Chapter 4 The metamorphic rocks of the Walls Peninsula

Introduction

Metamorphic rocks form an east-west trending outcrop, 1 to 2 miles (1.5–3 km) wide, which extends along the northern coast of the Walls Peninsula and the adjoining islands from Melby in the west eastward to Papa Little, where it is truncated by the Walls Boundary Fault (Plate 2). The succession is made up of four major lithological units and gives rise to relatively rugged terrain with a high proportion of rocky outcrops. The foliation of the metamorphic rocks has an overall east to north-easterly trend and an inclination which ranges from 40° to over 70° to the south or south-east. As the inclination of the foliation agrees roughly, both in direction and amount, with that of the bedding of the overlying Old Red Sandstone sediments, it is assumed that prior to the deposition of these sediments the foliation of the metamorphic rocks was approximately horizontal.

The succession is composed of the following groups, from north to south:

Vementry Group	Hornblende-schists and amphibolites interbedded with quartzo-feldspathic semi-pelites and some quartz-granulites.
Neeans Group	Platy feldspathic muscovite-biotite-schists with large lenticular masses of coarse hornblende-schist and a few thin bands of limestone and calc-silicate rock.
West Burra Firth Group	Tremolite- and mica-schists with numerous limestones.
Snarra Ness Group	Hornblende- and mica-schists with bands and lenses of amphibolite. Subordinate tremolite-schist and quartz-granulite.

The outcrops of these groups do not form continuous bands.

The Vementry Group is exposed only in the north-western peninsula of Vementry and the outcrop of the West Burra Firth Group thins out westwards between Bousta [HU 223 576] and Norby, apparently interdigitating with the Snarra Ness Group. The latter is present only in the area west of Brindister Voe. In the east the West Burra Firth Group is interdigitated with rocks similar to those of the Neeans Group. The present foliation is not everywhere concordant with the lithological boundaries, and detailed evidence (pp. 49–51) supports the view that it does not always coincide with the original bedding planes and other pre-foliation surfaces. The metamorphic rocks are cut by numerous faults and shear belts and the present boundaries between groups are, at least in part, tectonically modified.

A high proportion of the metamorphic rocks of the Walls Peninsula were originally sediments, probably siltstones and sandy siltstones with subordinate sandstones and limestones, together with one thick group of calcareous mud-stones and siltstones with fairly thick bands of limestone. The hornblende-schists and epidiorites of the hornblendic groups may have originated as basic lavas or pyroclastics, but the thick lenticular masses of coarse-grained hornblende-schist and amphibolite, which are present in all groups except the West Burra Firth Group, may represent thick basic intrusions.

The metamorphic rocks contain many quartzo-feldspathic lits and porphyroblasts as well as granite or pegmatite veins. The period of feldspar 'permeation' and granite veining commenced before the onset of the Main Phase of Folding (p. 49) and continued until after its completion. It probably spanned three metamorphic episodes (p. 54). Thermal metamorphism associated with 'permeation' may have been responsible for the local development of high temperature mineral associations (p. 57). Feldspar lits and granite veins are most abundant along the southern margin of the metamorphic belt, particularly within the Snarra Ness Group, which is now structurally the highest member of the series. Here granitic material makes up nearly 20 per cent of the total volume of the rock. Granite veining is intense in the West Burra Firth Group, but is much less pronounced in the Neeans Group, where it forms thinner and less closely spaced veinlets. In the Vementry Group, however, granite and pegmatite veining approaches the intensity of that in the Snarra Ness Group.

The mineral associations within the greater part of the metamorphic belt indicate that during the Main Phase of regional metamorphism pressure–temperature conditions were those associated with the greenschist-amphibolite transition facies (Turner 1968, pp. 303–7). Areas containing minerals indicative of higher temperatures are present only in the most intensely permeated and veined belt (p. 57). Over a large part of the outcrop the metamorphic rocks have suffered retrograde metamorphism which is associated with two periods of movement.

The probable metamorphic and tectonic history of the series can be summarized as follows:

	Deposition of sediments, extrusion of pyroclastics or lavas, emplacement of basic intrusions.
D_1 = MIS	?First folding. Evidence for this phase is inconclusive and based on the presence of planar and folded trains of inclusions in possible MIP porphyroblasts. Beginning of period of feldspar 'permeation' and granite-pegmatite veining.
D_2 = M2S	Main phase folding, producing the regional linear and planar tectonite fabric now seen in the rocks, by rotation and new growth of platy and acicular minerals. Texture fine-grained. New minerals include hornblende, biotite, muscovite. In calc-silicate rocks; epidote, clinozoisite, zoisite, tremolite, phlogopite.
M2P	Mimetic coarsening of fabric and late porphyroblast metamorphism. Annealing and growth of hornblendes, micas and epidote family minerals. Growth of porphyroblasts of garnet and albite-oligoclase. Near end of phase: Possible renewed movement causing rotation of garnets and new growth of mica.
D_3 = M3S	Intense shearing and granulitization, associated with east- to north-east trending faults. Local belts of mylonite and flinty crush. Retrograde metamorphism: garnet, biotite and, in part, hornblende to chlorite. Granulitization of quartz-feldspar aggregates.

The individual tectonic and metamorphic episodes described in this chapter have each been labelled with a combination of letters and numbers, so that a repetition of lengthy titles and descriptions could be avoided in the text.

The first letter of each combination indicates the type of deformation or alteration affecting the rocks. D thus stands for deformation and M for metamorphism.

The numbers 1 to 5 when preceded by D refer to the first to fifth period of deformation, or the first to fifth period of metamorphism if they follow on M.

The letter following the number in the combinations starting with M indicates that the metamorphism was either synchronous (S) with the deformation or has post-dated (P) it. The letter P also indicates that metamorphism took place in a passive environment in which new minerals, whose orientation was not affected by any stress pattern, could grow. Similarly the letter S indicates that the new minerals were formed in an environment subjected to directional stress, and that their alignment follows a planar or linear pattern.

D_4 = M4S	Dextral kink folds and belts of conjugate folds. Granulitization and 'mortar texture'. Bending of micas. Local biotite to chlorite. New chlorite parallel to axial planes of microfolds.
M5P	Thermal metamorphism, north-west Vementry. ?Associated with intrusion of Vementry Granite or Muckle Roe Granophyre. New minerals biotite, actinolite.
D_5	Regional tilting to south-south-east. (= F_1 affecting Sandness and Walls formations, see p. 126). Associated with formation of east to north-east trending faults and crushes close to and along junction between basement and Old Red Sandstone sediments. No mineral reconstruction.
D_6	NNE to NNW trending major faults with associated narrow belts of conjugate folding. These large-scale block movements of the basement may be contemporaneous with the NE to NNW trending folds in the Sandsting and Walls Formations, i.e. F_2 affecting Walls Sandstone. (p. 134).

Radiometric ages of samples from the metamorphic rocks, determined by the potassium-argon method, have been obtained by Dr. N. J. Snelling. These are as follows:

IGS 67.1	Muscovite from platy muscovite-biotite-gneiss, Neeans Group, south-west slope of Muckle Hoo Field [HU 267 585], 330 yd (300 m) E14°N of south end of Maw Loch. Percentage potash 8–22. Radiogenic argon 1–458.10^{-4} scc/gm. Age 399.5 15 m.y.
IGS 67.2	Muscovite from platy micaceous granulite, Neeans Group, shore between Ayre of Whalwick and Turl Stack [HU 258 586], 220 yd (200 m) N of Whalwick. Percentage potash 8.37. Radiogenic argon 1.558.10^{-4} scc/gm. Age 416 ± 16 m.y.
IGS 67.3	Muscovite from platy micaceous granulite, same locality as IGS 67.2. Percentage potash 8.55. Radiogenic argon 1.576.10^{-4} scc/gm. Age 413 1 16 m.y.
IGS 67.48	Hornblende from garnet-amphibolite, Snarra Ness Group, south shore of West Burrafirth [HU 244 570], 1250 yd (1150 m) W10°N of Burraview. Percentage potash 0816. Radiogenic argon 1.593.10^{-5} scc/gm. Age 435 + 20 m.y.
IGS 67.49	Hornblende from garnet-amphibolite. Same locality as IGS 67.48. Radiogenic argon 1.323.10^{-5}. Age 415 ± 20 m.y.

Snelling states that the ages obtained do not differ significantly within the limits of experimental error. The average of these ages is 415.5 m.y., which is virtually the same as that of the ages obtained by Miller and Flinn (1966, pp. 100–3) from specimens from the Shetland East Mainland succession which is 422 m.y., and from the zone of Read's second metamorphism in the Valla Field Block of Unst (Read 1934) which is tentatively dated at 418 m.y. The ages from Western Shetland are not thought to date any of the metamorphic or tectonic events listed above. They merely set a younger limit to the time of metamorphism, possibly pinpointing the last time at which the temperature of the rocks fell below 200°C (cf. Harper 1967). They may thus date the period of uplift that preceded the deposition of the Old Red Sandstone sediments.

Lithology

Vementry Group

The outcrop of the Vementry Group is confined to the north-western peninsula of the Island of Vementry and possibly to a narrow strip along the southern margin of the Vementry Granite in central Vementry. The group consists of feldspathic and quartzose schist and granulite together with hornblende-schist and garnet- or epidote-amphibolite. The acid and basic rock types are inter-banded and occur in roughly equal proportions. Two distinct varieties of hornblendic rocks are present. The massive poorly foliated, generally coarse-grained hornblende-rich types are here termed amphibolite. They form distinct lenses which give rise to marked topographic features, and probably originated as sills of melanic dolerite or gabbro. The second type are strongly foliated finer-grained hornblende-schists which form an integral part of the metasedimentary succession and may originally have been basic lavas or tuffs.

Amphibolite and epidotic amphibolite form bodies, which range in size from massive, coarse-grained lenses over 110 yd (100 m) wide, like that forming Heill Head, to narrow finer-grained black bands only inches wide. Coarse amphibolites (S30780) [HU 343 532], (S49310) [HU 283 614] consist of poorly aligned moderately acicular crystals of dark grey hornblende, which in thin section is pale yellowish green and only faintly pleochroic, together with porphyroblasts of pink garnet, which are up to 0.4 in (10 mm) in diameter and generally contain aligned or helicitically arranged inclusions of quartz or epidote. Though epidote forms inclusions within the garnets of some rocks neither epidote nor clinozoisite normally occur together with garnet in the same rock. These calc-silicate minerals form up to 40 per cent by volume of some amphibolites and occur as either slightly elongated crystals of subhedral to euhedral shape, or as crystal networks. The feldspar is albite-oligoclase, which in some cases forms porphyroblasts enclosing bent hornblende crystals. Accessory minerals are sphene, which commonly forms parallel trains of inclusions in hornblende, apatite, zircon, ilmenite, and pyrite. The composition of hornblende-schists (S30720) [HU 286 615], (S49315) [HU 289 616] is similar to that of amphibolites, though they are finer-grained, have a stronger fabric and contain a higher proportion of albite-oligoclase and subordinate quartz.

The feldspathic schists (S30730) [HU 286 603], (S30728) [HU 286 612] consist of albite-oligoclase, large garnet porphyroblasts, and epidote, which in some instances (S49311) [HU 284 615] forms a high proportion of the rock. The plagioclase is either partially altered to clay minerals and sericitized or has aligned patches of clinozoisite. Micas are subordinate in amount and the biotites are commonly retrogressively altered to chlorite.

