Chapter 7 Old Red Sandstone: Sandness Formation

Introduction

The exposed thickness of the sediments and contemporaneous volcanic rocks forming the Sandness Formation (Plate 9), (Plate 10) ranges from 4500 ft (1370 m) to nearly 7000 ft (2130 m) in the central and eastern parts of their outcrop, but thickens considerably to possibly 12 000 ft (3650 m) farther west. Over the greater part of their outcrop the strata dip consistently to south-south-east at angles ranging from 30° to vertical and they are locally inverted in the Clousta area. In the ground between the Voe of Snarraness and Sandness Hill the consistent south-south-easterly dip is interrupted by two east-north-east trending folds, the Djuba Water Syncline and the almost isoclinal Mousavord Loch Anticline (Plate 12).

A complete sequence through the Sandness Formation is available only in the area east of West Burra Firth, where the following sub-divisions, shown diagramatically in (Plate 10), have been recognized:

6. Alternating beds of fine-grained sand- stone, siltstone and calcareous mud-stone, with impersistent beds of argillaceous limestone.
5. These sediments are intercalated with the Clousta Volcanic Rocks (5), composed of basalt and basic andesite lavas, ignimbrites, thick beds of basic tuff and tuffaceous sandstone, and cones of acid agglomerate. Also concordant intrusions of felsite.
4. Sandstone, fine- to medium-grained, cross-bedded with pebbly beds near base. Some argillaceous intercalations.
3. Conglomerate, forming several lenses, possibly at slightly varying horizons (e.g. Clousta Conglomerate).
2. Sandstone, cross-bedded with scattered pebbles and subordinate argillaceous bands.
1. Basal beds of pebbly sandstone and grit with lenses of breccia.

Plant remains in sediments interbedded with the Clousta Volcanic Rocks appear to be of Lower or Middle Old Red Sandstone age. Whole rock potassium-argon age determinations of basalts by N. J. Snelling are as follows: Basalt lava, Ness of Clousta [HU 299 577] (KA ref 71/73), p.p.m. radiogenic ^{40}Ar = 0.075, Age 323 ± 9 m.y.; basalt lava, Ness of Clousta [HU 304 579] (KA ref 71/74), p.p.m. radiogenic ^{40}Ar = 0.063, Age 336 ± 9 m.y. Both these ages are too low when compared with the age based on the plant evidence. It is likely that the basalts suffered argon loss, possibly during the phase of uralitization which affected most basic lavas in the Sandness Formation (p. 94). Flinn and others (1968, p. 14) obtained a potassium-argon age of 255 ± 4 m.y. from rhyolite, just west of Burga Water [HU 225 543]. This date indicates that the rhyolite suffered argon loss at some later period.

Junction between sediments and metamorphic rocks

The junction between the Walls Sandstone and the metamorphic rocks which occupy the northern fringe of the Walls Peninsula was stated to be a major fault by both Peach and Horne (1879 p. 786, 1884 p. 365; *in* Tudor 1883 p. 395) and Finlay (1930 p. 673) but the officers of the Geological Survey who mapped the area between 1931 and 1934 (*in* Summ Prog. 1934; p. 73; 1935; p. 68) concluded that along the greater part of its course it is an unconformity locally obscured by small shear planes.

Along its western outcrop, between Sandness and the Bay of Brenwell (Plate 9), there are no good exposures of the contact of the two formations, but the curved nature of its outcrop, the presence of lenticular masses of sedimentary breccia at or near the junction, and the occurrence of thin but persistent beds of conglomerate at a constant vertical distance above it (Plate 10) suggest that it approximates closely to the original unconformity. In the ground [HU 208 568] 1 mile (1.6 km) W of the Bay of Brenwell there is a small outlier of breccia and sandstone which occupies an area of 110 yd (100 m) by 40 yd (36 m) and rests with a near-horizontal base on highly inclined metamorphic rocks (Plate 9). The outlier is approximately 250 yd (230 m) N of the outcrop of the main junction whose inclination in this area is approximately 50° to the south. The presence of this outlier suggests that the junction north of its present outcrop (i.e. above ground level) was undulating and in places very nearly horizontal and that it may have been stepped down northwards by faulting. Faults of this type are not easily recognized in the metamorphic terrain.

Another very small fault-bounded mass of indurated greenish sandstone is exposed on the east shore of the Geo of Bousta [HU 223 577] 800 yd (730 m) N of the nearest outcrop of Old Red Sandstone sediments (Figure 7). The presence of this faulted outlier supports the supposition that above the present western outcrops of the metamorphic rocks the original junction was displaced by a number of faults the throw of which may have been of the order of several hundred feet.

On the headland [HU 229 570] between the Bay of Brenwell and the Voe of Snarraness (Figure 7), where conglomerate with pebbles of metamorphic rock is underlain by at least 90 ft (27 m) of predominantly mudstone and siltstone (p. 76), the only well-exposed junctions between Old Red Sandstone and metamorphic rocks are two faults trending respectively W10°N and N30°W, which have produced a north-west trending graben of Old Red Sandstone sediments bounded by metamorphic rocks. On the shores of the Voe of Snarraness the junction is formed by a large fault inclined at 50°–55° to the south.

The junction is well exposed on the south shore of West Burra Firth [HU 242 569] between 300 and 420 yd (275 and 385 m) E of Snarra Ness. In this area it is formed by one of a series of sub-parallel faults trending roughly west-north-west and inclined at 50°–80° to the south. These faults cut both the metamorphic rocks and the sediments. The fault plane separating the two rock types is inclined at 68°–80° to S10°–15°W, which is steeper than the foliation of the gneiss (35°–40° to SSW) and the dip of the sandstone (55° to SSW). It forms a belt of fault clay only 1 to 6 in (2.5–15 cm) thick and has produced very little shattering in the adjoining rocks. The adjacent sub-parallel faults are, on average, 8 to 10 yd (7.3–9 m) apart, and form a series of step faults. The west-north-west trending faults are themselves cut by a suite of south-south-west trending faults, which in this area displace the former in a sinistral sense by distances ranging from 10 to 27 ft (3–8 m) thus giving the junction a stepped outcrop.

Farther east the boundary between the sandstone and the metamorphic rock is again exposed in the upper reaches of West Burra Firth, where it is a fault plane inclined at 62° to S10°W. On the east coast of West Burra Firth there is a 10-ft (3-m)-wide fault slice of sedimentary breccia along the faulted junction. This contains angular pebbles of metamorphic rock and appears to have been deposited near the base of the group, suggesting that here the displacement along the fault has not been large. Between 100 and 250 yd (90 and 230 m) E of West Burra Firth the boundary between the metamorphic rocks and the Old Red Sandstone basal conglomerate is undulating and may be a normal junction, but exposures are not sufficiently good to verify this. Farther east, between Longa Water [HU 265 570] and Brindister Voe, the junction is marked by a straight depression, suggesting that it is a fairly large fault (*in* Summ. Prog. 1935, p. 68). One exposure along this junction shows a band of hard mylonite 1 ft (30 cm) thick separating sandstone from gneiss.

In the area east of Brindister Voe the outcrop of the junction between sandstone and metamorphic rock is fairly undulating, suggesting that it may be an unconformity, but as in the areas farther west all exposures of the junction are to some extent sheared. Close to Vementry House the junction is near-vertical and locally inverted, and the overlying sediments contain a basal breccia several inches thick, passing upwards into a pebbly sandstone. On the west shore of the Stead of Aithness the junction is inclined at 30°–45° to the south-south-west, and shows no obvious sign of shearing. This exposure is the only one in the whole peninsula which can be classed as an unconformity not markedly affected by subsequent faulting, though in a number of the cases described above there is little doubt that faulting along the contact is of a minor nature and that the true base of the Sandness Group is not far below the lowest exposed beds.

On the island of Papa Little all junctions between metamorphic rocks and sediments appear to be faulted.

Sediments below the Clousta Volcanic Rocks

Lithology

Basal sediments (1 of (Plate 10))

In the eastern part of the area the basal sediment is a grey, medium-grained, poorly graded sandstone with small scattered pebbles of metamorphic rocks and some well-rounded quartz grains. The sequence contains rhythmic units composed of thick cosets of cross-bedded sandstone grading up into greenish siltstone or, less commonly, reddish mudstone. The fine-grained phases of the units are only up to 2 ft (60 cm) thick. Clasts of mudstone, now practically converted to slate, are present both at the bases and within the sandstone cosets.

The characteristic feature of the basal beds is the presence of thin lenticular bands of breccia. In the vicinity of South Loch of Hostigates [HU 313 593] breccia lenses occur 700 to 800 ft (215–245 m) above the lowest exposed sediments. Traced westwards towards Sonso Ness [HU 302 589] the breccias gradually approach the base of the formation. They contain angular to subangular fragments of gneiss and schist up to 1 in (2.5 cm) long and subangular to rounded clasts of vein quartz and their thickness nowhere exceeds 50 ft (15 m). Thin lenticular masses of breccia, conglomerate and pebbly sandstone occur at several localities farther west close to the base of the group (p. 73, (Plate 10)). In the sectors between Brindister Voe and Longa Water and between West Burra Firth and Snarra Ness, however, pebbly beds are completely absent, suggesting that in these areas some of the basal sediment has been cut out by faulting. Between these two sectors the conglomerate exposed close to the east shore of West Burra Firth reaches a thickness of 60 ft (18 m) and contains clasts of metamorphic rocks up to 1 ft (30 cm) in diameter set in a purple sandy matrix.

A sandstone with thick lenses of conglomerate containing pebbles of metamorphic rock up to 18 in (40 cm) in diameter, is exposed between the Bay of Brenwell and the Voe of Snarraness (Figure 7). This is underlain by at least 80 ft (24 m) of purple silty mudstone, siltstone and sandy siltstone with lenses of intraformational conglomerate and with some bands of calcareous sandstone.

In the area between the Bay of Brenwell and Sandness a thin basal breccia is exposed at intervals. This contains angular pebbles mainly of granite-gneiss and mica-schist set in a sandy matrix. It is overlain by reddish brown sandstone with many small angular pebbles of locally-derived metamorphic rock, and, somewhat higher in the sequence, with thin lenticular beds of intraformational conglomerate consisting of clasts of purple mudstone set in a sandy matrix. Approximately 130 ft (40 m) above the base of the sequence there is a 10-ft (3-m) bed of conglomerate, containing rounded to subrounded pebbles and cobbles up to 6 in (15 cm) in diameter of white and pinkish vein-quartz and a somewhat lower proportion of pale purplish quartzite. Locally derived metamorphic rocks are absent. This conglomerate appears to maintain its thickness and lithological character for a distance of over 1 mile (1.6 km) along the strike. Close to the horizon of the conglomerate an impersistent band of impure limestone closely comparable to a concretionary cornstone (Allen 1960, p. 45) is present within a sequence of pebble sandstones. Above the conglomerate thin impure limestones are present within beds of reddish purple shale, which locally reach a thickness of 2 ft (60 cm).

Conditions of deposition

In the eastern half of the area the basal sediments appear to have filled the valleys and depressions of an undulating metamorphic terrain. This is suggested by the apparently diachronous base of the sequence (Plate 10) and by the presence of thin breccias within its basal 1000 ft (300 m). The absence of very thick wedge-shaped breccias and fanglomerates suggests that the topography, though undulating, was not mountainous. The available data fit most closely with deposition in alluvial fans by braided streams, rather than by stream floods or sheet-floods. (Allen 1965, pp. 160–1.) The presence of rounded quartz grains could suggest considerable wind erosion within the source area.

In the western part of the area there is no evidence for an undulating base to the sequence and the presence of a thin but extensive sheet of conglomerate at a consistent height above the base (p. 73) suggests that the metamorphic terrain on which the first deposits were laid down was relatively flat. The basal sediments in this area are slightly finer grained than in the east. They contain more thin beds of shale, siltstone and limestone and have lenses of sandstone full of flakes of mudstone and siltstone. It is suggested that these sediments may be the flood-plain deposits of a river whose source was a considerable distance from the area of deposition.

Sedimentary structures indicative of the direction of transport during the deposition of the basal sediments have not been investigated, but the evidence from the overlying beds and the overall decrease of grain size of the beds in a west-south-westerly direction suggests that these beds may have been derived from a north-easterly source.

Sandstones and conglomerates below Clousta Volcanic Rocks (2 to 4 of (Plate 10))

In the area east of Brindister Voe the sediments between the basal beds and the Clousta Volcanic Rocks consist mainly of massive sandstone, with a lenticular conglomerate, up to 280 ft (85 m) thick, near the middle. West of Brindister Voe (Plate 9), however, the conglomerate is not present. Between Brindister Voe and Mousavord Loch the group appears to thicken rapidly westward and to consist largely of massive, cross-bedded sandstone. Still further west the cross-bedded sandstone in turn gives way to flaggy sandstone with thin silty and shaly partings.

Area east of Brindister Voe

The succession in this area contains the following four lithological groups, listed from base to top:

Sandstones with pebbly bands and thin shaly partings (thickness 900 to 1500 ft (275–450 m); 2a on (Plate 10)).

The arenaceous bands in this subdivision resemble those below the Loch of Hostigates breccia (p. 74), which is taken as the highest unit of the basal beds. The rocks are mainly grey or pinkish in colour and range from pebbly grit to a very fine-grained quartzitic sandstone. They are almost continuously exposed on the north shore of the North Voe of Clousta where thin beds of purplish shale or slate, which make up between 3 and 5 per cent of the total sequence, alternate with the arenaceous beds. Both the upper and lower junctions of the slates are sharp, and slate chips are present in the sandstones. Pebbles of granite and quartzite are scattered throughout the sandstones but they are not sufficiently concentrated to form conglomerates. One impersistent pebbly horizon can, however, be traced for some distance on either side of South Loch of Hostigates.

