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ULTRA-HIGH TEMPERATURE METAMORPHISM IN THE LEWISIAN COMPLEX, SOUTH HARRIS, NW SCOTLAMD

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Abstract: Two types of sapphirine-bearing granulites have been found in South Harris, NW Scotland. Both indicate ultra-high temperature conditions (over 900°C). Sapphirine-bearing orthopyroxene-sillimanite granulite contains orthopyroxene+sillimanite+sapphirine+garnet±cordierite as the pre-stable assemblage, indicating *P-T* conditions of 930-980°C and 8-9 kbar. The other type, sapphirine-bearing orthopyroxene-kyanite granulite, contains two types of orthopyroxene (porphyroblast and intergrowth with kyanite), and sapphirine inclusions within aluminosilicate (mainly sillimanite). The orthopyroxene porphyroblasts have Al_2O_3 up to 9.7 wt%, indicating *P-T* condition of 1000-1050°C and 10-11 kbar, while orthopyroxene intergrown with kyanite only have Al_2O_3 up to 7.5 wt%, indicating *P-T* conditions of 900°C and 12-14 kbar. The inferred *P-T* path, mainly based on the orthopyroxene-kyanite granulite, had an anticlockwise trajectory with sapphirine+quartz breaking down to produce sillimanite+orthopyroxene intergrowths, followed by the aluminosilicate transition from sillimanite to kyanite. This is the first record of such ultra-high temperature metamorphism in South Harris. The UHT metamorphism may be a significantly distinctive thermal event that will prove important in reconstruction of the evolutional history of the Lewisian Complex at Palaeoproterozoic period.

key words: Lewisian Complex, sapphirine-bearing granulites, orthopyroxene-sillimanite/kyanite association, ultra-high temperature metamorphism.

1. Introduction

The Lewisian Complex in northwest Scotland has been studied intensively for many years, and is one of the type areas for Archaean high-grade terrains. Proterozoic granulite-facies metamorphic phase relations and the possible *P-T* path in the Leverburgh Belt of South Harris have been studied by the auther in order to re-evaluate the Lewisian evolution history for South Harris. During the couse of this study, sapphirine-bearing orthopyroxene-kyanite/sillimanite granulites were found (BABA, in submitted). The present study reports the occurrences of two types of sapphirine-bearing granulite by using color microphotographs, and suggests the possibility of a Proterozoic ultra-high temperature metamorphism in the Lewisian Complex in South Harris.

2. Geological Setting

The Lewisian Complex is dominantly composed of tonalitic-granodioritic gneisses with numerous mafic-ultramafic enclaves and local intercalations of layered mafic-ultramafic complexes and supracrustal metasediments (TARNEY and WINDLEY, 1977). In the Stoer and Scourie regions, the orthogneisses are widely exposed, and preserve relatively fresh Archaean metamorphic assemblages and fabrics. The protolith of these gneisses was differentiated from the mantle at *c.* $\geq$2.95 Ga (HAMILTON *et al.*, 1979; WHITEHOUSE and MOORBATH, 1986; FRIEND and KINNY, 1995), and underwent granulite facies metamorphism accompanied by intense sub-horizontal deformation at *c.* 2.7–2.5 Ga (HUMPHRIES and CLIFF, 1982; COHEN *et al.*, 1991; CORFU *et al.*, 1994; ZHU *et al.*, 1997). The peak metamorphic conditions of the Scourian (Badcallian) event have been considered to be 1000 ± 50°C and >12 kbar (*e.g.*, CARTWRIGHT and BARNICOAT, 1989; CARTWRIGHT, 1990) and 850–900°C and 10 kbar (SILLS and ROLLINSON, 1987). The previous assumption was that the Lewisian Complex had a clockwise *P-T-t* history with a single prograde event (Scourian event at 2.7 Ga) followed by cooling and unloading at 2.5 Ga Inverian event and at 1.9–1.7 Ga Laxfordian event (SILLS and ROLLINSON, 1987; CARTWRIGHT and BARNICOAT, 1989; CARTWRIGHT, 1990). The tectono-thermal history of the Lewisian Complex has been summarized by PARK and TARNEY (1987). However, recent isotopic studies revealed possible event of the Laxfordian kyanite-forming metamorphism and a 2.5 Ga granulite facies metamorphism for the mainland Lewisian Complex (CORFU *et al.*, 1994; FRIEND and KINNY, 1995; ZHU *et al.*, 1997).

The South Harris Complex, to the northwest from the Stoer and Scourie regions, have been described by several authors (*e.g.*, JEHU and CRAIG, 1927; DEARNLEY, 1963). 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. 1). The former two belts are dominated by metasediments (DEARNLEY, 1963). The combination of voluminous metasedimentary rocks, Proterozoic high-pressure granulite-facies metamorphism and early Proterozoic igneous activity (South Harris Igneous Complex) consisting of anorthosite, gabbro, diorite and norite at *c.* 2.17–1.84 Ga (CLIFF *et al.*, 1983), is significantly different from the mainland gneiss complex (PARK and TARNEY, 1987). Mineral assemblages of high-pressure granulite facies metamorphism are well preserved in the Leverburgh Belt and South Harris Igneous Complex. This high-pressure metamorphic event, dated at around *c.* $\geq$1.87 Ga (early Laxfordian event: CLIFF *et al.*, 1983), preserves estimated metamorphic conditions of 800–860°C and 13 kbar (WOOD, 1975; DICKINSON and WATSON, 1976. BABA *et al.*, 1996; BABA, 1998). The Leverburgh Belt consists mainly of quartzo-feldspathic gneiss (garnet+clinopyroxene±orthopyroxene+quartz+plagioclase±K-feldspar assemblage), pelitic gneiss (garnet+kyanite±biotite+quartz+K-feldspar±plagioclase) and mafic-ultramafic gneiss with minor marble and calcsilicate rocks (BABA, 1997). The Leverburgh Belt is further subdivided into three lithological units; the Rodel Series, the Benn Obbe Quartzite and the Chaipaval Pelitic Series (DEARNLEY, 1963). The sapphirine-bearing orthopyroxene-kyanite/sillimanite granulites crop out in two separate localities in the Rodel Series and the Benn Obbe Quartzite.