The schists are traversed by veins of granite and contain many feldspathic lits. There are also a number of pale non-foliated bands, tens of metres thick, which are composed entirely of sodic plagioclase, quartz and epidote group minerals. Many feldspathic granulites contain small ovoid pods of amphibolite and at one locality quartzo-feldspathic schist contains irregular streaks and patches of pyrite.

The outcrop of the Vementry Group is cut by a number of major north-east to east-north-east trending Crush belts (Plate 2), and the entire area is traversed by innumerable sub-parallel and intersecting minor crush planes, which are present in almost every thin section from the area (Phase D_3 of p. 41). The intensity of the crushing increases northwards, and in the northern half of the peninsula intersecting shear planes have in part obliterated the D_2 foliation and lineation. Crush-rock approaching mylonite in texture (S49316) [HU 291 617], (S49345) [HU 291 616], (S49313) [HU 289 616] is developed in many crush belts. On the east coast of Swarbacks Head the hornblende-schists are largely reduced to fine-grained greenish chlorite-schist. Over the greater part of the outcrop oligoclase and quartz are intensely granulitized and streaked out into lenticles (S30721) [HU 286 617], with minute grains of new epidote (S49345) [HU 291 616] and patches of chlorite developed in the feldspar. The lenticles are thinly sheathed in chlorite or in irregular bands of mylonite. In the less sheared specimens (S49308) [HU 289 612] quartz is granulitized, but the plagioclase is bent and fractured. Garnets are shattered, rotated and in many cases streaked out (S47806) [HU 283 612]. They are altered to chlorite, either completely or to varying extents along cracks, and generally enclosed in a sheath of chlorite flakes. Amphibole is in most cases only bent and shattered. Only in the north-east of the peninsula is there appreciable retrogression of hornblende to chlorite (S49315) [HU 289 616]. Epidote and clinozoisite show little evidence of mechanical break-up and none of secondary alteration, suggesting that much of it may have recrystallised during this phase of movement.

Neeans Group

Platy feldspathic muscovite-biotite-schist forms two belts separated, in the eastern part of the area, by the West Burra Firth Group (Plate 2). In both belts the predominant rock type is pink to buff platy feldspathic and garnetiferous mica-schist or granulite. The texture is locally almost gneissose, but regular feldspar lits, characteristic of true gneiss, are nowhere present. The group contains a number of thick belts of more massive quartz-epidote-feldspar-granulite which form prominent escarpments in the Neeans peninsula (Plate 5A). In the eastern and southern parts of Vementry Island the group contains a number of silvery mica-schists which are almost phyllitic.

Though the ratio of hornblende-schist and amphibolite to mica-schist is considerably lower than in the two hornblendic groups, amphibole-rich bands and lenses, which commonly contain a high proportion of epidote and clinozoisite, are present throughout the group. Lenticular masses of poorly foliated amphibolite or amphibolite-epidosite, which may originally have been basic sills, are up to 75 yd (70 m) wide and 380 yd (350 m) long and form prominent topographic features. Rather better foliated hornblende-schist forms many smaller lenses and bands. The latter show intense internal folding and regular alignment of hornblende needles. Limestone and epidosite bands, some over 10 ft (3 m) thick, are present throughout the group, but form less than 1 per cent of the total volume of rock. The limestone and epidosite ribs are associated with both mica-schists and hornblende-schists. Though thin granite and pegmatite veins are present throughout the group, they are generally much thinner than in the other groups and form a lower proportion of the total rock volume.

A small, almost round, outcrop of serpentinite, 55 yd (50 m) in diameter, occurs within the group on Vementry Island, close to the north-west corner of Maa Loch [HU 297 604]. This is composed of 70 per cent antigorite, and 20 per cent talc which forms irregular fibrous patches, together with small grains of opaque ore minerals (S30733) [HU 298 603]. The serpentinite has no planar or linear fabric, but its field relationships suggest that it was involved in at least some of the deformation undergone by the metamorphic rocks.

The feldspathic schists and granulites (S30715) [HU 302 600], (S47760) [HU 275 594], (S47745) [HU 277 594], (S47753) [HU 269 594] are composed of quartz, albite-oligoclase, muscovite, biotite and garnet. Muscovite forms large plates whereas biotite, which is either strongly pleochroic, deep brown to greenish brown or reddish brown, forms smaller plates, generally bounding the muscovite. Chlorite normally occurs as the retrograde alteration product of biotite and garnet. It is abundant in areas adjoining the major N–S and ENE trending faults and along belts of strong D_4 folding (S49324) [HU 307 606]. Chlorite plates are also developed along and parallel to the axial planes of some D_4 folds (S49319) [HU 295 595]. The thinly foliated phyllitic muscovite-schist exposed in the eastern and southern peninsulas of Vementry Island (S49319) [HU 295 595], (S49320) [HU 295 589], (S49326) [HU 311 604] contains small needles of tourmaline (pp. 52, 58). Some of the pale granulites within the group contain varying amounts of epidote and clinozoisite and, more rarely, tremolite. Some contain interstitial calcite which has partially replaced quartz and plagioclase. Abundant accessory minerals are sphene, apatite, zircon, rutile and pyrite.

The limestones (S50135) [HU 264 590], (S30746) [HU 285 591] consist of calcite, quartz, clinozoisite and epidote together with accessory cloudy feldspar and muscovite. Both tremolite and phlogopite (S49321) [HU 294 588], (S47754) [HU 260 588] have been recorded in subordinate amounts in the northern part of the group's outcrop, but are more abundant near the junction with the West Burra Firth Group. Limestones commonly grade into, or are interbanded with almost calcite-free calc-silicate-rock, which in many outcrops is closely associated with amphibolite. The most common constituents of calc-silicate-rocks within this group (S47758) [HU 265 589], (S47759) [HU 275 595] are epidote and clinozoisite, which forms euhedral to subhedral, frequently zoned, crystals, set in an interstitial matrix of quartz. Some epidotes have central zones of allanite. Sphenes forming both large euhedral and small aligned crystals are abundant. In several specimens (e.g. (S47749) [HU 267 588], the sphene crystals contain rutile, which forms symplectic intergrowths with sphene. Many calc-silicate rocks contain interstitial calcite, others contain varying amounts of bluish green hornblende or, more rarely, needles of tremolite.

The essential constituents of the amphibolites of this group (S31005) [HU 271 589], (S50137) [HU 267 584] are hornblende, which in most areas is pleochroic from pale greenish yellow to bluish green, but in Vementry Island, close to the junction with the Vementry Group (S30729) [HU 291 603], is pale green and garnet, which forms large porphyroblasts, in many cases with inclusions of albite-oligoclase or oligoclase, quartz, and sphene. Epidote and clinozoisite form bands within many non-garnetiferous amphibolites. These bands are of slightly finer grain than the adjoining hornblendic bands.

Retrograde metamorphism (M3S) associated with the D_3 phase of shearing (pp. 57–58) is much less pronounced than in the Vementry Group and most zones of intense crushing, granulitization and conversion of garnet and biotite to chlorite are associated with the major north–south trending faults. These form belts up to 110 yd (100 in) wide within which the schist is intensely crushed and chloritized and partially mylonitized.

West Burra Firth Group

The West Burra Firth Group is characterized by the presence of abundant ribs of limestone and bands of tremolite-phlogopite-schist. The limestones are commonly 2 to 12 yd (2–10 m) thick, but in the area between Norby and Bousta one persistent limestone locally reaches a thickness of 65 yd (60 m). Owing to the intense folding undergone by most limestones in the group during the D_2 phase it is not possible to estimate their original thickness. Many of the thinner limestones are closely associated with amphibolite and hornblende-schist, which are more common than in the Neeans Group. Feldspathic muscovite-biotite-schists and quartz-granulite form approximately 40 per cent of the total volume of the group.

The rocks of the group are intensely veined by microgranite and pegmatite and 'permeated' by feldspar porphyroblasts, particularly in the eastern part of the outcrop where the group directly underlies the faulted or locally unconformable junction with the Old Red Sandstone sediments.

The characteristic mineral assemblage of the limestones (S49299) [HU 222 578], (S30595) [HU 216 581], (S31013) [HU 259 580] is calcite, clinozoisite or zoisite, tremolite, phlogopite, feldspar (oligoclase in (S31012) [HU 259 571] and quartz. The latter is partially replaced by calcite. Epidote is subordinate to clinozoisite in this group. In some of the limestones exposed in the area between the Bay of Garth and Bousta (S33779) [HU 223 579] the interstitial feldspar is partially altered to a symplectic intergrowth of zoisite and quartz or a more irregular intergrowth of zoisite and sodic plagioclase. In contrast to the limestones of the Neeans Group, most of these limestones contain a much higher proportion of tremolite than zoisite, clinozoisite or epidote. Diopside had been recorded in limestones in two restricted areas within the group: on the south-east shore of the Bay of Garth (S30599) [HU 219 581] and close to the east shore of West Burra Firth (S31012) [HU 259 571]. In the first locality diopside is largely altered to tremolite and clinozoisite, in the second the diopside is associated with clinozoisite and is partly altered to carbonate and rimmed by pale acicular amphibole (tremolite). No forsterite or pseudomorphs after forsterite have been detected. Sphene is present in nearly all limestones.

Calc-silicate rocks composed largely of epidote and clinozoisite together with quartz, feldspar and muscovite are present within the central part of the group's outcrop (i.e. around Brindister Voe, (S47737) [HU 277 577], but in the more western (S47786) [HU 257 571], (S47787) [HU 253 573], (S50805) [HU 206 569] and eastern (S47792) [HU 318 601] parts of the outcrop, the original impure calcareous sediments are now represented by strongly lineated tremolite-phlogopite-schists, which in most cases contain subordinate calcite, epidote, clinozoisite, quartz, sodic plagioclase, sphene, apatite, ilmenite, pyrite and, in places, chlorite. Near the eastern end of West Burra Firth diopside forms an important component of some tremolite-schists (S50132) [HU 259 575], No. 4 of (Table 1). In these the diopside is shattered and streaked out parallel to the lineation, patchily altered to calcite and partly replaced by tremolite (p. 57).

A characteristic feature both within this group and in the other groups is the euhedral to subhedral shape of most minerals of the epidote family, even in areas affected by later retrograde metamorphism. Many epidotes are zoned (S47734) [HU 275 577], and some have a central zone of allanite (S47738) [HU 280 577]. The zoning suggests that growth took place in a number of stages during the phase of static metamorphism. In some instances the alignment of the epidote crystals is at a slight angle to the regional foliation, indicating that crystallisation was not always mimetic. Minerals of this family display no compositional and relatively little mechanical alteration in areas strongly affected by later shearing and retrograde metamorphism. Some crystals in specimens from these areas are slightly broken and re-annealed, indicating that these minerals continued to grow under conditions of much lower temperature and pressure. The growth of members of the epidote and zoisite groups appears thus to have spanned several major tectonic episodes.

In the vicinity of Bousta (S33774) [HU 220 579] zoisite or clinozoisite forms symplectic intergrowths with quartz and acid plagioclase. These intergrowths appear to result from the breakdown of plagioclase porphyroblasts.

The mineral content of amphibolites and hornblende-schists in the West Burra Firth Group does not significantly differ from that of the amphibolite of other groups. Both pleochroic bluish-green varieties and pale varieties of hornblende have been recorded. Garnet poikiloblasts up to 10 mm in diameter with inclusions of quartz, hornblende and sphene are present in the massive amphibolites. Both the interstitial and porphyroblastic feldspar is albite-oligoclase. Greenish brown biotite is present in many hornblende-schists, and in some cases the orientation of the mica cleavage-plates is at an angle to the long axes of the hornblende (S47761) [HU 269 591].