Beds with well-rounded sand grains have been recorded throughout the sequence and with them are associated wind-faceted pebbles, chiefly of white vein-quartz. There are, however, few dreikanter pebbles and when these are found their edges are usually rather rounded. This seems to indicate that the wind faceting took place before they were transported by water to their present position.

Much of the sandstone and perhaps more especially that with well-rounded grains, has a pinkish tinge. This is mainly due to the colour of the grains themselves which include pink and rose-coloured quartz, reddish feldspar and pink felsite. In other beds there is a greenish tinge due to the presence of interstitial chloritic matter.

There is at least one locality on the northern slope of the North Voe of Clousta where tuffaceous sandstone is present, thus anticipating the volcanic rocks which are well developed higher in the sequence.

Medium-grained cross-bedded sandstones (thickness 500 to 800 ft (150–240 m), 2b on (Plate 10)).

The pebbly sandstone with shaly or slaty partings passes upwards into more massive strongly cross-bedded sandstone with even thinner shaly partings. This sandstone is grey to pink, medium-grained, usually rich in muscovite, and forms cosets up to 5 ft (1.5 m) thick, separated by thin beds (up to 4 in (10 cm)) of grey siltstone and silty mudstone.

On the shores of Muckle Head [HU 297 582] which forms the headland between the North and South Voes of Clousta (Plate 9), the sandstone is trough-crossbedded with individual troughs up to 3 ft 6 in (1 m) deep. The predominant trend of the troughs is north-north-east and the dip of foresets along the trough axes to the south-south-west. Many troughs have been affected by penecontemporaneous deformation which has resulted in the steepening and local overturning of their north-eastern or, in some cases, north-western slopes. The tops of the overturned troughs are usually truncated by planar erosion surfaces. Within this sequence some thinly bedded fine-grained sandstones with small-scale cross-stratification show convolute lamination. The sandstones with disturbed bedding underlie the Muckle Head Tuff (see below) and it is likely that earth tremors preceding its eruption were responsible for the deformation of the unconsolidated sediment (cf. Jones 1962, p. 238). Near the top of the sequence the sandstone becomes coarser and small subangular pebbles, up to 0.75 in (2 cm) in diameter, composed almost invariably of felsite, become common. There are also thin lenses of conglomerate with pebbles, mainly of quartzite and felsite up to 1.5 in (4 cm) in diameter.

Muckle Head is formed from a lenticular mass of basaltic lapilli-tuff (possibly originally a volcanic cone) which has a maximum recorded thickness of 120 ft (36 m). The length of its present outcrop, on land, is 400 yd (360 m). In the lower part of the mass lenses of tuff are intercalated with beds of sandstone and conglomerate containing small subrounded pebbles of white and pinkish feldspar, quartz, felsite, microgranite and some deep red jasper. Certain conglomerate bands contain small pebbles of greenish siltstone, and in many bands the pebbles are set in a deep green clayey matrix (p. 82). The lowest tuffs contain irregular lapilli of altered glassy, vesicular basalt, which in many cases enclose small quartz grains. The presence of these grains suggests that the lava may have fallen into the unconsolidated ash as fluid droplets. The quartz grains could also have been picked up by the magma on its way up the vent. The basalt lapilli do not normally exceed 0.5 in (1 cm) in diameter though larger fragments up to 2 in (5 cm) long have been recorded. The tuff also contains grains of quartz, feldspar, garnet, epidote and sphene (p. 82), some of which are well rounded. Fragments of quartz, feldspar and felsite become progressively less common near the top of the tuff cone. The matrix of the tuff is hard, argillaceous, dark green in colour and full of very small quartz grains.

Clousta Conglomerate (3 on (Plate 10)).

A thick band of conglomerate and pebbly grit can be traced as a fault-stepped outcrop from the shore south of Muckle Head eastwards for about 2 miles (3.2 km) almost to the Stead of Aithness (Plate 9). It attains a maximum thickness of 140 ft (43 m) and is composed of subrounded to subangular pebbles of vein-quartz, pinkish quartzite, felsite, granite and quartz-porphyry set in a sandy matrix. There are also some clasts of shale and siltstone. A high proportion of the coarser sand grains are composed of pink feldspar derived from granite and felsite. The pebbles average 1.5 in (3.2 cm) in diameter but may exceptionally reach 5 in (12 cm). They show no indication of sand blasting but the interstitial sand grains are in many cases well rounded.

The conglomerate contains a high proportion of unstable clasts which are readily destroyed by chemical and mechanical weathering (see Pettijohn 1957, pp. 254–5). It has abundant pebbles of granite, felsite and quartz-porphyry, which are comparable with the Vementry Granite and its associated minor intrusions (pp. 207–9). Apart from felsites, pebbles of acid igneous rocks are absent in the underlying sediments. As none of the north-north-east trending quartz-porphyry and porphyry dykes associated with the Vementry Granite cut the Old Red Sandstone sediments (Plate 24) it is thought likely that the intrusion of the Vementry Granite antedates the deposition of the Sandness Formation. The deposition of the Clousta Conglomerate may thus mark the stage at which the Vementry Granite or a similar late-Caledonian granite mass became uncovered by erosion in the source area.

On the Ness of Nounsbrough [HU 294 574] there is a lenticular mass of conglomerate which is probably on a slightly higher horizon than the Clousta Conglomerate but has a similar pebble content. It attains a maximum thickness of about 100 ft (30 m) and contains, in the southern part of its outcrop, a proportion of tuffaceous material. Traced southward along the strike the conglomerate and interbedded pebbly sandstone give place to a series of acid lavas and tuffaceous sediments. The lavas are described on pp. 85 and 96.

Cross-bedded sandstone between Clousta Conglomerate and Clousta Basalt (4a in (Plate 10)).

The sediment between the Clousta Conglomerate and Clousta Basalt is mainly composed of thick medium- to coarse-grained, locally pebbly, sandstone with large-scale, mainly planar cross-stratification and with a predominant dip of foresets to south-south-east. Disturbed cross-bedding similar in type to that seen on Muckle Head (p. 78) is common.

At Aithness, in the extreme east of the area (p. 85) and on the east shore of Clousta Voe thin flows of basalt are interbedded with the sandstone. These are the lowest exposed flows of basic lava within the Sandness Group. Immediately below the Clousta Basalt there are a number of thin beds of tuffaceous sandstone containing a high proportion of basaltic detritus.

Area west of Brindister Voe

In the ground extending from Brindister Voe to the west coast of the Walls Peninsula it has not been found possible to recognize the subdivisions established further east. Conglomerates are absent and the scattered pebbles within the sediments are composed mainly of siltstone and mudstone of Old Red Sandstone type. The salient features of the sediments in the western area are (1) a gradual westward thickening from approximately 2700 ft (820 m) near Brindister Voe to 4000 ft (1220 m) at the longitude of Mousavord Loch and thence a more pronounced westward thickening to possibly 9000 ft (2750 m) at the longitude of Sandness Hill, and (2) the presence of a thick series of massive cross-bedded sandstones with virtually no intervening argillaceous beds. This series forms the rugged, hilly terrain which extends from Brindister Voe westward as far as Mousavord Loch and is up to 2500 ft (760 m) thick. Further west the sandstones become progressively more flaggy and micaceous, with much thinner cross-bedded sets and some shaly and silty partings.

Cross-bedded sandstones (eastern facies)

East of Mousavord Loch the series consists predominantly of grey to buff-coloured medium- to fine-grained sandstone. It contains beds of flaggy fine-grained micaceous sandstone which have alternate pale and dark grey bands with high concentrations of heavy minerals in the latter (p. 82). Siltstone bands are virtually absent in the lower and middle parts of the sequence.

Cross-bedded sets are up to 4 ft (1.2 m) thick and a high proportion of the foresets had an original sedimentary dip to between south and south-west. Disturbed and slumped cross-bedding is seen at a number of horizons north-east of Sulma Water, the most common structures being tight-crested anticlines overturned to the south-south-west. Intraformational conglomerates with shale and siltstone clasts are present throughout the sequence, but pebbles of metamorphic or igneous rock are very rare.

Flaggy sandstone with siltstone partings (western facies)

The westward transition from massive sandstone with predominantly large-scale cross-stratification to flaggy sandstone with subordinate siltstone bands takes place at approximately the longitude of Burga Water, but thick sets of massive, often cross-bedded and sometimes pebbly, sandstones have been recorded west of this line, particularly in the lower part of the sequence. Flaggy sandstones with subordinate trough-and planar-cross-bedded sets form the entire sequence exposed on the west shore of the Walls Peninsula between the north shore of the Bay of Deepdale and the Voe of Dale (Plate 9).

The most common rock type in this sequence is a hard fine-grained grey, greenish grey, pinkish, brown or locally purple, somewhat micaceous quartzose sandstone. This forms cosets ranging from 2 to 10 ft (60 cm-3 m) in thickness. The cosets are generally planar-bedded but there is a fair proportion of sets with both planar- and trough-cross-stratification. Disturbed cross-bedding has also been recorded. Many foresets in the cross-stratified sets dip to the south and south-east. The alignment of troughs suggests current movement from north-west to south-east. In the upper part of the sequence there are bands of medium-grained sandstone with small isolated pebbles of felsite and vein quartz. Some bands are slightly tuffaceous.

The beds of siltstone and fine-grained sandstone separating the sandstone cosets are up to 18 in (45 cm) thick, but in many cases much thinner. They are greenish grey to deep purple in colour. Many are tectonically deformed with microfolds, incipient cleavage and, in places, a vague lineation. Sedimentary structures are largely obliterated, but in the lower part of the exposed section (in the Bay of Deepdale) straight asymmetrical ripple-marks and sand-filled polygonal sun-cracks are common.

Petrography

Though pebbly sandstones, conglomerates and breccias form an appreciable proportion of the sediments below the volcanic horizon, 80 to 90 per cent of the total rock is grey to buff, medium- to fine-grained sandstone with micaceous partings and with some thin dark laminae containing concentrations of heavy minerals.

The arenaceous rocks have the following characteristics:

Grain size

The specimens examined are poorly to very poorly graded and have an extreme range in grain size from 0.9 to 0.03 mm

Shape of grains

The grains of the sandstone are normally subrounded to subangular ((Plate 13), fig. 1), but in some sandstones in the extreme west they are angular. The smaller grains are generally more angular than the larger ones and the feldspars are more angular than the quartzes, but in one specimen (S52736) [HU 307 583] the feldspar grains are more rounded than the quartz. Highly rounded grains, which may have been rounded by wind in the source area, have only been recorded in the basal sandstones at Sonso Ness [HU 297 587] and along the south shore of North Voe of Clousta (S49334) [HU 298 579]. Many grains are strongly elongated, with the long axes mostly parallel to bedding, but in some instances there is a marked imbrication, with the long axes inclined at 20°–30° to the bedding.

Many quartz and feldspar grains have serrate margins due to the ingrowth of white mica and, less commonly, chlorite. The thin sections provide evidence for varying degrees of induration, such as frilling of grain boundaries, the partial resorption of margins of adjoining quartz grains (S49334) [HU 298 579] and the development of authigenic sericite.

Composition of grains

All specimens examined have a relatively high proportion of feldspar grains and the ratio of quartz to feldspar clasts within the group ranges from 80:20 to 50:50 with a slight increase of the mean ratio from 65:35 in the eastern sector to 75:25 in the central and western sectors of the outcrop. This suggests a westward increase in the maturity of the sediment or a difference in the source areas. In many cases there is a marked difference in the proportions of quartz to feldspar in adjacent laminae, with a higher proportion of feldspar in the coarser laminae.

Quartz

The quartz grains of the medium- to fine-grained sandstone are in all cases devoid of strain shadows and cracks. Small liquid inclusions of the kind found in the quartz of the Sandsting Granite are absent, and solid inclusions are rare. In one specimen (S30914) [HU 252 558] the quartz grains contain inclusions of rutile. Though the authigenic ingrowth of sericite and chlorite fibres into quartz grains is common in many specimens, the complete replacement of quartz is rare. In one specimen (S30874) [HU 232 546] some quartz grains are partially replaced by carbonate.

Feldspar

Several distinct varieties of feldspar are present in varying proportions in nearly all thin sections. They are, in order of abundance:

1. Untwinned potash feldspar, generally clear or slightly cloudy, less commonly completely sericitized. In some specimens the feldspar shows rudimentary perthitic texture.
2. Plagioclase, fresh or slightly cloudy. The grains are somewhat smaller in size than the average grain size of the rock. Most plagioclase grains are oligoclase-andesine, though in one specimen albite-oligoclase has been recorded.
3. Microcline, generally fresh, less often slightly cloudy. Common in most slides but absent in some.
4. Microperthite, usually fresh.

The composition of the feldspar grains indicates that they could have been derived either from a granite-granodiorite complex or from metamorphic terrain. There appears to be some regional and stratigraphical variation in the relative abundance of the various types of feldspar grains, of particular note being the westward disappearance of plagioclase clasts. With the exception of two specimens (S30905) [HU 235 554], (S30914) [HU 252 558] the percentage of plagioclase is less than that of potash feldspar throughout the area and in the extreme west plagioclase is absent in all but the highest horizons.

Other minerals

Scattered flakes of faintly pleochroic pale green to colourless muscovite commonly about 0.3 mm long are present in most sections. In the micaceous partings of the sandstone both muscovite and biotite are abundant.

