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Geology and geochemical characteristics of the Leverburgh Belt in South Harris, Outer Hebrides, Northwest Scotland

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Abstract

The Lewisian rocks in the southwestern part of South Harris consist of two groups of high-grade metamorphic rocks; a metasedimentary-meta-igneous complex and the South Harris Igneous Complex. The metasedimentary rocks occur in two zones (the Leverburgh Belt and the Langavat Belt) separated by the South Harris Igneous Complex. The Leverburgh Belt and the South Harris Igneous Complex contain high-pressure granulite-facies metamorphic assemblages, whereas those in the Langavat Belt show amphibolite-facies mineral assemblages. The Leverburgh Belt consists mainly of quartzofeldspathic and pelitic gneisses, mafic to ultramafic gneisses and marble/calc-silicate units. The metamorphic rocks in the Leverburgh Belt have been lithologically divided into four series, namely the Rodel Series, the Benn Obbe Series (A), the Benn Obbe Series (B) and the Chaipaval Pelitic Series. Based on various geochemical discrimination diagrams, basic metamorphic rocks from the Rodel Series shows affinities with both the mid-ocean ridge basalt (MORB) and oceanic island tholeiite (OIT), the associated supracrustal rocks being interpreted as blocks or lenses of oceanic material. Island-arc basalt (IAB)-type basic metamorphic rocks occur in the Benn Obbe Series (A) and (B), with associated trench-type metasedimentary rocks. The Chaipaval Pelitic Series contains both the within-plate type basalt (WPB) and OIT-type basic metamorphic rocks, intruded into hemipelagic sediments. The precursors of each series, deduced from the geochemical characteristics of the basic metamorphic rocks and the lithological assemblages are summarised as follows: the Rodel Series- melange with oceanic-type basalt; the Benn Obbe Series (A), (B)- trench sediments with island-arc type basalt; the Chaipaval Pelitic Series- hemipelagic sediments with oceanic island-type basalt. These precursors are exposed in a narrow area, suggesting that the Leverburgh Belt consists of an accretionary complex, and considered to have been formed during the subduction of an oceanic plate prior to regional metamorphism.

Key Words: Lewisian Complex, Leverburgh Belt, lithological assemblage, geochemistry, accretionary complex.

1. Introduction

The Lewisian Complex in South Harris, Outer Hebrides (Fig.1), has been attracted much attention, owing to the following distinct geological composition and structure: 1) the predominance of metasedimentary rocks metamorphosed under granulite-facies conditions during early Laxfordian time; 2) the existence of large amounts of early Laxfordian meta-igneous intrusives of tholeiitic to calcalkaline suites (the South Harris Igneous Complex); 3) the development of a strong shear zone (the Langavat Belt); and 4) the juxtaposition of a wide zone of Laxfordian granite-injection (Dearnley, 1962; Myers, 1968; Cliff *et al.*, 1983; Coward and Park, 1986; Fettes *et al.*, 1992). The metasedimentary rocks occur in two zones (the Leverburgh Belt and the Langavat Belt) separated by meta-igneous intrusives (Fig.2). In the Leverburgh Belt they contain high-pressure, granulite-facies assemblages, including kyanite- and almandine-pyrope garnet bearing rocks, whereas those in the Langavat Belt have amphibolite-facies mineral assemblages. The occurrence of calc-alkaline intrusives suggests that the South Harris region was an orogenic belt formed at a continental margin. Fettes *et al.* (1992) considered that the high-pressure metasedimentary granulites were formed by subduction or faulting of Archaean metasediments to deep crustal levels, and thermally affected by intrusion of the South Harris Igneous Complex. In contrast, Coward and Park (1986) argued that the granulites were part of deep continental crust that was thrust over the Langavat Belt along a low-angle, mid-crustal shear zone.

I have carried out geological surveys in South Harris for several years, and have studied the metamorphic

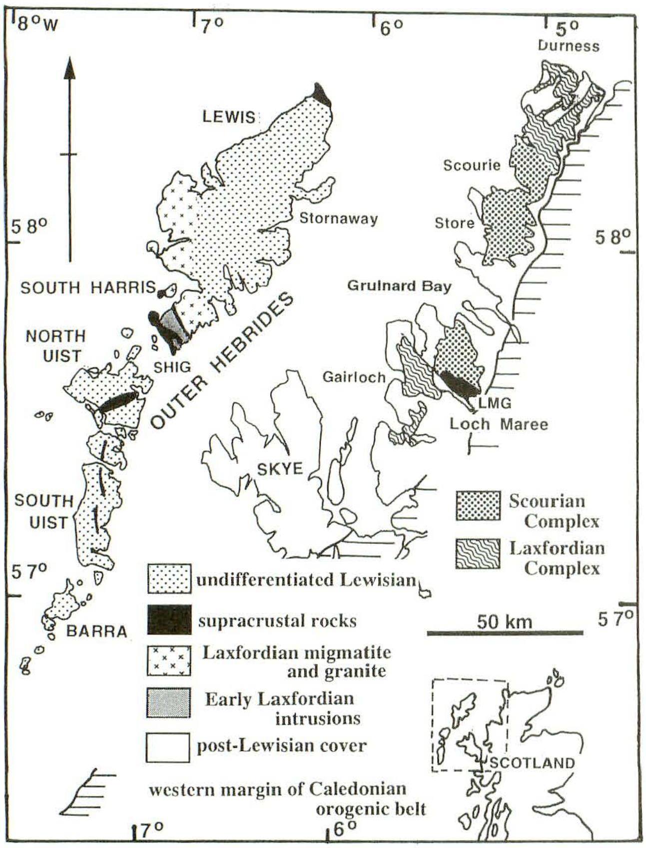


Fig. 1. Distribution of the Lewisian Complex in Northwest Scotland. SHIC, South Harris Igneous Complex; LMG, Loch Maree Group. (after Park and Tarney, 1987; Whitehouse, 1989).

phase relations and *P-T* paths of the granulites. The aim of this paper is to describe the occurrence of the metamorphic rocks and the geochemical characteristics of mafic gneisses in order to deduce the tectonic environment, and hence to reconstruct the evolutionary history of the South Harris Belt.

2. Regional geology

2.1. Lewisian Complex

The Lewisian Complex comprises the basement of Northwest Scotland and has been regarded as a part of the North Atlantic Craton (Windley, 1995). It is composed predominantly of tonalitic-granodioritic gneisses with numerous mafic-ultramafic enclaves and with local intercalations of layered mafic-ultramafic complexes and supracrustal metasediments (Tarney and Windley, 1977). In the Scourie-Lochinver region, the tonalitic orthogneisses are widely exposed, preserving little-altered Archaean metamorphic assemblages and fabrics. The protolith of these gneisses was differentiated from the mantle at ca. 2.95Ga (Hamilton *et al.*, 1979; Whitehouse and Moorbath, 1986), and underwent granulite-facies metamorphism accompanied by intense sub-horizontal deformation at 2.7Ga (Badcallian event) (Humphries and Cliff, 1982; Cohen *et al.*, 1991). The metamorphic conditions were 1000±50℃ and >12 kbar (e.g. Cartwright and Barnicoat, 1989; Cartwright, 1990), Following the Badcallian event, the metamorphic complex locally underwent intense hydrous retrogression at 500-650℃ and 3-7 kbar associated with the fomation of dip-slip shear zones, accompanied by folding and pegmatite intrusion in the ca. 2.5 Ga (Inverian event). The Inverian event marks the major tectonic break in the Lewisian history of the central block, giving rise to segmentation of the Lewisian Complex and to juxtaposition of different crustal levels with each other. The event is regarded as marking the Archaean-Proterozoic boundary (Park, 1970; Park and Tarney, 1987). During and following the Inverian disturbance, the Scourie dykes were intruded at depths of >14 km in two episodes in the period 2.0-2.4 Ga (Waters *et al.*, 1990; Heaman and Tarney, 1989). Most Lewisian workers, following Peach *et al.* (1907) and Sutton and Watson (1951), have used the Scourie dykes as markers to define the beginning of the Laxfordian period, and the end of the Scourian. The Laxfordian is a period of extensive retrogression and shearing that occurred mainly between 1.9 and 1.7 Ga, following the emplacement of the Scourie dykes (Park and Tarney, 1986). The assumption that the Lewisian Complex has a clockwise *P-T-t* history with a single prograde event (Badcallian event at 2.7 Ga) followed by cooling and unloading at 2.5 Ga (Inverian event) and at 1.7-1.9 Ga (Laxfordian event) is now widely accepted (Sills and Rollinson, 1987; Barnicoat, 1987; Cartwright and Barnicoat, 1987, 1989; Barnicoat *et al.*, 1987; Cartwright, 1990).

2.2. South Harris Complex

The Lewisian Complex in South Harris (the South Harris Complex) is exposed in the southwestern end of the island of Lewis-Harris in the Outer Hebrides, northwest Scotland. The South Harris Complex consists of three belts of high-grade metamorphic rocks: the Leverburgh Belt, the Langavat Belt, and the South Harris Igneous Complex (Fig.2). The former two belts are characteristically dominated by metasediments (Dearnley, 1963; Fettes *et al.*, 1992). The Leverburgh Belt and the South Harris Igneous Complex were metamorphosed under granulite-facies conditions during the early Laxfordian event (Dearnley, 1963; Cliff *et al.*, 1983). The Leverburgh Belt consists of pelitic, quartzo-feldspathic, mafic and ultramafic gneisses with marble/calc-silicate gneisses. The peak metamorphic *P-T*

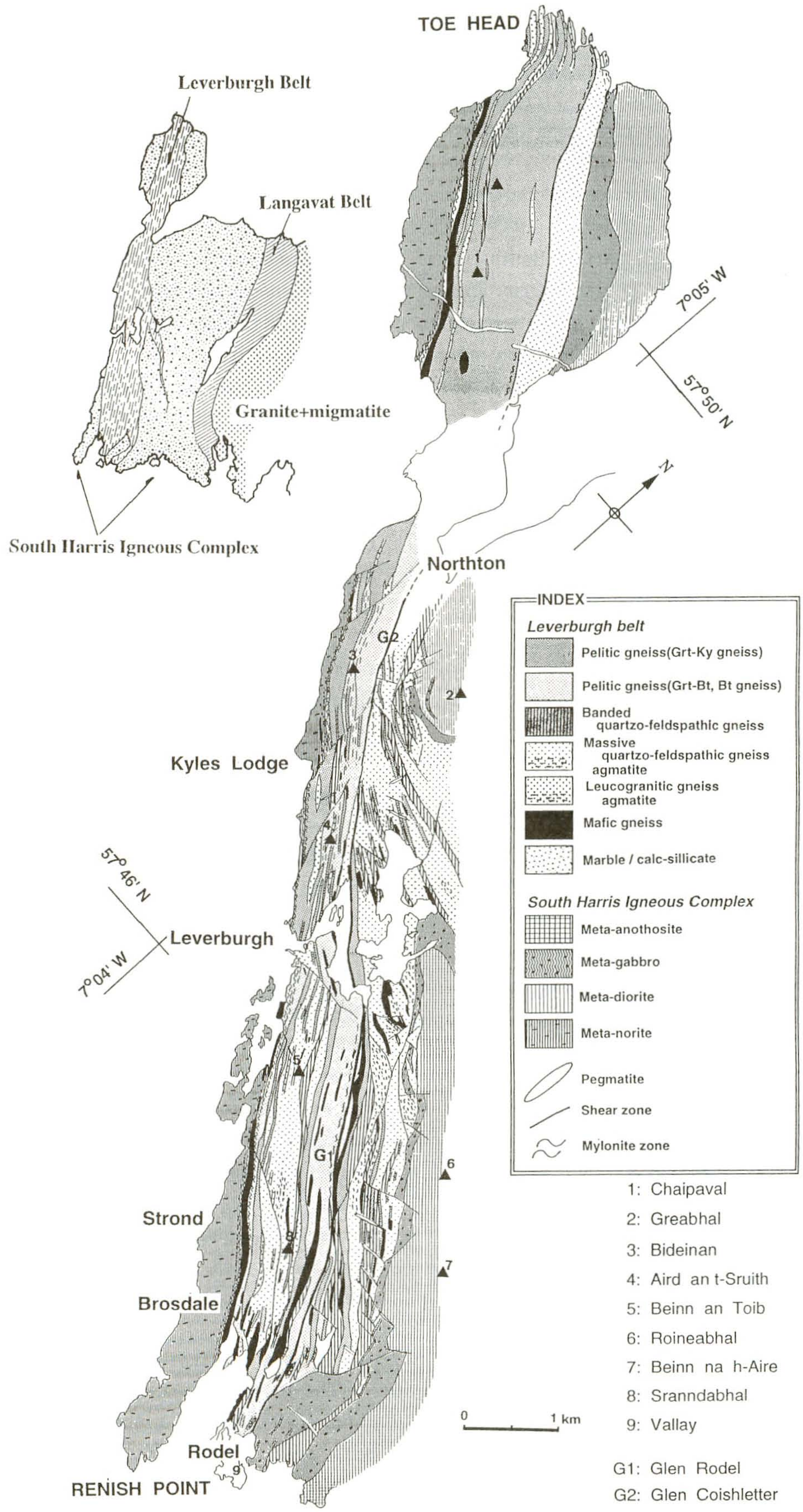


Fig. 2. Geological map of the South Harris Complex and the Leverburgh Belt.

conditions have been estimated to be 13 kb and 825±25℃ (Horsley, 1978; Dickinson and Watson, 1976; Wood, 1975). The South Harris Igneous Complex includes a variety of rocks of different magmatic affinities (olivine tholeiite and calc-alkaline), representing igneous activity in magmatic arcs (Fettes *et al.*, 1992). Sm-Nd studies indicate that the South Harris Igneous Complex was intruded around 2.18 Ga (Cliff *et al.*, 1983). The Langavet Belt occupies the eastern part of South Harris Complex and is bounded by the South Harris Igneous Complex on its western side, and by a granite-injection complex on its eastern side, although its eastern margin is not clearly defined. Langavat Belt rocks are strongly sheared in part and the belt is a major shear zone, formed during the late Laxfordian. The Langavat Belt rocks consist of regularly thin-banded, fine-grained biotitic and hornblendic acid gneiss, amphibolite, mafic gneiss, pelitic gneiss, quartzite and a rare marble band, but there is a lack of agreement between different authors as to the original lithology and lithological associations.