Snarra Ness Group

The Snarra Ness Group is characterized by a preponderance of hornblende-schists over quartz-feldspar-granulite and feldspathic muscovite-biotite-schist. Large and small lenses and pods of poorly foliated amphibolite are abundant. Limestones and epidote-rich rocks are virtually absent over the greater part of the outcrop, but on the south-west shore of the Bay of Brenwell (Plate 2) there is a small area in which the lithology is that characteristic of the West Burra Firth Group. It is probable that this outcrop is not an integral part of the Snarra Ness Group, but an infolded or infaulted portion of the West Burra Firth Group.

The amphibolites of the Snarra Ness Group (S47763) [HU 269 572], (S47784) [HU 255 569], (S49298) [HU 222 578], (S50131) [HU 280 579]; (Table 1) consist of large vaguely aligned plates of hornblende which are pleochroic from yellowish green to bluish green ((Plate 6), fig. 4), garnet porphyroblasts sieved with quartz, feldspar and hornblende, together with interstitial quartz and sodic plagioclase. Some amphibolites contain porphyroblasts of deep brown biotite (S47779) [HU 246 570] and many contain abundant sphenes which are aligned in trails that pass through the coarse crystals of hornblende and biotite without displacement (S47762) [HU 268 571] (p. 55). Both epidote and clinozoisite are present in variable amounts within garnet-free amphibolites, where they are commonly concentrated in bands.

In the area west of the Bay of Brenwell the distinction between the West Burra Firth Group and the Snarra Ness Group is ill defined. Limestones less than 3.5 ft (1 m) thick are present in the cliffs on the Neap of Norby, which consist of hornblende-schist and muscovite-biotite-schist with lenses of amphibolite. These rocks are intensely veined by granite and pegmatite and permeated by feldspathic lits and porphyroblasts. They are cut by a number of sub-parallel north-east trending faults and are intensely shattered throughout. Most of these faults, which are parallel to the Melby Fault (p. 265), are fractures apparently formed at a high crustal level as they have produced brittle fracturing and have soft clay in the fault planes.

Granite and pegmatite veins and intrusions

The Snarra Ness, Vementry and West Burra Firth groups are intensely veined by both trondhjemitic microgranite, which is locally almost felsitic in texture and trondhjemitic granite and pegmatite. These trondhjemitic rocks (S49926), (S50804) [HU 202 572] are composed of sodic plagioclase (oligoclase or albite-oligoclase), quartz and subordinate muscovite and/or biotite. Potash feldspar is present in minute interstitial patches in a number of pegmatites. Many of the veins are pre-or syn-tectonic as they have been involved in the D_2 tectonic episode, being themselves weakly foliated and folded either with the foliation or by differential slip along the foliation (Plate 5B), rodded or mullioned parallel to the lineation or lensed out into discrete pods. The foliation is not always obvious owing to the virtual absence of platy minerals.

Non-foliated post-D_2 trondhjemitic intrusions are equally common. These form either cross-cutting veins, or veins which mimetically follow the folded foliation of the country rock (Plate 4B). Some amphibolites are patchily net-veined by microgranite to produce areas of agmatite. In such intensely veined areas parts of the amphibolite contain feldspar porphyroblasts up to 0.75 in (2 cm) in diameter, which are round or oval-shaped in cross-section.

In the areas just north of Longa Water and Djuba Water within the Neeans peninsula, and in the ground south of Loch of Collaster [HU 208 571], near Norby, there are some larger masses of trondhjemitic granite. These are not obviously foliated, but some are elongated parallel to the foliation. The largest is 170 yd (150 m) long and up to 55 yd (50 m) wide. They are similar in composition to the granite veins, being composed of oligoclase, slightly granulitized quartz, subordinate greenish brown biotite partially altered to chlorite, muscovite and apatite. Potash feldspar forms only small interstitial patches.

(Table 1) Chemical analyses of Walls Peninsula metamorphic rocks

	1	2	3	4	5	6
SiO_2	47.85	48.69	32.85	50.62	72.08	61.62
Al_2O_3	13.74	14.89	8.72	5.31	12.61	13.80
Fe_2O_3	2.81	3.29	0.53	0.17	0.99	4.31
FeO	10.14	6.47	2.71	1.94	3.28	1.10
MgO	7.65	8.12	4.70	19.10	1.50	2.21
CaO	9.85	12.01	2740	1621	1.15	13.74
Na_2O	1.71	2.16	1.04	0.55	2.52	0.10
K_2O	1.09	0.53	2.18	0.86	2.58	0.15
H_2O >105°	2.11	1.96	1.17	1.79	1.68	1.22
H_2O <105°	0.21	0.13	0.17	0.22	0.18	0.12
TiO_2	1.94	1.17	0.38	0.22	0.66	0.77
P_2O_5	0.15	0.11	0.13	0.07	0.12	0.03
MnO	0.21	0.19	0.07	0.06	0.10	0.14
CO_2	0.24	0.04	17.66	2.80	0.14	0.35
FeS_2	0.13	n.d.	n.d.	n.d.	n.d.	n.d.
Organic C	—	—	—	0.04	—	—
Allowances for minor constituents	0.16	0.14	0.22	0.29	0.20	0.19
	99–99	99.90	99.93	100.25	99.79	99.85
	ppm	ppm	ppm	ppm	ppm	ppm
*Bo	82	20	470	125	580	50
*Co	35	20	<10	<10	<10	<10
*Cr	92	220	80	30	45	56
*Cu	74	22	<10	<10	10	<10
*Ga	<10	10	<10	<10	22	30
Li	12	7	15	25	12	10
*Ni	65	86	22	<10	40	54
*Sr	100	150	740	230	190	480
*V	390	270	60	40	80	120
*Zr	140	85	70	20	260	490
B	6	9	5	3	10	4
F	450	300	800	4000	500	380
S	—	—	—	200	250	—

*Spectrographic determination

n.d. not determined

- 1. Garnetiferous hornblende-schist, Snarra Ness Group. South coast of West Burra Firth, 220 yd (200 m) N7°E of Hogan [HU 247 569]. (S50131), Lab. No. 1990. Anal. W. H. Evans and J. M. Nunan, spectrographic work by C. Park, (*A. Rep. Inst. geol. Sci.,* 1967, p. 96).
- 2. Hornblende-schist, Neeans Group. 370 yd (340 m) E7°S of south-west corner of Maa Loch, Neeans peninsula. [HU 267 584]. (S50137), Lab. No. 1984. Anal. W. H. Evans, spectrographic work by C. Park, (*A. Rep. Inst. geol. Sci.,* 1967,p. 95).
- 3. Limestone with talc-silicate minerals, West Burra Firth Group. 470 yd (430 m) N38°W of Engamoor, Neeans peninsula [HU 257 576]. (S50133), Lab. No. 1988. Anal. W. H. Evans, spectrographic work by C. Park, (A. *Rep. Inst. geol. Sci.,* 1967,p. 95).
- 4. Tremolite-schist with calcite, diopside and phlogopite, West Burra Firth Group. 240 yd (220 m) N46°W of Engamoor [HU 259 575]. (S50132), Lab. No. 1989. Anal. W. H. Evans, spectrographic work by C. Park, (*A. Rep. Inst. geol. Sci.,* 1967,p. 95).
- 5. Feldspathized garnetiferous muscovite-biotite schist, Neeans Group. West side of Geo of Djubaberry, 710 yd (650 m) N16°W of south-western end of Maw Loch [HU 263 590]. (S50134), Lab. No. 1987. Anal. W. H. Evans, spectrographic work by C. Park, (*A. Rep. Inst. geol. Sci.,* 1967,p. 95).
- 6. Calc-silicate rock with epidote, calcite and hornblende. Neeans Group. East side of Geo of Djubaberry, 630 yd (560 m) N12°W of south-western end of Maw Loch [HU 264 590]. (S50135), Lab. No. 1982. Anal. W. H. Evans, spectrographic work by C. Park, (*A. Rep. Inst. geol.* Sci., 1966, pp. 76–7).

Structure

Introduction

The probable stages in the structural development of the metamorphic rocks are set out in tabular form on pp. 40–41. The original bedding planes of the metasediments and contacts of igneous extrusive and/or intrusive bodies are now largely obliterated and the evidence for the deformation or deformations which produced the planar fabric of the rock prior to the Main Phase cannot be demonstrated in the field (p. 55). The foliation, lineation and related minor folds now visible in the rocks were formed during the Main Phase (D_2) of folding and during the subsequent mimetic coarsening of the fabric (p. 56). In parts of the area, especially in the north-west corner of Vementry Island, both lineation and foliation have been partly obliterated by intense shearing and shattering along innumerable east to north-east trending crush belts (D_3). At a later period (D_4) dextral kink folds and belts of conjugate folds with consistently east-south-east trending axes were formed, probably at a high crustal level. These did not greatly modify the D_2 fabric, but in the belts of intense D_4 folding the D_2 lineation is, in places, slightly obscured. In north-west Vementry shear planes attributed to the D_3 phase of crushing are folded by D_4 conjugate folds.

The period of folding which produced the complex east-north-east trending synclinorium within the Walls Sandstone (p. 126) appears to be responsible for the present east to north-easterly trend and the south-south-easterly inclination of the foliation of the metamorphic rocks (D_5). Apart from many sub-parallel fault planes close to the junction between the two formations, this period of folding does not appear to have produced minor structures within the metamorphic basement. The second phase of folding recognized within the Walls Sandstone (p. 134) may here have produced open north–south trending synforms and antiforms (D_6) which express themselves as bulges in the outcrop of the junction between the metamorphic rocks and Old Red Sandstone (Plate 2). Major faults with trends in the north-north-west to north-east sector, which traverse the Neeans peninsula may also be associated with this phase of earth-movement. Some of these faults are accompanied by belts of box- and conjugate-folds, whose axial trends are unrelated to those of the D_4 folds.

Geometry of main structural elements

Foliation

The strike and dip of the foliation in the metamorphic succession are roughly parallel to those of its upper, partially sheared, junction. The strike varies from S20°W to W40°N and its mean is W10°S ((Plate 3)A). The inclination of the foliation close to the junction is almost everywhere roughly parallel to the dip of the adjoining Old Red Sandstone, though discordances of up to 30° are locally recorded. As the junction between the two formations does not have the appearance of a major dislocation (pp. 73–74 and p. 53) it is assumed that prior to the D_5 phase of folding the foliation was horizontal or gently undulating with local 'dips' not greatly exceeding 30°.

Lineation

Linear structures are very pronounced in all areas except the northern peninsula of Vementry. Their mean plunge is 30° to S20°W and the variations in inclination and trend are shown in (Plate 3)A. The local reversals in inclination to the north-east close to the east shore of the Neeans peninsula and along the west shore of The Rona may be due to late large-scale (?D_6) flexuring associated with major NNW-trending faults. If the succession is 'rotated' and unfolded back to its pre-D_5 attitude, it is seen that the pre-Old Red Sandstone plunge of the linear structures ranged from horizontal to possibly 30° to NW.