Heavy mineral grains form up to 15 per cent of the total volume of grains in the dark laminae, which are in some cases up to 4 mm thick and are present throughout the sequence. They also occur as scattered grains, forming up to about 2 per cent of the total volume in many thin sections of the unlaminated sandstone, but are completely absent in others. The heavy mineral grains include, in approximate order of abundance, epidote, opaque minerals (ilmenite partly altered to leucoxene, hematite, pyrites and magnetite), sphene, apatite, allanite and tourmaline. Grains of garnet, which are present higher in the sequence (p. 99) have not been recorded. Epidote is extremely common in the dark laminae and common in the micaceous partings, but, in contrast to the sediments higher in the sequence (p. 99), it is virtually absent in the unlaminated grey fine- to medium-grained sandstones. Sphene and apatite are abundant in the dark heavy mineral laminae and in the micaceous partings, and they are also present in the unlaminated sediment.

Lithic clasts

Grains, ranging from 0.5 to 0.2 mm in diameter, of porphyritic felsite, basalt and andesite are abundant in the higher parts of the sequence, particularly in sediments associated with or adjacent to tuff and agglomerate lenses. In some bands (pp. 77–78) lava clasts form 10 to 30 per cent of the total volume. A number of thin sections of sandstone with igneous clasts also contain scattered grains with a small-scale mosaic texture which may be quartzite or silicified felsite.

Matrix and cement

The matrix of the sediments below the volcanic rocks forms between 15 and 25 per cent of the total volume of the rock. Two kinds of material can be distinguished in the matrix:

1. Authigenic chlorite and clay-mica which enclose the grains in a thin film, on average about 0.15 mm thick, and which in some cases penetrate into the quartz and feldspar.
2. Interstitial patches of carbonate, and more rarely, cryptocrystalline quartz. In some sliced rocks the interstitial carbonate is associated with finely disseminated mica (S30874) [HU 232 546], (S30918) [HU 254 565]. The carbonate is usually coarsely crystalline, indicating that it formed as a chemical cement, but in several sections finely granular carbonate, which may be of detrital origin, is also present. In one thin section (S30905) [HU 235 554] the rock contains over 30 per cent of matrix, some of which has clearly been formed by the alteration of feldspar grains.

Nomenclature

According to the classification of Pettijohn (1957, p. 291) feldspathic sandstones containing over 15 per cent of detrital matrix are termed feldspathic greywacke. In the case of these sediments, however, a proportion at least of the matrix is calcareous cement and of the rest a substantial part appears to be due to partial authigenic replacement of the mineral grains. It is therefore considered that the majority of specimens in this group are true arkoses. Some rocks contain an exceptionally high proportion of lava clasts, most of which may have been deposited directly as volcanic fall-out. These rocks are most aptly termed tuffaceous arkoses rather than subgreywackes, which would be the case if the clasts and detrital matrix had been incorporated through the erosion of nearby volcanic rocks.

Conditions of deposition

The main features of the strata between the basal beds and the volcanic rocks are as follows:

1. The westward transition from pebbly, strongly cross-bedded sandstone and conglomerate full of detritus of local origin, firstly to fine- to medium-grained cross-bedded sandstone with no extraformational conglomerates and only very rare siltstone partings, and then to flaggy sandstones with thin siltstone partings.
2. The relatively uniform direction of dips of foresets and trends of cross-bedding troughs indicating current movement from the north to north-east sector, though in the extreme west there is some evidence of current movement from the north-west.

3. The marked south-westward increase in the total thickness of sediment.

In the area east of Brindister Voe the beds contain a high proportion of coarse, apparently locally derived, readily weathered components which are generally fresh, and only a small proportion of sediment of shale or silt grade. Deposition probably took place close to the source area, probably at least in part, within alluvial fans. The character of the sandstone in the area between Brindister Voe and Mousavord Loch implies deposition by braided or straight rivers which did not have access to locally derived coarse detritus. The western, relatively flaggy, facies with its many thin grey and purplish siltstones, some with sun-cracks and ripple-marks, suggests deposition by rivers on a more extensive flood plain on which both channel and overbank deposits were preserved.

Clousta Volcanic Rocks and associated sediments

Introduction

Though the first local manifestations of volcanism within the Sandness Formation appear fairly low in the sequence, the bulk of the Clousta Volcanic Rocks are confined to the upper half of the formation (Plate 10). The lavas and tuffs form single flows or cones which, in many instances, are completely enclosed in sediment. The volcanic rocks belong to the calc-alkaline suite and are comparable with the Lower Old Red Sandstone extrusive rocks of Central Scotland.

The following extrusive rocks are present:

Basic and sub-basic lavas

These flows range in composition from pyroxeneandesite (p. 92) to basalt (p. 93). They usually form single highly vesicular flows, either closely associated with basaltic tuff, or entirely enclosed in sediment. East of Brindister Voe, individual flows range in thickness up to 200 ft (60 m) and have a maximum length of outcrop of 1.5 miles (2.4 km). Between Brindister Voe and Sulma Water up to three flows with a total thickness of about 600 ft (180 m) are locally present. West of Sulma Water basic lavas are thin and impersistent, and only two outcrops of thin flows have been recorded west of the longitude of Mousavord Loch (p. 91).

Ignimbrites and acid lavas

A number of flows of ignimbrite are present in the Ness of Nounsbrough (Plate 9). They range in thickness from over 100 ft (30 in) to less than 10 ft (3 m). The thinner flows are intercalated with thin flows of altered basic andesite or basalt and with coarse acid tuffs. It is possible that some of the thin concordant acid bodies within the Sandness Formation are true rhyolite lava flows. One example is the thin sheet of fine-grained 'rhyolite' which crops out between Burga Water and Upperdale [HU 196 531], in the western part of the area.

Basic tuffs and agglomerates

Coarse tuff and agglomerate which contains a higher proportion of basic than acid detritus forms a number of flat 'cones' which are interbedded with basic lava in the area between Galta Water and Brindister Voe. Fairly thick beds of lithic tuff with clasts of both basic and acid lava, set in a matrix with a vitroclastic texture, crop out just west of Brindister Voe and one such bed is exposed on the south shore of the Voe of Dale, in the extreme west of the area.

Acid lapilli-tuffs and agglomerates

These form two lenticular masses, probably originally cones, at least 1300 ft (390 m) thick, at Clousta and Aithness, in the eastern part of the area. A much flatter lenticular mass of acid tuff is present in the western part of the area between Burga Water and Upper Dale. Ignimbrite clasts are abundant in the coarse tuffs exposed between Sulma Water and Brindister Voe.

In addition to contemporaneous lavas and pyroclastic rocks, the Sandness Formation contains a number of roughly concordant intrusions of porphyritic felsite. The lenticular mass of felsite forming Smith's Hamar [HU 252 548] just west of

Sulma Water reaches a thickness of approximately 1400 ft (425 m) and the sill cropping out on the north shore of Voe of Dale attains possibly 500 ft (150 m). A number of felsite masses, like that cropping out on the west shore of UM Firth, are strongly discordant. Many of the smaller felsite bodies are highly irregular in shape suggesting that they were intruded into loosely consolidated ashes and sediments.

Area east of Brindister Voe

Volcanic rocks and intrusions

Clousta Basalt

The Clousta Basalt is the largest and most extensive flow of basic lava in the area east of Brindister Voe. Its outcrop forms the backbone of a prominent fault-stepped ridge which extends eastwards from the north shore of the Voe of Clousta to the west shore of the Loch of Clousta. The outcrop can be traced further east-north-eastward through a string of small islands in this loch.

The basalt is approximately 200 ft (60 m) thick between the western shore of the Loch of Clousta and the central part of its outcrop, but thins westwards to about 100 ft (30 m) on the shore of the Voe of Clousta and has not been found on the Ness of Nounsbrough. Near the western end of its outcrop the basalt is underlain by a thin bed of basic tuff but farther east it rests directly on sandstone which only locally contains small fragments of volcanic detritus.

Throughout the length of its outcrop the Clousta Basalt appears to consist of only one flow. It is usually vesicular throughout, even where its thickness approaches 200 ft (60 m). Its base contains well-developed pipe amygdales which are well seen on the north slope of the ridge, 720 yds (660 m) NNW of Clousta School. The top of the flow is in many places highly scoriaceous and usually has hollows and cracks filled with sand from above. It is best exposed at Little Head [HU 297 576] on the north shore of the Voe of Clousta, where the top of the basalt is seen to be highly irregular with elongate bulbous protrusions aligned roughly east–west. The basalt is here overlain by 2 to 3 ft (60–90 cm) of purple mudstone which is full of large elongate vesicles. This is, in turn, overlain by up to 4 ft (1.2 m) of well-bedded reddish purple siltstone. The presence of vesicles in the mudstone suggests that in this area the basalt was either intruded into thin unconsolidated mud or that it was covered by mud immediately after its intrusion, before all volatiles had escaped. As neither mudstone nor siltstone shows signs of marked induration, the latter explanation seems more likely.

Aithness and Papa Little basalts

Three bands of vesicular basalt are present in the Aithness peninsula. The lowest of these is interbedded with massive cross-bedded sandstone and crops out near the north shore of Aithness. It can be traced for about 850 yd (770 m) along the strike from the head of the Stead of Aithness to The Rona, and may originally have been continuous with the basalt lava which traverses the island of Papa Little from its south-west shore north-north-eastward to the Walls Boundary Fault. In Aithness the flow is approximately 50 ft (15 m) thick at the south-western end of its outcrop, but thickens to about 100 ft (30 m) on the north-east shore of Aithness. In Papa Little it appears to be up to 150 ft (30 m) thick at the coast and is possibly thicker inland. Both the Aithness and Papa Little basalts are vesicular throughout. The latter is intensely sheared and amphibolized in the vicinity of the Walls Boundary Fault.

The higher basalts of Aithness are intercalated with agglomerate and tuff (pp. 85–86) but, though both are vesicular, only one appears to be a true lava flow. The other, thinner, bed which is exposed at intervals for 300 yd (280 m) seems to cut across the bedding planes of the tuffs and associated sandstones. The field characteristics suggest that it formed an intrusive sheet, probably in loosely consolidated country rock.

Ness of Nounsbrough Ignimbrites and Basic Lavas

The Ness of Nounsbrough contains a number of concordant sheets of fine-grained acid rock, which form several strong topographic features. The lower features exposed in the northern part of the peninsula appear to be sills of porphyritic felsite (p. 86). The coast section on the east shore of Brindister Voe, both north and south of the Head of Lahamar [HU 287 564], contains four large and several smaller flows of pink to purplish ignimbrite, which bear a superficial resemblance to sills of highly porphyritic felsite, but are quite distinctive in thin section (p. 96). The lowest ignimbrite flow, which crops out on the coast 250 yd (230 m) N of the Head of Lahamar, is approximately 30 ft (9 m) thick and is separated from the Head of Lahamar ignimbrites by approximately 180 ft (55 m) of tuffaceous sediment with lenses of tuff. The Head of Lahamar is formed of three flows of ignimbrite, one of which is over 130 ft (40 m) thick, separated by thin beds of finely banded tuff and purple slate with lenses of limestone. Two further thin flows of ignimbrite, interbedded with acid lapilli-tuff and with four flows of basalt or andesite, crop out on the east shore of Uni Firth, some 450 ft (140 m) higher in the sequence. The basic lava flows average 30 ft (9 m) in thickness and have markedly vesicular tops and bases.

Both the ignimbrite and lava flows described above thin out in a north-easterly direction. The ignimbrite forming the Head of Lahamar thins very gradually and can be traced inland for a distance of 750 yd (700 m). All interdigitate northeastward with the agglomerates and lapilli-tuffs of the Clousta area.

Lapilli-tuffs of Clousta and Aithness

The lenticular outcrop of lapilli-tuff, agglomerate and lavas, which extends from the east shore of Uni Firth to the south shore of Clousta Voe, is here termed the Clousta Tuff. It attains a maximum exposed thickness of possibly 1300 ft (400 m) and is exposed in numerous rocky knolls south of the Voe of Clousta and on the east shore of Uni Firth. The 'tuff' is well bedded and composed of roughly alternating layers of coarse lapillituff and medium- to coarse-grained sandstone, in places with thin partings of buff or purple siltstone. The clasts in the lapilli-tuff normally range from 0.25 to 1.5 in (6 mm-4 cm) in diameter but there are isolated angular blocks up to 18 in (45 cm) in size. Many of the fragments consist of pink sparsely porphyritic felsite and ignimbrite. Clasts of dark purple basalt or andesite are less common. In some exposures however the latter predominate over felsite.

The Aithness Tuff also reaches a maximum exposed thickness of 1300 ft (400 m) and its outcrop extends from the Loch of Clousta north-eastwards to The Rona. It consists of acid lapilli-tuff with lenticular masses of agglomerate, which grades downwards into sandstone with thin beds of acid tuff. The composition of clasts is similar to that in the Clousta Tuff.

Relatively short impersistent flows of basic lava are present both in the Clousta and Aithness tuffs (pp. 85 and 94.)

Felsites

Sheets of felsite with feldspar phenocrysts are fairly common within the Clousta Tuff just south of the Voe of Clousta. Some of these are much brecciated and seem to grade into beds of tuff. Felsites with obscure field relationships appear to be interbedded with the coarse Aithness Tuff on the east shore of the Loch of Clousta. Elsewhere they show distinctly intrusive and transgressive features often with highly irregular margins. These characters suggest that intrusion took place under very shallow cover in loose ash.

Sediments intercalated with and overlying the volcanic rocks

The rocks overlying the horizon of the Clousta Basalt are extremely variable when traced along the strike. At the Ness of Nounsbrough and the Stead of Aithness, they are composed largely of pyroclastic and extrusive rocks (p. 85) but between these two areas the basalt is overlain by up to 2000 ft (650 m) of essentially non-tuffaceous sediment.