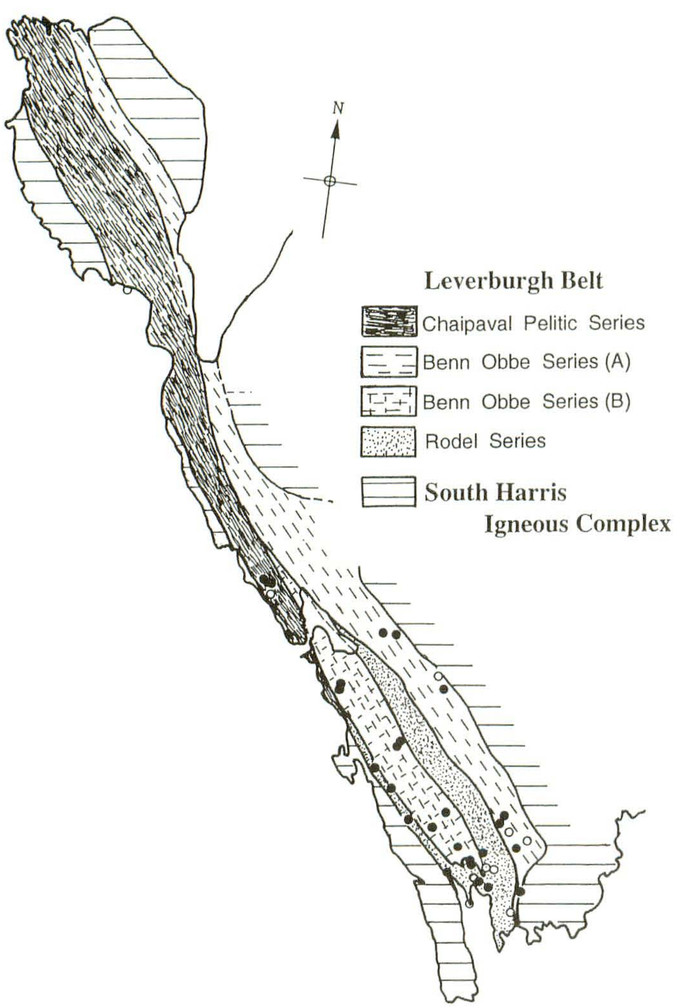


Fig. 3. Modified distribution of the Rodel Series, Chaipaval Pelitic Series, Benn Obbe Quartzite (A) and (B), showing sample localities of mafic gneiss in the Leverburgh Belt.

3. Geology of the Leverburgh Belt

This belt, 1 to 1.7 km wide, dominated by metasediments, lies on the southern flank of the South Harris Igneous Complex. It stretches northwestward from Vallay Island and Rodel through Leverburgh to Toe Head (Fig.2). Various lithological types are distinguished in the Leverburgh Belt (Fig.2). Dearnley (1963) divided the metasediments into three units: the Benn Obbe Quartzites, the Rodel Series and the Chaipaval Pelitic Series. In the view of the difficulties of lithological correlations along the strike of the Leverburgh Belt and of the gradational nature of the boundaries between the various rock types, formal stratigraphical terms have not been used. In this study, the Leverburgh Belt metasediments are attributed to four lithological series by modifying the Benn Obbe Quartzites of Dearnley (1963) to the Benn Obbe Series and dividing it into two series, (A) and (B).

3.1. Benn Obbe Series (A)

The Benn Obbe Series (A) is exposed along the western side of Roineabhal, Beinn na h-Aire and Greabhal in a north-west striking zone, extending from Vallay island to Northton (Figs. 2 and 3). This series is bounded on the east by a metagabbro belonging to the South Harris Igneous Complex, on the south by the Rodel Series, and on the west by the Chaipaval Pelitic Series. Generally, gneissose banding trends northwestward and dips steeply northeastward. In the Loch Steisevat region, northwest of Leverburgh, the gneissose banding trends westward to west-northwestward. The Benn Obbe Series (A) consists of quartzofeldspathic gneiss, pelitic gneiss, mafic gneiss and rare ultramafic gneiss. The quartzofeldspathic gneiss can be divided into two types, well-banded and massive, reflecting their field occurrence.

(a) Banded quartzofeldspathic gneiss

The banded quartzofeldspathic gneiss can itself be subdivided into two types, one of which is interbedded with pelitic gneiss (P-type banded quartzofeldspathic gneiss) and the other which lacks pelitic gneiss interbeds (N-type banded quartzofeldspathic gneiss). The P-type banded quartzofeldspathic gneiss occurs adjacent to pelitic gneiss and massive quartzo-feldspathic gneiss, alternating with mafic (grt-cpx-opx-hbl-rich) layers. The gneiss is exposed in the eastern part of the Benn Obbe Series (A), and is bounded by meta-gabbro on the eastern side. It is up to 300 m in width and is traceable for several kirometres. Various mineralogical types of gneisses, including garnet-biotite-hornblende gneiss, garnet-orthopyroxene gneiss, garnet-clinopyroxene-orthopyroxene gneiss, garnet-kyanite gneiss, orthopyroxene-bearing quartzose gneiss and biotite-bearing quartzite alternate with each other on the scale of several centimetres. The garnet-kyanite gneiss, orthopyroxene-bearing quartzite, and intercalations of garnetiferous layers of a few centimetres thickness are characteristic in this unit. These gneisses are equivalent to the garnet-hornblende-, garnet-biotite- and hypersthene-bearing quartz-rich gneisses of Dickinson (1974). N-type banded quartzofeldspathic gneiss is exposed in the western part of the Benn Obbe Quartzite (A), and is bounded by the Rodel Series. The gneissose banding is well developed. The gneiss is 5-100 m in thickness, with interbanded mafic (garnet-clinopyroxene-hornblende rich) layers, and occurs adjacent to pelitic gneiss and massive quartzofeldspathic gneiss. The common assemblage is garnet-plagioclase-K feldspar-quartz, with varying amount of orthopyroxene, clinopyroxene, hornblende and biotite. The gneiss is characterized by intercalations of numerous mafic layers and by the relative abundance of mafic components such as clinopyroxene and garnet.

(b) Massive quartzofeldspathic gneiss

The massive quartzofeldspathic gneiss is dominant in this series, occurring in the northwestern part of the Leverburgh Belt. The gneiss has a monotonous aspect in an outcrop, but locally includes a large amount of mafic gneiss blocks, commonly giving it an agmatitic appearance. The gneissose banding is generally not clear, although fine-spaced foliations are developed in or near shear zones. The gneiss is quartz-poor, compared with the banded quartzofeldspathic gneiss. The mineral assemblage is similar to that of the N-type banded quartzofeldspathic gneiss, but it is relatively poor in orthopyroxene.

(c) Pelitic gneiss

Two types of pelitic gneiss are distinguished, based on mineral assemblages: (1) feldspar-rich (Na-K rich); and (2) feldspar-poor and spinel-, staurolite- and/or corundum-bearing (Fe-Al rich) ones.

Na-K rich pelitic gneiss: Na-K rich gneiss occurs mainly as thin layers up to 100 m in thickness, and is traceable for a few kirometres in the western part of this series. It consists of garnet-kyanite-K feldspar-plagioclase-quartz and alternates with layers of quartz-feldspar-garnet gneiss and quartzofeldspathic gneiss. In a few areas, small mafic pods up to 1 m long are observed within the pelitic gneiss layers. In some layers rich in quartz-feldspar-garnet, kyanite-garnet-bearing gneiss also occurs as layers a few centimetres thick, and layers or pods up to 50 cm in diameter. Garnet and kyanite in Na-K rich pelitic gneiss display a pale lilac and blue-grey colour, respectively. In shear zones, the high-grade assemblage changes to retrograde sillimanite-biotite, and quartz, biotite and sillimanite form the foliations.

Fe-Al rich pelitic gneiss: Fe-Al rich pelitic gneiss is observed as narrow bands or pods within or adjacent to garnetiferous mafic gneiss, and as thin layers within banded quartzofeldspathic gneiss. The gneiss has a massive aspect, and garnet + kyanite attain 50-70 per cent of the modal volume. In well-banded layers, garnet + kyanite rocks are boudinaged in places. The gneiss consists of garnet-kyanite-ilmenite-plagioclase-quartz with a small amount of K feldspar, and characteristically contains relict staurolite, spinel and corundum and retrograde staurolite and cordierite. In this gneiss, the red garnet and dark grey to black kyanite are prominent.

(d) Mafic gneiss

Mafic gneiss occurs as layers or pods up to 50 m in width within pelitic gneiss and quartzofeldspathic gneiss, and as very thin layers interbedded with quartzofeldspathic gneiss. Mafic gneiss also occurs as small lenses in pelitic gneisses and massive quartzofeldspathic gneiss. The gneiss is now commonly a clinopyroxene-plagioclase-quartz rock with varying amounts of garnet, orthopyroxene, hornblende and biotite.

3.2. Benn Obbe Series (B)

The Benn Obbe Series (B) is exposed around Beinn an Toib and Sranndabhal. The gneissose banding trends northwestwards and dips northeastwards on the southwestern hillside, whereas it dips southwestwards on the northeastern hillside. This Series is bounded on the southwest by meta-norite (South Harris Igneous complex) and on the northeast by the Rodel Series. The series consists of massive quartzofeldspathic gneiss, pelitic gneiss, banded quartzofeldspathic gneiss (N-type), mafic gneiss and a small amount of leucogranitic gneiss. Banded quartzofeldspathic gneisses (P-type) and Fe-Al rich pelitic gneiss are absent in this series. Along the western boundary, these gneisses are mylonitized and show a fine-spaced foliation and retrograde assemblages. The structural features and lithological pattern strongly suggest that they are folded into a tight synform, with axis trending northwestwards. This synform was described by previous workers (Dearnley, 1963; Witty, 1975). In the small outcrop north-west of the Pier road, the axial part of this major synform is seen, with axial foliations oblique to gneissose banding. Second-order tight folds are associated with the major closure. Retrograde biotite forms the axial foliation, which lies parallel to the mylonitic foliation. The fold axis is parallel to the stretching lineation seen in the mylonite, suggesting that the synformal folding was related to the shearing and was accompanied by retrograde metamorphism.

(a) Massive quartzofeldspathic gneiss

The massive quartzofeldspathic gneisses are particularly well exposed in this area. These gneisses shows a monotonous aspect in outcrop, although, in a few places, banding of a few millimetre to a few centimetre thickness, consisting of the alternation of salic-rich and mafic-rich layers, is observed. The common assemblage is garnet-plagioclase-quartz-K feldspar, with varying amounts of clinopyroxene, hornblende and biotite. In sheared zones, garnet and clinopyroxene are replaced by hornblende and biotite, with these minerals forming the foliation. Mafic gneiss forms thin layers or lenses up to 2 m in width and shows an agmatitic aspect in these sheared zones. In general, it forms agmatitic zones that are traceable for a few hundred metres.

(b) Banded quartzofeldspathic gneiss

Banded quartzofeldspathic gneiss also occurs as layers up to 50 m in width which are traceable for 1.5 km in the central part of this series. They consists of garnet-clinopyroxene-hornblende gneiss alternating with orthopyroxene-bearing gneiss, mafic gneiss (garnet-clinopyroxene, garnet-clinopyroxene-orthopyroxene and clinopyroxene-orthopyroxene gneiss) and quartzofeldspathic gneiss. Gneissose banding is well developed and quartz-rich bands up to 5 cm are commonly observed. In shear zones, these bands are more highly foliated, with a reduced grain size.

(c) Pelitic gneiss

Pelitic gneiss is exposed on each side of the northwest-trending ridge of Sranndabhal. In Beinn an Toib, northwest of Sranndabhal, several thin layers are included in massive quartzofeldspathic gneiss. Pelitic gneiss is a Na-K rich type and consists of garnet-kyanite-K feldspar-plagioclase-quartz alternating with thin layers of quarz-feldspar-garnet gneiss and quartzofeldspathic gneiss. Lithologically they are similar to the Na-K rich pelitic gneiss in the Benn Obbe Series (A). These gneisses do not include layers or lenses of mafic gneiss. Pelitic gneiss lies adjacent to massive quartzofeldspathic gneiss, with a sharp boundary, but where the pelitic gneisses lie adjacent to the leucogranitic gneiss, the boundary is gradational. Near the shear zone, notably on the western slope of Sranndabhal and Beinn an Toib, garnet is replaced by biotite and rare sillimanite, which form the foliation.

(d) Leucogranitic gneiss

Leucogranitic gneiss occurs as thin lenses or layers up to 20 m wide, adjacent to pelitic gneiss or in massive, quartzofeldspathic gneiss. They generally show a massive, aspect, although where they include mafic gneiss pods or blocks, the gneisses are typically agmatitic. The gneiss consists of garnet-K feldspar-plagioclase-quartz, with variable development of biotite and hornblende. Rarely, minor kyanite is observed.