Main phase of folding (D_2)

Fabric

The D_2 tectonite fabric is strongly developed in most rock types except some quartzites and some epidote-clinozoisite rocks, which superficially have no preferred mineral orientation. The fabric pattern which ranges from planar (s-tectonite) to linear (l-tectonite) is, in this area, determined by the rock type rather than the local or regional stress pattern. Throughout the area the micaceous schists, gneisses and granulites have a predominantly planar fabric owing to the parallel orientation of platy minerals. The linear fabric in these rocks is largely due to a poorly developed small-scale rodding of the feldspathic lits, and the elongation of feldspar augen and the 'bending' of platy minerals around these structures. Micaceous schists with a strong linear fabric (l-s tectonites) (Plate 4A) contain a fairly high percentage of an acicular mineral, such as tremolite, or, less commonly, hornblende. Some lenses of epidotic amphibolite have a pronounced s-fabric, which is brought out by the banding of hornblende-and epidote-rich layers, but this fabric is in many cases disrupted by irregular internal folding (p. 50) along the margins of such basic lenses. Strong l-fabrics are present in tremolite-schists, tremolite-bearing limestones and the outer zones of amphibolite pods. Limestones and calc-silicate-rich limestones which are devoid of nematoblastic minerals have an internal banding which is intensely folded around axes parallel to the lineation (Plate 4C). As these minor folds weather out into parallel rods or tubes they impart a strong macroscopic linear fabric to the outcrop. In areas where the foliation is not folded, the limestone has a strong layering due to the differential weathering of limestone and calcsilicate or feldspar-rich ribs.

Though there are no zones which have a predominantly l- or s-tectonite fabric which is independent of lithology, there are areas in which the linear elements are partially obliterated by later folding or shearing parallel to the foliation. Thus D_2 lineations are very faint in belts of intense D_4 folding, in the intensely shattered parts of north-west Vementry, and in the narrow belt of sheared and faulted rocks close to the junction with the Old Red Sandstone.

Apart from minor folds the most commonly developed megascopic linear structures within the series are the rodding of feldspar lits and, less commonly, of microgranite veins. Along the coast of the Bay of Garth [HU 216 581] bands of quartzite and quartz-granulite adjoining a thick limestone have a well-developed mullion structure. In cross-section the mullioned quartzite ribs have a characteristic lobate form with narrow embayments.

Early D_2 minor folds

Small similar folds, which range in wavelength from several millimetres to 5 ft (1.5 m) are present in all lithological units throughout the series. In rock types with a predominantly planar fabric the axial planes of the folds are parallel to the regional foliation and the tightness of the folds ranges from isoclinal to tight (cf. Fleuty 1964, p. 47). The folds generally have rounded hinge zones and long, straight limbs (Plate 4B),(Plate 4C). The folds in the Vementry Group appear to be tightest being isoclinal with intensely corrugated hinge zones. Isoclinal folds with less corrugated hinge zones occur in the northern part of the Neeans peninsula, but farther south the folds are more open and less complex.

In the lithological units characterized by a linear fabric, such as limestones, tremolite-schists, and some amphibolites, the D_2 minor folds have axial planes whose inclination bears no obvious geometrical relationship to the attitude of the regional foliation. Many axial planes are curved and adjacent planes are not necessarily parallel. Flow folds in which the thickness of individual folia varies widely are developed in amphibolites and, more rarely, in platy mica-schists. In limestones the style of folding is in places extremely plastic, with individual laminae disrupted and feldspar lits or granite veins reduced to small irregular fragments. The plunge of fold axes in most limestones is, however, parallel to the regional lineation.

Flinn (1967, p. 283) has shown that, in Eastern Shetland, the most common folds in his East Mainland Succession are 'internal folds' in the flaggy semipelites. These folds are found in 'beds' whose bounding planes are not deformed, but which exhibit intricate flowage folds within them. Flinn suggests that these folds are associated with pinch- and swell-structures and result from inhomogeneous flow within them. In West Shetland the flow folds in the limestones and the disharmonic folds in the pods of banded epidotic amphibolite are of similar origin.

Granite veins cutting the schist commonly exhibit ptygmatic folding and, in some instances, stepping of the vein along the planes of schistosity is seen (Plate 5B). Many granite veins follow the folded foliation of the country rock. These veins are usually thicker in the axial zones of the folds than in their limbs. As many of these veins have branches which cut the regional foliation without displacement, it is likely that most are 'mimetic' in the sense that they follow originally deformed planes and were intruded just after or during a late stage of the folding (Plate 4B).

Local post-D_2 pre-D_4 minor folds

All the folds described above are thought to have been formed during the main phase of folding, when the rock acquired its present schistosity. These folds have axial planes which are either parallel to the schistosity or are curved or disrupted by flowage. In addition to these folds there are a number of small isolated areas with folds whose axes are parallel to the regional lineation but whose axial planes are almost normal to the foliation. Minor folds of this type are seen on the south shore of West Burra Firth [HU 244 571]. Many have a narrow or acutely angled hinge area, an interlimb angle of 100°–120° and a rudimentary axial plane cleavage which is almost normal to the main schistosity. Small interconnected veins of microgranite follow both the original schistosity and the later cleavage, indicating that this folding took place before the phase of granite and pegmatite vein emplacement had ceased. It thus appears to be the result of a weak localized phase of movement which took place after the main phase folding but before the D_4 phase of folding, which everywhere post-dates the granite and pegmatite veining.

Phase of intense shearing and granulitization (D_3)

The north-western peninsula of Vementry Island is traversed by a number of major east to north-east trending shear-belts as well as innumerable intersecting minor faults of variable trends and small throws (Plate 5B). In the northern part of this peninsula the faulting is in places sufficiently intense to have obliterated both the lineation and foliation of the rocks. In the less intensely sheared parts of the area the faults make an angle of 15°–40° with the foliation. Most of these are normal faults with throws of less than 8 in (20 cm). The faults invariably cut the microgranite and pegmatite veins but are themselves folded by D_4 conjugate folds. All fault planes are sharply defined and contain no soft crush-rock, suggesting that they were formed under relatively high confining pressures. Similar faults intersecting the foliation at a low angle are present on the northern coast of the Neeans peninsula.

Kink bands and conjugate kink-folds (D_4)

Small straight-hinged angular monoclines of the type which have been termed kink bands, kink zones and knee-folds (Ramsay 1967, p. 436) are developed in the thinly foliated rocks throughout the series. The axes of these folds have a consistent east-south-easterly trend (Plate 3)B, which in many areas is normal to the trend of the D_2 linear structures. The steep limb of the folds, which varies in length from 2 in (5 cm) to just over 1 ft 8 in (50 cm) is almost always on the south side of the fold-crest when viewed from the west-north-west, producing a consistent dextral shift of the foliation planes. In rare cases the axial plane of the fold has become a slip plane along which small displacement has taken place. Individual folds can be traced for several yards along the crest, and adjacent folds are arranged *en échelon.* These folds have folded but not obliterated the D_2 linear fabric. In areas with closely and regularly spaced kink folds joint planes with slight or negligible displacement are developed roughly parallel to the axial planes of the folds.

Along a number of fairly well-defined east-south-east trending belts the intensity and amplitude of the D_4 folds is greatly increased. In these zones kink bands are accompanied or replaced by conjugate folds, which are straight-hinged angular folds with two intersecting axial planes (Johnson 1956). Conjugate folds are best developed in flaggy or platy granulites or schists, and many fine examples are exposed on the north coast of the Neeans peninsula, 300 yd (270 m) N of Whalwick [HU 258 585]. In the most intensely deformed parts of these zones the style of the folds becomes less brittle. Thus along the coast just north-east of the Bay of Garth [HU 217 582] a series of tight E 10°S trending flexural-slip folds with rounded hinge zones are seen. In both zones of intense D_4 folding which cross Vementry Island (Plate 3)B, the folds locally lose their conjugate symmetry and box-shaped outline and become flexural-slip folds with one axial plane. In the most intensely deformed area of the northerly zone fairly open east–west trending similar folds with an axial-plane cleavage are developed. In the areas of intense D_4 folding bedding-plane slip has partially obliterated the macroscopic D_2 linear fabric. There is also some correlation between the intensity of D_4 folding and the platiness of the mica-schists and granulites involved. As the axes of the kink-folds and conjugate folds throughout the series lie within the plane of the D_2 schistosity, their plunge varies according to the trend and inclination of this schistosity, and in some areas such as 250 yd (230 m) N of Houlma Water [HU 268 579], where there is a marked local variation in the attitude of the foliation along the hinge of a D_5 fold, the plunge of the D_4 kink folds changes abruptly. Evidence such as this suggests that the D_4 folding preceded and was unconnected with the D_5 phase of folding and regional tilting.

Regional tilting to the south-south-east (D_5)

As the regional trend and inclination of the foliation within the metamorphic rocks is more or less parallel to the strike and dip of the adjoining sedimentary rocks of Old Red Sandstone age it can be assumed that the tilting of the two formations took place during the first phase of folding that affected the Walls Sandstone (F_1 of p. 126). The mean trend of the F_1 fold axes within the latter is E15°N. This phase of folding has produced no minor folds or other small-scale penetrative structures within the metamorphic succession.

In the southern part of the Neeans peninsula there is a marked change in the regional strike of the foliation along a line trending approximately E10°S. This line appears to mark the outcrop of a fold hinge which has developed into a rotational fault plane. Another example of late rotation of entire blocks within the metamorphic succession is found on the north-west coast of the Neeans peninsula, south-west of Turl Stack [HU 257 586] where, in an area bounded by faults, the lineation has been rotated clockwise by 60° relative to the regional lineation (Plate 3).

Late north-north-west trending folds (D_6)

Both the metamorphic rocks and the overlying Old Red Sandstone are affected by two gentle NNW-trending folds. In the Norby–Bousta area a large open N15°W trending syncline extends from the Bay of Garth southwards to the junction with the Old Red Sandstone rocks and can be traced for a short distance into the latter. Along the eastern margin of the Neeans peninsula the lineation of the metamorphic rocks is folded into a NNW-trending anticline and probably, to the east, a complementary syncline. These folds are reflected by the sinuous outcrop of the junction between the metamorphic rocks and the Old Red Sandstone and also, to some extent, by the dips within the Old Red Sandstone. It is possible that these folds belong to the same period of deformation as the F_2 folds within the Walls Sandstone (p. 134).

North-east to north-north-west trending faults and associated conjugate folds

The major north-east to north-west trending faults cutting the metamorphic rocks are shown on (Plate 2). In addition to the exposed faults, major faults are probably present in Brindister Voe, close to the east coast of the Neeans peninsula, and in The Rona, near the east coast of Braga Ness. There is no definite evidence as to the age relationships of these faults to the NNW-trending D_6 folds.

These faults have wide crush belts, and where they traverse platy schist or granulite they are associated with zones up to 110 yd (100 m) wide, of conjugate or chevron-folding. The fault crossing the shore at the Ayre of Starastet [HU 254 584], 770 yd (700 m) SW of Turl Stack has a number of branches which converge southwards. Along the coast the zone of sharp-crested folds is 88 yd (80 m) wide and the fold axes plunge at 10°–30° to between S15°E and S40°E, which is at a slight angle to the trend of the main fault. Most folds in this zone are conjugate, but have slightly larger wavelengths and amplitudes than the typical D_4 folds. Many folds are cut by small contemporaneous faults which have soft clay in their shear planes.

Conjugate and chevron-folds which plunge to S10°E and are associated with branch-faults of the N–S trending fault, which crosses the coast [HU 260 587] just south of Turl Stack, are seen to traverse and locally refold a belt of east-south-east trending D_4 conjugate folds. It can thus be demonstrated that the folds associated with the major faults are younger than the regionally developed D_4 folds.