The lower 400 to 600 ft (120–180 m) of this sediment (4b in (Plate 10)) is mainly massive medium- to fine-grained sandstone composed of thick sets with large-scale cross-stratification. Foresets of the planar cross-bedded sandstone dip, in the majority of cases, to the south to south-south-west sector. Small-scale disturbed cross-bedding is common near the base. The sandstone has a limited lateral extent, being confined to the same length of outcrop as the basalt.

The upper 1500 ft (460 m) of sediment (6 in (Plate 10)) consists of flaggy sandstones interbedded with shales and siltstones containing thin irregular sandstone ribs. The section of these strata and some of the underlying beds, as seen on the north shore of Clousta Voe, between 350 and 680 yd (320 and 620 m) W of Clousta School [HU 308 573] is shown in (Figure 8)a. This sequence shows the following features:

1. The units composed predominantly of sandstone range in thickness from 3 to 25 ft (0.91–7.6 m). They are usually flaggy with planar-bedding and contain partings of purple or purplish grey siltstone or shale which are up to 3 in (7.6 cm) thick and 1 to 4 ft (0.3–12 m) apart. The upper surfaces of the sandstone ribs often have straight asymmetric ripple marks and both sandstone and siltstone are locally ripple-laminated. Desiccation polygons with sand-filled cracks are very common in the shale layers. Intraformational conglomerates are, however, absent.
2. Units composed of purplish shale, silty shale and siltstone with thin, often irregular, ribs of fine-grained sandstone range in thickness from 2 to 30 ft (60 cm-9 m). The total thickness of shale and siltstone usually exceeds that of the sandstone ribs which are from 1 in (2.5 cm) to, exceptionally, 2 ft 6 in (76 cm) thick. Ripplecross-lamination is present in both sandstone and siltstone. Straight asymmetric ripple marks are seen on bedding surfaces, though the primary structures in the finer sediments are partially obscured by tectonic crinkling associated with a fracture-cleavage. Desiccation cracks are less common than in the siltstone partings within the flaggy sandstone. Penecontemporaneous disturbed lamination is seen at a number of horizons. True convolute lamination with the characteristic sharp-crested 'anticlines' and basin-shaped 'synclines' (p. 107) is absent, and the characteristic structures are overturned folds with local rupture and small-scale thrusting in the sandy laminae. This type of convolution is considered to be the result of true slumping (down-slope movement) triggered off by earthquake tremors associated with the contemporaneous volcanicity. Pseudonodules (ball and pillow structure) are seen in one bed of purplish silty mudstone with irregular sandy ribs.

The beds of this group become progressively more tuffaceous as they are traced eastwards towards Aith Ness. Close to the Aith Ness Tuff a high proportion of the sediment consists of mudstone and siltstone, now highly indurated and partially altered to slate. Slates are particularly well exposed on the east shore of the Loch of Clousta. The westward transition of the fine-grained sediments into the Clousta Tuff is not exposed.

The sediments overlying the Clousta Tuff are best seen along the north-west shore of Mo Wick [HU 293 562] where they consist largely of black and greenish siltstone and shale, as is shown in the following section:

—	feet	(metres)
Sandstone, medium- to fine-grained, intensely jointed	—	—
Silty shale, purplish, cut by close-set corrugated joints	30 to 35	9–10.5
Sandstone, hard, with small pebbles of felsite		
Shale, black, cherty, with numerous small quartz veinlets	2	0.6
Sandy siltstone, well banded, composed of alternating silty and sandy laminae 0.5 to 0.75 in (12.5–20 mm) thick, small tectonic corrugations and recumbent folds (wavelength = 1.5 in–4 cm)	30	9
Shale and silty shale, greenish, strongly corrugated into small folds with angular crests	9	2.7
Siltstone and shale with sandy ribs. Small-scale folds particularly pronounced in upper 10 ft (3 m) but developed in argillaceous layers throughout	125	38

Alternating bands of sandstone and siltstone with ripple-cross-lamination and small-scale disturbed lamination in sandy beds; passing down into grey siltstone with shale ribs. Minor tectonic corrugations in the shale bands..	85	26
Alternating laminae of siltstone, shale and sandstone with strong corrugations, pronounced cleavage in the shaly bands. Passing down into black shale	0	12
Flaggy sandstone with many siltstone and shale partings and with small felsite fragments	14	4.3
Sandstone with angular felsite fragments passing down into tuff and ignimbrite (top of Clousta Tuff)	—	—

Many of the siltstones and shales in the above sequence are to some extent calcareous and thin impersistent ribs of clayey limestone are present. A characteristic feature of the shales and siltstones, particularly at the calcareous horizons, is the presence of the small folds noted in the above section. These have a range in wavelength from 1 to 5 in (2.5–13 cm), an axial plunge averaging 65° to 90° and an axial trend from NE to N (Figure 12). Their tectonic significance is discussed on p. 135.

The siltstone and shale sequence overlying the Clousta Tuff can be traced north-eastward for 1 mile (1.6 km) to the south shore of the Voe of Clousta. Beyond this longitude, which also marks the approximate eastern limit of the Clousta Tuff, the argillaceous sediments give way to a predominantly sandy succession with tuffaceous debris.

It is perhaps significant that both the Clousta and Aithness tuff 'cones' are in part, at least, associated with fine-grained sediment which both overlies and abuts against the tuff. The thick argillaceous and calcareous sediment at Mo Wick shows little sign of large-scale cross-stratification or other structures of a type associated with rapidly flowing water, and structures such as sun cracks which indicate deposition in very shallow water have not been seen. This suggests that it may have been deposited in the standing water of a lake or lakes. The thick irregular accumulations of pyroclastic material may have radically changed the topography of the area of deposition which was earlier controlled by a fluvial regime. By damming a river valley they could have been responsible for the formation of such a lake. The sandstone which overlies the fine-grained sediment at Mo Wick and Aithness suggests a return to a more normal fluvial regime.

Area west of Brindister Voe

Sector between Brindister Voe and Smith's Hamar

Because of incomplete exposure and the presence of a number of strike-and-dip-faults within the area between Brindister Voe and Sulma Water, it is not possible to make a reliable interpretation of the stratigraphical relationships within the volcanic group in this area. A possible interpretation, shown in (Plate 10), suggests that there are five isolated lenticular flows of andesite and basalt within a sequence of coarse, predominantly basic, tuffs and tuffaceous sandstones.

In this area the group has an approximate thickness of 2000 ft (600 m) and is intruded by several lenticular masses of porphyritic felsite, the largest of which, the Smith's Hamar Felsite, extends from the south-east corner of Sulma Water westwards to Smith's Hamar (Plate 9).

Basic lavas

The lavas which include both pyroxene-andesites and albitized basalts (p. 93) range in colour from pale grey to deep purplish grey, and range from fine-grained aphanitic to macroporphyritic with locally fluxion-banded plagioclase laths.

They are commonly brecciated and some pass in places imperceptibly upwards into coarse agglomerate which, at one locality, 200 yd (180 m) E of the south-east corner of Sulma Water, is up to 30 ft (9 m) thick and passes in turn upwards into tuffaceous sandstone. The brecciated lava is in many places intensely veined by carbonate and both the spaces between individual lava fragments and vesicles within the lava are filled with sandstone or fine tuff.

Lapilli-tuffs with matrix exhibiting vitroclastic texture

In the area between Brindister Voe and the Loch of Hollorin there are several thick, somewhat lenticular, masses of compact lithic tuff with abundant clasts in the lower range of the lapilli-grade size, interbedded with basic lava and tuffaceous sandstone (Plate 9). The tuff is dark grey in colour with angular clasts of fine-grained dark grey lava predominating over somewhat smaller clasts of pink felsite and isolated crystals of pale pink potash feldspar, set in a fine-grained vitroclastic matrix, with a texture which is similar to that of the ignimbrites east of Brindister Voe. These tuffs pass westwards into lapilli-tuffs which have a sandy matrix, but the nature of the transition has not been investigated.

Lapilli-tuffs and agglomerates

In the area between Brindister Voe and Sulma Water, well-bedded lapilli-tuff and agglomerate forms a number of roughly lenticular masses some of which are closely associated with basic lava. In the eastern part of the area the matrix of the tuffs is partly vitroclastic but in the west it is entirely sandy, with sandstone partings separating individual tuff bands. The sandstones and shales between these tuffs contain small angular fragments of both basic lava and felsite. In most pyroclastic deposits in this area there is a slight preponderance of clasts of basalt or andesite over those of ignimbrite and felsite. Fragments of baked sandstone and siltstone are present in certain bands. In the coarser deposits isolated angular blocks up to 1 ft (30 cm) long are set in a matrix of lapilli-tuff in which fragments range in size from 0.25 to 0.5 in (6–12.5 mm) or, exceptionally, 1 in (25 mm). Felsite and ignimbrite clasts are commonly angular to subangular and show an extensive range in size. Clasts of decomposed glassy basalt are more consistent in size (average 2.5 cm) and are generally rounded to subrounded, suggesting that they may have consolidated in flight following ejection.

To the west of Sulma Water one small isolated cone of coarse agglomerate is exposed on the north slope of Smith's Hamar (Plate 9). This contains many subrounded blocks of banded felsite up to 3 ft (0.9 m) long, set in a matrix of rhyolitic tuff.

Felsites

In addition to the Smith's Hamar Felsite which is a lenticular somewhat transgressive intrusion up to 1500 ft (450 m) thick, with a length of outcrop of 1.5 miles (2.4 km), there are a number of thin sill-like concordant felsite bodies in the vicinity of Sulma Water and Hamari Water [HU 250 556] and some strongly transgressive felsite masses of highly irregular shape in the ground north of Loch of Hollorin [HU 276 558] and on the west shore of Uni Firth [HU 286 560]. As in the area east of Brindister Voe, these felsites are comparable in both texture and mineral composition with the felsite clasts in the pyroclastic deposits of the group. It is therefore reasonable to assume that these intrusions belong to the same general phase of volcanic activity as the somewhat earlier felsites from which the clasts were derived. The irregular shape of some of the bodies suggests that they were intruded into only partially consolidated sediments and tuffs.

Sector west of Smith's Hamar

Basic lavas and pyroclastics

In the area between Smith's Hamar and the longitude of Mousavord Loch there is a gradual westward decrease in the amount of contemporaneous basic rock, both lava and pyroclastic. Basic clasts occur as scattered pebbles and within discrete tuff bands which are not more than 18 in (45 cm) thick. In the lower part of the sequence these clasts are embedded in sandstone, in the upper part they occur mainly in mudstone and siltstone. West of Burga Water basic clasts are extremely rare.

The basic lavas exposed in the area west of Smith's Hamar are all relatively thin, never exceeding 50 ft (15 m), and are widely separated from each other by tuffaceous sediments (Plate 10). Because of indifferent exposure these flows cannot be continuously traced along the strike, and it is not certain if the isolated outcrops are parts of one thin flow or represent a number of flows of restricted lateral extent. They are composed of relatively fresh fine-grained microporphyritic pyroxene-andesites and subordinate albitized basalts which, unlike the basalt flows further east, are almost everywhere devoid of vesicles along the junctions with the sediments. There is thus a possibility that some may be concordant minor intrusions rather than lava flows.

West of the longitude of Stanevatstoe Loch [HU 216 545] there are only two records of basic lava within the volcanic horizon: in a small quarry 55 yd (50 m) ESE of the school house at Netherdale [HU 181 523] where fine-grained purplish grey basalt overlies purple silty mudstone, and in an isolated exposure 150 yd (135 m) S of the Voe of Dale. The thickness and extent of these lavas are unknown.

Acid lavas, ignimbrites and concordant felsite intrusions

Between Burga Water and Littlapund [HU 201 532] a concordant body of fine-grained acid rock up to 80 ft (24 m) thick underlies a coarse felsitic tuff and tuffaceous sandstone. This is a fine-grained pink to pale purplish rock which in thin section has the characteristics of felsite (p. 98). Because of the poor exposure of its margins it is not possible to determine if this is a concordant intrusion or a lava flow. Smaller concordant bodies of felsite are seen at higher horizons on the west shore of Burga Water and in the vicinity of Littlapund (Plate 9). Again their mode of origin is uncertain.

Along the south and south-east shores of Burga Water there are a number of thin beds to which the field description 'tuffaceous mudstone' has been given. Only one specimen from these beds has been sliced (S30898) [HU 239 541] and its argillaceous matrix has a vitroclastic texture with relics of welded shards, suggesting that the rock is an ignimbrite.

The sill of sparsely porphyritic felsite which forms a continuous outcrop between the north shore of the Voe of Dale and Upper Dale [HU 196 531] reaches a thickness of possibly 600 ft (180 m). Its upper junction is exposed on the north shore of the Voe of Dale, where it is seen to be intrusive but concordant with the overlying sediment. A number of small irregular felsite dykes, not usually exceeding 2 ft (60 cm) in thickness, cut the sediments underlying this sill.

Acid pyroclastic rocks and sediments

A thick bed of coarse lapilli-tuff which is here termed the Dale Tuff extends west-south-westwards from Burga Water to Upperdale. Near its eastern end it contains bands of agglomerate with felsite clasts normally up to 3 in (8 cm) in length, as well as some much larger blocks, set in a matrix of finer igneous detritus. There appears to be a gradual westward decrease in the size of component clasts coupled with a westward increase in the proportion of sandy matrix in the tuff. West of Upperdale the tuff gradually passes into a sandstone with abundant pebbles of felsite and some bands of tuff. This tuff and tuffaceous sandstone is intercalated with fine-grained argillaceous, silty and locally calcareous, sediments, which appear to thicken westwards towards the Voe of Dale, where the sequence of strata, thought to comprise the entire spread of volcanic rocks and associated sediments, is as shown graphically in (Figure 8)b.