(e) Mafic gneiss

Mafic gneiss is present as layers or lenses up to 50 m in width, included in massive quartzofeldspathic gneiss and leucogranitic gneiss. Thin layers and lenses are also interbedded within banded quartzofeldspathic gneiss. The mineral assemblage of the mafic gneiss is similar to that of the other series.

(f) Mylonite Zone

Mylonites are exposed at the southwestern boundary of this series. Biotite-muscovite gneiss, K feldspar-biotite-muscovite gneiss and hornblende-biotite gneiss with finer grained quartz and plagioclase dominate in this zone. Fine foliations, with mica fish and ribbon quartz, are well developed and sometimes porphyroclasts of garnet and K feldspar are observed. The former two assemblages are possibly derived from pelitic gneiss, and the latter from mafic gneiss.

3.3. Rodel Series

The Rodel Series is mainly exposed between the Benn Obbe Series (A) and the Benn Obbe Series (B), and stretches north-westword along Glen Rodel. In view of the field occurrence of marble/calc-silicate gneiss exposed in south-east Brosdale, the Rodel Series occurs flanking the Benn Obbe Series (B) and it forms both limbs of the tight major synform. The Rodel Series consists mainly of alternating assemblages of strongly foliated garnet-biotite gneiss, biotite-hornblende quartzose gneiss, mafic gneiss (garnet-clinopyroxene-orthopyroxene, garnet-amphibolite, clinopyroxene-amphibolite gneiss), ortho-amphibole-biotite gneiss, sulphides-bearing quartzite and pelitic gneiss. Pelitic gneiss occurs as lenticular bodies up to 50 m in width, surrounded by garnet-biotite gneiss and/or biotite-hornblende quartzose gneiss; it is not readily traceable along the strike. Mafic gneiss is found as layers up to 100 m wide, and includes ultramafic blocks. Layered mafic gneiss shows alternating garnetiferous and clinopyroxene-amphibolite-rich layers. Small, lensoid mafic gneiss bodies are present, and they contain the assemblage clinopyroxene-amphibole, typically with a finer grain size compared to that of the layered mafic gneiss. Lenses and blocks of marble/calc-silicate are well exposed in this series, occurring as small lenses up to 8 m in width and 20 m in length. They are included within the garnet-biotite gneiss, and more rarely form thin layers adjacent to ultramafic gneiss and mafic gneiss. Ultramafic gneisses are found as blocks in mafic gneiss in northwest Rodel, where they attain up to 50 m in width and alternate with mafic gneiss. Sulphide-bearing quartzite and ortho-amphibole-biotite gneiss occur as thin layers up to 10 m wide, forming thin, intercalated layers in the garnet-biotite gneiss and biotite-hornblende gnaiss. The Rodel Series, in contrast to the other main groups, shows the following distinctive characteristics: 1) it is finely foliated, with common alternations of rock-types; 2) it consists of a wide variety of metamorphic rock-types such as pelitic gneiss, mafic gneiss, ortho-amphibole-bearing gneiss, sulphide-bearing quartzite and marble/calc-silicate rocks all of which occur as lenses or thin layers; 3) garnet in pelitic gneiss is generally finer grained compare to that in the other series; 4) the presence of marble or calc-silicate blocks and lenses, which occur at several stratigraphic horizons, but appear to be restricted to the Rodel Series.

3.4. Chaipaval Pelitic Series

This series stretches north-westwards from Aird an t-Sruith through Northton to Toe Head. It is composed of pelitic gneiss, leucogranitic gneiss, quartz-biotite gneiss, mafic gneiss, with rare, interbanded quartzofeldspathic gneiss. These gneisses trend north-northwestwards and dip east-northeast, and they are bounded on the northeast by the Benn Obbe Series (A) and metagabbro of the South Harris Igneous Complex. To the southwest lies the meta-norite of the South Harris Igneous Complex. The boundary is a fault, associated with a northwest-trending sheared and mylonitic zone. Towards the boundary, the Chaipaval Pelitic Series become both more mylonitized and finer grained, with the development of retrograde mineral assemblages. The boundary on the northeastern side is not clear, due to lack of outcrop, although on Toe Head, gneisses exposed near this boundary are strongly deformed and again shows retrograde assemblages. Shear zones with mylonitic foliation subparallel to the gneissose banding are present at the boundary and also within the Series. Again, here, the gneisses show retrograde mineral assemblages.

(a) Pelitic gneiss

The pelitic gneisses are best developed in the Northton - Toe Head region. Gneissose banding and foliation are well developed here. The gneisses range from quartz- or feldspar- rich acid gneisses with kyanite /biotite and/or garnet, through to spectacular rocks in which kyanite attains 10 per cent of the mode. Around Chaipaval hill, garnets up to 20 mm across and kyanites up to 8 mm long are abundant. Such big garnets are normally mantled by kyanite. K feldspar-rich garnet-bearing gneisses are common in the Toe Head region, interbanded with kyanite-bearing pelitic gneiss. In the southern region, interbanded biotite-quartzofeldspathic gneisses are common. Sillimanite-bearing gneiss is well-exposed around Kyles Lodge, where garnet is overgrown by sillimanite. A large number of shear zones were observed. In and near the shear zones, the pelitic gneisses are more highly foliated, with garnet replaced by biotite and sillimanite; these secondary minerals (biotite and sillimanite) form the shear foliation.

(b) Leucogranitic gneiss

Leucogranitic gneiss occurs widely in the pelitic gneiss on the west side of Chaipaval. It is a K feldspar-rich quartzofeldspathic gneiss, occuring as thin layers alternating with pelitic gneiss. In parts the leucogranitic gneisses contain garnet-kyanite-biotite lenses up to 20 cm long in a quartz-K feldspar matrix, which itself contains garnet up to 1 cm across and subsidiary kyanite up to 1 cm long. In the southern part, around Aird an t-Sruith, the gneiss contain pods or lenses of mafic gneisses up to several meters long and shows agmatitic features. Leucogranitic gneiss is equivalent to the perthitic microcline acid gneisses described by Dickinson (1974).

(c) Quartz-biotite gneiss

Quartz-biotite gneisses alternating with pelitic

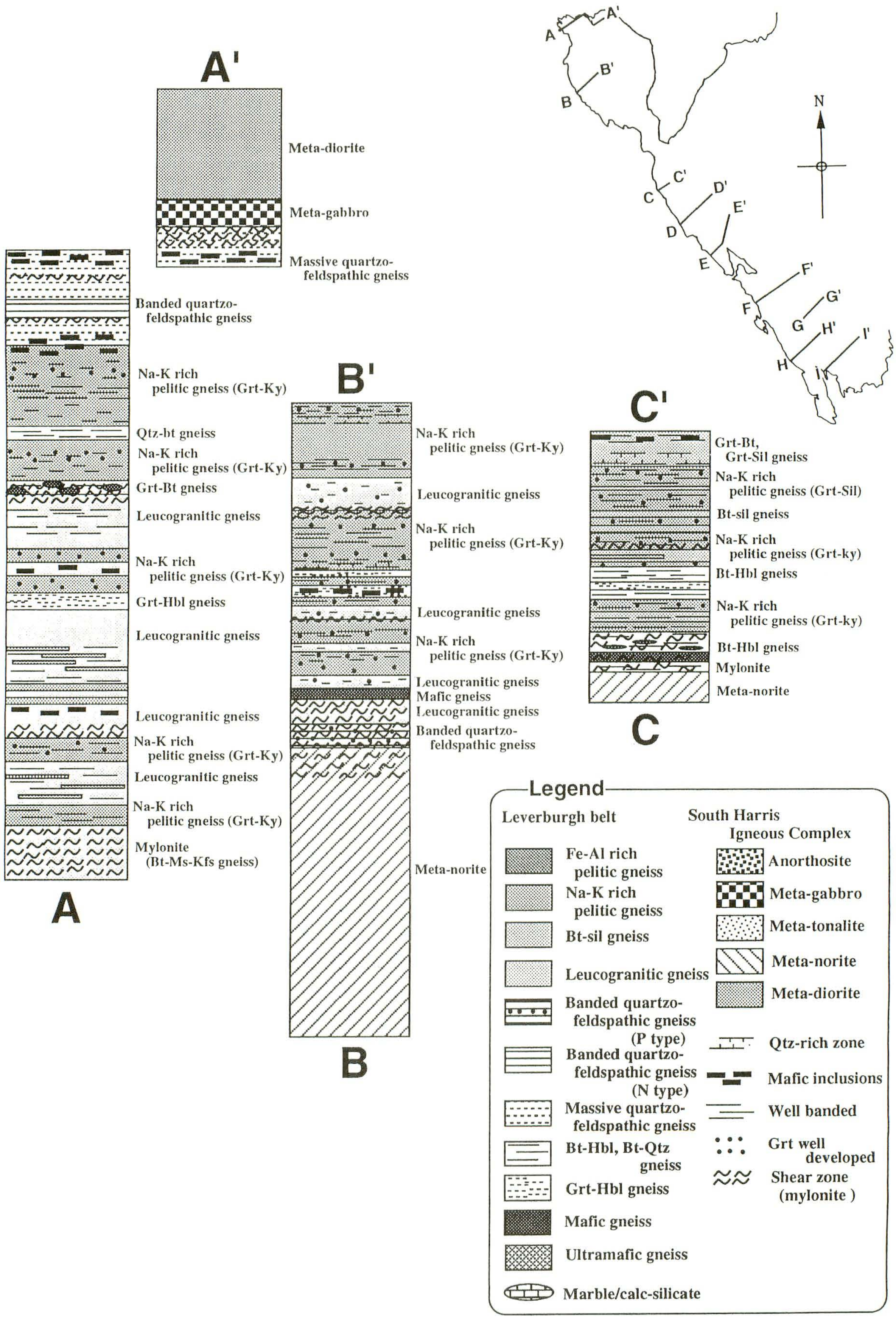


Fig. 4. Cross sections of the Leverburgh Belt. Caution: these sections not represent the true upper to lower sequence.

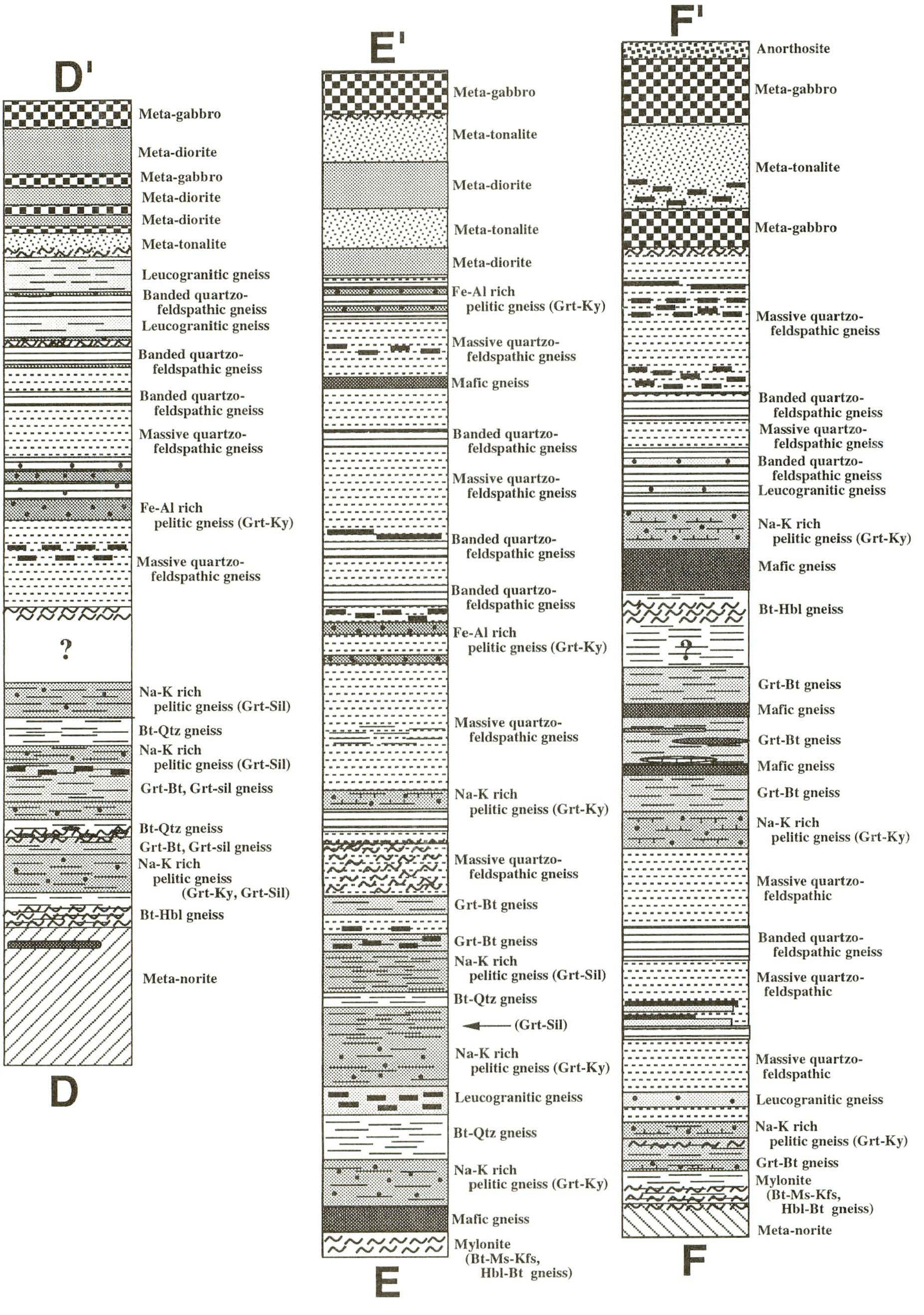


Fig. 4. (continued)