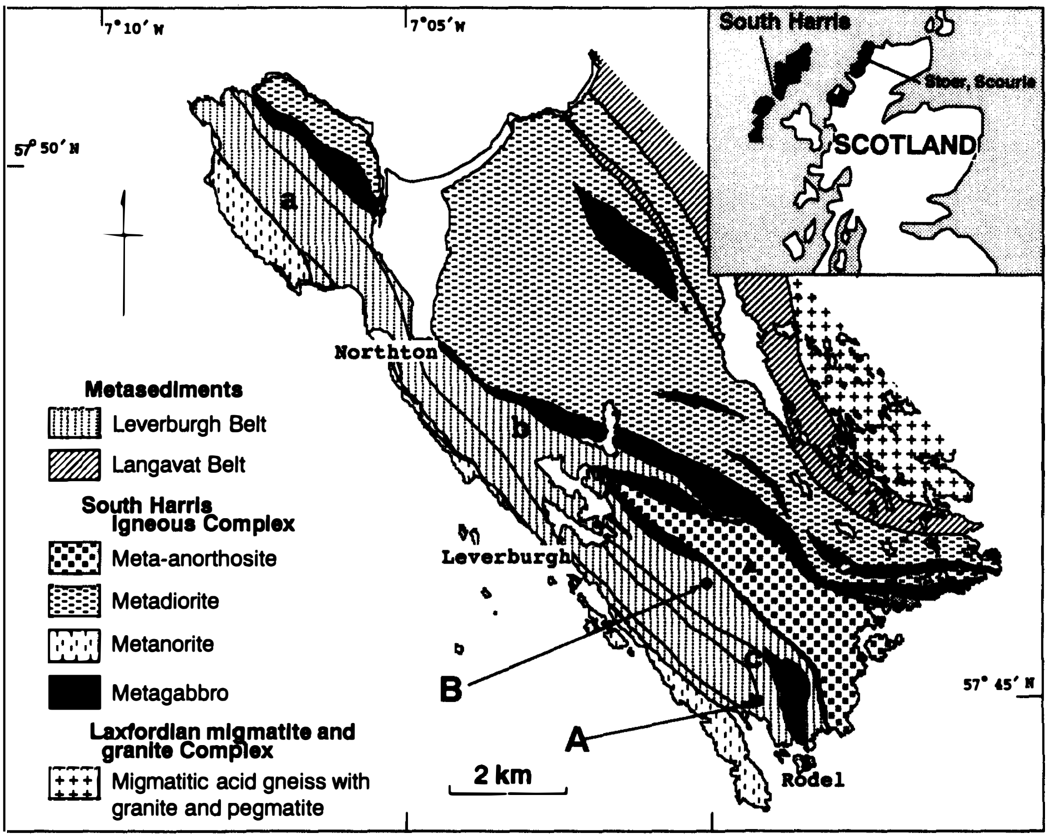

Fig. 1. Simplified geological map of the South Harris Complex (modified after Dearnley, *1963;* Baba, *1997). a: Chaipaval Pelitic Series, b: Benn Obbe Quartzite, c: Rodel Series. A and B represent sample localities of sapphirine-bearing orthopyroxene-sillimanite granulite (95918-10) and orthopyroxene-kyanite granulite (96820-sp1) respectively.*

3. Petrography

Sapphirine-bearing orthopyroxene-sillimanite granulite (opx-sil granulites: sample no. 95918-10) from the Rodel Series is composed chiefly of orthopyroxene, plagioclase, biotite, cordierite, quartz and sillimanite (Fig. 2a). Sapphirine, garnet, kyanite, corundum, zircon, apatite and ilmenite were observed as subsidiary minerals. Two types of orthopyroxene occur; one as porphyroblasts, up to 20 mm in diameter, and the other as a secondary symplectic phase coexisting with cordierite that occurs in corona textures consisting marginal to sillimanite crystals (Fig. 3c). Pale-blue sapphirine up to 0.1 mm across occurs as inclusions within sillimanite, that is in turn replaced by cordierite in the corona, and as discrete small grains in inner zone of coronas (Fig. 3a). Garnet and kyanite are present as resorbed grains enclosed by these coronas (Fig. 3b). Biotite occurs as secondary crystals replacing the orthopyroxene porphyroblasts and outer zone of the corona. Plagioclase and small amount of quartz are present in matrix.

Sapphirine-bearing orthopyroxene-kyanite granulite (opx-ky granulites: sample no. 96820-sp1) in the Benn Obbe Quartzite consists mainly of quartz, K-feldspar, orthopyroxene, kyanite, biotite and cordierite (Fig. 2b). The accessory minerals are sillimanite,