In this coast section the group has the following features:

1. Contemporaneous extrusive rocks are absent on the shore, though two exposures of basic lavas have been recorded just inland.
2. Agglomerates and lapilli-tuffs form only thin bands, which are closely associated with thick beds of coarse pebbly sandstone and conglomerate. The latter contain abundant subrounded boulders, cobbles and pebbles of pink and purple felsite, locally up to 2 ft (60 cm) long. There are several good exposures of channel-fill structures and of large-scale cross-bedding in the sandstone, suggesting that the beds were deposited by fast flowing rivers. The felsite clasts were probably derived by erosion from a nearby felsite agglomerate cone which may still have been active at the time and may have been the direct source of the thin beds of tuff and agglomerate.
3. The group contains a high proportion of reddish purple shale and siltstone and a few thin calcareous beds. The thickest argillaceous horizon consists of deep purple silty shale with thin ribs and irregular lenticles of sandstone and is 200 to 250 ft (60–75 m) thick. Several thinner beds of purple silty mudstone with thin ribs of tuffaceous sandstone occur in the lower part of the sequence.

4. Close to the top of the group there is a 100-ft (30-m) thick bed of very fine-grained pale purplish tuff, which contains shards of devitrified glass as well as quartz grains and fragments of felsite. Because of lack of exposures this tuff band cannot be traced far eastward from the coast.

There is a marked westward decrease in the total thickness of the beds containing the volcanic rocks. This is due, in part, to the westward decrease in the number and thickness of extrusive and pyroclastic bodies and, in part, to the westward transition of predominantly arenaceous beds into deep purple argillaceous sediments. Within the partially arenaceous sequence ripple-cross-lamination and desiccation cracks are present. The latter suggest deposition under shallow-water conditions with periodic drying out. The reddish colour of most of the fine-grained sediment might imply deposition in an arid environment free from reducing conditions, but the reddening may also be the result of iron staining from the products of weathering of basic lavas.

In the western part of the area the volcanic group passes upwards into grey micaceous flaggy sandstone with thin pebbly bands containing felsite clasts and thin partings of siltstone.

Flora

Traces of plant remains have been found in two localities within the sediments interbedded with the Clousta Volcanic Rocks ((Figure 11), p. 86). Those on the east shore of the Loch of Clousta are unidentifiable graphitic streaks and patches. The specimens collected from the east shore of the Voe of Clousta, 30 yd (27 m) due west of Clousta School [HU 309 573] have been examined by Prof. W. G. Chaloner who has identified *Psilophyton* sp.,and a minute spineless axis of cf. *Hostimella.* Chaloner stated that 'The plants do not give precise evidence of age, and *Hostimella* in particular is not decisive. The presence of *Psilophyton* however suggests a Lower or Middle Devonian age.'

Petrography

Pyroxene-andesites

Pyroxene andesites are most abundant in the area west of Brindister Voe. They are generally sparsely porphyritic with feldspar phenocrysts of both square and lath-shaped outline ranging in length up to 4 mm. The andesites forming the highest flows just west of Burga Water are conspicuously porphyritic with abundant feldspar phenocrysts up to 7 mm long. Some of the lowest flows in this area are non-porphyritic (S30888) [HU 226 543], (S30889) [HU 226 543], (S30890) [HU 229 544]. Phenocrysts of augite have been recorded in only one specimen (S30913) [HU 246 544]. The groundmass of most of the andesites consists of feldspar laths which make up 75 to 85 per cent of its total volume, ophitic or intersertal plates of augite and interstitial patches of finely fibrous chlorite and carbonate. Iron ore and pyrites occur as skeletal crystals, locally arranged in clusters. Other common accessory minerals are apatite, rutile and sphene.

The arrangement of the feldspar laths is in most cases decussate, but in the finer-grained specimens (S30884) [HU 226 543], (S30911) [HU 244 546] the laths are flow-aligned. Devitrified glass has been seen in the matrix of a number of specimens, and one such rock (S30901) [HU 289 539] contains a radiating fibrous aggregate of crystallites of plagioclase, associated with finely granular iron ore.

The composition of both groundmass feldspars and phenocrysts ranges from calcic oligoclase to calcic andesine (S30893) [HU 226 538], (S30897) [HU 235 540], (S30913) [HU 246 544]. In many thin sections (e.g. (S30888) [HU 226 543], (S30889) [HU 226 543]) the feldspars are partially albitized but commonly contain irregular residual blebs of the original more basic plagioclase. Zoning has been recorded in only one specimen (S30991) [HU 270 567] and in this it affects the outer rim only. In the area between Burga Water and Sulma Water the plagioclases of the highest flow appear to be more calcic (mid- to calcic andesine) than those of the lower flows (sodic- to mid-andesine).

Fresh augite is preserved in only about half of the specimens examined and no orthopyroxene has been recorded. In the highest flow of the Burga Water area (S30897) [HU 235 540] augite forms nearly 20 per cent of the total volume of the rock and occurs mainly as ophitic crystals up to 1 mm in diameter. In most specimens, however, augite forms less than 15 per cent of the total volume. In some sliced rocks it forms sub-ophitic crystals, but in a number of slices it is intersertal or granular with grains not exceeding 0.3 mm in size. The pyroxene is commonly partly altered to chlorite.

The andesites are saussuritized to varying degrees, and some specimens (e.g. (S30893) [HU 226 538]) contain scattered grains and irregular anastomosing veinlets of epidote. Euhedral blades of actinolite, which is pleochroic from yellow to bluish green, are present in some specimens, either within small chlorite–calcite veins (S30913) [HU 246 544], (S30987) [HU 286 565] or as a lining to and within calcite- and chalcedony-filled amygdales (S30901) [HU 289 539], (S30855) [HU 196 486]. Amphibole crystals are only rarely found within the matrix of the andesites (e.g. (S30893) [HU 226 538]).

Basalts

Basalt lavas form most of the flows in the areas east and immediately west of Brindister Voe. Only two basalt flows have been recognized in the Burga Water area. The more westerly basalts are highly porphyritic with phenocrysts of labradorite up to about 2.4 mm long (S30885) [HU 228 541], (S30902) [HU 236 541]. The phenocrysts have corroded margins and some have a narrow reaction rim. Most basalts in the east are only sparsely microporphyritic, with plagioclase phenocrysts not normally exceeding 1.5 mm in length. The feldspar laths of the groundmass (also labradorite) generally show some flow alignment with intervening decussate zones. The basalts west of the longitude of Clousta contain sub-ophitic to ophitic plates of augite, which make up nearly 35 per cent of the total volume of the rock (S30987) [HU 286 565], (S30760) [HU 300 577], (S30902) [HU 236 541]. Specimens (S30773) [HU 328 596], (S30772) [HU 329 594] from flows north-east of Clousta, however, are uralitized to varying extents and the interstices between the feldspar laths are filled in part by chlorite and in part by aggregates composed of minute flakes of green mica and euhedral needles and blades of actinolite ((Plate 13), fig. 4). In the Clousta Loch and Aithness areas the secondary actinolite forms a very high proportion of the patchy intersertal aggregate which also contains abundant granular epidote and less than 5 per cent of chlorite. Throughout the area the original chlorite within the veins and vesicles has also been partly or completely altered to a green, highly pleochroic, fibrous aggregate of actinolite and biotite.

The development of secondary amphibole and biotite at the expense of pyroxene and chlorite becomes progressively more pronounced in a northeasterly direction and is most marked in the vicinity of the Walls Boundary Fault. A similar development of amphibole and biotite has been recorded in basic minor intrusions in the northern part of the area described in this memoir (p. 244), a swell as in the area just east of the fault (F. May, personal communication) and in the basalt dykes of western Fair Isle (Mykura 1972, pp. 38–9). This alteration cannot be attributed to the progressively increased effects of shearing near the fault as the effects of shearing are confined to a much narrower strip adjoining the fault and also because the mineral assemblage in the amphibolized lava is not that of a basalt subjected to retrograde dynamic metamorphism. It is more likely to be due to the thermal or, more likely, late magmatic activity of a nearby or underlying major intrusive body.

In several thin sections of basalt chalcedony is observed both in the matrix and in epidote-chlorite veins. Amygdales generally contain calcite and chalcedony and they are in most cases bounded by an outer zone of acicular actinolite.

An unusual flow of autobrecciated macroporphyritic non-ophitic basalt, which occurs low in the volcanic sequence, crops out on the west shore of Burga Water (S30917) [HU 257 553]. This contains abundant phenocrysts, up to 5 mm in diameter, of sericitized plagioclase and euhedral crystals up to 2 mm in diameter of fresh augite set in an almost aphanitic groundmass. This lava also contains an appreciable proportion of quartz grains, which may have been incorporated during the passage of the lava over loose sand.

(Table 2) Chemical analyses of sandstone, felsite sill and basalt lava in Walls Sandstone

	1	2	3
SiO_2	73.31	71.25	50.45
Al_2O_3	10.68	13.54	16.63
$Fe2O_3$	0.30	0.45	3.79
FeO	2.37	1.91	5.50
MgO	1.18	0.99	6.95

CaO	2.97	0.20	7.10
Na_2O	3.29	1.84	2.35
K_2O	1.46	7.84	1.84
H_2O >105°	1.21	0.94	2.80
H_2O< 105°	1.10	0.27	2.26
TiO_2	0.45	0.15	1.34
P_2O_5	0.14	0.01	0.31
MnO	0.05	0.05	0.12
CO_2	2.12	0.28	0.22
Allow for minor constituents	0.14	0.19	0.28
Total	99.77	99.91	99.94
*Ba	350 ppm	700 ppm	1000 ppm
*Co	<10	<10	20
*Cr	44	<10	26
*Cu	10	<10	20
*Go	<10	<10	20
Li	12	8	40
*Ni	20	<10	60
*Rb	n.d.	330	n.d.
*Sr	150	42	450
*V	54	10	220
*Zr	300	440	200
B	17	2	7
F	250	120	500
*Spectrographic determination	n.d. = not determined.		

NORMS

	2	3
Q	27.31	3.59
C	1.69	0.00
or	46.33	10.87
ab	15.57	19.89
an	0.93	29.40
di	0.00	3.04
by	5.45	20.83
of	0.00	0.00
mt	0.65	5.50
il	0.28	2.54
ap	0.02	0.72
Others	1.68	3.56
Total	99.91	99.94
Q	30.61	10.46
or	51.94	31.65
ab	17.45	57.89
Total	100.00	100.00
or	73.74	18.08
ab	24.78	33.06
an	1.48	48.87
Total	100.00	100.00
ab	94.38	40.35
an	5.62	59.65
Total	100.00	100.00

- 1. Sandstone, fine-grained, with calcareous matrix, 900 yd (820 m) E2°S of Efrigarth, Walls [HU 277 503]. (S50128), Lab. No. 1992. Anal. J. M. Nunan and W. H. Evans, spectrographic work by C. Park. (*Summ. Prog.* 1967, p. 96).
- 2. Felsite sill cutting Walls Sandstone, hillside south of Longa Water, 800 yd (730 m) W37°S of West Burrafirth 'School' [HU 263 567]. (S50129), Lab. No. 1991. Anal. J. M. Nunan and W. H. Evans, spectrographic work by C. Park. (*Summ. Prog.* 1967, p. 96).
- 3. Basalt lava flow, Water Head, west coast of Loch of Clousta, 850 yd (790 m) N 28°E of Grind [HU 314 583]. (S50138), Lab. No. 1983. Anal. W. H. Evans, spectrographic work by C. Park. (*Summ. Prog.* 1966, pp. 76–7).

Ignimbrites

Head of Lahamar [HU 289 564]

The greater part of the Head of Lahamar flows ((Plate 9), p. 85) is composed of ignimbrite (S53767) [HU 288 565] in which clasts that are clearly visible in hand specimen make up to 20 to 30 per cent of the total volume. The clasts consist mainly of subhedral to euhedral crystals of patchily kaolinitized untwinned potash-feldspar. There are also fragments of felsite and some flattened pieces of pumice which show axiolitic recrystallization of feldspar and quartz into crystallites up to 0.25 mm long and 0.04 mm thick. The matrix is formed largely of flattened shards on average 0.4 mm long and 0.03 mm wide aligned parallel to the bedding. Locally, however, shards display the original arcuate and Y-shaped structure with little flattening. There are also a number of narrow elongate zones in which the shards are twisted and distorted. These zones may either be narrow penecontemporaneous shear planes or passages used for the escape of residual gases. The shards show intense distortion and flattening both below and above the feldspar crystal-clasts. The matrix is largely recrystallized into an irregular granular mosaic of quartz and feldspar, with individual quartz patches exceptionally up to 0.045 mm in diameter. Axiolitic or spherulitic textures of the type common in the rhyolites of Papa Stour (pp. 1678) are rarely developed. The purplish grey colour of the rock is due to a uniform dusting of hematite.

Certain parts of the Head of Lahamar flows (S30750) [HU 288 565] are, however, composed of lapilli-tuff made up of 80 per cent of rounded clasts in the coarse tuff grade (5 to 6 mm diameter), set in a matrix made up of a fine-grained aggregate of carbonate and clay minerals with irregular patches of quartz and feldspar.