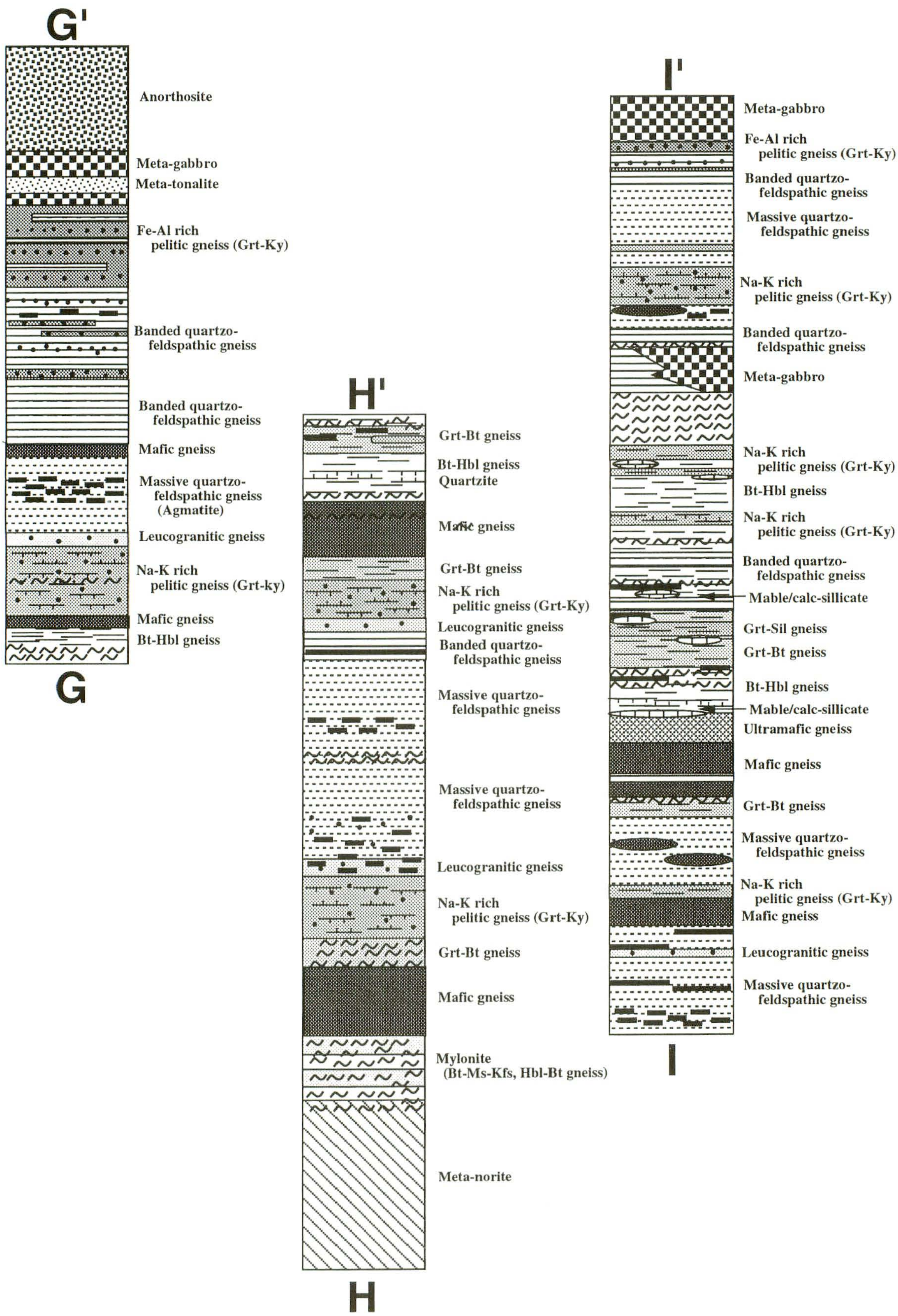


Fig. 4. (continued)

Table 1. Mineral assemblage of metasedimentary and meta-igneous gneisses from the Leverburgh Belt

Assemblage	M1 Inclusions in grt and cpx	M2 porphyroblast	M3 corona or symplectite	M4 foliation
Rodel Series				
Na-K rich pelitic gneiss				
grt-ky-(bt)-qtz±kfs±pl	bt-sil-qtz-pl	grt-ky	(bt)±(sil)±(crd)	(bt)±(sil)
grt-ky-crn-(bt)-pl-kfs±qtz	bt-sil-crn-pl	grt-ky	(±crd)	(bt)±(sil)
Banded quartzo-feldspathic gneiss				
grt-opx-qtz-pl±kfs±(bt)	bt-qtz-pl	grt-opx	(opx+pl)	(bt)
grt-cpx-qtz-pl±opx±kfs±(bt)±(hb)	bt-hbl±opx	grt-cpx	(opx+pl)	(bt)+(hbl)
Mafic gneiss				
grt-cpx-pl±opx±qtz	qtz-pl±ap	grt-cpx	(opx+pl)	(bt)+(hbl)
Ultramafic gneiss				
grt-cpx-pl±spl	spl	grt-cpx	?	(hbl)
Marble/calc-silicate				
cc-dol-fo-di±(phl)±(prg)	?	fo-di	?	(phl)±(prg)
Benn Obbe Series (A) & (B)				
Na-K rich pelitic gneiss				
grt-ky-(bt)-qtz±kfs±pl	bt-sil-qtz-pl	grt-ky	(bt)±(sil)±(crd)	(bt)±(sil)±(ms)
*Fe-Al rich pelitic gneiss**				
grt-ky-spl-qtz-pl±crn±Kfs±(bt)	sil-qtz±st±spl±crn±bt	grt-ky-spl±crn	(spl+crd), (opx+crd), (opx+pl)	(bt)±(chl)
grt-opx-ky-qtz-pl±kfs±(bt)	sil-bt±qtz±pl	grt-ky-opx	(spl+crd), (opx+pl)	(bt)±(chl)
Banded quartzo-feldspathic gneiss				
grt-opx-qtz-pl±kfs±(bt)	bt-qtz-pl	grt-opx	(opx+pl)	(bt)
grt-cpx-qtz-pl±opx±kfs±(bt)±(hb)	bt-hbl±opx	grt-cpx	(opx+pl)	(bt)+(hbl)
opx-cpx-pl-qtz±(bt)±(hbl)	opx-cpx	grt-cpx-opx	(opx+pl)	(bt)+(hbl)
opx-(bt)-qtz-kfs±pl±(hbl)*	bt-qtz±pl**	opx	(bt)±(hbl)	(bt)
Massive quartzo-feldspathic gneiss				
grt-cpx-pl-qtz±opx±kfs±(Hbl)±(bt)	qtz-pl±bt±hbl	grt-cpx	(opx+pl)	(hbl)±(bt)
Mafic gneiss				
grt-cpx-(hbl)-pl±opx±qtz±(bt)	qtz-pl±ap	grt-cpx	(opx+pl)	(hbl)±(bt)
Ultramafic gneiss				
grt-cpx-(hbl)-pl±spl	spl	grt-cpx	(hbl)	(hbl)
Leucogranitic gneiss				
grt-qtz-kfs-pl±(bt)±(hbl)	bt	grt	(bt)	(bt)±(hbl)
Chaipaval Pelitic Series				
Na-K rich pelitic gneiss				
grt-ky-(bt)-kfs-pl-qtz	sil-bt-pl-qtz	grt-ky	(bt)±(sil)	(bt)±(sil)±(ms)
grt-(sill)-(bt)-kfs-pl-qtz	sil-bt-pl-qtz	grt	(bt)±(sil)	(bt)±(sil)±(ms)
Leucogranitic gneiss				
grt-(bt)-kfs-pl-qtz±(hbl)	bt	grt	(bt)	(bt)-(ms)±(hbl)
Banded quartzo-feldspathic gneiss				
grt-cpx-(hbl)-(bt)-qtz-pl±kfs	bt-hbl	grt-cpx	(opx+pl)	(bt)±(hbl)
Mafic gneiss				
grt-cpx-(hbl)-pl±opx±qtz±(bt)	qtz-pl±ap	grt-cpx	(opx+pl)	(hbl)±(bt)

grt:garnet, bt:biotite, ky:kyanite, sil:sillimanite, crn:corundum, spl: spinel, crd:cordierite, opx:orthopyroxene, cpx:clinopyroxene, hbl: hornblende, scp:scapolite, chl:chlorite, ms:muscovite, qtz:quartz, pl:plagioclase, kfs:K feldspar, cc:calcite, dol:dolomite, fo:forsterite, di:diopside, phl:phlogopite, prg:pargasite, ap:apatite. Secondary minerals are shown in brackets. *: Benn Obbe Series (A) only. **: inclusions in opx gneiss are well exposed around Kyles Lodges. They consist dominantly of quartz and biotite with varying amounts of plagioclase, K feldspar, sillimanite, muscovite and small amounts of hornblende. The rare, K feldspar-rich variety is similar to the leucogranitic gneiss.

(d) Mylonitized zone

Mylonitized zones stretch parallel to gneissose banding along the western boundary. Biotite-muscovite-bearing pelitic mylonite and hornblende-bearing mafic mylonite are observed; in parts they form alternating bands. Smaller mylonitic zones are also seen throughout the Chaipaval Pelitic Series.

3.5. Character of each Series

The mineral assemblages from these series are presented in Table.1. In each series similar gneisses show the same mineral assemblage in thin section. Fig.4 shows the detailed lithological cross sections measured across the Leverburgh Belt. However, they do not represent the complete lower sequence to upper sequence. The character of each series is summarized as follows: Benn Obbe Series (A) is characterized by quartzo-feldspathic gneiss with small amounts of the two types of pelitic gneisses (Na-K rich and Fe-Al rich); Benn Obbe Series (B) is dominated by massive quartzo-feldspathic gneiss, but lacking Fe-Al rich pelitic gneiss; pelitic gneisses are notably well developed in the Chaipaval Pelitic Series. These pelitic gneisses are rich in aluminosillicates (kyanite or sillimanite) and contain leucogranitic gneiss sheets (K feldspar rich quartzo-feldspatic gneiss). The Rodel Series is characterized by abundant and variable, even exotic, lenticular lithologies, such as marble/calc-silicate rocks, pelitic gneiss, mafic gneiss, quartzite and ultramafic pods. Boundaries between the four series are typically marked by shear zones.

4. Petrography

4.1. Pelitic gneiss

(a) Na-K rich pelitic gneiss

This gneiss generally contains the assemblage garnet, kyanite, biotite, sillimanite, quartz, K feldspar and plagioclase, and rare corundum. It has compositional layering a few centimetres to 10 cm thick, with varying amounts of garnet, kyanite and biotite. In places, lenses and pods rich in garnet and kyanite (with modal amounts up to 90 per cent) are observed. Garnet commonly occurs as porphyroblasts up to 20 mm in diameter. Larger garnet grains tend to be subrounded, though locally they form irregular lobate shapes, marginal to which secondary biotite has developed. Garnet porphyroblasts typically include sillimanite, biotite, ilmenite, quartz, K feldspar and, rarely, corundum. These inclusions show a distinct zonal distribution, with biotite and quartz generally concentrated in the cores of larger garnets, whereas sillimanite occurs near the rims. Furthermore, garnet porphyroblasts are, in places, overgrown by kyanite at the rims. Garnet grain boundaries are strongly embayed by secondary biotite and sillimanite, and rarely replaced by cordierite. Kyanite generally occurs as porphyroblasts up to 20 mm long, and contains inclusions of quartz, ilmenite, biotite and, rarely, corundum; it generally shows euhedral shapes, but is replaced by fibrous sillimanite in intensely sheared rocks. Locally, kyanite is surrounded by cordierite coronas. Biotite generally occurs marginal to garnet and between garnet and kyanite. In sheared rocks, biotite is generally aligned with the foliation, together with kyanite, sillimanite and muscovite. Quartz is present both as inclusions in garnet and as discrete grains in the matrix of the rock. In the matrix, quartz occurs in bands with plagioclase or in K feldspar-rich bands. In sheared rock, grains are elongate and exhibit wavy extinction. Plagioclase generally occurs as small grains concentrated in bands, alternating with quartz. K feldspar is mainly a microcline microperthite with a blebby exsolution texture. In the matrix, the grain size is generally large (2-5 mm); in sheared rocks it occurs as porphyroclasts with an ellipsoidal shape. Ilmenite, rutile, apatite and zircon occur both as inclusions in garnet and as accessory minerals in the matrix.