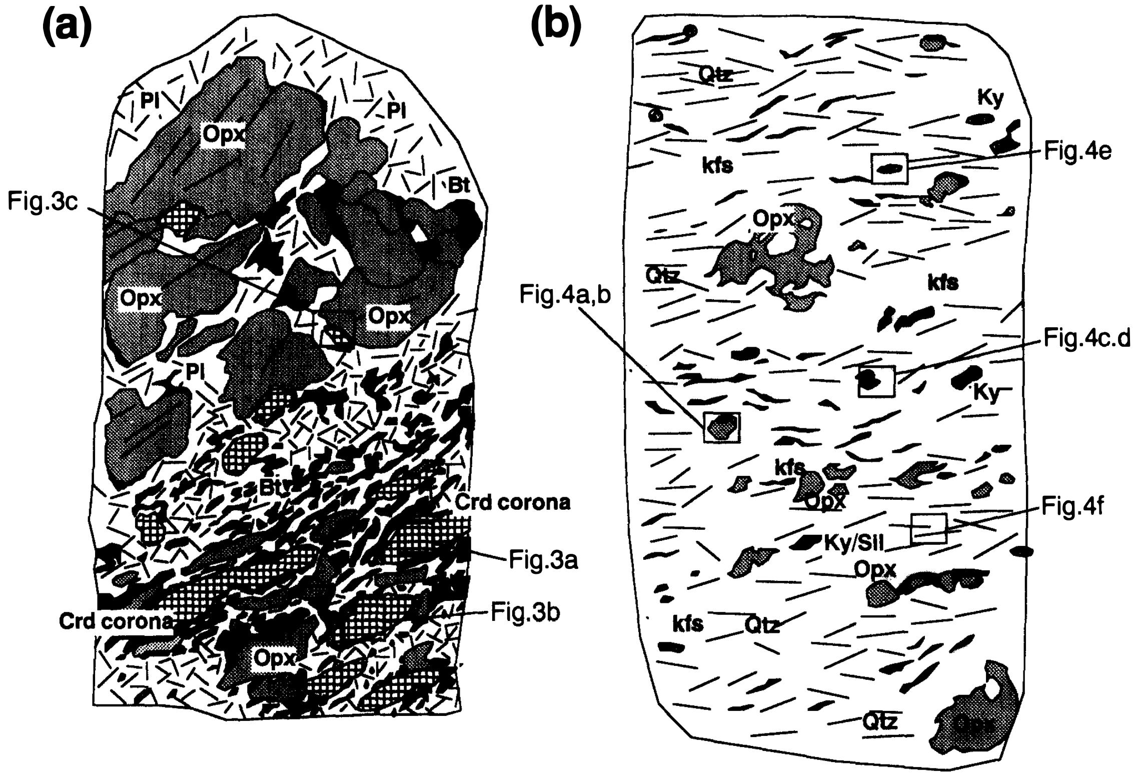

Fig. 2. Sketch of two thin sections (approximately 2.5 × 4.5 cm) representing the two types of sapphirine-bearing granulites in the Leverburgh Belt. (a): Orthopyroxene-sillimanite granulite (95918-10). (b): Orthopyroxene-kyanite granulite (96820-sp1).

muscovite, surinamite, sapphirine, zircon and apatite. Two types of orthopyroxene occur: one as porphyroblast up to 20 mm across, and the other as intergrowths with kyanite (sometime with sillimanite). The intergrowths are replaced by secondary cordierite along their grain boundary, and the texture is wholly surrounded by quartz (Fig. 4a, b). Rarely, pale-blue sapphirine crystals occur as small inclusions within sillimanite or kyanite (Fig. 4c, e), and as relict grains within orthopyroxene-kyanite intergrowths (Fig. 4d). Sapphirine could be found only in six thin-sections out of a hundred. Pale-blue surinamite occurs as discrete grains up to 1 mm across, surrounded by a cordierite corona, which in turn is surrounded by quartz and K-feldspar. The surinamite crystals are difficult to distinguish from sapphirine under microscope (Fig. 4f), but can be distinguished by EPMA analysis. Biotite and muscovite occur as secondary minerals replacing the cordierite coronas, and form the foliation. Zircon and apatite were observed as inclusions in the these minerals and in the matrix.

4. Whole Rock Compositions

Whole rock compositions were determined by X-ray fluorescence spectrometry (Phillips PW2400) of Ehime University. The results are presented in Table. 1, and the composition of surrounding metasedimentary rocks in the Leverburgh Belt are also presented for comparison.

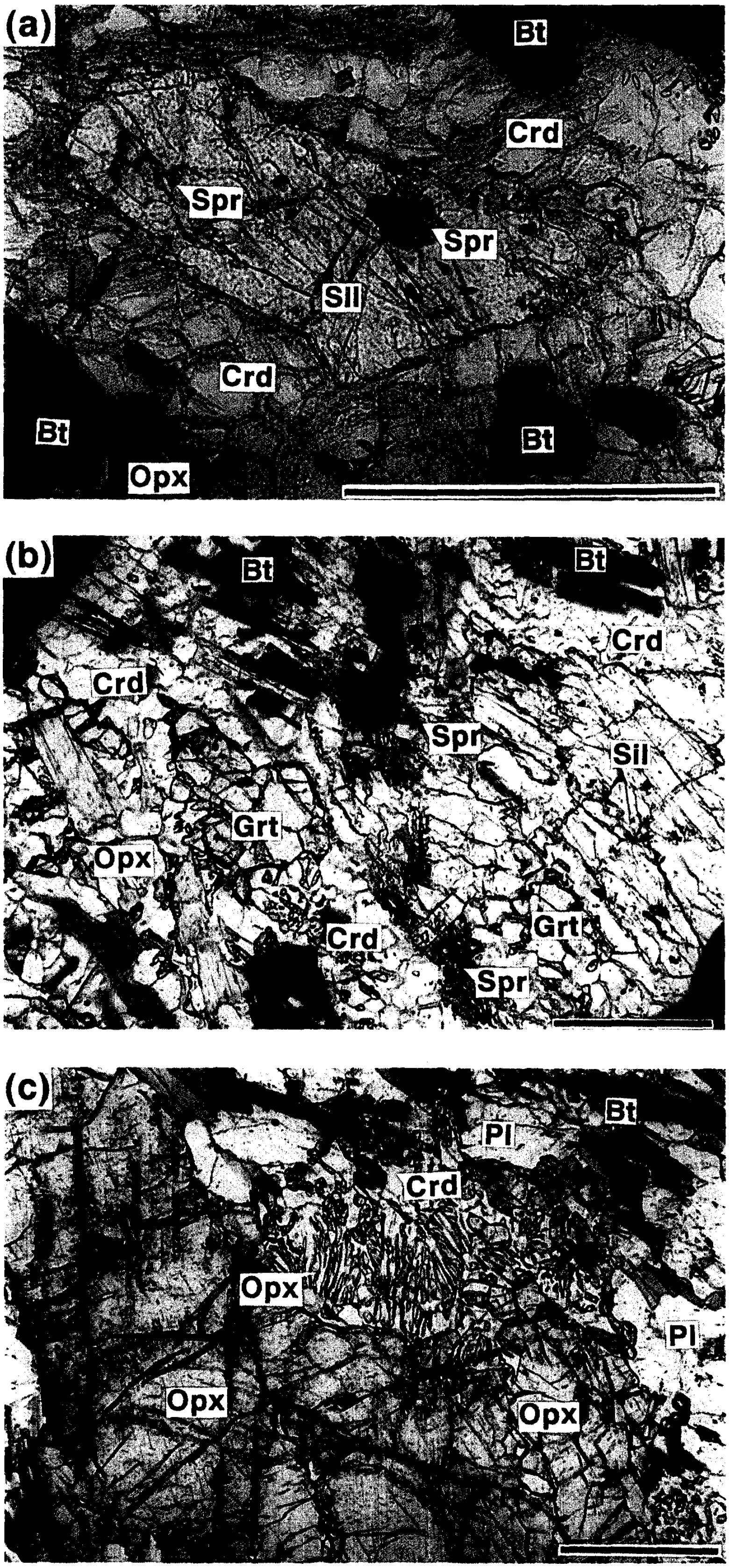

Fig. 3. *Photomicrographs of orthopyroxene-sillimanite granulite (sample: 95918-10). Photographs were taken under open nicols, and scale bar represent approximately 0.5 mm. (a) primary sillimanite (Sil) is enclosed by corona consisting of cordierite (Crd) and cordierite + orthopyroxene (Opx) symplectite. Sapphirine (Spr) inclusions were observed within sillimanite. (b) Primary sillimanite and resorbed garnet (Grt) are observed within cordierite corona. Sapphirine occurs at the edge of sillimanite. In places, they show symplectitic shape. Secondary orthopyroxene is observed around the garnet. (c) orthopyroxene porphyroblast (approximately 5 mm in long) is replaced by secondary orthopyroxene (Opx) and cordierite (Crd) at its rim, and by secondary biotite at edge.*