The highest thin flows of ignimbrite exposed at the Head of Lahamar, which are interbedded with basalt or andesite flows (p. 85), contain up to 40 per cent by volume of clasts. The latter consist of porphyritic and non-porphyritic felsites, basalts and andesites, euhedral feldspars, and some small scattered crystals of zircon. The matrix has some relict traces of flattened shards (S30767) [HU 290 563] but is completely altered into an aggregate of clay minerals and sericite. One flow (S51531) [HU 312 440] contains flattened inclusions with wispy flame-like ends. These are similar to the 'fiamme structures of flattened particles of black devitrified glass, which have been recorded in many ignimbrites and tuff lavas elsewhere (Bersenev and others *in* Cook 1966, pp. 114–6).

The fabric of the flows in this area has been affected by subsequent shearing and small scale folding (p. 135) which has produced two distinct planar structures parallel to the limbs of the minor folds.

Burga Water

The thin flows of ignimbrite cropping out on the south and southeast shores of Burga Water (S30898) [HU 239 541] consist of a compact dark grey rock with abundant subhedral to euhedral crystal clasts of pink potash feldspar, up to 2.6 mm in diameter, and rare fragments of altered andesite. Its groundmass is composed of flattened and, in places, intensely distorted shards, replaced by a fine mosaic of quartz and clay minerals with an irregular scatter of larger patches of quartz.

Voe of Dale

The flow of fine-grained 'tuff' near the top of the Sandness Formation just south of the Voe of Dale (p. 92) is a compact pink rock without the abundant crystal clasts of feldspar characteristic of the ignimbrites farther east. Clasts form a relatively small proportion of the rock and include rounded fragments of spherulitic felsite up to 2.8 mm in diameter, near-euhedral crystals of potash feldspar, scattered detrital grains of quartz and felsite together with rare iron ore, tourmaline and muscovite. The matrix is composed of a very fine-grained structureless aggregate of quartz, feldspar and clay minerals and has a dusting of hematite which gives it a red colour. Though much of its original texture is obliterated, there are some traces of structures comparable with those of the ignimbrites from other areas.

Acid tuffs and agglomerates

Clousta and Aithness

The megascopic textural variations within the Clousta and Aithness tuffs have already been described. The clasts consist predominantly of fine-grained acid rock, but in certain areas fragments of basic lava predominate over the acid ones.

Acid clasts within the Clousta Tuff include the three varieties of felsite described on p. 98, ignimbrite with flattened and welded shards, and feldspar crystals, which are either euhedral or broken but never markedly rounded. The matrix of the tuff consists of particles of quartz and feldspar ranging from 0.25 to 0.03 mm in diameter. The ratio of quartz to feldspar grains varies from 70:30 to 60:40. Accessory minerals include sphene, epidote, iron ore and muscovite.

The Aithness Tuff contains a higher proportion of clasts of basalt and a small proportion of pebbles of sediments. Grains of garnet have been recorded in the sandy matrix.

Area between Galta Water [HU 248 544] and Loch of Hollorin [HU 276 559].

A characteristic feature of the coarse tuffs in this area is the presence of a higher proportion of ignimbrite clasts than in the tuffs of the Clousta area. The ignimbrites (S49343) [HU 266 551], (Plate 13), fig. 3) contain small fragments of both felsite and basic lava, as well as euhedral crystals up to 1.5 mm in diameter of both potash feldspar and quartz set in a matrix of shards which are only slightly flattened and locally retain their Y-shaped bifurcations. Small fragments of non-flattened pumice are also preserved.

Concordant felsite intrusions

The felsites which form concordant intrusions within the upper part of the Sandness Formation show a considerable variation in their petrographic character. Most felsites are porphyritic and the most common phenocrysts are clear potash feldspar, potash feldspar with radiating twin lamellae (see (S29918) [HU 186 533]), microcline and microcline-microperthite. Many feldspar phenocrysts are partly kaolinitized. The phenocrysts vary greatly in size and can range up to 3 mm in diameter. In many thin sections they are arranged in clusters. Some felsites are very sparsely porphyritic (S30906) [HU 242 550], (S30916) [HU 260 554] or non-porphyritic (S30913) [HU 246 544].

The matrix of the felsites varies considerably. In the Sulma Water (S30906) [HU 242 550] and Smith's Hamar felsites (S30922) [HU 253 550], (S30923) [HU 249 547], (S30944) [HU 167 619], (S30974) [HU 277 558] it consists of a micrographic quartz-feldspar intergrowth full of patches containing slightly higher concentrations of quartz. There are also large irregular patches of clear quartz and smaller patches of chlorite with muscovite in the centres, as well as small euhedral grains of zircon. Matrices of this kind grade into the matrix found in the felsites from the Ness of Nounsbrough (S30751) [HU 290 572] and Upper Dale (S29974) [HU 203 534] and (S29975) [HU 221 541]. In these it consists of small stumpy laths of potash feldspar, up to 0.025 mm long, set in poikilitic plates of quartz which are in optical continuity within areas extending over several millimetres. Where the feldspar laths are very minute, adjoining laths are in places joined to produce an irregular micrographic texture. Patches of chlorite and calcite are commonly found in this matrix.

In some decomposed felsite sills in the Ness of Nounsbrough (S30976) [HU 286 565] the matrix of the rocks is altered to a very fine-grained aggregate of clay minerals with small irregular patches of quartz. This matrix is traversed by curved cracks which may be the remains of a perlitic texture in the original glass.

Two acid or intermediate intrusions near Upperdale (S30585) [HU 196 535], (S30586) [HU 196 535] consist of aligned laths of sodic oligoclase, which form 75 per cent of the total volume of the rock, set in a hematite-dusted chloritic matrix containing amoeboid patches of quartz.

Sediments associated with the volcanic rocks

Sandstones

Many of the sandstones associated with the volcanic rocks, particularly in the western and central sectors, contain small pebbles of felsite, and basalt or andesite. The pebbles are in most cases concentrated in bands or lenses, separated by bands of medium- to fine-grained arkose in which lithic clasts are small and less abundant. In the eastern sector, the sandstone overlying the Ness of Clousta Basalt is virtually devoid of volcanic detritus.

The sandstones of Clousta ((Plate 13), fig. 2) are medium- to fine-grained, well- to poorly-graded with angular to subrounded grains which range in diameter from about 0.5 to 0.08 mm. The ratio of quartz to feldspar grains ranges from 80:20 to 50:50, and averages 65: 35. The quartz grains are, with the exception of one specimen (S52739) [HU 300 577], unstrained. The relative abundance of the various types of feldspar grains varies greatly in different specimens. In sliced rocks from the western and central zones the only feldspar that has been recognized is a slightly cloudy potash feldspar. This is accompanied by microcline and rare plagioclase in only one thin section from the central area. In the sandstone from the eastern sector, however, potash feldspars of various types and plagioclase are present, in one specimen (S52739) [HU 300 577] in roughly equal amounts. In others, cleavage fragments of plagioclase predominate, but in two thin sections (S30759) [HU 302 581], (S49329) [HU 305 575] untwinned potash feldspar provides the most common feldspar grains. This distribution suggests that, whereas the detritus in the western and central sectors could have originated from a potassic granite, that in the eastern sector had its source in an area which may have included granite and possibly also members of a dioritic complex. The feldspars could also have been derived from metamorphic terrain.

Most of the sandstones interbedded with volcanic rocks contain a small percentage of heavy minerals which are particularly concentrated in the dark bands. The minerals are, in approximate order of abundance: epidote, sphene, iron ores, apatite, tourmaline and zircon. Large grains of garnet, peripherally altered to carbonate, have been recorded in only one thin section (S30759) [HU 302 581]. Clasts of devitrified glassy basalt are found in some of the lower sandstones (S30759) [HU 302 581]. They have an irregular outline and contain angular xenoliths of quartz which may have been incorporated in the lava during its extrusion through loose sand, or when the still plastic lava lapilli were embedded in the sand.

The proportion of matrix to clasts ranges from 10:90 (S30886) [HU 228 541], (S49329) [HU 305 575] to over 50:50 (S30757) [HU 304 585], but is most commonly between 20:80 and 25:75. The matrix of most specimens consists of a thin greenish film of chlorite and subordinate clay-mica which mantles the grains. In some specimens there are large flakes of pale mica. Interstitial patches of carbonate are closely associated with the chlorite.

Local partial replacement of feldspar grains by sericite produces serrate margins in many grains. The effects of induration in these sediments are less marked than in the sediments below the volcanic rocks.

Siltstones, mudstones and subordinate limestone bands

The thick series of siltstone and shale with subordinate limestone exposed on the shores of Brindister Voe (p. 88) is locally deformed by the second major phase of folding which has affected the Walls Sandstone (p. 134). This has produced intense small-scale similar folding and a local axial plane cleavage (p. 135). The red shales and siltstones exposed on the shores of the Voe of Dale, in the extreme west of the area, are only slightly affected by folding. Small-scale crinkling producing a rudimentary lineation is developed in some of the thinner argillaceous bands along the shores of Galta Water [HU 249 543] and strong slaty cleavage is present in some of the fine-grained sediments above the Aith Ness Tuff in the vicinity of the Loch of Clousta [HU 316 583].

The ribs of argillaceous limestone interbedded with corrugated sediment on the east shore of Brindister Voe (S52360) [HU 288 565] show little sign of intense deformation and there is no development of new minerals. In the limestone, irregular laminae of clay minerals with a small admixture of finely granular calcite are interbedded with laminae composed of calcite grains whose size is within the silt to fine sand range (0.015 to 0.005 mm). Angular quartz grains ranging from 0.16 to 0.07 mm, usually partially replaced by carbonate along the margins, are present in some thin layers in the limestone.

The fine-grained sediments rhythmically interbedded with sandstone around Clousta Voe show little sign of tectonic deformation or induration, but in the area around the Loch of Clousta these fine sediments are intensely indurated, with the development of new colourless mica. In this area the calcareous ribs consist of crystalline carbonate with abundant newly formed irregular grains of epidote and clinozoisite. These alterations may have resulted from the thermal or late magmatic effects of an underlying plutonic body which may also have been responsible for the formation of actinolite and biotite in the basalts (p. 93).

Environment of deposition

The Clousta Volcanic Rocks belong to the calc-alkaline suite of igneous rocks, and the extrusive members of this suite consist of basalt, pyroxene-andesite and ignimbrite together with a high proportion of mainly acid tuff and agglomerate. Their petrographic characters are comparable with those of the Lower Old Red Sandstone extrusive rocks of Argyll and the Midland Valley of Scotland, though the proportion of pyroclastic deposits is here somewhat greater. All these volcanic provinces were formed during the post-tectonic phase of the Caledonian magmatic activity of the Scottish Mainland. In the Western Shetland area the explosive activity of gas-charged acid magma gave rise by explosion to the tuff-cones and probably also formed extensive sheets of ignimbrite. Though only small flows of ignimbrite are at present exposed within the series, the presence of abundant ignimbrite clasts in the tuffs and agglomerates suggests that ignimbrite flows were widely developed, and may have been present in the lowest horizons of the volcanic series.

Ignimbrites are commonly associated with calderas, and it is possible that the tuff-cones and ignimbrite flows exposed in the area were formed within or near the margins of calderas. Because of the steep dip of the strata and the presence of many faults of non-volcanic origin it is not possible to define the bounding faults of caldera basins, if such existed.

The volcanic rocks and fine-grained sediments are underlain by and, in many parts of the area, interbedded with, cross-bedded sandstones and rhythmic sequences which are very similar to the underlying fluvial deposits. These beds appear to have been laid down by braided and, in places, meandering rivers. It is probable that the lavas and pyroclastic rocks were extruded on river-plains bounded perhaps to the north or north-east by alluvial fans. The new landforms created by the extrusive rocks would greatly modify the existing drainage system, restricting the width of the flood plains of some of the existing rivers and damming up others to produce small lakes. Elsewhere again, the newly formed volcanic hills would be the source of local streams which produced alluvial cones full of coarse debris at their foot. This topography would be further modified by the possible development of calderas in which lake deposits could also have been formed.

References

ALLEN, J. R. L. 1960. Cornstone. *Geol. Mag.,* 97, 43–8.

ALLEN, J. R. L. 1965. A review of the origin and characteristics of recent alluvial sediments. *Sedimentology,* 5, 89–191.

COOK, E. F. 1966. Editor. *Tuff lavas and Ignimbrites.* Amsterdam: Elsevier.

FINLAY, T. M. 1930. The Old Red Sandstone of Shetland. Part II: North-western Area. *Trans. R. Soc. Edinb.,* 56, 671–94.

FLINN, D., MILLER, J. A., EVANS, A. L. and PRINGLE, I. R. 1968. On the age of the sediments and contemporaneous volcanic rocks of western Shetland. *Scott. Jnl. Geol., 4,* 10–19.

JONES, G. P. 1962. Deformed cross-stratification in Cretaceous Bima Sandstone, Nigeria. *Jnl sedim. Petrol.,* 32, 231–9.

MYKURA, W. 1972. Igneous intrusions and mineralization in Fair Isle, Shetland Islands. *Bull. geol. Surv. Gt Br.,* No. 41, 33–53.

PEACH, B. N. and HORNE, J. 1879. The Old Red Sandstone of Shetland. *Proc. R. Phys. Soc. Edinb.,* 5, 80–7.

PEACH, B. N. and HORNE, J. 1884. The Old Red Volcanic Rocks of Shetland. *Trans. R. Soc. Edinb.,* 32, 359–88.

PETTIJOHN, F. J. 1957. *Sedimentary Rocks.* New York: Harper and Brothers.