(b) Al-Fe rich pelitic gneiss

This is a coarse-grained, crudely foliated rock, consisting essentially of garnet, kyanite, cordierite, plagioclase, quartz and a small amount of K feldspar; the accessory minerals of ilmenite, spinel, and staurolite are distinctive. The gneiss is highly garnetiferous (modal composition above 40 per cent), with garnet porphyroblasts up to 30 mm in diameter. Garnet grains shows anhedral or resorbed outlines, although they generally occur as irregular forms because they lie in contact with each other. Garnet in aluminosilicate-rich domains show strongly embayed or lobate shapes. Rarely garnet and kyanite are intergrown with each others. Sillimanite, staurolite, ilmenite, spinel, biotite, quartz, plagioclase, K feldspar and sparse kyanite have been observed as inclusions in garnet. The assemblages spinel-ilmenite, spinel-ilmenite-sillimanite, and staurolite-spinel-sillimanite-ilmenite have all been observed within garnet. Cordierite coronas are more prominent in this rock than in the Na-K rich pelitic gneiss. Coronas of spinel-cordierite symplectite, orthopyroxene-cordierite and orthopyroxene-plagioclase are found around garnet. Kyanite occurs as porphyroblasts up to 30 mm in length, as both euhedral and irregular, anhedral shapes. Kyanite contains inclusions of spinel, ilmenite, quartz, plagioclase, corundum and biotite, but corundum, spinel and quartz are not in direct contact. Anhedral, irregular kyanites which include or lie in contact with spinel, are intergrown with garnet. Coronas of spinel-cordierite symplectite and cordierite are also observed around kyanite and fine mats of secondary sillimanite. Spinel occurs in three distinct forms: (1) inclusions in garnet and kyanite; (2) inclusions in magnetite or ilmenite in the matrix; (3) forming a symplectite together with cordierite. Cordierite and orthopyroxene occur only within coronas around garnet and kyanite/sillimanite. Corundum occurs as inclusions in garnet and kyanite. Some corundum and garnet intergrowths are seen near garnet rims. Plagioclase occurs as subhedral porphyroblasts of medium- to coarse-grained size (<3 mm). Plagioclase shows pericline and albite twining but lacks zonal structure. Rarely, it includes quartz and kyanite. Quartz is present within garnets and in the matrix. Within garnet, subrounded quartz lies in contact with sillimanite, staurolite and biotite. In the matrix, quartz forms more irregular shapes. Compositional layering of quartz-rich and plagioclase/K feldspar rich zones is not as clear as that seen in Na-K rich gneisses. Coronas of cordierite, orthopyroxene-cordierite and orthopyroxene-plagioclase are formed of euhedral grains and seem to have grown at the expense of quartz. K feldspar is a microcline microperthite. In the matrix, the grain size ranges from 1 to 4 mm. Locally, K feldspar includes quartz and kyanite. Ilmenite, rutile, apatite and zircon are accessory minerals that form inclusions in garnet and occur in the matrix.

4.2. Quartzofeldspathic gneiss

(a) Banded quartzofeldspathic gneiss

The compositional layering which ranges from a few millimetres to 20 mm in thickness reflects the variable relative amounts of different minerals in thin sections. The typical overall mineral assemblage is garnet-clinopyroxene-orthopyroxene-biotite-hornblende-quartz-plagioclase-K feldspar. The variations reflect the abundance of garnet, clinopyroxene, orthopyroxene and K feldspar in each layer. Garnet forms porphyroblasts, normally up to 3 mm in diameter, but rarely reaching up to 30 mm. It consists mainly of anhedral grains, and contains inclusions of quartz, biotite, hornblende, ilmenite and apatite. Garnet inclusions do not show a zonal distribution. Grain boundaries are strongly embayed, suggesting that garnet has been partially resorbed. Coronas consisting of orthopyroxene-plagioclase are normally present, replacing garnet. Clinopyroxene also occurs as subhedral porphyroblasts, ranging in size from 0.3 to 5 mm across. Rarely, clinopyroxene includes orthopyroxene and quartz, and exsolution of ilmenite and plagioclase is noted. The outer parts of clinopyroxene are replaced by hornblende, and locally whole porphyroblasts are pseudomorphed. Orthopyroxene occur as porphyroblasts up to 20 mm in diameter or again shows reaction coronas; the former one are subrounded and contain inclusions of quartz, plagioclase, biotite and ilmenite. Occasionally, small garnets are present at the rims. The orthopyroxene porphyroblasts are commonly embayed by secondary biotite. The orthopyroxenes in garnet coronas show reaction rims and vermicular patterns. Furthermore, these are replaced by secondary biotite and hornblende. Quartz is present both as inclusions in garnet, clinopyroxene and orthopyroxene and in the matrix. Here, it occurs in bands alternating with those rich in plagioclase and ferromagnesian minerals. Plagioclase occurs as discrete grains, as noted above, and more rarely as porphyroblasts with included quartz and biotite. In sheared rocks, it is recrystallized to fine-grained aggregates. K feldspar is generally microcline microperthite with a blebby exsolution texture. Scapolite occur as discrete grains replacing the plagioclase. Ilmenite, rutile, apatite and zircon occur both as inclusions in garnet and in the matrix.

(b) Massive quartzofeldspathic gneiss

In this gneiss the mineral assemblage is similar to that found in banded quartzofeldspathic gneiss. Its massive, more homogeneous nature is reflected in the small amounts of orthopyroxene, K feldspar, and orthopyroxene coronas. Inclusions in garnet porphyroblasts and development of secondary biotite also occur less commonly than in the qrtzofeldspathic gneiss.

4.3. Mafic gneiss

This gneiss is generally a coarse-grained, poorly-foliated rock. It consists essentially of garnet, clinopyroxene, orthopyroxene, hornblende, plagioclase and quartz. Various minerals dominante, giving rise to garnetiferous types, clinopyroxene-rich types and intermediate types. Garnet occurs as porphyroblasts up to

Table 2. Representative major- and trace element analyses of metamorphic rocks from the Leverburgh Belt.

NO.	1	4	6	8	9	11	12	16	18	20	27
Sample	83-804-1.2	90-814-17b	93-1001-6up	931001-2	93-1008-5	93-1012-top	93-1013-8	93-929-3	94-630-1.2	94-630-in	94-709-7
Series	Benn (A)	Benn (B)	Rodel	Rodel	Rodel	Benn (B)	Benn (A)	Rodel	Chaipaval	Chaipaval	Rodel
Rock type	G-C-O-h	C-O-h-b	G-C-h	G-C-h	G-C-h	G-C-o-h	G-C-o-h	G-O-o-h-b	G-h-u	G-h	G-C-h
SiO2	49.04	46.39	46.73	48.33	45.85	48.93	48.71	50.65	49.83	50.09	45.83
TiO2	0.54	1.02	2.63	2.89	2.25	0.67	3.30	1.42	1.84	1.36	2.06
Al2O3	13.45	11.14	14.06	14.39	13.34	16.21	15.79	14.93	16.52	14.67	13.86
FeO*	11.87	12.84	15.34	12.64	15.50	14.12	13.70	13.08	10.53	14.73	15.27
MnO	0.26	0.23	0.28	0.17	0.27	0.25	0.18	0.22	0.16	0.22	0.24
MgO	11.41	11.93	5.44	3.97	6.04	4.74	3.38	7.18	8.02	6.09	7.21
CaO	10.90	13.35	12.20	12.81	13.05	10.09	8.99	8.16	9.71	9.33	11.69
Na2O	1.52	1.59	1.12	2.47	1.68	3.25	3.16	1.67	0.85	0.54	1.56
K2O	0.32	0.68	0.22	0.51	0.26	0.34	0.24	0.86	0.78	0.90	0.39
P2O5	0.26	0.06	0.27	0.30	0.20	0.11	0.52	0.12	0.34	0.14	0.17
LOI	-	-	-	-	-	-	-	-	-	-	-
Total	99.55	99.21	98.30	98.48	98.43	98.70	97.98	98.27	98.56	98.06	98.30
V	326.6	377.5	340.5	399.0	360.0	470.3	169.0	375.7	210.9	414.2	387.3
Cr	309.1	1219.7	49.0	66.1	80.7	10.3	877.4	156.4	291.9	45.4	89.9
Ni	68.5	423.5	60.6	61.0	92.2	5.7	99.4	119.2	143.3	41.3	97.7
Rb	2.4	6.6	3.3	6.4	3.6	2.3	27.0	19.3	21.4	24.7	6.6
Sr	349.9	89.6	267.6	227.3	215.2	213.7	815.7	135.3	576.9	84.2	119.2
Y	17.7	19.8	36.5	27.4	26.6	14.9	13.9	26.6	22.1	36.4	26.0
Zr	41.7	41.3	122.7	150.5	94.0	26.3	75.7	82.6	88.6	51.5	78.3
Ba	169.1	191.7	33.7	95.4	40.2	157.0	1209.9	177.5	537.8	206.3	67.6
Th	0.4	0.1	0.2	1.7	0.3	0.2	1.3	1.0	0.4	1.2	0.7
La	5.2	2.7	7.7	18.9	5.2	-	17.3	2.9	16.0	1.4	1.7
Ce	34.8	2.5	22.2	37.0	23.5	11.0	32.0	16.5	35.5	21.5	14.5
Nb	1.8	1.5	14.3	19.8	12.2	1.3	2.0	12.3	15.2	5.4	10.9
Pb	3.5	1.9	1.8	4.7	2.1	6.2	8.9	4.4	5.7	2.9	1.9
Cu	90.1	18.4	16.6	70.5	73.6	14.9	11.0	238.5	12.8	37.8	25.2
Co	54.2	66.3	-	11.3	13.3	59.4	36.7	41.6	29.0	56.0	26.6
V	326.6	377.5	340.5	399.0	360.0	470.3	169.0	375.7	210.9	414.2	387.3
Sc	57.7	34.8	42.4	41.8	40.7	57.6	20.6	45.0	30.6	45.2	46.1

Rodel: Rodel Series, Benn (A): Benn Obbe Series (A), Benn (B): Benn Obbe Series (B), Chaipaval: Chaipaval Pelitic Series. Rock types are represent as mineral assemblage. Minerals are follows; G: garnet, C: clinopyroxene, O: orthopyroxene, o: retrograde orthopyroxene corona, b: secondary biotite, h: secondary hornblende, u: secondary cummingtonite.

10 mm in diameter, and generally shows anhedral or resorbed outlines; it is partly replaced by orthopyroxene coronas. Garnet porphyroblasts contain ilmenite, quartz and clinopyroxene inclusions, with clinopyroxene intergrown with garnet near the rims. Clinopyroxene also occurs as subhedral to anhedral porphyroblasts up to 20 mm across. Clinopyroxene contains subrounded inclusions of orthopyroxene, hornblende, ilmenite and quartz and exsolution lamellae of plagioclase. Clinopyroxene is typically rimmed by secondary hornblende, locally accompanied by ilmenite. In sheared rocks, and in places in the unsheared mafic gneiss, it is pseudomorphed by hornblende. Orthopyroxene occurs as porphyroblasts, as inclusions in clinopyroxene, and in reaction coronas. Generally, orthopyroxene porphyroblasts occur as discrete grains with resorbed margins, surrounded by clinopyroxene. Orthopyroxene coronas occur between garnet and clinopyroxene. Typically, secondary hornblende grows at the boundaries of clinopyroxene and orthopyroxene reaction coronas. Plagioclase commonly separates the ferromagnesian minerals, with some grain boundaries showing a sutured structure. Quartz is present in the matrix and in porphyroblasts; in the matrix it shows irregular grain shapes and sizes. Quartz inclusions within porphyroblasts are subrounded. Sphene occurs locally as discrete grains up to 1 mm in diameter, surrounded by ilmenite. Scapolite occurs as discrete grains replacing plagioclase. Ilmenite, apatite and minor zircon are observed both in the porphyroblasts and in the matrix.

4.4. Ultramafic gneiss

This is a coarse-grained, poorly-foliated rock consisting mainly of clinopyroxene, orthopyroxene, garnet, spinel and plagioclase. Clinopyroxene occurs as porphyroblasts up to 5 mm across. It is the dominant mineral, modally constituting 80-90 per cent of the rock. Rarely, orthopyroxene inclusions are seen. Orthopyroxene forms anhedral to sub-rounded grains, in places, replaced by secondary ortho-amphiboles. Spinel occurs as small, discrete grains, mantled by garnet. Hornblende and biotite occur as secondary minerals marginal to clinopyroxene and orthopyroxene. Minor plagioclase occurs filling small spaces between ferromagnesian minerals; accessory magnetite, ilmenite, rutile, apatite are also present.

4.5. Leucogranitic gneiss

This gneiss contains the assemblage garnet-biotite-quartz-K feldspar-plagioclase-quartz and with small amounts of muscovite and hornblende. Garnets occur as porphyroblasts up to 5 mm in diameter, with rounded inclusions of biotite, quartz and ilmenite. Generally, garnet is replaced by secondary biotite and rare hornblende. In sheared rocks, biotite and muscovite form the foliation. Biotite, muscovite and hornblende occur only as secondary minerals replacing garnet. K feldspar and plagioclase are generally more fine-grained than quartz, and these minerals form irregular bands showing variable amounts of quartz and feldspar. Ilmenite, rutile, zircon and apatite occur both as inclusions in garnet and in the matrix.

4.6. Marble / Calc-silicate

These units consists of the assemblage calcite-dolomite-forsterite-diopside-phlogopite with small amounts of pargasite and scapolite. Calcite is generally clouded, in contrast to the dolomite, which is clear and invariably twinned. Forsterite, up to 3 mm across and commonly serpentinised, and diopside grains up to 5 mm in diameter are common. The phlogopite are often kinked or bent.

5. Geochemistry

5.1. Analtycal methods

Major and trace element contents of the mafic gneisses were determined for 43 samples by X-ray fluorescence spectrometry (XRF) at Ehime University. Representative major and trace element data are presented in Table2. A total of 43 mafic gneisses from the Leverburgh Belt, taken from outwith the shear zones, were selected for chemical analyses. Sample localites are shown in Fig.3. In this papar, I treat the mafic

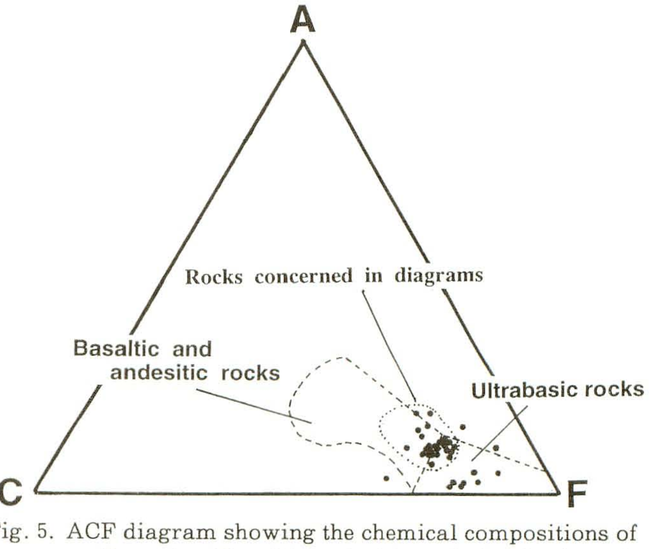


Fig. 5. ACF diagram showing the chemical compositions of mafic gneiss. Basaltic-andesitic and ultrabasic rock fields are from Winkler (1979).

gneisses with SiO_2 within range 45 to 53 (±0.5) wt percent originally as basaltic rocks. This is confirmed in ACF diagrams, where the bulk of the rocks plot in and /or near the basaltic field and some were selected for use in discrimination diagrams. Fig.5 shows the chemical compositions of selected mafic gneisses chosen in light of their SiO_2 contents, and the field of the selected 22 basic metamorphic rocks. Basaltic and andesitic rocks and ultramafic rock fields are after Winkler (1979). Fe_2O_3 has not been calculated, so all plotted points will be shift a little towards A and C.