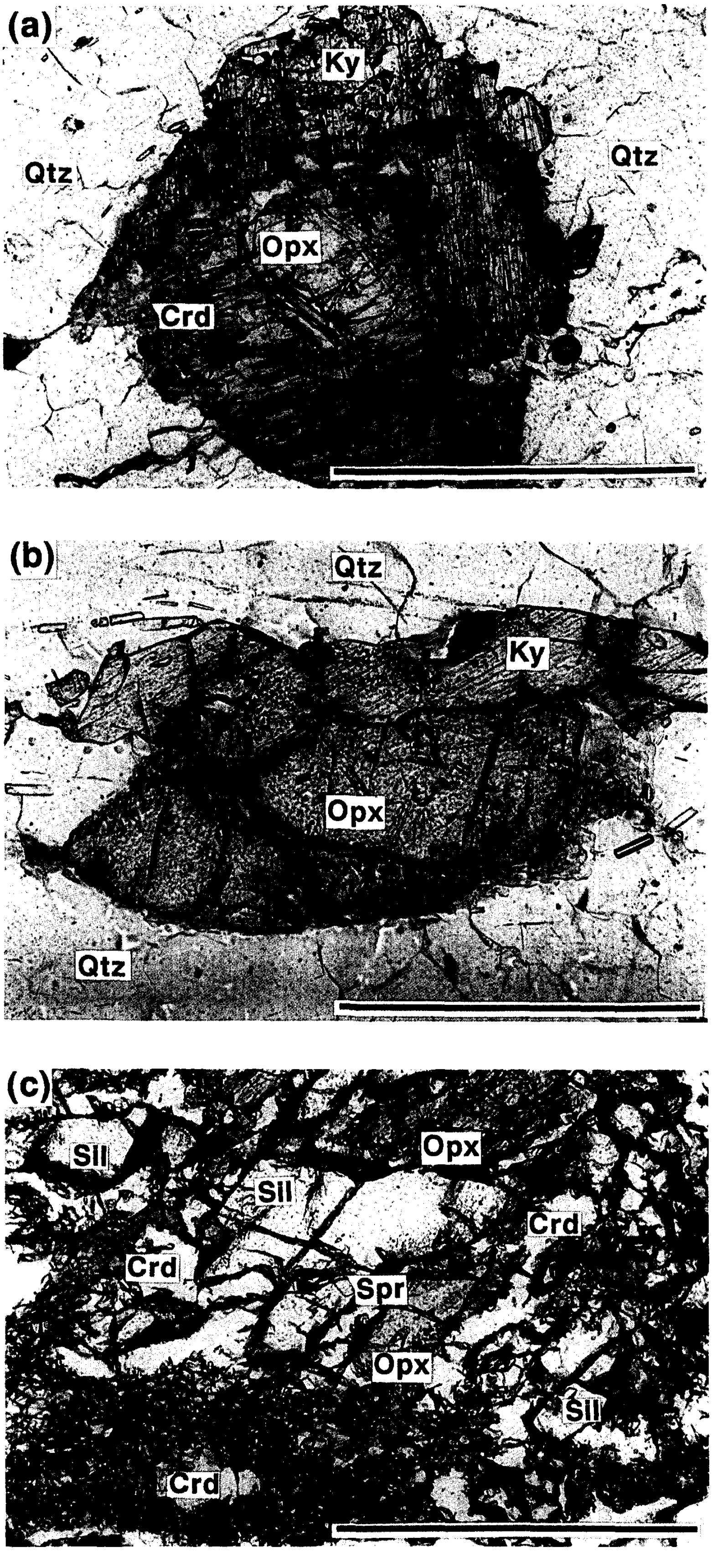

Fig. 4. Photomicrographs of orthopyroxene-kyanite granulites (sample: 96820-sp1). Photomicrographs were taken under open nicols. (a and b) orthopyroxene (Opx) and kyanite (Ky) intergrowth within quartz (Qtz) matrix. Grain boundary between orthopyroxene and kyanite is replaced by secondary cordierite (a). (c) sapphirine inclusion within sillimanite (Sil). Sillimanite is associated with orthopyroxene. (d) relic sapphirine (Spr) occurs as inclusion within kyanite and cordierite. The texture is wholly surrounded by quartz. (e) sapphirine inclusion within sillimanite. Sillimanite is rimmed by cordierite, that is in turn surrounded by quartz. (f) pale-blue surrinamite(sur) is replaced by secondary cordierite, and whole texture is surrounded by quartz.