SUMMARY OF PROGRESS 1934. *Mem. geol. Surv. Gt Br. Summ. Prog. for* 1933

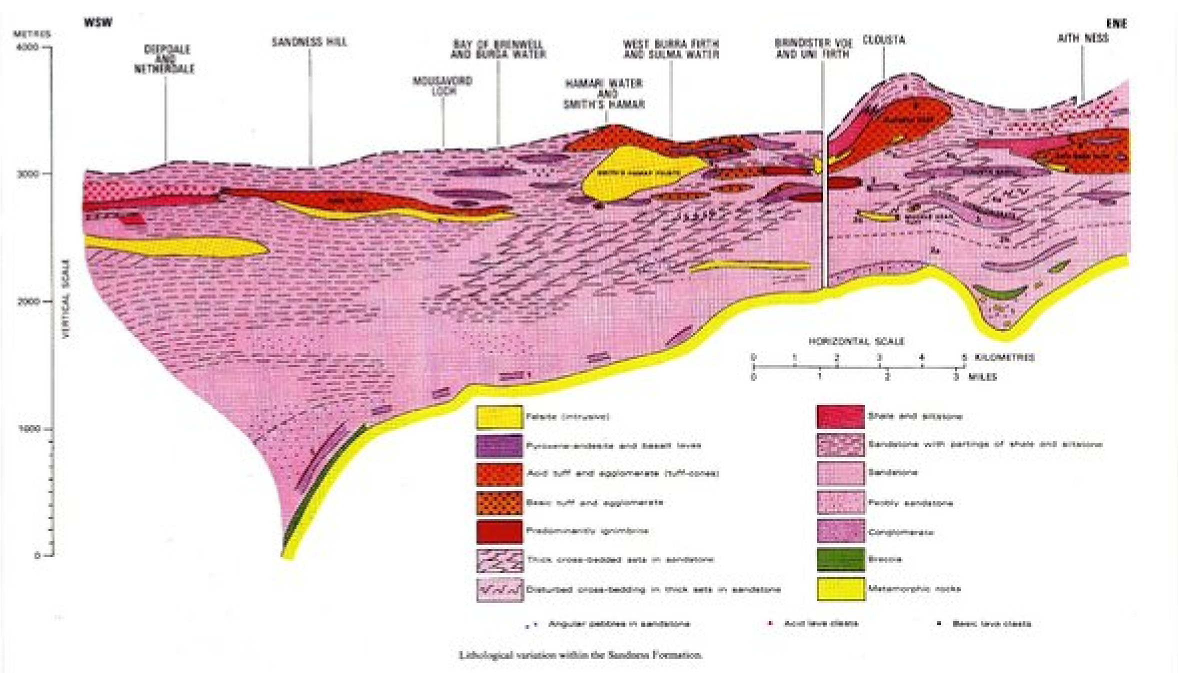
SUMMARY OF PROGRESS 1935. *Mem. geol. Surv. Gt Br. Summ. Prog. for* 1934

SUMMARY OF PROGRESS 1966. *Mem. geol. Surv. Gt Br. Summ. Prog. for* 1965.

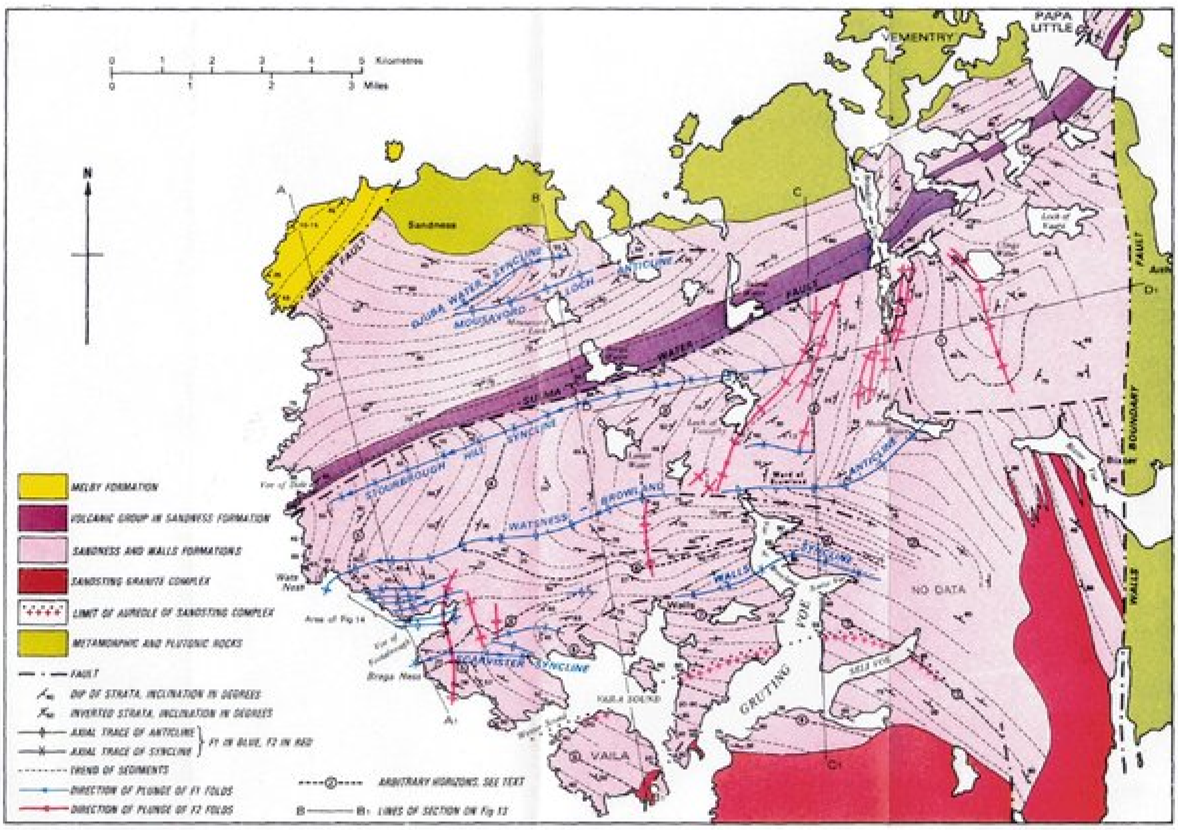
SUMMARY OF PROGRESS 1967. *Mem. geol. Surv. Gt Br. Summ. Prog. for* 1966.

TUDOR, J. R. 1883. *The Orkneys and Shetland. Their Past and Present State.* London.

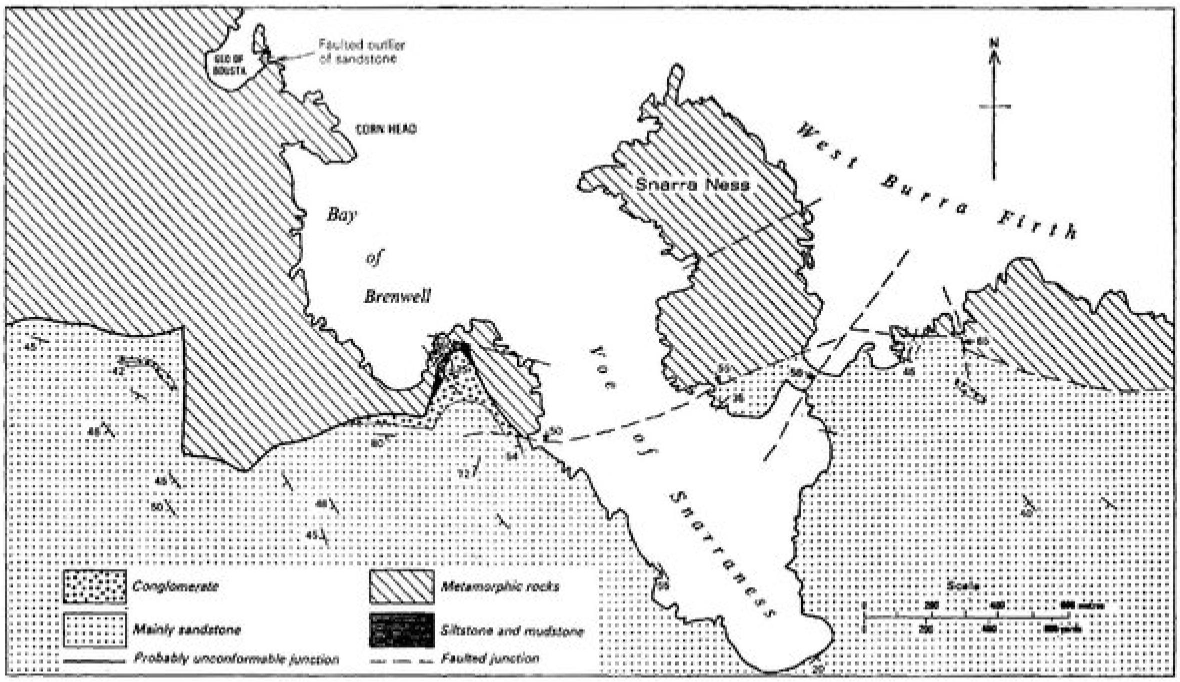
(Plate 9) Geological sketch map of the Sandness Formation.



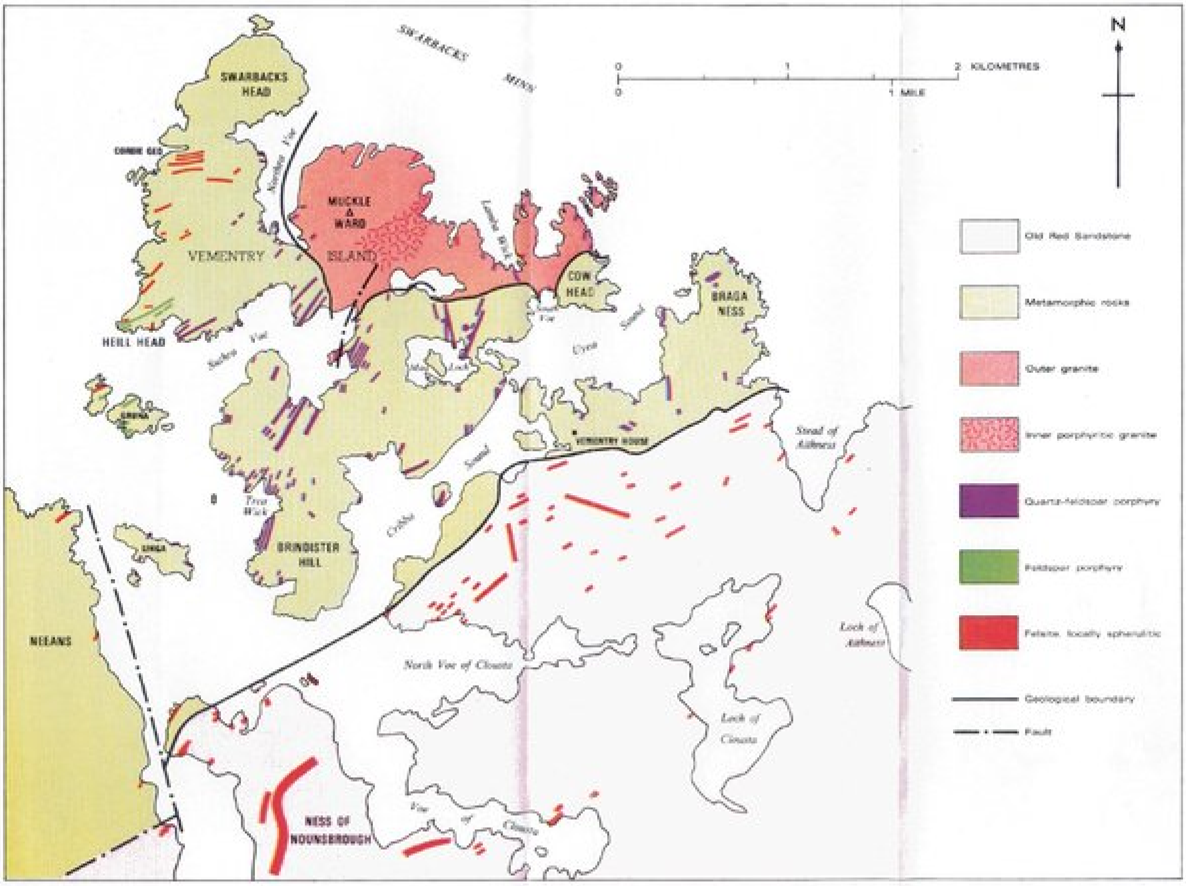
(Plate 10) Lithological variation within the Sandness Formation.