5.2. Geochemistry of basic metamorphic rocks

In the following sections I describe the chemical characteristics of the basic metamorphic rocks, and use major and trace elements to determine the tectonic enviroment of the protolith in comparison with modern plate-tectonic systems. The plate-tectonic systems and related lithological associations in the Proterozoic are considered to be very similar to those of the Phanerozoic (see Condie, 1989a).

During the medium- to high-grade metamorphism, the large-ion lithophile elements (LILE) such as K, Rb, Sr and Ba, as well as Th and U, were probably mobilized (Tarney and Windley, 1977; Condie, 1981). However, the elements with high ionic potential (Ti, Zr, Y, V, Cr, Ni) and REE are interpreted to have been effectively immobile (Rollinson and Windley, 1980; Weaver and Tarney, 1981; Condie, 1981) and, therefore, they are suitable for determining protoliths (Osanai *et al.*, 1992).

Basic metamorphic rocks occur in all series as layers or lenses. The rocks for discrimination were selected from the central parts of thick, mappable mafic layers and mafic lenses, based on the assumption that these parts are free from influx of LILE elements which were mobilized from the surrounding rocks during high-grade metamorphism. Condie (1989b) has proposed a classification of Archaean and Proterozoic metabasaltic rocks using the ratios of immobile elements (e.g. Ti/V, Ti/Y, Zr/Y, Ti/Zr). Fig.6 shows the Ti/V ratios of basic metamorphic rocks from each series. The rocks from the Rodel Series and the Chaipaval Pelitic Series show a wide range of Ti/V ratios, but most of those from the Benn Obbe Series (A) and (B) have low ratios (<30). Condie (1989b) proposed that the ratio of Ti/V=30 is the boundary between arc basalt (ARCB) (or N-type mid-oceanic ridge basalt (NMORB)) and MORB (or within-plate basalt (WPB)). Other diagrams, such as Y-Cr (Pearce and Norry, 1979: Fig.7), Zr-TiO_2 (Pharaoh and Pearce, 1984: Fig.8), and Ti-Ni (Ishizuka, 1981: Fig.9) are also applied in order to discriminate between original tectonic environments. In Y-Cr and Zr-TiO_2 diagrams (Figs,7, 8), many of the basic

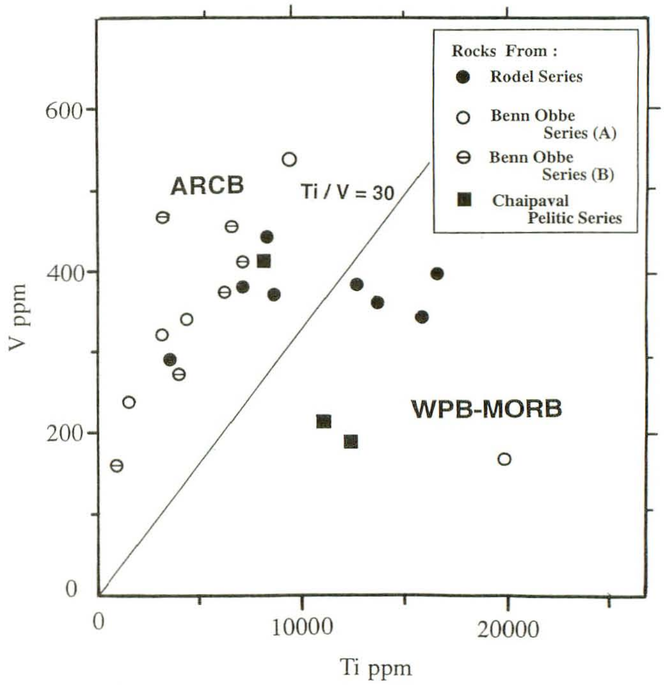


Fig. 6. Distribution of basic metamorphic rocks on a Ti-V diagram. ARCB, arc basalt; WPB, within plate basalt; MORB, mid-oceanic ridge basalt.

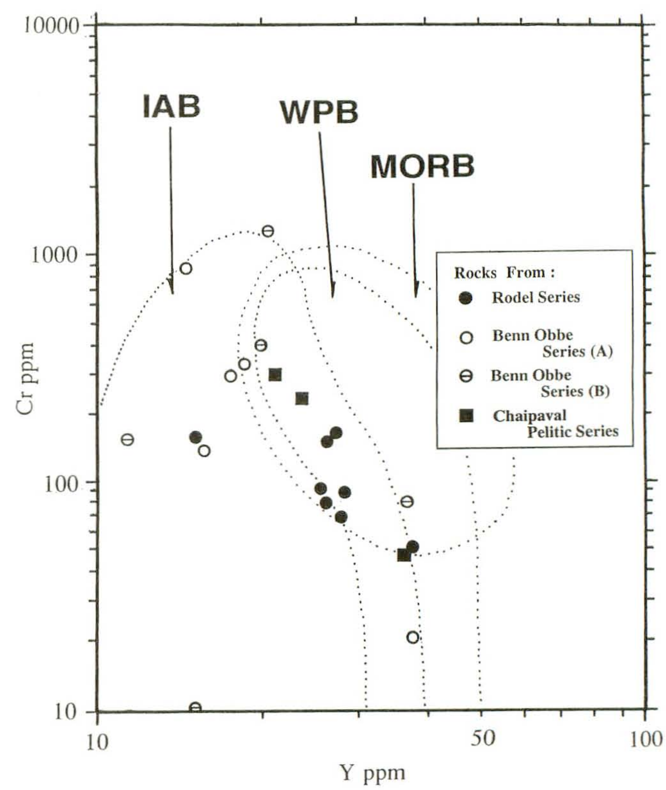


Fig. 7. Chemical relationships of basic metamorphic rocks between Y and Cr. Field from Pearce and Norry (1979). IAB, island-arc basalt.

metamorphic rocks from the Rodel and Chaipaval Pelitic Series plot in the MORB and WPB field, whereas those from the Benn Obbe Series (A) and (B) plot in the island-arc basalt (IAB) and/or arc basalt (ACB) fields. In Ti-Ni diagrams (Fig.9), the rocks from the Rodel and Chaipaval Pelitic Series plot in oceanic island tholeiitic basalt (OIT) and MORB fields, whereas those in the Benn Obbe Series (A) and (B) plot in IAB. Generally, the rocks from the Rodel and Chipaval Pelitic Series plot in MORB, WPB and/or OIT fields, and rocks from the Benn Obbe Series (A) and (B) plot in the ACB and IAB fields. Chemical characteristics of basic metamorphic rocks from each of the units described above are also plotted on the Ti/100-Zr-Y.3 diagrams (Pearce and Cann, 1973). The rocks from the Rodel and Chaipaval Pelitic Series plot in within-plate basalt and island-arc tholeiite affinites, and the rocks from the Chaipaval Pelitic Series (A) and (B) plot in a wide range of enviroments but not in the within-plate basalt field. Table. 3 shows the type of protolith deduced from each discrimination diagrams.

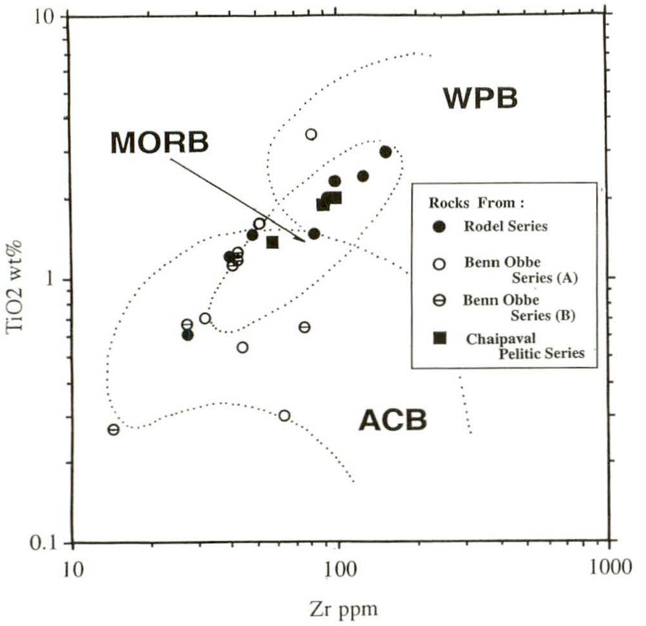


Fig. 8. Chemical variations of basic metamorphic rocks on a Zr-TiO_2 diagram. Fields are after Pharaoh and Pearce (1984). ACB, arc basalt.

MORB-normalized patterns of trace-element abundances for basic metamorphic rocks from each series are shown on spider diagrams in Fig.12. They should be compared to the MORB-normalized, trace-element abundances of mafic flows and sheeted dikes from selected different tectonic settings shown in Fig.11 (from Condie, 1989). The basic metamorphic rocks from the Rodel Series clearly show NMORB, TMORB to EMORB affinities. The spider diagrams of rocks from the Chaipaval Pelitic Series show that one specimen has TMORB affinity, whereas the others shows complicated spider patterns that, except for the Th-negative anomaly, resemble WPB and/or EMORB. Chemical compositions of the basic metamorphic rocks from the Benn Obbe Series (A) and (B) are characteristic of island-arc tholeiite and/or calk-alkaline basalt from island arcs (CABI). The spider patterns show the selective enrich-

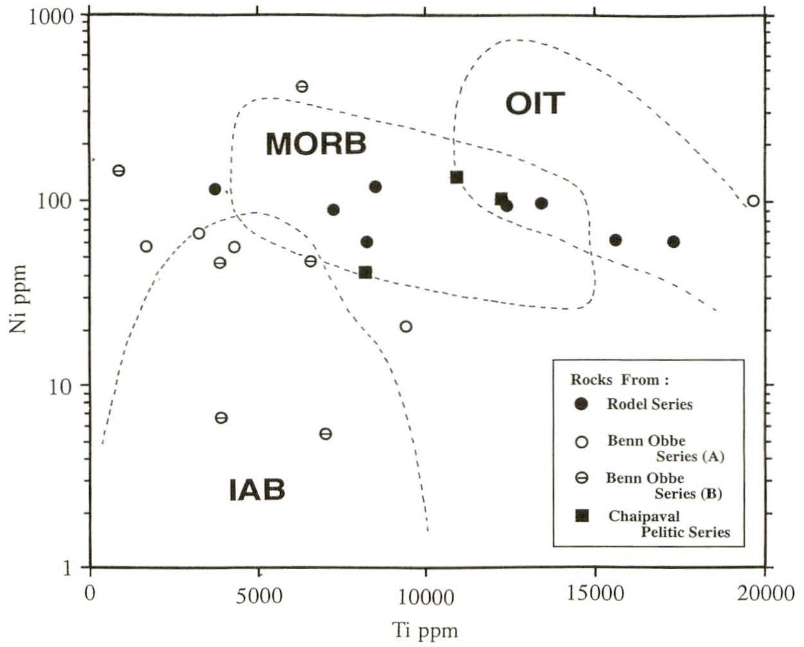


Fig. 9. Ti-Ni discrimination diagrams for basic metamorphic rocks. Field from Ishizuka (1981). OIT, ocean-island tholeiite.

ment of large-ion lithophile elements, such as Ba, over high-field strength elements, relative to MORB, and a negative Nb anomaly. These patterns are typical of basalts from back-arc basins (Saunders and Tarney, 1984) and supra-subduction-zone enviroments (Pearce *et al.*, 1984).

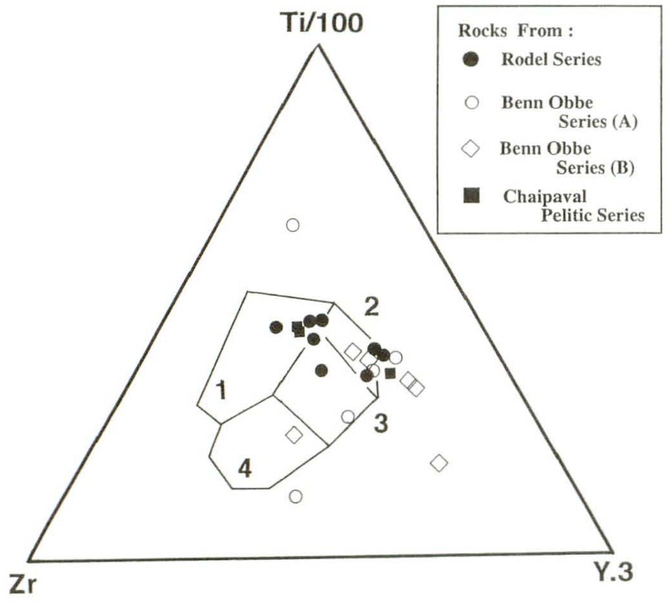


Fig. 10. Ti-Zr-Y tectonomagmatic discrimination diagram for basic metamorphic rocks from four series. 1: Within-plate basalt (oceanic island or continental basalts), 2 & 3: island-arc tholeiite, 3: ocean-floor basalt, 3 & 4: calc-alkali basalts. Fields for various basalt types are after Pearce and Cann (1973).