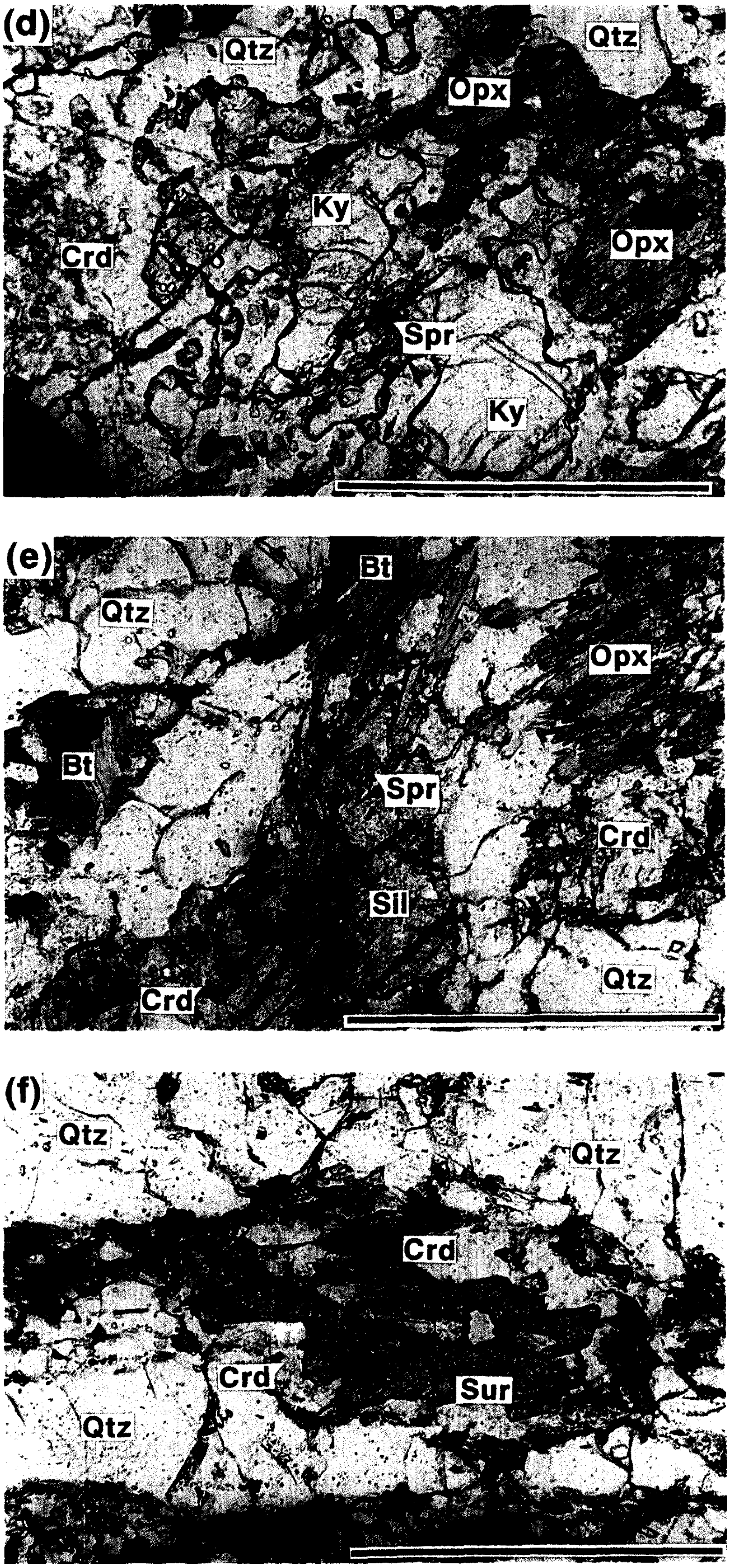

Fig. 4. Continued.

Table 1. Whole-rock analyses of sapphirine-bearing orthopyroxene-kyanite (96820-spl), orthopyroxene-sillimanite (95918-10) granulites and surrounding metasedimentary rocks in the Leverburgh Belt.

Sample No.	96820-spl	95918-10	1	2	3
SiO_2	83.15	51.77	67.36	66.35	70.80
TiO_2	0.09	1.18	0.64	0.65	0.40
Al_2O_3	9.35	16.97	14.61	14.47	14.38
Fe_2O_3	0.46	1.75	2.45	2.37	
FeO	0.34	7.07	3.31	4.98	
FeO*					4.14
MnO	0.01	0.04	0.06	0.08	0.06
MgO	1.59	13.88	2.86	3.15	1.20
CaO	0.25	0.82	3.20	3.06	4.48
Na_2O	0.78	2.88	2.52	2.56	3.53
K_2O	3.45	2.13	2.75	2.07	0.63
P_2O_5	0.02	0.06	0.13	-	-
Total	99.49	98.55	99.89	99.74	99.62
Bulk XMg*	0.81	0.71	0.48	0.42	0.29

FeO* : total iron as FeO. Bulk X_{Mg}* : adjusted for Fe^{3+}. 1 : average value of 21 metasediment (SHERATON *et al.*, 1973), 2 : 4 fresh garnet-kyanite metapelite (PALMER, 1971 in FETTES *et al.*, 1992), 3 : 9 quartzose gneiss (FETTES *et al.*, 1992).

Occurrence of sapphirine largely depends on its host rock composition, especially on Al_2O_3 and SiO_2 contents and Mg/(Mg+Fe) values (*e.g.*, HARLEY *et al.*, 1990). Mg/(Mg+Fe) values of sapphirine-bearing granulites are 0.81 for opx-ky granulite and 0.71 for opx-sil granulite. In contrast, surrounding metasedimentary rocks have lower Mg/(Fe+Mg) values such as 0.42 for metasediment, 0.48 for garnet-kyanite metapelite and 0.29 for the quartzose gneiss (Table 1). The distinctive high Mg/(Fe+Mg) values of the opx-ky and opx-sil granulites probably allowed the formation of sapphirine, orthopyroxene and kyanite/sillimanite during high-grade metamorphism. The bulk composition for opx-sil granulite has compositions indicative of a volcanogenic origin which was previously reported by WARREN (1979). Considering the mode of field occurrence of the opx-sil granulites adjacent to the large ultramafic and mafic gneiss bodies, the rock probably show volcanogenic affinity. In contrast, opx-ky granulite has an extremely high SiO_2 content (83%), and occurs as thin layer within garnet-kyanite bearing quartzose gneiss. Such SiO_2 rich sapphirine-bearing granulites have only been reported from Enderby Land, East Antarctica (ELLIS *et al.*, 1980; GREW, 1982), and is considered to be of sedimentary origin.

5. Mineral Chemistry

Mineral analyses were made by using the JOEL JXM-8800 wavelength-dispersive analyzer housed at Ehime University using an accelerating voltage of 15 kV and beam width of 10 μm. Representative analyses are shown in Table 2.

Table 2. Representative microprobe analyses of minerals from sapphirine-bearing orthopyroxene-kyanite (96820-spl) and orthopyroxene-sillimanite (95918-10) granulites in the Leverburgh Belt.

