedded siltstone and mudstone of Walls Formation, showing relationship of convolute lamination to cleavage. (W.M.).



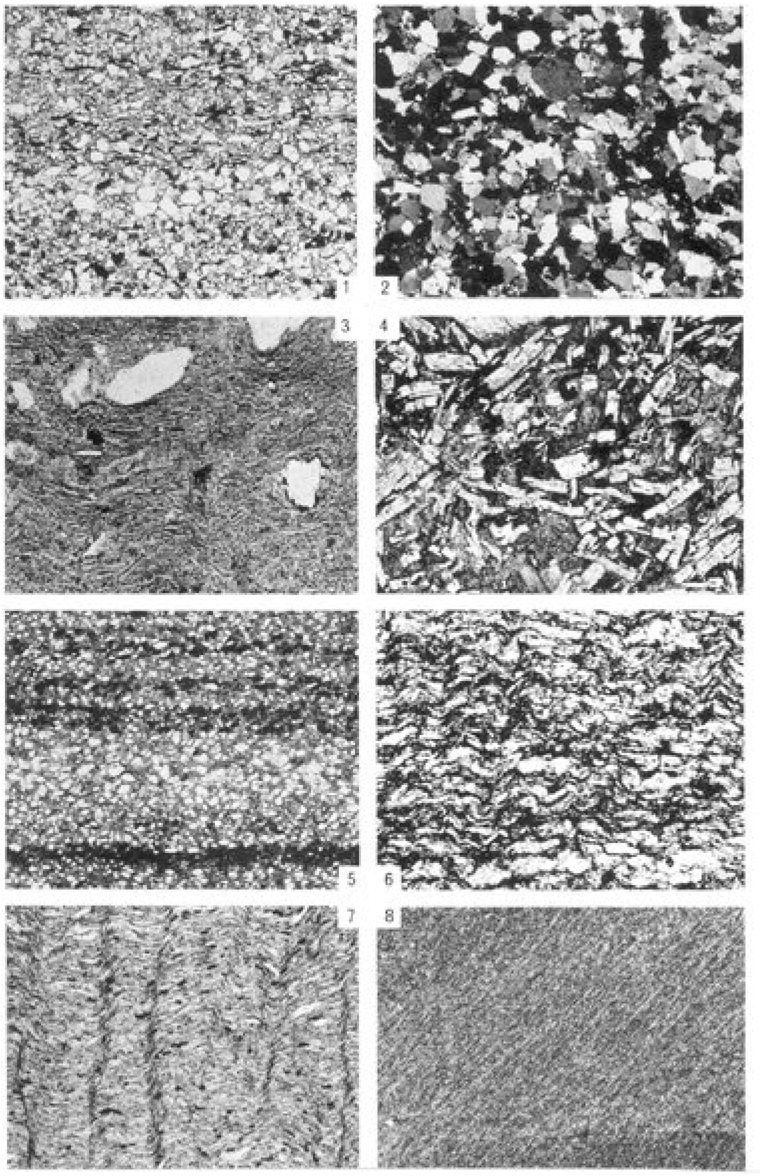
(Plate 14C) Fidlar Geo, south-west shore of Walls Peninsula [HU 190 494]. Thinly bedded siltstone and mudstone of Walls Formation, showing relationship of convolute lamination to cleavage. (W.M.).



(Figure 25) Hornfelsed limestones and associated calcareous shales, east coast of Voila [HU 242 464]. Mineral composition of specimens: (S52541) [HU 241 464] finely granular diopside, zoisite-clinozoisite, poikiloblasts of calcic *scapolite, acicular amphibole associated with zoisite; (S52542) [HU 241 464] finely poikiloblasts of calcic scapolite, acicular amphibole associated with zoisite; (S52542) [HU 241 464] finely granular dlopside, veins and patches of zoisite-clinozoisite; (S52534) [HU 241 464] cordierite poikiloblasts, calcic scapolite, veins of clinozoisite, calcite and actinolite; (S52535) [HU 241 464] calcite, calcic scapolite diopside; (S52536) [HU 241 464] poikilitic grossularite and idocrase, finely granular diopside, veins and patches of zoisite; (S52540) [HU 241 464] calcite, calcic scapolite, idocrase, amphibole, veins of calcite and zoisite; (S52539) [HU 241 464] calcite, poikiloblasts of grossularite with diopside grains, calcic scapolite, veins of calcite; (S52538) [HU 241 464] shale; amphibole laths and poikiloblasts. biotite, clinozoisite; siltstone: diopside amphibole, zoisite, calcic scapolite; (S52537) [HU 241 464] poikiloblasts of calcic scapolite with finely granular diopside, veinlets of clinozoisite.*



(Figure 11) Fossiliferous localities in the Old Red Sandstone of the Walls Peninsula.



(Plate 13) Photomicrographs of sedimentary and volcanic rocks of the Walls Sandstone Fig. 1. Slice No. (S52737) [HU 296 581]. Magnification × 20. Plane polarized light. Fine-grained flaggy sandstone, Sandness Formation, showing alternate quartz-feldspar and micaceous laminae. Scattered small grains of epidote throughout. West shore of Muckle Head. [HU 297 581]. Fig. 2. Slice No. (S52738) [HU 299 577]. Magnification × 20. Crossed polarisers. Medium-grained arkose, Sandness Formation. Well-graded subangular to subrounded grains. The ratio of quartz to feldspar grains is 60:40. Matrix forms less than 10 per cent of total volume and is composed predominantly of carbonate. North shore of Voe of Clousta, 1225 yd (1100 m) WNW of Clousta School. [HU 298 577]. Fig. 3. Slice No. (S49343) [HU 266 551]. Magnification × 40. Plane polarized light. Part of ignimbrite clast in lapilli-tuff in Clousta Volcanic Rocks, showing flattened and welded shards. Note the bending of shards around quartz clasts. Hillside, 710 yd (650 m) SW of western end of Loch Hollorin [HU 267 552]. Fig. 4. Slice No. (S30773) [HU 328 596]. Magnification × 38. Plane polarized light. Basalt flow in Clousta Volcanic Rocks. Flow-aligned laths of sodic labradorite set in matrix composed largely of secondary amphibole with subordinate grains of epidote and a dusting of iron ore. Aithness peninsula, 220 yd (200 m) SE from north-west corner of peninsula [HU 327 597]. Fig. 5. Slice No. (S51496) [HU 276 498]. Magnification × 16. Plane polarized light. Fine-grained feldspathic sandstone in Walls Formation with laminae of heavy mineral concentrates. Black grains are predominantly iron ore, other heavy mineral grains are apatite, sphene, epidote and tourmaline. North shore of Scutta Voe, 520 yd (475 m) WSW of Lee of Houlland [HU 275 498]. Fig. 6. Slice No. (S52748) [HU 317 564]. Magnification × 100. Plane polarized light. Microfolded sandy siltstone, Walls Formation. Roadside, close to west shore of Loch Vaara [HU 565 316]. Fig. 7. Slice No. (S53696) [HU 278 499]. Magnification × 100. Plane polarized light. Silty shale with F_1 slaty cleavage (horizontal) refolded by F_2 minor folds with incipient fracture cleavage developed along some fold limbs. Walls Formation. North shore of Scutta Voe, 520 yd (470 m) WSW of Lee of Houlland [HU 275 498]. Fig. 8. Slice No. (S53688) [HU 261 503]. Magnification × 100. Crossed polarisers. Microfolded dark grey shale with axial-planar strain-slip

cleavage inclined at 44° to bedding. West shore of Voe of Browland, 1620 yd (1480 m) S4°E of Browster [HU 261 503].