In summary, the protoliths of the basic metamorphic rocks of the Rodel Series appear to have been derived from MORB and OIT (EMORB generally occur near seamounts or oceanic islands) and those of the Benn Obbe Series (A) and (B) from IAT and/or CABI. The Chaipaval Pelitic Series may be derived from OIT or WPB, in view of the differing affinities given by the discrimination diagrams and MORB normalized patterns.

6. Discussion and Conclusion

6.1. Original lithology and tectonic setting

In this section, I describe the tectonic setting of the precursors of the Leverburgh Belt as deduced from lithological assemblages, in the light of the "Petrotectonic Assemblages" proposed by Condie (1989a) and the geochemical character of basic metamorphic rocks described above.

Benn Obbe Series: Garnet-pyroxene-bearing quartzofeldspathic gneiss is dominant in the Benn Obbe Series (A) and (B). Vielzeuf and Montel (1994) demonstrated, from experimental studies, that garnet-orthopyroxene-plagioclase-quartz assemblages can be readily produced by partial melting of Ca-poor,

Table 3. Summary of the tectonic setting deduced from discrimination diagrams.

No	Sample	Series	Rock type	Ti-V	Y-Cr	Zr-TiO2	Ti-Ni	Zr-Y-Ti
1	**83-804-1.2**	Benn (A)	G-C-O-h	ARCB	IAB-MORB	ACB	IAB	3
2	**90-814-17**	Benn (B)	C-O-h-b	ARCB	IAB	*	*	*
3	**90-814-17b**	Benn (B)	C-O-h-b	ARCB	*	ACB-MORB	*	2
4	**93-1001-6up**	Rodel	G-C-h	WPB-MORB	MORB-WPB	MORB-WPB	OIT	1
5	**931001-2**	Rodel	G-C-h	WPB-MORB	I-W-M	MORB-WPB	OIT	1
6	**93-1008-5**	Rodel	G-C-h	WPB-MORB	IAB-MORB	MORB-WPB	OIT-MORB	1
7	**93-1012-top**	Benn (B)	G-C-o-h	ARCB	IAB	ACB	IAB	2
8	**93-1013-8**	Benn (A)	G-C-o-h	WPB-MORB	IAB	WPB	*	*
9	**93-1015-23**	Rodel	G-C-O-h	ARCB	I-W-M	ACB-MORB	MORB	*
10	**93-927-13**	Benn (B)	G-C-O-o-h-b	ARCB	*	ACB-MORB	IAB	*
11	**93-927-6**	Rodel	G-C-h	ARCB	I-W-M	ACB-MORB	MORB	2
12	**93-929-3**	Rodel	G-O-o-h-b	ARCB	I-W-M	A-M-W	MORB	3
13	**94-630-1.1**	Chaipaval	u-b-h	WPB-MORB	I-W-M	MORB-WPB	OIT-MORB	1
14	**94-630-1.2**	Chaipaval	G-h-u	WPB-MORB	I-W-M	MORB-WPB	OIT-MORB	1
15	**94-630-3.2**	Benn (A)	G-C-h	ARCB	IAB-WPB	ACB-MORB	*	*
16	**94-630-in**	Chaipaval	G-h	ARCB	I-W-M	ACB-MORB	MORB	*
17	**94-705-01**	Benn (B)	G-C-h	ARCB	MORB-WPB	ACB-MORB	IAB	*
18	**94-705-02**	Benn (B)	G-C-O-o-h-b	ARCB	I-W-M	ACB	IAB	4
19	**94-707-64**	Rodel	G-C-o-h	ARCB	IAB	ACB	*	2
20	**94-709-10b**	Benn (A)	G-C-o-h	ARCB	IAB	ACB-MORB	IAB	2
21	**94-709-7**	Rodel	G-C-h	WPB-MORB	IAB-MORB	MORB-WPB	OIT-MORB	1
22	**83-812-5**	Benn (A)	G-C-o-h	ARCB	IAB	ACB	*	*

Rock type are same as Table.2. *: Plot outwith the fields or diagrams. I-W-A and A-M-W: Plot in all field.

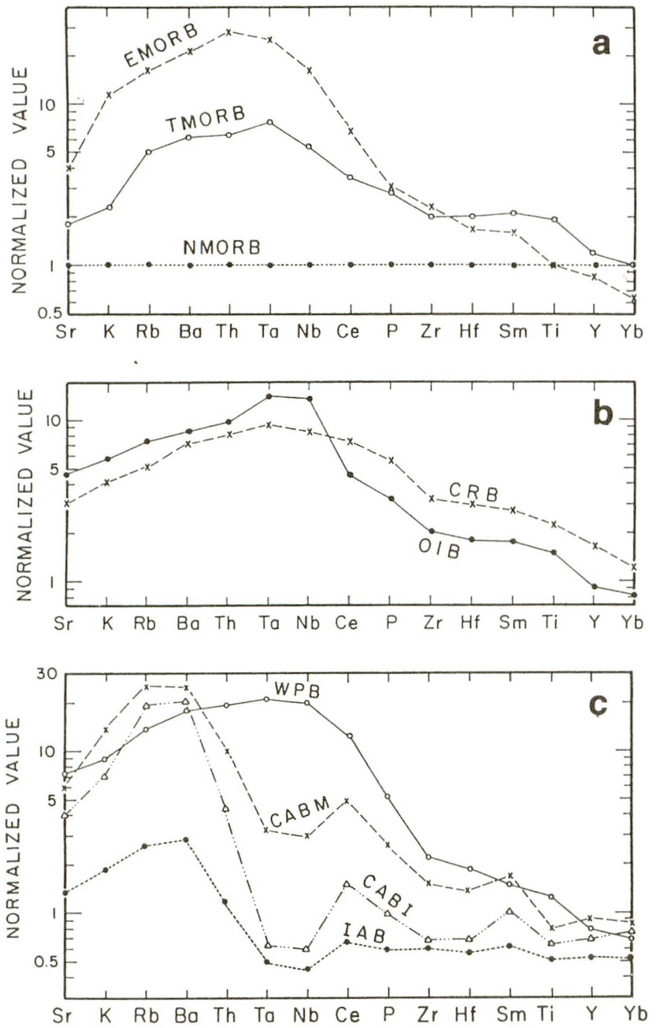


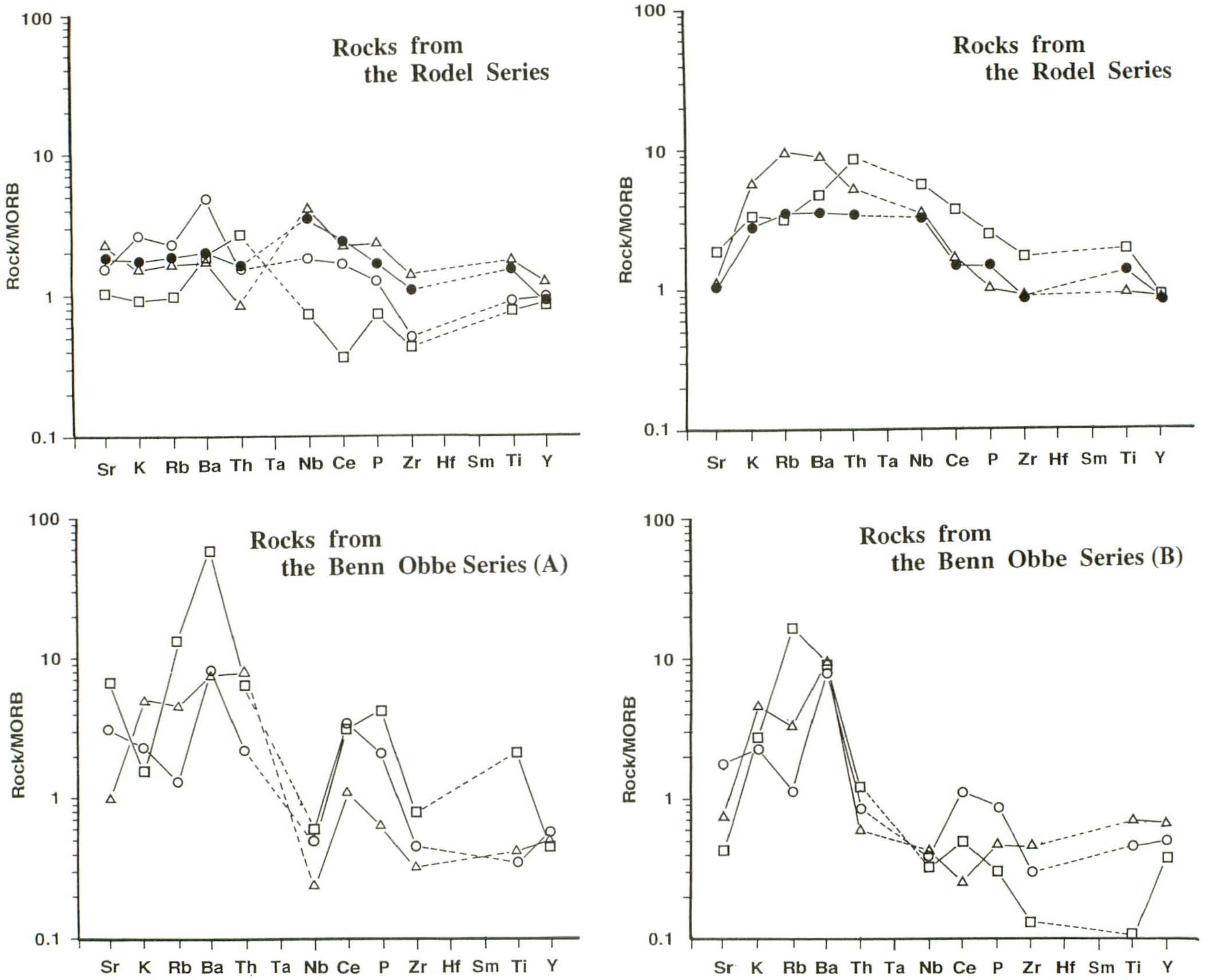
Fig. 11. NMORB-normalized spider diagrams of basalt from different tectonic settings. a) MORB-normalized incompatible element distributions in ocean-ridge basalt. NMORB, normal MORB; TMORB, transitional; EMORB, enriched basalt. b) NMORB-normalized incompatible element distributions in within-plate basalts. CRB, continental rift basalt; OIB, ocean island basalt. c) NMORB-normalized incompatible element distributions in basalt. IAB, island-arc tholeiite; CABI, calc-alkaline basalts from island arcs; CABM, continental-margin arcs; WPB, within-plate basalt. (from Condie (1989a))

alminous meta-greywackes. Taking into acount that clinopyroxene is a major component of these gneisses, and that their mineral assemblages are similar to the experimental product, the precursors of these quartzofeldspathic gneisses are considered to be Ca-rich greywackes. The well-banded quartzofeldspathic gneisses having minor intercalcations of Fe-Al rich pelitic gneiss and occur adjacent to Na-K rich pelitic gneiss, indicating that these rocks were formerly graywacke turbidites alternating with pelites (shales). Graywacke turbidites with a minor pelagic component are considered to have been trench sediments (Condie, 1989). Al-Fe rich pelitic gneiss, which only occurs in the Benn Obbe Series (A), may have been deposited as a proximal facies at the trench. The basic metamorphic rocks from the Benn Obbe Series (A) and (B) show island-arc tholeiitic and island-arc calc-alkaline affinities; therefore, the turbidite sequence was intruded by basic intrusions (sheet dike or sill) at the island arc or the continental-margin arc.

Chaipaval Pelitic Seres: Kyanite- or sillimanite-bearing pelitic gneiss and K feldspathic gneiss (leucogranitic gneiss) are dominant in the Chaipaval area, and these gneisses alternate with subsidiary biotite- and hornblende-bearing quartzose gneiss. The precursors of the Chaipaval Pelitic Series are considered to be K-Al rich pelites partly alternating with a small amount of psammitic rocks. They may have been deposited as detrital sediments in the proximal facies of the trench or as hemipelagic sediments on the oceanic crust. Basic metamorphic rocks are sparse, but the few sampled rocks from this series show TMORB and EMORB affinities. The basic rocks occur as lenses and pods in this series, suggesting that they may have been taken up by sediments as small blocks during the subduction of oceanic crust.

Rodel Series: The Rodel Series is characterized by lack of continuous bedding and the inclusion of fragments of impure limestone (marble/calc-silicate rocks), greywacke (quartzofeldspathic gneiss), mudstone (pelitic gneiss), chert (sulphide-bearing quartzite?), basalt (basic gneiss) and ophiolite fragment (ultramafic gneiss and garnetiferous mafic gneiss). These occurrences indicate typical melange assemblages, and the Rodel Series is interpreted as a possible melange in the accretionary prism. The basic metamorphic rocks show NMORB, TMORB, and EMORB-like affinities. Rock assemblages and the geochemistry of basic metamorphic rocks from the Rodel Series clearly suggest that this series was formed by oceanic materials related to the subduction of oceanic lithosphere.