Sample No.	96820-spl											95918-10			
Anal. No.	38 Spr(in)	14.1 Spr(in)	27 Spr(in)	19.39 Opx(p)	11.36 Opx(p)	5 Oxp(i)	19.23 Opx(i)	15.6 Crd	11.7 Sur	2.1 Sur	11.3 Crd(sur)	A-21 Spr(in)	A-22 Spr(in)	99 Opx(p)	A-35 Crd
SiO_2	14.75	15.75	11.40	49.90	51.19	51.46	49.82	49.31	33.78	32.60	50.19	13.06	11.69	50.88	49.51
TiO_2	0.00	0.00	0.13	0.17	0.12	0.03	0.00	0.37	0.05	0.25	0.10	0.00	0.17	0.07	0.14
Al_2O_3	59.59	58.90	65.48	9.68	9.22	7.32	6.71	33.31	37.38	37.63	32.13	61.50	63.96	6.32	33.17
Cr_2O_3	0.03	0.00	0.24	0.01	0.07	0.07	0.00	0.20	0.11	0.21	0.00	0.00	0.13	0.00	0.00
FeO*	8.00	7.82	7.56	13.85	13.72	14.54	18.77	2.03	5.59	4.94	2.38	9.56	9.05	17.20	3.40
MnO	0.08	0.06	0.11	0.00	0.22	0.37	0.48	0.27	0.12	0.26	0.03	0.00	0.14	0.34	0.11
MgO	16.37	17.20	15.38	27.07	26.22	26.87	24.26	11.85	21.33	20.92	11.79	15.97	15.37	24.90	11.67
CaO	0.00	0.03	0.00	0.16	0.09	0.05	0.06	0.12	0.14	0.27	0.02	0.00	0.00	0.19	0.00
Na_2O	0.04	0.01	0.01	0.04	0.03	0.04	0.06	0.13	0.00	0.10	0.02	0.01	0.00	0.02	0.16
K_2O	0.01	0.02	0.00	0.00	0.01	0.00	0.00	0.11	0.00	0.10	0.41	0.01	0.00	0.01	0.00
ZnO	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Total	98.87	99.79	100.31	100.88	100.89	100.75	100.16	97.70	98.50	97.28	97.07	100.11	100.51	99.92	98.16
O	20	20	20	6	6	6	6	18	15	15	18	20	20	6	18
Si	1.78	1.88	1.35	1.77	1.81	1.83	1.82	4.98	2.97	2.90	5.10	1.57	1.40	1.85	5.00
Ti	0.00	0.00	0.01	0.00	0.00	0.00	0.00	0.03	0.00	0.02	0.01	0.00	0.02	0.00	0.01
Al	8.46	8.27	9.17	0.40	0.38	0.31	0.29	3.97	3.87	3.95	3.85	8.70	9.00	0.27	3.95
Cr	0.00	0.00	0.02	0.00	0.00	0.00	0.00	0.02	0.01	0.01	0.00	0.00	0.01	0.00	0.00
Fe	0.81	0.78	0.75	0.41	0.41	0.43	0.57	0.17	0.41	0.37	0.20	0.96	0.90	0.52	0.29
Mn	0.01	0.01	0.01	0.00	0.01	0.01	0.01	0.02	0.01	0.02	0.00	0.00	0.01	0.01	0.01
Mg	2.94	3.05	2.72	1.43	1.38	1.43	1.32	1.78	2.80	2.78	1.78	2.86	2.74	1.35	1.75
Ca	0.00	0.00	0.00	0.01	0.00	0.00	0.00	0.01	0.01	0.03	0.00	0.00	0.00	0.01	0.00
Na	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.03	0.00	0.02	0.00	0.00	0.00	0.00	0.03
K	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.00	0.01	0.05	0.00	0.00	0.00	0.00
Zn	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Total cation	14.00	13.99	14.04	4.03	4.00	4.01	4.03	11.02	10.08	10.11	11.00	14.09	14.08	4.01	11.04
$X_{Mg}=$	0.78	0.80	0.78	0.78	0.77	0.77	0.70	0.91	0.87	0.88	0.90	0.75	0.75	0.72	0.86

FeO*, total Fe as FeO ; in, inclusion ; p, porphyroblast ; i, intergrowth ; sur, around surinamite. M_{Mg}=Mg/(Mg+Fe)

Sapphirine inclusions within sillimanite from the opx-sil and opx-ky granulites have various compositions (Table 2). Sapphirine inclusions from opx-ky granulite (sample no. 96820-spl) have two distinctive compositions, close to 2 : 2 : 1 [2(Mg, Fe)O : 2(Al, Cr, $Fe^{3+})_2O_3$: $1SiO_2$] and 7 : 9 : 3 end member composition of sapphirine, although in opx-sil granulites (sample no. 95918-10), they only have a composition of around 7 : 9 : 3. The opx-ky granulite have X_{Mg} values of 0.78–0.80, and opx-sil granulite have values of 0.75.

Orthopyroxene are common in opx-ky and opx-sil granulites, and occur as porphyroblasts (opx-ky and opx-sil granulites) or in intergrowth with kyanite/sillimanite (opx-ky granulite). In opx-ky granulite, orthopyroxene porphyroblasts are very aluminous, containing up to 9.7 wt% Al_2O_3 (with Fe^{+3}/Fe^{+2} ratio of 0.23), while the orthopyroxene intergrowths are slightly poor in Al_2O_3 (up to 7.5 wt%). Former have X_{Mg}[Mg/(Fe+Mg)] values of 0.74–0.83, while later have values of 0.67–0.77. Orthopyroxene porphyroblasts from opx-sil granulites are relatively poor in Al_2O_3 (up to 6.32 wt%), and have fairly flat values of X_{Mg} (0.72–0.73). Secondary symplectic orthopyroxene grains in the opx-sil granulites have Al_2O_3 content of 4.6 wt% and X_{Mg} of 0.67.

Cordierite grains, in opx-sil and opx-ky granulites, occur as secondary coronas replacing sillimanite and orthopyroxene-kyanite intergrowth. They have X_{Mg}[Mg/(Fe+Mg)] values of 0.89–0.92 for opx-ky granulite, and 0.86–0.87 for opx-sil granulite.

Surinamite is found in the opx-ky granulite. The total weight percentage is generally 97–98 wt%, probably implying the presence of the BeO. GREW (1981) reported that the surinamite contains up to 3.5 wt% of BeO.

6. Metamorphic Conditions and Possible *P-T* Path

6.1. *Opx-sil granulite*

The orthopyroxene-sillimanite rock has a more aluminous bulk composition than orthopyroxene-kyanite granulite. In addition, quartz does not coexist with orthopyroxene and sillimanite, and thus relative *P-T* conditions can be estimated by petrogenetic grids for quartz undersaturated system. Most of the sapphirine occurs as inclusions within sillimanite and cordierite coronas, suggesting that sapphirine was a stable mineral prior to the formation of sillimanite and cordierite coronas. In places, garnet is present and is surrounded by cordierite coronas. These textures indicate that the orthopyroxene porphyroblast + sapphirine + sillimanite + garnet assemblage was stable prior to the formation of secondary cordierite. Figure 5 shows a Schreinmakers grid for sapphirine-bearing assemblage after HARLEY *et al.* (1990). The relevant divariant field of stable minerals is ornamented. [Qtz Bt] invariant point in FMAS system has been estimated to occur near 950°C and 8–9 kbar (HENSEN, 1987; HENSEN and HARLEY, 1990), but would be shifted to lower-*T* conditions with the preferential incorporation of minor components (*e.g.*, Ca, Mn) into garnet (a reduction in temperature of 20–30°C is calculated from the field of low measured grossular and spessartine contents in the garnet). It follows from the petrogenetic grids (Fig. 5), orthopyroxene + sillimanite + sapphirine + garnet assemblage in opx-sil granulite will probably stable around the invariant point of [Qtz Bt] (930–980°C and over 8–9 kbar). Further information, such as *P-T* path, can not be deduced for this rock because of the development of secondary cordierite during decompression.