Metamorphic history

The relationships of the various phases of mineral growth in the metamorphic rocks to the major tectonic episodes can sometimes be determined by an interpretation of the textural relationships of the constituent minerals. Some evidence is provided by porphyroblasts of garnet and feldspar, which contain relict fabrics of aligned or helicitic inclusions of other minerals (cf. Rast 1958 ; Sturt and Harris 1961; Zwart 1960a, b). Provided that the mode of origin and the history of crystallisation of the inclusions within the porphyroblasts can be satisfactorily established, the relationship of the mineral fabric within the crystal (Si) to the surrounding fabric (Se) provides evidence for the ages of the two relative to the growth of the porphyroblast. Thus, if the internal fabric is aligned throughout the crystal and set at an angle to the external fabric it may mean that the two fabrics are of different generations, and that the porphyroblast was formed under static conditions prior to the onset of the period of stress which shaped the external fabric. Rotation of the porphyroblast during this kinematic phase would lead to a bending of platy minerals producing an 'eyed' structure, around the crystal. Porphyroblasts which continued to grow during the kinematic phase would have an outer zone of spirally curved trails of possibly larger inclusions (cf. Powell and Treagus 1970). Post-kinematic porphyroblasts, which grew under static conditions after the tectonite fabric of the rock had formed, do not distort the surrounding fabric and may contain inclusion trails continuous with that fabric (Sturt and Harris 1961, fig. 1).

Unfortunately, the evidence from porphyroblasts in this area is less conclusive than that in the ideal case mentioned above. Garnet porphyroblasts with an internal fabric set at an angle to the plane of the schistosity and around which the latter is deflected are common (S47741) [HU 285 580], (S47784) [HU 255 569] (Plate 6), fig. 1. In most of these, however, there is some evidence of movement and rotation after the Se fabric had formed (S47795) [HU 297 597]. Many garnet porphyroblasts in this series show marked changes in the character and distribution of inclusions from the centre outwards. Several have a core of small aligned or helicitic inclusions and an outer part in which rather larger quartz, biotite and hornblende inclusions are either concentrically arranged or show no definite pattern. Others have inner inclusion-free zones and outer zones with concentrically arranged inclusions (S30729) [HU 291 603]. The shape and alignment of the inclusions in some garnets in this area suggest that these may, in fact, be zones of secondary dissolution, formed by preferential resorption of relatively unstable zones in the garnet (S49322) [HU 308 605].

The size of the inclusions in the outer zones of many garnets, however, suggests that they were formed during the phase of post-kinematic static coarsening and annealing of the fabric which coincided with the final growth of the porphyroblasts. In addition to the porphyroblasts of garnet and feldspar, elongate crystals of amphibole, epidote and clinozoisite and their inclusions provide evidence for post-kinematic (M2P) mimetic coarsening and annealing of the tectonic fabric (S47761) [HU 269 591], (S47762) [HU 268 571] (Plate 6), fig. 3.

New fabrics and diaphthoretic minerals developed during the D_3 and D_4 episodes are more easily recognized. Apart from the extensive development of chlorite at the expense of biotite and garnet, nearly all minerals of the affected rocks show signs of shearing and distortion or fracturing which took place at low temperatures and low confining pressures. Textures and alignments of new minerals are directly related to axial planes or other geometric features of newly developed microfolds or shear planes which can, in turn, be related to the large-scale structural features.

Possible deformation (D_1) and mineral growth (MIS AND M1P) prior to main tectonizing metamorphism

Evidence for the existence of a tectonite fabric (D_1) prior to the formation of the main penetrative fabric (D_2) is inconclusive. There are many garnet porphyroblasts with an aligned or folded fine-grained Si fabric which is discontinuous with the 'eyed' Se fabric (S47741) [HU 285 580], (S47784) [HU 255 569], (S47795) [HU 297 597]. The rotation of the garnets could, however, have occurred at some stage after D_2. Feldspar 'permeation' and granite veining commenced either before the D_2 folding or during an early stage in the M2S phase, as a high proportion of feldspar lits and porphyroblasts and microgranite veins were deformed both on a megascopic and microscopic scale during the D_2 folding.

Main phase folding (D_2) and associated metamorphic episodes (M2S AND M2P)

The preferred orientation of the platy (phylloblastic) and elongate (nematoblastic) minerals, which imparts the foliation and lineation to the metamorphic rocks, was developed by recrystallization during and just after the Main (D_2) Phase of folding. The following two phases of mineral growth were involved in this process:

1. Syn-kinematic phase (M2S). The evidence for the formation of a fine-grained fabric during D_2 is provided by the presence of aligned trails of small inclusions, notably in amphibole. These consist of quartz, epidote, hornblende, biotite and, particularly, sphene and lie parallel to the main fabric. The trails of inclusions pass from one large amphibole crystal to another without deflection.
2. Porphyroblast growth and mimetic coarsening (M2P). It is thought that the growth of some garnets commenced before there was any marked mimetic coarsening of aligned minerals, though both processes were to a large extent contemporaneous. Thus there are some garnets which contain inclusions that are finer grained in the centre than near the periphery and others whose Si fabric remains consistent in both size and orientation throughout the crystal. Minerals included in garnets are usually only quartz and calcite (minute patches) in the central zones, but in the outer parts both biotite and amphibole are present. Many of the smaller garnets are enclosed in amphibole crystals (S47761) [HU 269 591], (Plate 6), fig. 3 and it is suggested that both developed during this period of mineral growth.

The evidence for mimetic coarsening of the entire fabric is best preserved in the amphibolites and in some talc-silicate rocks in which large amphiboles, biotites and epidotes contain aligned inclusions the fabric of which coincides in direction with that of the new fabric. In micaceous schists and gneisses the evidence for static coarsening of the fabric is less obvious, but many plagioclase porphyroblasts contain aligned inclusion trails which are parallel to the external fabric (S47799) [HU 291 604].

Metamorphic facies

The peak of regional metamorphism appears to have been attained during the static phase of mimetic coarsening and porphyroblast development (M2P). Over a large part of the area the mineral assemblages are characteristic of the greenschist-amphibolite transition facies (pp. 42–47). There are, however, two areas, at the eastern end of West Burra Firth and on the shore of the Bay of Garth, where diopside is present in the calc-silicate rocks and limestones, and this is indicative of the amphibolite facies (p. 45). The position of the pockets of diopside-rich limestone and talc-silicate rock coincides with areas of intense feldspathization and granite veining, and may be due to the local effects of thermal metamorphism associated with feldspathization. It is possible that the original extent of the diopside-bearing rock was considerably greater than at present, and that the diopside has been retrograded to tremolite during a late- or post-mimetic phase of deformation (p. 51) described above. The early stages in the break-down of diopside are seen on the eastern shore of West Burra Firth where diopside is rimmed by fibrous amphibole (p. 45).

Retrograde metamorphism associated with D_3 phase of shearing and faulting (M3S)

Retrograde metamorphism resulting from intensive shearing and shattering has affected the entire north-western peninsula of Vementry Island, parts of the remainder of Vementry Island, and the northern part of the Neeans peninsula. The principal textural and mineralogical changes are as follows:

1. Intense granulitization and partial mylonitization along narrow shear planes (S49294) [HU 216 581], (Plate 7), fig. 8 which are most abundant close to faults. These are associated with the alteration of garnet and biotite to chlorite and extensive fracturing and partial chloritization of amphibole (S49315) [HU 289 616], (S49345) [HU 291 616].
2. In less intensely sheared areas quartz is invariably streaked out into bands of fine-grained mosaics, and individual crystals have polygonal or amoeboid outlines (S30728) [HU 286 612], (S49307) [HU 289 609], (S49322) [HU 308

605], (Plate 6), fig. 5. Feldspars are fractured with stepped and strained twin-planes, show turbid alteration and are patchily sericitized (S49308) [HU 289 612]. Biotite is in most instances completely altered to green chlorite, but muscovite, though fractured and bent, is unaltered. Garnets are broken up by rotation, streaked out and partially altered to chlorite (S47806) [HU 283 612], (Plate 6), fig. 6. The least altered garnets are enclosed in a sheath of chlorite (S30728) [HU 286 612]. Amphibole and minerals of the epidote family are slightly cracked or broken but the latter show no sign of alteration. New epidote has formed in some sheared feldspars during this phase. Iron ores are irregularly streaked out. Sphene, apatite and rutile are unaltered.

Retrograde metamorphism associated with D_4 folding (M4S)

Diaphthoretic changes resulting from D_4 folding are confined to the belts of intense folding. Mineral changes in these belts are similar to those in the areas less intensely affected by the earlier D_3 shearing but here the platy and elongate minerals are intensely folded, bent and fractured, and in the southern peninsula of Vementry Island new chlorite plates are formed along and parallel to the axial planes of the microfolds ((S49319) [HU 295 595], (S49320) [HU 295 589], (Plate 7), fig. 7. In the D_4 fold belts traversing the southern and eastern peninsulas of Vementry Island there are abundant small needles of tourmaline, usually closely associated with chlorite. These commonly have their c-axes parallel to the axes of the D_4 micro-folds, but this alignment may be mimetic, as the formation of tourmaline may have been due to a subsequent influx of boron-bearing solutions, possibly during the emplacement of porphyry dykes.

Late thermal metamorphism (M5P)

The effects of thermal metamorphism, possibly by the Muckle Roe Granophyre or an unexposed plutonic body, are strongly marked along the east shore of the Swarbacks Head peninsula of Vementry Island. Here the sheared and partly mylonitized schists are hornfelsed, with original chlorite altered to deep green biotite, and radiating needles of pale bluish green amphibole cutting all the earlier fabrics (S49315) [HU 289 616], (S49316) [HU 291 617], (Plate 7), fig. 6). In sheared amphibolites needles of bluish amphibole commonly grow out from the original fractured hornblendes. Feldspar porphyroblasts are usually turbid or have a newly developed twinning pattern. A specimen of intensely hornfelsed metamorphic rock from Swarbacks Skerry [HU 290 622], just off Swarbacks Head, contains subhedral porphyroblasts of andalusite (S30726) [HU 291 621].