Thus, the rock assemblages in the Leverburgh Belt can be classified into the following types: melange (Rodel Series) with oceanic-type volcanics; trench sediments with arc-type volcanics (Benn Obbe Quartzie (A) and (B)); and trench or hemipelagic sediments with ocean-type volcanics (Chaipaval Pelitic Series). The various rocks that show different protoliths and are observed in a narrow region are similar to those of modern arc-trench systems. The Leverburgh Belt, which is only exposed in an area 1 to 1.7 km wide and 15 km



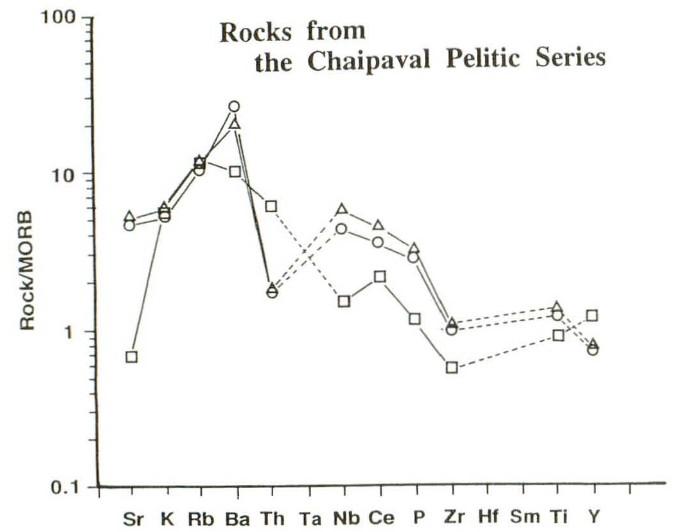


Fig. 12. MORB-normalized trace-element patterns of basic metamorphic rocks from the Leverburgh Belt. Normalized values are from Pearce (1983).

long, seems to be too small to compare with a modern arc-trench system. However, the visible belt is considered to be only the part uplifted by structural disturbance after peak metamorphism, from the evidence that the secondary hydrous minerals form the foliations and shear planes. Therefore, the main body may remain to be laid on under middle crustal levels, or it was modified by later shearing (see Coward and Park, 1987;

Graham, 1980). Thus, there is no room for argument on this point. The idea of which Archaean and early-Proterozoic context is similar to a modern arc-trench system has been well documented by several workers recently (Helmstaedt and Scott, 1992; Kimura *et al.*, 1993; Windley, 1993). Archaean oceanic assemblages have comparable HFS/REE relative to MORB and oceanic plateaus, except for their being generally richer in FeO than modern MORB (i.e. Storey *et al.*, 1991) and this supports the tectonic setting deduced from the chemical compositions of mafic gneiss and the lithological constitution discussed above.

In contrast, a small intracratonic basin with Archaean basic intrusives may be considered as alternative enviroment. Such an intracratonic enviroment, for example, an Archaean greenstone succession, would be rich in mafic rocks compared to sediments, which generally comprise between 10 and 30 percent of Archaean greenstone successions (Lowe, 1980). However, this would not explain the various protoliths of mafic gneiss which occur as layers and lenses (fragments) within sediments, nor the presence of the South Harris Igneous Complex, which has continental margin-type chemical affinities (Fettes *et al.*, 1991). It is concluded that the Leverburgh Belt represents an Archaean or early Proterozoic accretionary prism. The complex, original rock associations were formed during the subduction of an oceanic plate prior to regional metamorphism and deformation.

6.2. Evolutionary history of the South Harris Complex

The exposed metasedimentary gneisses in the South Harris region show a wide range of lithologies compared to other parts of the Lewisian complex, and the Proterozoic igneous activity and granulite metamorphism of Early Laxfordian age are distinctive. According to the evolutionary model of the Lewisian complex proposed by Park and Tarney (1987), the Archaean crust was reworked during the Early to Late Proterozoic. In South Harris, Fettes *et al.*, (1992) considered that the Leverburgh Belt and the Langavat Belt were strongly deformed and metamorphosed under amphibolite-grade conditions (Badcallian metamorphism (2.8 Ga)) while being tectonically 'transported' (perhaps subducted or faulted) to lower crustal levels. Subsequently, at about 2.2 Ga-2.0 Ga (Cliff *et al.*, 1983), the sequence was extensively intruded by South Harris Igneous Complex at these deep levels. This hypothesis agrees basically with that of Park and Tarney (1987). Thus, it has been considered that metasediments of the South Harris Complex were coeval with one part of the Archaean metasedimentary rocks exposed on the mainland. However, there are no critical reasons for such conclusions and little attention has been given to the precursors of these metasediments. In this paper, I postulate that the precursors of the Leverburgh Belt were formed in relation to the subduction of oceanic plate. The tectonic setting of the metasedimentary rocks, as deduced from detailed lithological studies and the geochemistry of metabasic rocks that occur within the metasedimentary succession, have not previously been reported from the Leverburgh Belt.

The tectonothermal trend of the Leverburgh gneisses is summarized as follows: (M1) prograde metamorphism with increasing temperature; (M2) static prograde metamorphism with increasing pressure; (M3) static retrograde metamorphism with decreasing pressure and temperature; (M4) retrograde hydrous metamorphism accompanied by shearing (Baba *et al.*, 1996). M1 prograde metamorphism was caused by intrusion of the South Harris Igneous Complex (SHIC), as elements of the South Harris Igneous Complex preserve evidence of the pressure increase during M2 (Baba *et al.*, 1996). Fettes *et al.* (1992) suggested that SHIC intrudes the Leverburgh and Langavat Belt (South Harris Belt) at deep crustal levels, and that the South Harris Belt shows the thermal affects. However, this does not explain the SHIC-preserved, pressure-increasing history in the SHIC at M2. According to the anti-clockwise *P-T* history, the thermal effects of SHIC cannot be responsible for the kyanite-forming metamorphism (M2), but must relate to the earlier prograde metamorphism (M1). Therefore, another interpretation is required to account for the pressure increase from M1 to M2.

The tectonic setting of precursors of the Leverburgh Belt and the nature of the South Harris Igneous Complex are the key to the tectonic situation of the South Harris Belt. The precursors of the Leverburgh Belt can be readily related to subduction of an oceanic plate, and the SHIC is tholeiitic to calkcalkaline and alkalic in nature, resembling that of igneous rocks in magmatic arcs on continental margins (Fettes *et al.*, 1992).

The evolutionary history of South Harris deduced from the sedimentary precursors, igneous activity and metamorphic history, is as follows. The South Harris Belt was an early Proterozoic magmatic arc that was formed on the margin of the continental block (Lewis?), an oceanic plate having subducted from the other side, and the two continental blocks eventually colliding along the South Harris Belt after intrusion of SHIC. During the collision, the thrusting of a continental crust over the South Harris Belt caused the high-pressure metamorphism at M2 at around 1.86 Ga (Cliff *et al.*, 1983). The inferred anticlockwise path from M1 to M3 under static conditions is consistent with this hypothesis, and the inferred tectonic setting of the precursors of the Leverburgh Belt supports the idea of subduction and thrusting of continental crust over the South Harris Belt.

The anticlockwise *P-T* history and precursors of the Leverburgh Belt suggest that the tectono-thermal history of the South Harris Complex may be quite different from that of rocks of the mainland Lewisian. For example, South Harris lacks a major tectonic event, such as the any identification of obvious representatives of the Scourie dike suite, so that the classic stratigraphic marker from the mainland which separates the two metamorphic episodes (Peach *et al.*, 1907; Sutton and Watson, 1951), is absent (Cliff *et al.*, 1983; Park and Tarney, 1987). Very little information is available from the Outer Hebrides concerning the earlier sequence of events (Inverian to Laxfordian D1) recognized on the mainland (Coward and Park, 1987). These previous observations support the hypothesis that South Harris has a different evolutionary history from the mainland. Consequently, the South Harris Complex may be one part of another unit of high-grade terrain in the Lewison Complex with a different *P-T -t* history. There may have be a parallel to the Nagssugtoqidian of Greenland and/or, at least, it may relate to Early Proterozoic accretionary orogens (Windley, 1993) that extend from West USA to Finland. Further geochonological sutudies (including REE and isotope, age determinations) and structural work are needed to reveal the overall evolutionary history of the South Harris Complex.

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Explanation of Plate 1

Occurrence of two types of pelitic gneisses. a) Na-K rich pelitic gneiss from the Chaipaval Pelitic Series. Note the large, pale lilac garnet mantled by ple blue kyanite. b) Fe-Al rich pelitic gneiss from the Benn Obbe Series (A). Dark grey kyanite and ple red garnet are prominent. Lens cap is 55 mm acoss.

Explanation of plate 2

(a) : Alternation of Na-K rich peltic gneiss (melanocratic band) and leucogranitic gneiss (leucocratic band) from the Chaipaval Pelitic Series at Toe Head. (b) : Retrograded Na-K rich pelitic gneiss from the Chaipaval Pelitic Series at Kyle Lodge. Garnet is replaced by sillimanite (white pellets).

Explanation of Plate 3

Occurrence of two types of quartzofeldspathic gneiss. (a) : Massive quartzofeldspathic gneiss from the Benn Obbe Series (A). (b) : Banded quartzofeldspatic gneiss from the Benn Obbe Series (B). Distinct banding of mafic rich and felsic-rich bands are observed.

Explanation of Plate 4

(a) : Occurrence of foliated mafic gneiss from the Rodel Series. (b) : Mylonite showing dextral shears from the western margin of the Chaipaval Pelitic Series.

Plate 1

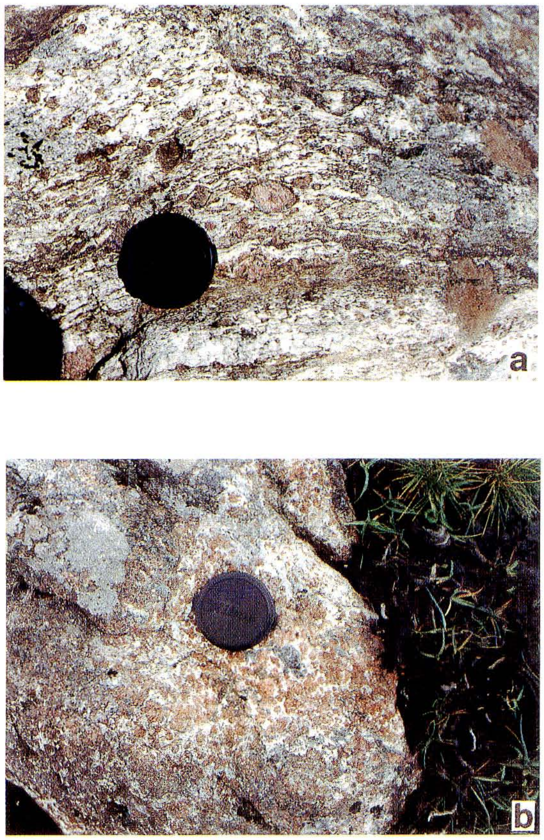

Plate 2

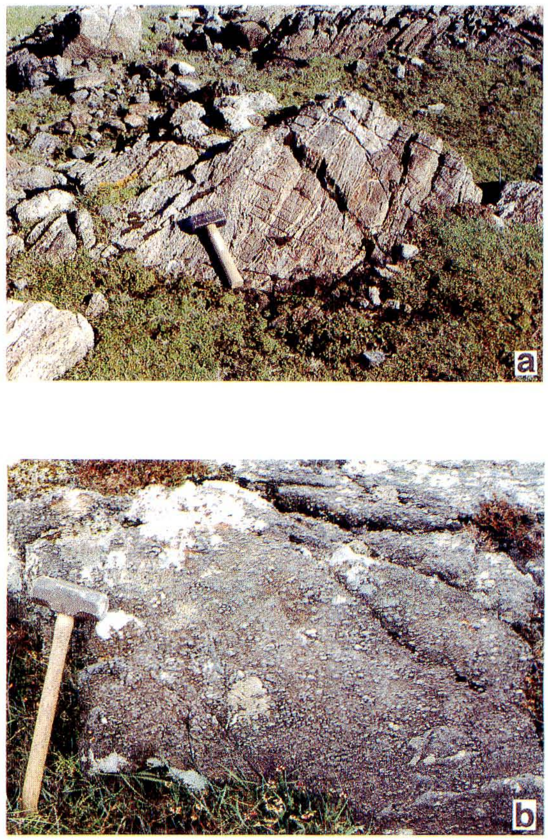

Plate 3

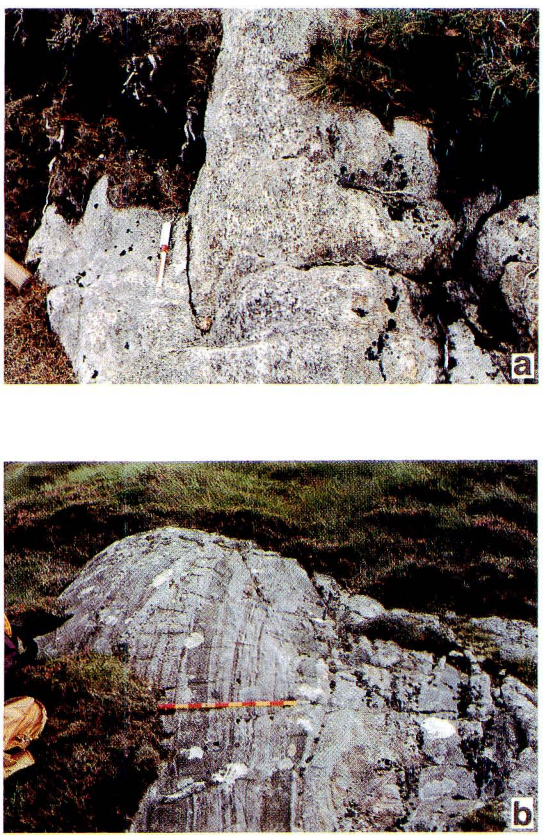

Plate 4