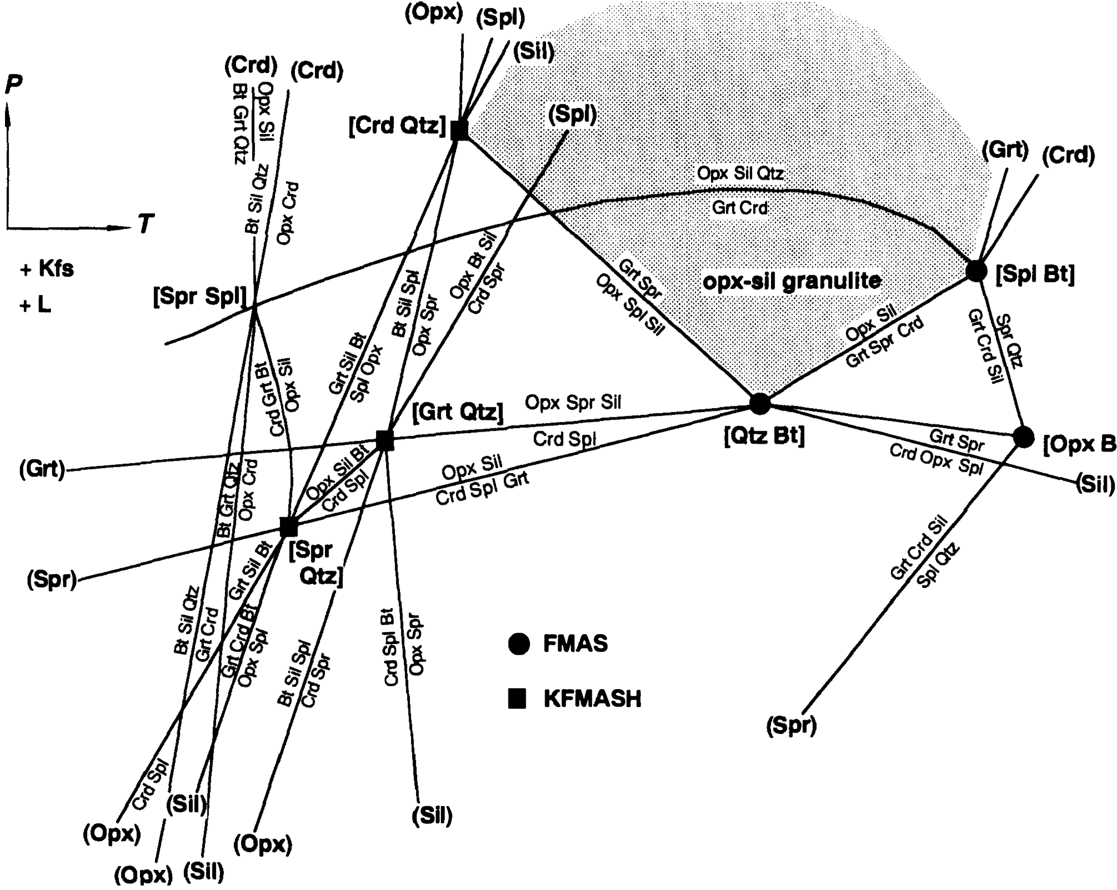

Fig. 5. *Schreinmakers grid depicting FMAS and KFMASH invariant points and related univariant curves (after* Harley *et al., 1990). The relevant divariant fields for orthopyroxene + sillimanite + sapphirine + garnet ± cordierite assemblage in opx-sil granulite are ornamented.*

6.2. Opx-ky granulite

The orthopyroxene-kyanite association has been reported only in two localities in the world: Kola peninsula in USSR (Bondarenko, 1972) and the Limpopo belt in South Africa (Chinner and Steatman, 1968). However, these studies have considered the association as a pre-stable assemblage, because orthopyroxene and kyanite are not in direct contact (Bondarenko, 1972) and kyanite was pseudomorphed to sillimanite (Chinner and Steatman, 1968). Orthopyroxene-kyanite intergrowths in the quartz matrix are considered to be a stable mineral assemblage in the opx-ky granulite. The aluminous orthopyroxene-sillimanite-quartz assemblage is indicative of typical ultra-high temperature metamorphic conditions of, at least, $\geq 900°C$ and ≥ 8 kbar (Carrington and Harley, 1995; Harley, 1998). Coexistence of orthopyroxene with kyanite, instead of sillimanite, implies higher pressure conditions $\geq 900°C$ and ≥ 12 kbar (Chinner and Sweatman, 1968). Considering the associated rare occurrence of sapphirine inclusions within aluminosilicate, it may be probably assumed that the orthopyroxene-kyanite-quartz-sapphirine assemblage were stable under very high temperature and high pressure conditions. The P-T condition, $\geq 1100°C$ and ≥ 14 kbar, can be assumable from experimentally determined opx+sil=