Within the metamorphic rocks adjoining the Vementry Granite the effects of thermal metamorphism are considerably less pronounced. Needles of bluish green amphibole cutting the earlier fabric are present but are less abundant than in specimens from Swarbacks Head. In some instances the only sign of thermal metamorphism is the turbid, patchily saussuritized character of feldspars. At the eastern end of Suthra Voe a rib of epidote-quartz rock, within an area cut by a north-east trending dyke swarm (Plate 24) consists of near-euhedral epidotes set in a matrix of clear quartz, which contains innumerable bundles of fine parallel fibres of amphibole (S50811) [HU 300 599], (Plate 7), fig. 5). These bundles are randomly orientated and commonly cross one another. This rock is probably a metamorphosed calc-silicate rock, but may be a recrystallized vein. The presence of tourmaline within chlorite-rich schists ((Plate 7), fig. 7) in areas cut by porphyry and felsite dyke swarms may be due to boron-metasomatism during or after the emplacement of the granite magma. ,

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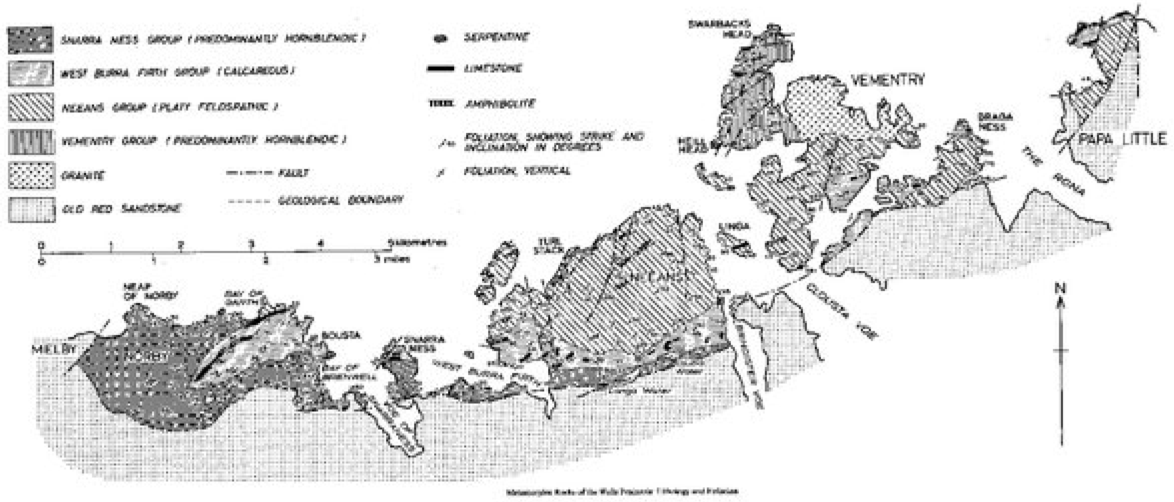
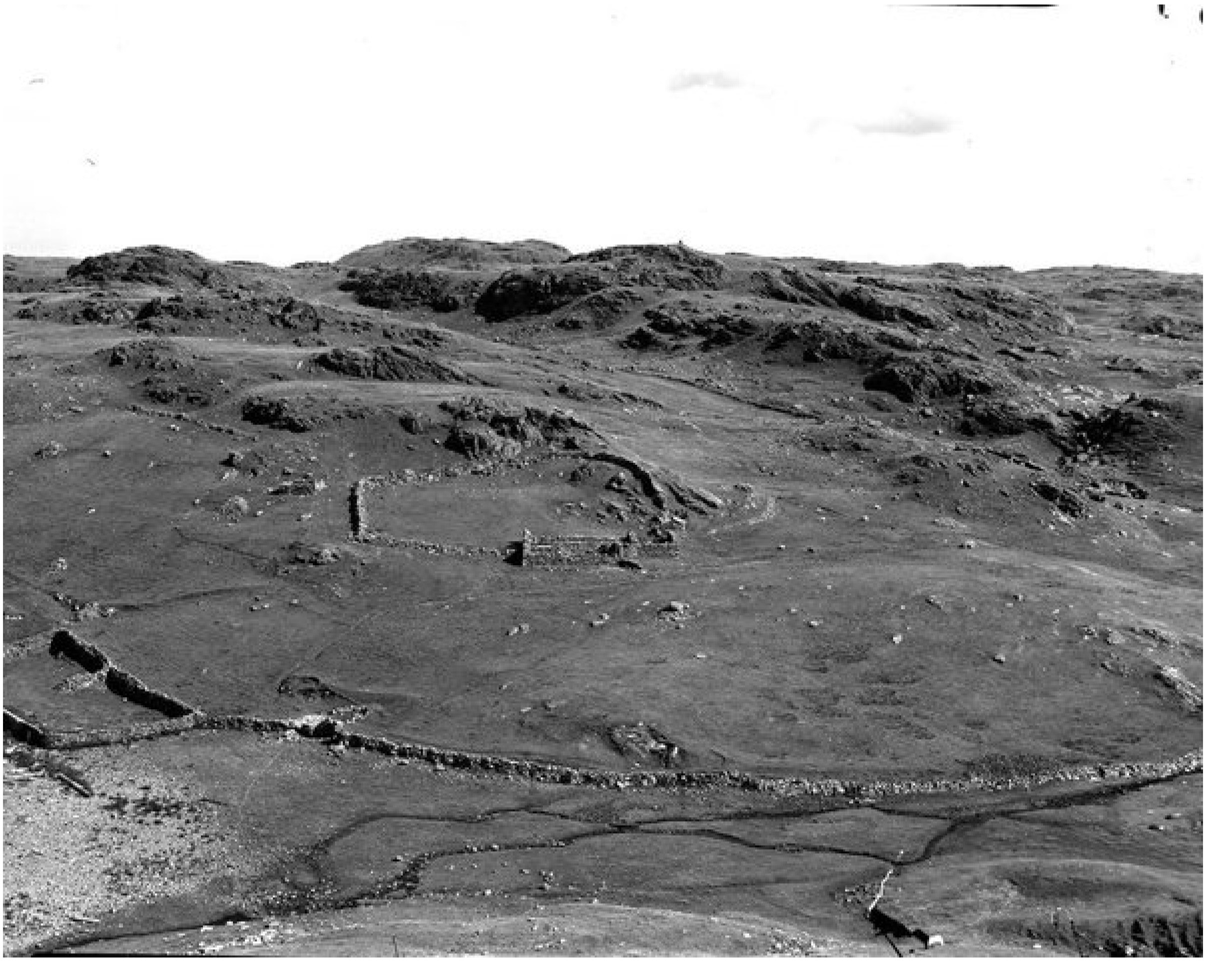
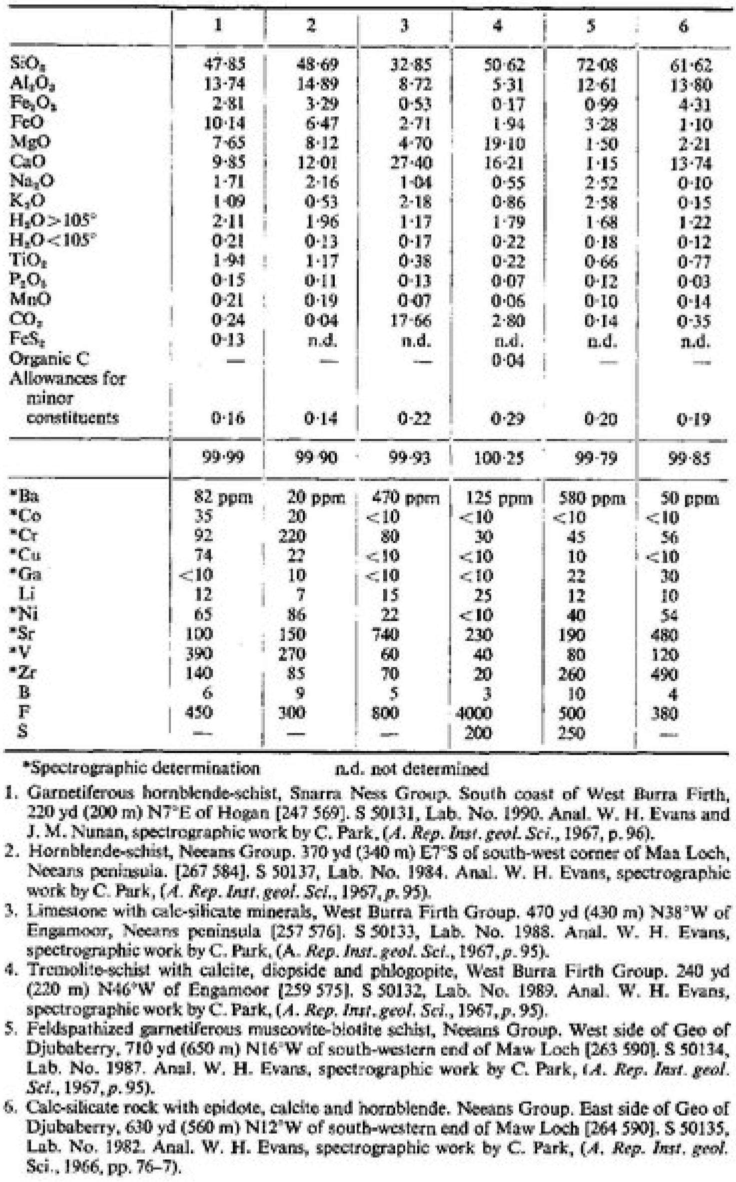


(Plate 2) Metamorphic rocks of the Walls Peninsula: Lithology and foliation.



(Plate 5A) General view of Neeans, looking east from north-east slope of Crockna Vord. [HU 257 583]. Characteristic topography formed by the metamorphic rocks of the Neeans Group. (D950).

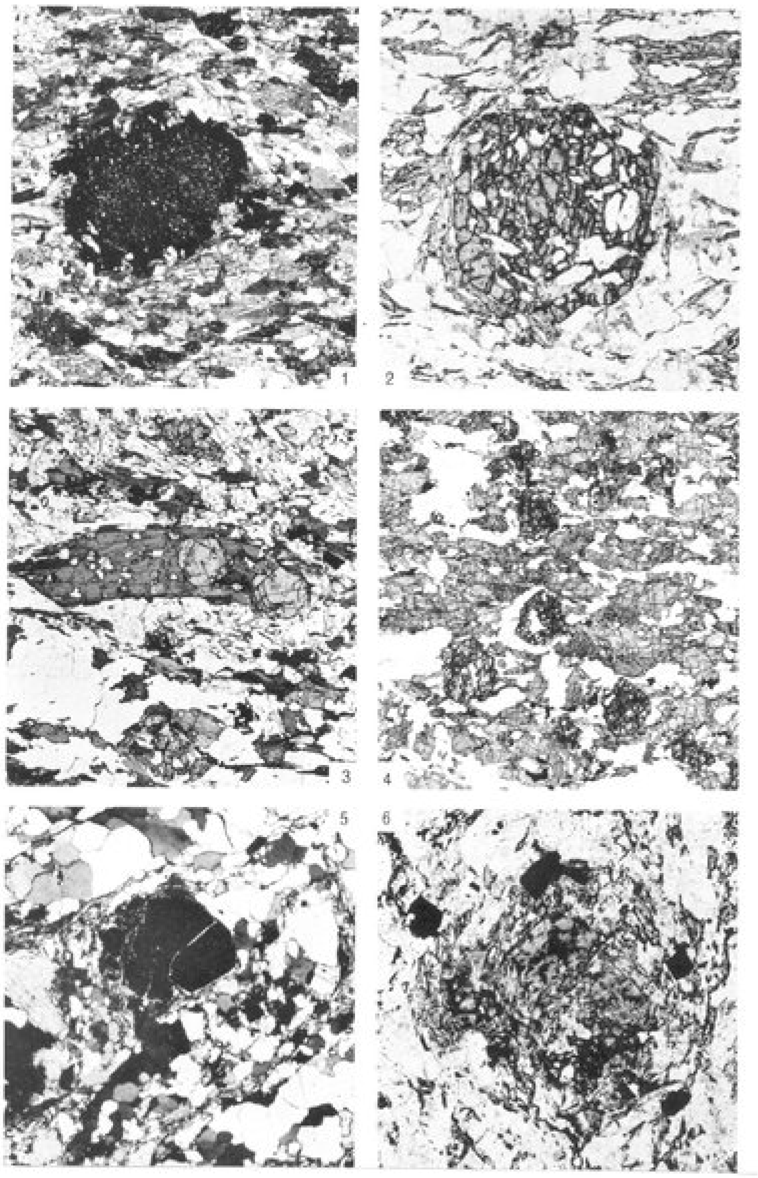


	1	2	3	4	5	6
SiO_2	47·85	48·69	32·85	50·62	72·08	61·62
Al_2O_3	13·74	14·89	8·72	5·31	12·61	13·80
Fe_2O_3	2·81	3·29	0·53	0·17	0·99	4·31
FeO	10·14	6·47	2·71	1·94	3·28	1·10
MgO	7·65	8·12	4·70	19·10	1·50	2·21
CaO	9·85	12·01	27·40	16·21	1·15	13·74
Na_2O	1·71	2·16	1·04	0·55	2·52	0·10
K_2O	1·09	0·53	2·18	0·86	2·58	0·15
$H_2O > 105°$	2·11	1·96	1·17	1·79	1·68	1·22
$H_2O < 105°$	0·21	0·13	0·17	0·22	0·18	0·12
TiO_2	1·94	1·17	0·38	0·22	0·66	0·77
P_2O_5	0·15	0·11	0·13	0·07	0·12	0·03
MnO	0·21	0·19	0·07	0·06	0·10	0·14
CO_2	0·24	0·04	17·66	2·80	0·14	0·35
FeS_2	0·13	n.d.	n.d.	n.d.	n.d.	n.d.
Organic C	—	—	—	0·04	—	—
Allowances for minor constituents	0·16	0·14	0·22	0·29	0·20	0·19
	99·99	99·90	99·93	100·25	99·79	99·85
*Ba	82 ppm	20 ppm	470 ppm	125 ppm	580 ppm	50 ppm
*Co	35	20	<10	<10	<10	<10
*Cr	92	220	80	30	45	56
*Cu	74	22	<10	<10	10	<10
*Ga	<10	10	<10	<10	22	30
Li	12	7	15	25	12	10
*Ni	65	86	22	<10	40	54
*Sr	100	150	740	230	190	480
*V	390	270	60	40	80	120
*Zr	140	85	70	20	260	490
B	6	9	5	3	10	4
F	450	300	800	4000	500	380
S	—	—	—	200	250	—