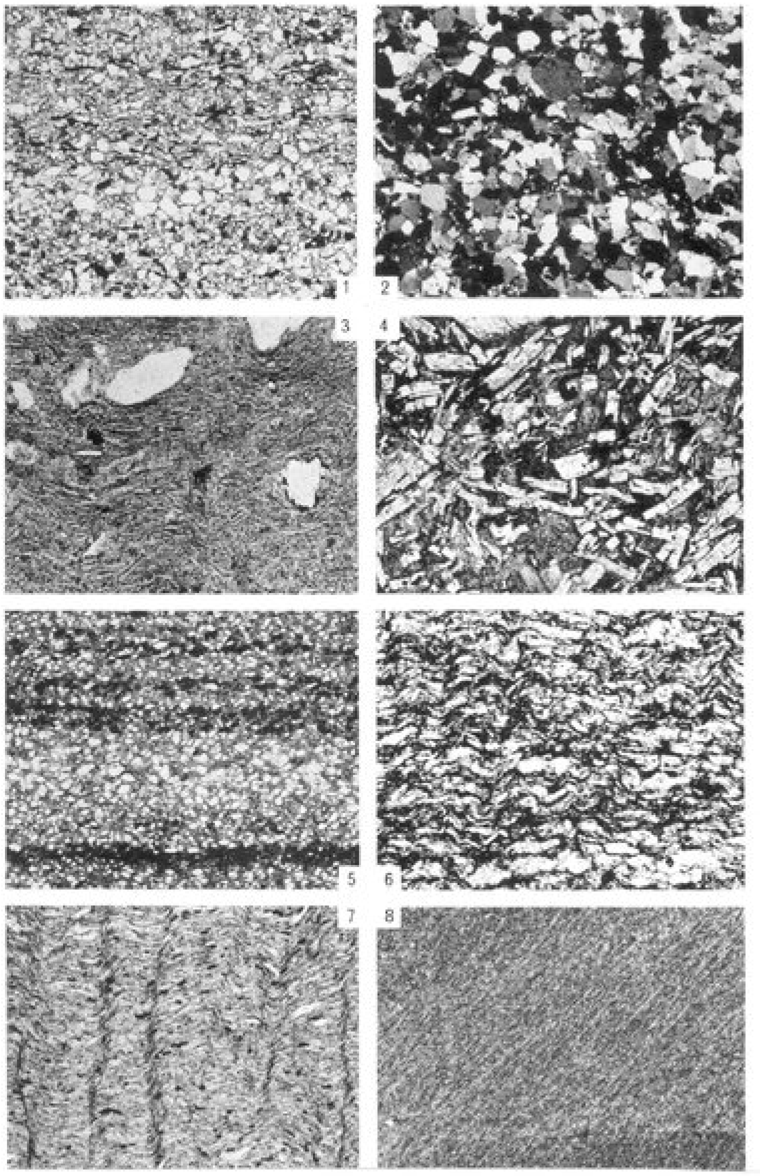
(Plate 12) Major stratigraphic and structural features of the Old Red Sandstone sediments and volcanic rocks of the Walls Peninsula.



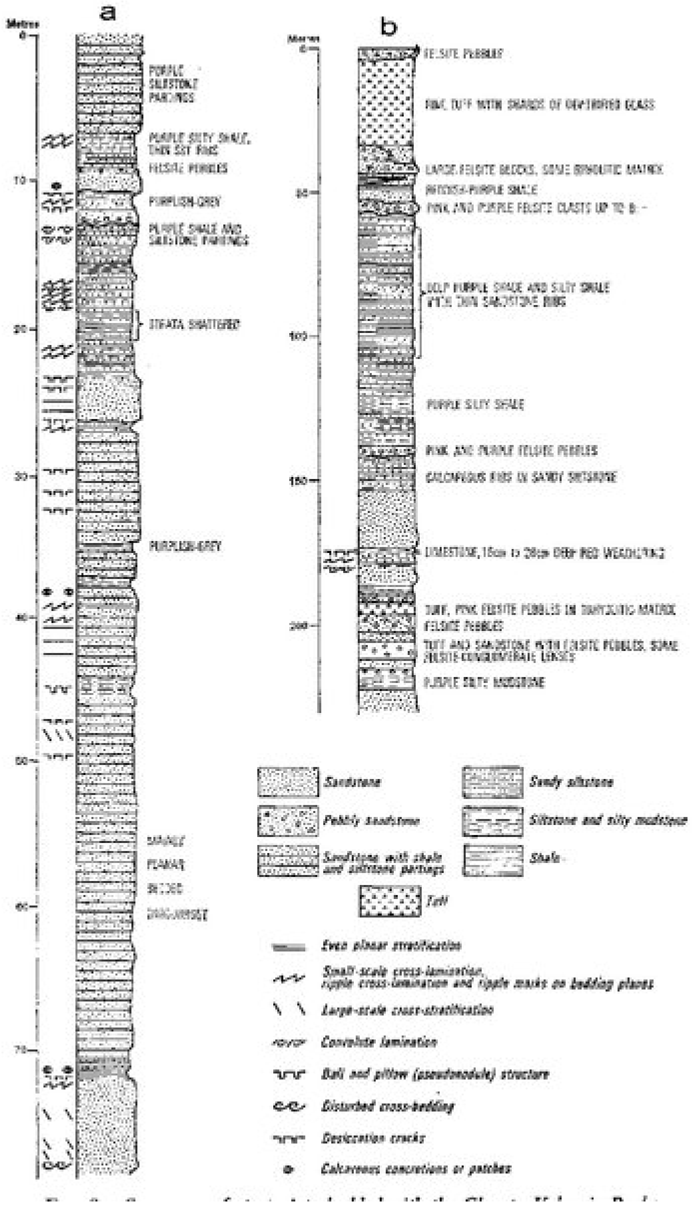
(Figure 7) Geological sketch-map of the junction between metamorphic rocks and Old Red Sandstone in the area between Bay of Brenwell and West Burra Firth.



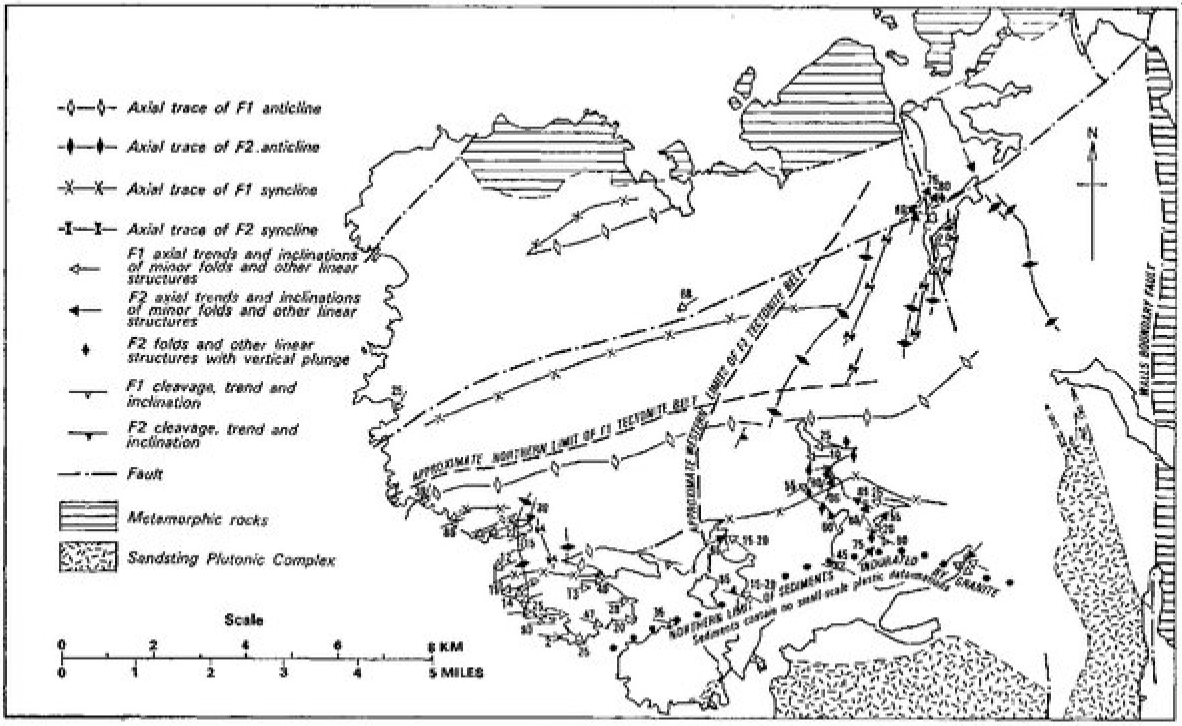
(Plate 24) Vementry Granite and related acid minor intrusions.



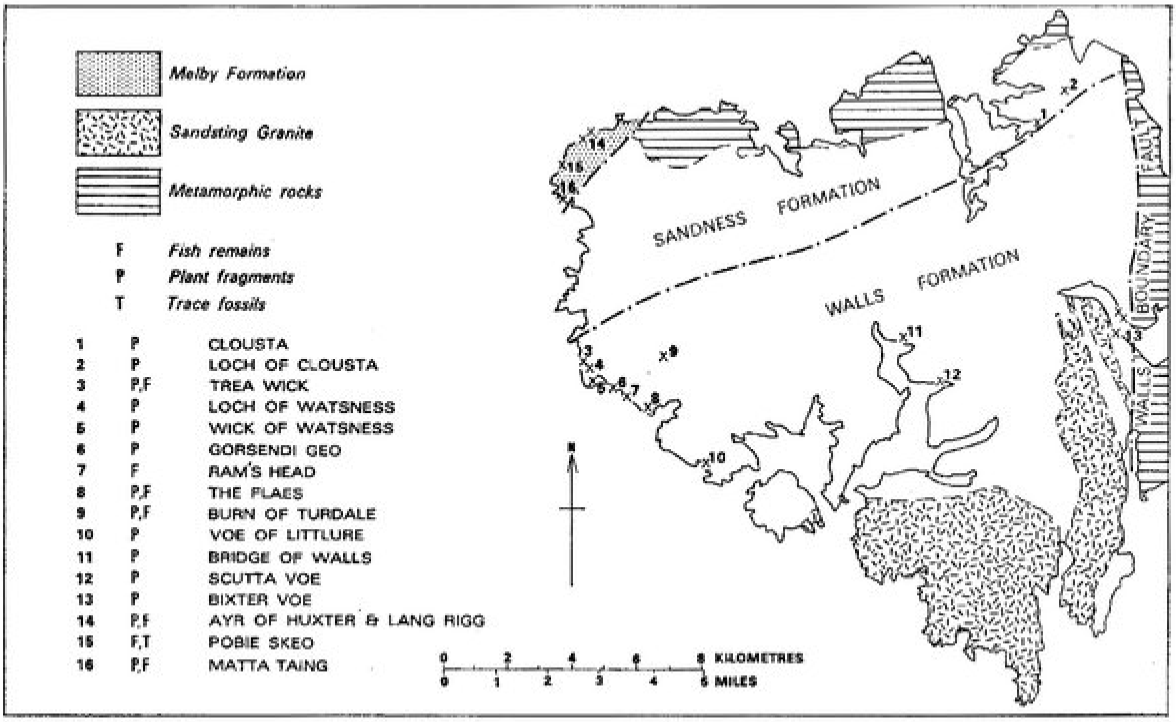
(Plate 13) Photomicrographs of sedimentary and volcanic rocks of the Walls Sandstone Fig. 1. Slice No. (S52737) [HU 296 581]. Magnification × 20. Plane polarized light. Fine-grained flaggy sandstone, Sandness Formation, showing alternate quartz-feldspar and micaceous laminae. Scattered small grains of 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].*



(Figure 8) Sequences of strata interbedded with the Clousta Volcanic Rocks a. Strata exposed on the north shore of Clousta Voe, between 320 m and 620 m west of Clousta School. Strata exposed at Voe of Dale.



(Figure 12) Location of tectonite belts and prominent linear and planar structures in the Old Red Sandstone of the Walls Peninsula.



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

	1	2	3
SiO_2	73·31	71·25	50·45
Al_2O_3	10·68	13·54	16·63
Fe_2O_3	0·30	0·45	3·79
FeO	2·37	1·91	5·50
MgO	1·18	0·99	6·95
CaO	2·97	0·20	7·10
Na_2O	3·29	1·84	2·35
K_2O	1·46	7·84	1·84
$H_2O > 105°$	1·21	0·94	2·80
$H_2O < 105°$	1·10	0·27	2·26
TiO_2	0·45	0·15	1·34
P_2O_5	0·14	0·01	0·31
MnO	0·05	0·05	0·12
CO_2	2·12	0·28	0·22
Allow for minor constituents	0·14	0·19	0·28
Total	99·77	99·91	99·94
*Ba	350 ppm	700 ppm	1000 ppm
*Co	< 10	< 10	20
*Cr	44	< 10	26
*Cu	10	< 10	20
*Ga	< 10	< 10	20
Li	12	8	40
*Ni	20	< 10	60
*Rb	n.d.	330	n.d.
*Sr	150	42	450
*V	54	10	220
*Zr	300	440	200
B	17	2	7
F	250	120	500

NORMS

	2	3
Q	27·31	3·59
C	1·69	0·00
or	46·33	10·87
ab	15·57	19·89
an	0·93	29·40
di	0·00	3·04
hy	5·45	20·83
ol	0·00	0·00
mt	0·65	5·50
il	0·28	2·54
ap	0·02	0·72
Others	1·68	3·56
Total	99·91	99·94
Q	30·61	10·46
or	51·94	31·65
ab	17·45	57·89
Total	100·00	100·00
or	73·74	18·08
ab	24·78	33·06
an	1·48	48·87
Total	100·00	100·00
ab	94·38	40·35
an	5·62	59·65
Total	100·00	100·00

*Spectrographic determination   n.d. = not determined.

1. Sandstone, fine-grained, with calcareous matrix, 900 yd (820 m) E2°S of Efrigarth, Walls [277 503]. S 50128, Lab. No. 1992. Anal. J. M. Nunan and W. H. Evans, spectrographic work by C. Park. (*Summ. Prog.* 1967, p. 96).
2. Felsite sill cutting Walls Sandstone, hillside south of Longa Water, 800 yd (730 m) W37°S of West Burrafirth 'School' [263 567]. S 50129, Lab. No. 1991. Anal. J. M. Nunan and W. H. Evans, spectrographic work by C. Park. (*Summ. Prog.* 1967, p. 96).
3. Basalt lava flow, Water Head, west coast of Loch of Clousta, 850 yd (790 m) N 28°E of Grind [314 583]. S 50138, Lab. No. 1983. Anal. W. H. Evans, spectrographic work by C. Park. (*Summ. Prog.* 1966, pp. 76–7).

(Table 2) Chemical analyses of sandstone, felsite sill and basalt lava in Walls Sandstone.