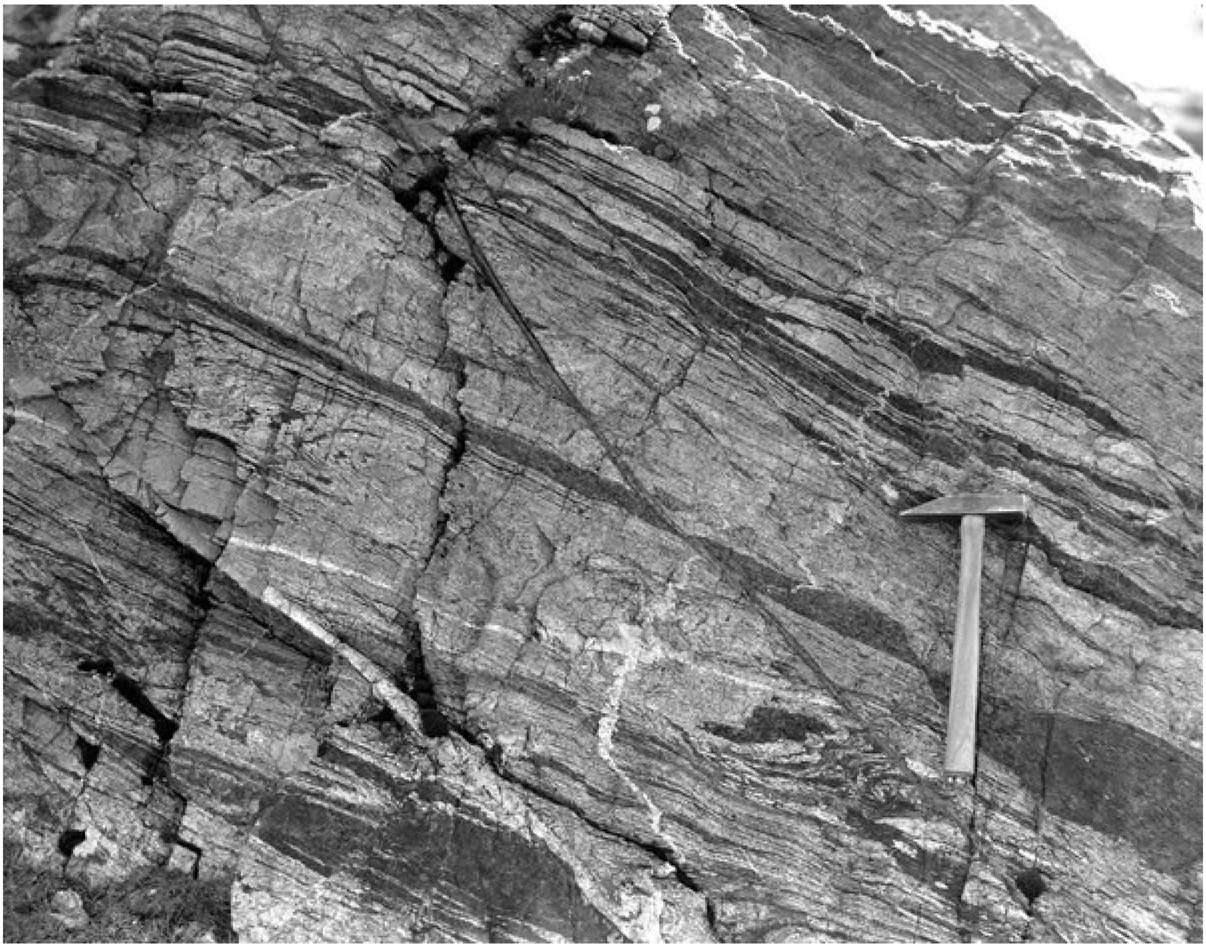
*Spectrographic determination   n.d. not determined

1. Garnetiferous hornblende-schist, Snarra Ness Group. South coast of West Burra Firth, 220 yd (200 m) N7°E of Hogan [247 569]. S 50131, Lab. No. 1990. Anal. W. H. Evans and J. M. Nunan, spectrographic work by C. Park, (*A. Rep. Inst. geol. Sci.*, 1967, p. 96).
2. Hornblende-schist, Neeans Group. 370 yd (340 m) E7°S of south-west corner of Maa Loch, Neeans peninsula. [267 584]. S 50137, Lab. No. 1984. Anal. W. H. Evans, spectrographic work by C. Park, (*A. Rep. Inst. geol. Sci.*, 1967, *p.* 95).
3. Limestone with calc-silicate minerals, West Burra Firth Group. 470 yd (430 m) N38°W of Engamoor, Neeans peninsula [257 576]. S 50133, Lab. No. 1988. Anal. W. H. Evans, spectrographic work by C. Park, (A. *Rep. Inst. geol. Sci.*, 1967, *p.* 95).
4. Tremolite-schist with calcite, diopside and phlogopite, West Burra Firth Group. 240 yd (220 m) N46°W of Engamoor [259 575]. S 50132, Lab. No. 1989. Anal. W. H. Evans, spectrographic work by C. Park, (*A. Rep. Inst. geol. Sci.*, 1967, *p.* 95).
5. Feldspathized garnetiferous muscovite-biotite schist, Neeans Group. West side of Geo of Djubaberry, 710 yd (650 m) N16°W of south-western end of Maw Loch [263 590]. S 50134, Lab. No. 1987. Anal. W. H. Evans, spectrographic work by C. Park, (*A. Rep. Inst. geol. Sci.*, 1967, *p.* 95).
6. Calc-silicate rock with epidote, calcite and hornblende. Neeans Group. East side of Geo of Djubaberry, 630 yd (560 m) N12°W of south-western end of Maw Loch [264 590]. S 50135, Lab. No. 1982. Anal. W. H. Evans, spectrographic work by C. Park, (*A. Rep. Inst. geol.* Sci., 1966, pp. 76–7).

(Table 1) Chemical analyses of Walls Peninsula metamorphic rocks.

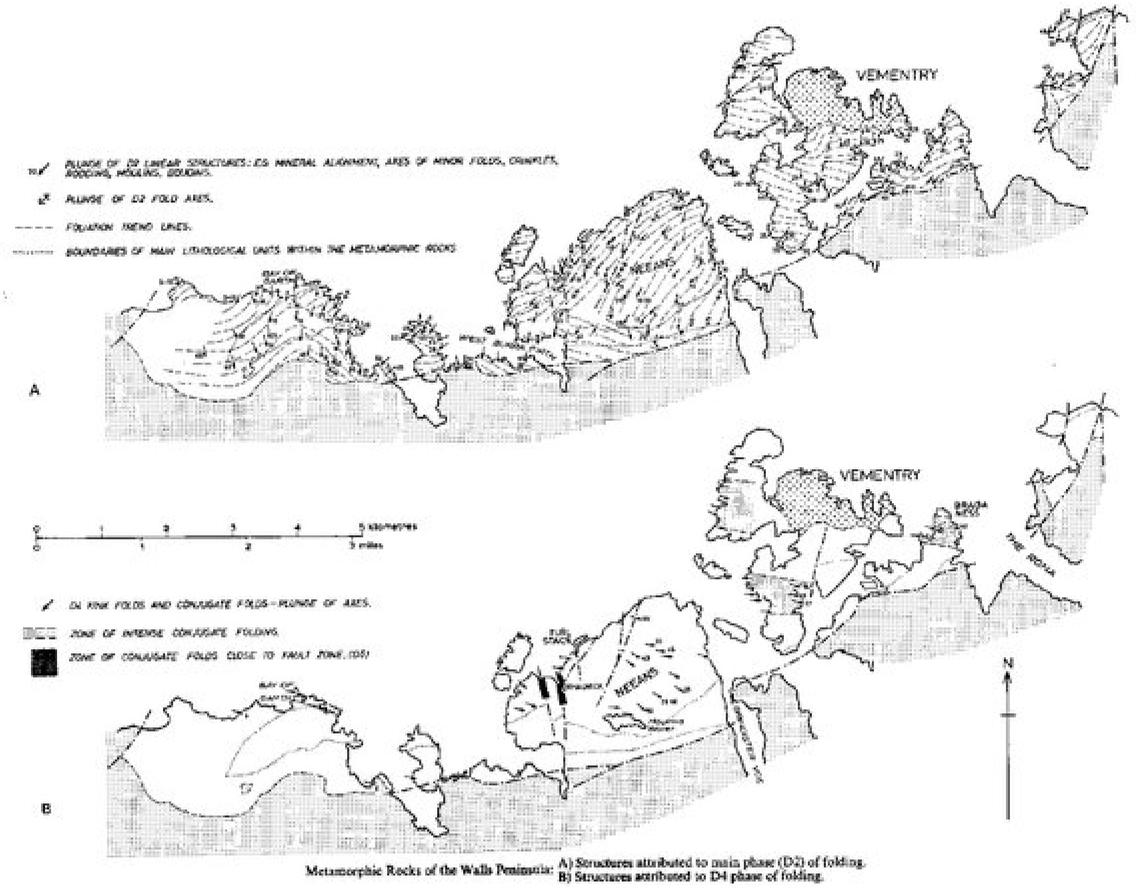


(Plate 6) Photomicrographs of metamorphic rocks of the Walls Peninsula Fig. 1. Slice No. (S47741) [HU 285 580]. Magnification × 16. Crossed polarisers. Garnet in hornblende-schist with small aligned inclusions, of which all but the outermost are aligned at a high angle to the external fabric. The internal (Si) fabric may be of M1P age, the outer (Se) fabric was developed during the M2P phase. Note the limited deflection of the Se fabric by the garnet. East coast of Neeans, 1235 yd (1130 m) N15°W of Brindister Broch [HU 283 584]. Fig. 2. Slice No. (S49322) [HU 308 605]. Magnification × 31. Plane polarized light. Garnet in micaceous gneiss with concentrically arranged penetration inclusions. These were probably formed by the preferential resorption of unstable zones in the garnet. Vementry Island, north-west shore of Uyea Sound, 700 yd (640 m) NNW of Vementry House [HU 304 603]. Fig. 3. Slice No. (S47761) [HU 269 591]. Magnification × 16. Plane polarized light. Hornblendic gneiss, with large hornblendes enclosing garnets. The growth of the large amphiboles appears to have taken place during a late stage of static growth (probably M2P) and its orientation may be mimetic after D_2 fabric. Neeans peninsula, 280 yd (255 m) N42°W of NE corner of Lang Loch [HU 270 592]. Fig. 4. Slice No. (S49298) [HU 222 578]. Magnification × 16. Plane polarized light. Amphibolite with garnets which show no trace of rotation and have not significantly eyed the external (Se) fabric. Sphenes are aligned parallel to the hornblende and mica. The coarsening of amphiboles and garnets is of M2P age. West coast of Geo of Bousta, 230 yd (210 m) NW of Muckle Bousta [HU 223 577]. Fig. 5. Slice No. (S30728) [HU 286 612]. Magnification × 42. Crossed polarisers. Sheared garnet-oligoclase-gneiss, with thin lenses and bands of mylonite. The garnet is rotated and peripherally altered to chlorite. Vementry Island, 250 yd (230 m) SSE of Head of Corbie Geo [HU 286 613]. Fig. 6. Slice No. (S47806) [HU 283 612]. Magnification × 38. Plane polarized light. Granulitized quartz-oligoclase-gneiss. Garnet rotated and largely altered to chlorite by post-M2P shear movements (S3). Vementry Island, near west coast, 800 yd (720 m) N18°E of SW tip of Hein Head [HU 283 612].



(Plate 5B) West coast of Vementry Island, 33 yd (30 m) N of Whal Geo. [HU 283 612]. Platy feldspathic gneiss with hornblendic bands, with tight D_2 folds, small normal faults and thin ptygmatically folded granite veins. (D913).

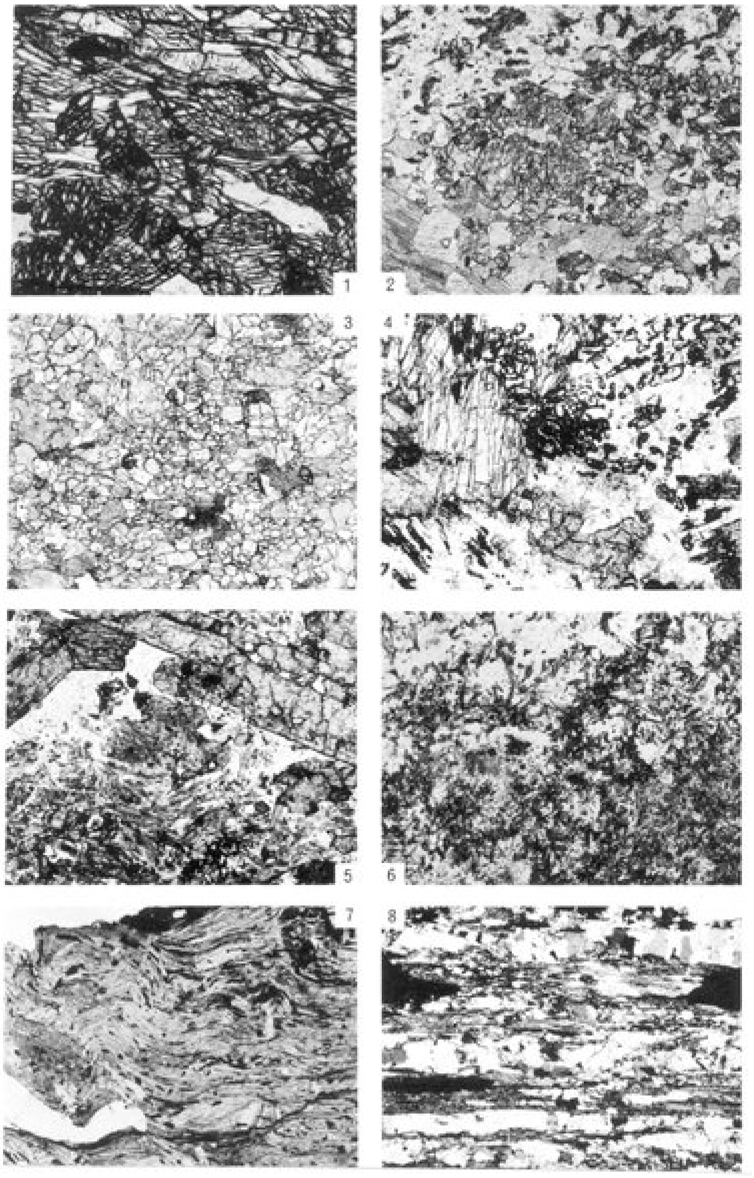
(Plate 4B) North shore of West Burra Firth at south-west corner of Crockna Vord peninsula. [HU 251 573]. D_2 *fold in hornblende-schist, with mimetic granite veins along folded foliation planes. (D953).*



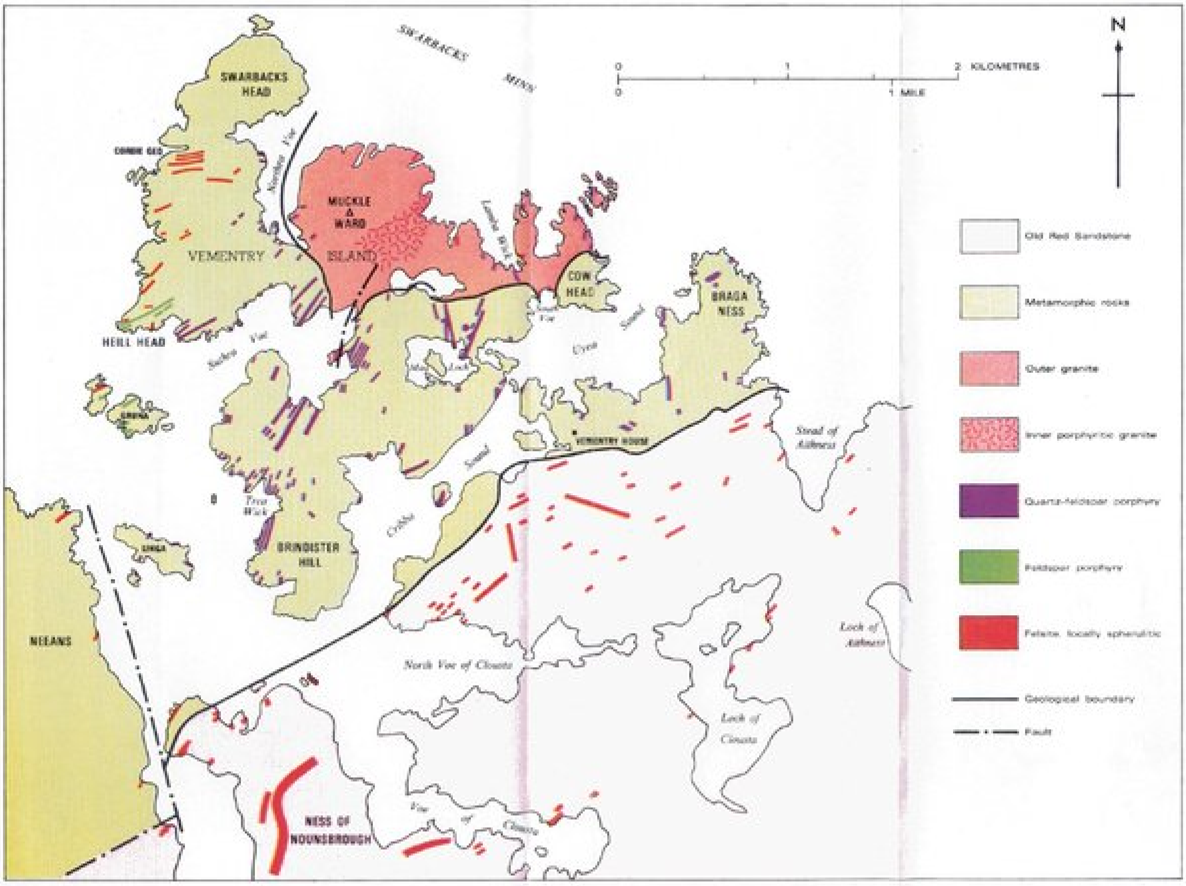
(Plate 3) Metamorphic rocks of the Walls Peninsula.

(Plate 4A) South shore of Bay of Garth. [HU 214 580]. D_2 *lineation in mica-schist. (D977).*

(Plate 4C) South-west slope of Crockna Vord, just north of West Burra Firth. [HU 251 575]. D_2 *fold in limestone. (D952).*



(Plate 7) Photomicrographs of metamorphic rocks of the Walls Peninsula Fig. 1. Slice No. (S47786) [HU 257 571]. Magnification × 42. Plane polarized light. Tremolite-schist, composed largely of euhedral laths of tremolite, flakes of phlogopite and subrounded crystals of epidote. East shore of West Burra Firth, 200 yd (180 m) S47°E of Broch at head of West Burra Firth [HU 257 571]. Fig. 2. Slice No. (S33779) [HU 223 579]. Magnification × 42. Plane polarized light. Crystalline limestone with calc-silicate bands, with calcite (bottom), clinozoisite, hornblende and quartz with zoisite inclusions. Skinhoga peninsula, 380 yd (350 m) SSE of Skerry of Stools [HU 223 579]. Fig. 3. Slice No. (S31005) [HU 271 589]. Magnification × 16.8. Plane polarized light. Epidote-amphibolite. Bluish green hornblende (with cleavage), subrounded crystals of epidote, interstitial calcite and rare small sphenes. Concentrations of epidote and hornblende occur in roughly alternate bands. Neeans Peninsula, 70 yd (64 m) N of Lang Loch [HU 272 589]. Fig. 4. Slice No. (S30589) [HU 208 578]. Magnification × 42. Plane polarized light. Hornblende-schist with symplectic intergrowth of zoisite and quartz. Norby, 550 yd (502) N10°E of west end of Loch of Collaster [HU 207 578]. Fig. 5. Slice No. (S50811) [HU 300 599]. Magnification × 42. Plane polarized light. Epidote-quartz rock composed of large euhedral epidote laths set in base of quartz full of tremolite needles. Vementry Island, near south-east shore of Suthra Voe, 1000 yd (910 m) S7°W of summit of Muckle Ward [HU 295 602]. Fig. 6. Slice No. (S49316) [HU 291 617]. Magnification × 42. Plane polarized light. Flinty crush rock with new growth of radiating needles of fibrous amphibole due to late thermal metamorphism. Vementry Island, east shore of Swarbacks Head, 900 yd (820 m) NNW of summit of Muckle Ward [HU 293 618]. Fig. 7. Slice No. (S49319) [HU 295 595]. Magnification × 16. Plane polarized light. Muscovite-chlorite-schist with phylloblastic minerals folded by F_3 movements. New chlorite plates developed sub-parallel to axial planes of folds and tourmaline prisms (seen in section) parallel to fold axes. Vementry Island, west shore of Cribba Sound, 1520 yd (1400 m) N of SW corner of Muckle Head [HU 296 595]. Fig. 8. Slice No. (S49294) [HU 216 581]. Magnification × 17.6. Crossed polarisers. Mylonitized quartz-mica-schist composed of alternate streaks of quartz with mortar texture and mylonite containing *newly-grown phlogopite and muscovite. South-east shore of Bay of Garth, 1020 yd (930 m) NE of Muckle Bousta. [HU 215 580].*



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