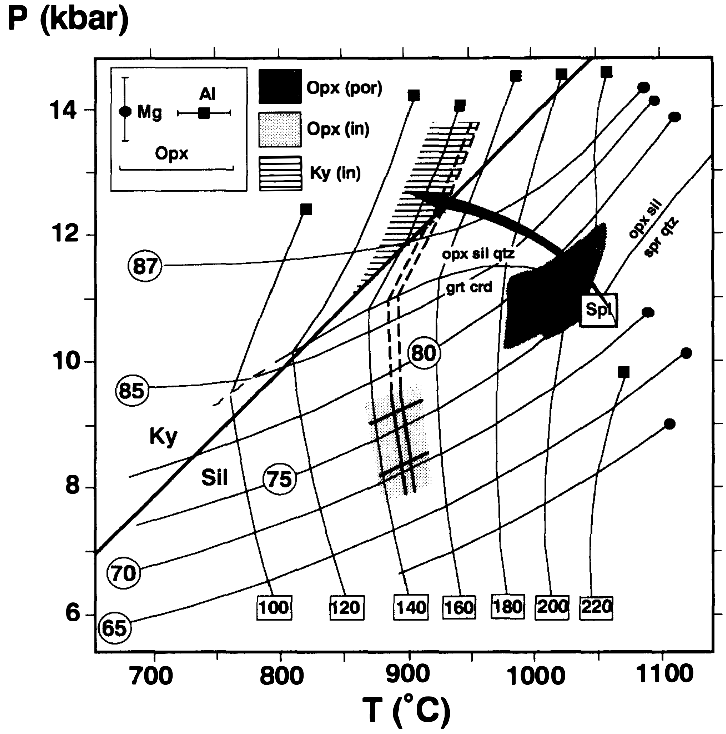

Fig. 6. Isopleths diagrams for orthopyroxene (modified after HENSEN *and* HARLEY, *1990). The garnet and orthopyroxene is in equilibrium with quartz and either cordierite (at pressure below those of the curve) or sillimanite (at higher pressure above the curve). Isopleths are as follows.* X_{Mg} *values in units* × *100 and* X_{Al} *values expressed as units of (Al cations/2, per 6 oxygen units)* × *1000. Thin black line with solid circle symbols indicate* X_{Mg} *(Opx). Thin line with solid square symbols* X_{Al} *(Opx). Ornamented field labeled Opx(por) is P-T condition deduced from the compositions of orthopyroxene porphyroblasts, and Opx(in) is P-T condition from orthopyroxene intergrowths. Ornamented field labeled Ky(in) is best-fit P-T condition considering the coexistence with kyanite.*

qtz+spr univariant line (*e.g.* BERTRAND *et al.*, 1991) by extending to kyanite stability field. Two types of orthopyroxene, as porphyroblasts and in intergrowth with kyanite, have enstatite contents ranging from 65 to 85%. The compositions are not consistent with such high-pressure conditions (≥ 14 kbar) since orthopyroxene composition is expected to be pure enstatite (*e.g.*, HENSEN and HARLEY, 1990). Thus the two types of orthopyroxene were probably formed under different conditions. The metamorphic conditions were estimated by using the intersection between X_{Mg}[Mg/(Mg+Fe)] and X_{Al}(1000×Al/2, per 6 oxygen unit) isopleths for orthopyroxene (HENSEN and HARLEY, 1990). Orthopyroxene porphyroblast in sample no. 96820 spl have X_{Mg} of *c.* 0.79 and X_{Al} of 202 (Table 2). The compositions indicate that it was stable at 1000–1050°C and about 10–11 kbar (Fig. 6). On the other hand, composition of orthopyroxene intergrowth indicate that it was stable at around 900°C and about 8–9 kbar (Fig. 6). However, the intergrowth were replaced by secondary cordierite, suggesting the possibility of the modification of X_{Mg} ratios by Fe-Mg re-equilibration, since X_{Mg} of orthopyroxene is expected to be higher. From the textural relationships, coexistence of orthopyroxene and kyanite within the intergrowth, and X_{Al} ratios of such orthopyroxene, the intergrowth was stable at around 900°C and 12–14 kbar

(Fig. 6).

Orthopyroxene-kyanite intergrowths in the quartz matrix are considered to be a stable mineral assemblage, and coexistence of orthopyroxene with kyanite, instead of sillimanite, imply higher *P-T* conditions of ≥900°C and ≥12 kbar (Chinner and Sweatman, 1968). The occurrence of rare sapphirine, as a relict mineral within aluminosilicate or within orthopyroxene-kyanite intergrowths, indicates that this mineral may have been stable prior to replacement by the aluminosilicate and orthopyroxene intergrowth. From the textural relationships and sapphirine occurrence in the silica-saturated rocks, although sapphirine and quartz contact were not seen, the following reaction of sapphirine+quartz=orthopyroxene+sillimanite could be considered as responsible for the conversion of the pre-existing sapphirine to a sillimanite-orthopyroxene intergrowth. Orthopyroxene-kyanite intergrowth can then be attributed to the transition, from sillimanite to kyanite, at higher pressure conditions. According to high-temperature experimental studies on FeO-MgO-Al_2O_3-SiO_2 systems (Hensen and Green, 1973; Bertrand *et al*., 1991), sapphirine-quartz associations are stable at *P-T* conditions of ≥1050°C and 8-12 kbar. The estimated conditions based on the composition of orthopyroxene porphyroblasts, are close to those required for the coexistence of sapphirine and quartz.

7. Discussion

Three metamorphic phases, M1-M2-M3, are recognized from the South Harris area (Baba, 1998), these trace out an anti-clockwise *P-T* path in which M1 represents a thermal increasing derived from the intrusion of SHIC occurred at 8-10 kbar and 800-880°C. M2 also a prograde granulite event, progressed at *c*. 800±30°C involved an up-pressure transition to 13-14 kbar. The retrograde event, M3, involved decompression retrograde conditions of 550-650°C, 6.5±1 kbar. The evidence for these events this history is recorded in the following feature observed in pelitic, quartzo-feldspathic and mafic gneiss; 1) garnet grains in pelitic gneisses include sillimanite in their outer core but are overgrown by kyanite on their rims; 2) garnet in the pelitic gneiss shows a progressive increase in grossular content from outer core to rims; 3) the Al^{VI}/Al^{IV} ratios of clinopyroxene from mafic gneiss in the Leverburgh Belt, meta-gabbro and meta-norite in the South Harris Igneous Complex, increase from core to rim; 4) retrograde reaction coronas of cordierite and spinel+cordierite are formed between garnet and kyanite, and orthopyroxene+cordierite and orthopyroxene+plagioclase reaction coronas develop between garnet and quartz; 5) a *P-T* path is deduced from inclusion assemblages in garnet and from staurolite-breakdown reactions to produce garnet+sillimanite and garnet+sillimanite+spinel with increasing temperature (Baba *et al*., 1996; Baba, 1998). Ml stage metamorphism, constituting the thermal maximum stage, has been considered to be caused by the intrusion of the South Harris Igneous Complex from the evidence of the clinopyroxene composition recording an increasing pressure history (Baba, 1998). The thermal effects caused by the emplacement of South Harris Igneous Complex, have been also postulated by Fettes *et al*. (1992). The ultra-high temperature conditions characterized by aluminous orthopyroxene-aluminosilicate(sillimanite)-sapphirine-quartz assemblage may be formed during the local temperature rise (950-1050°C), due to the emplacement of the South Harris Igneous Complex (*c*. 2.17-1.84 Ga), before the formation of kyanite. Previous assump-

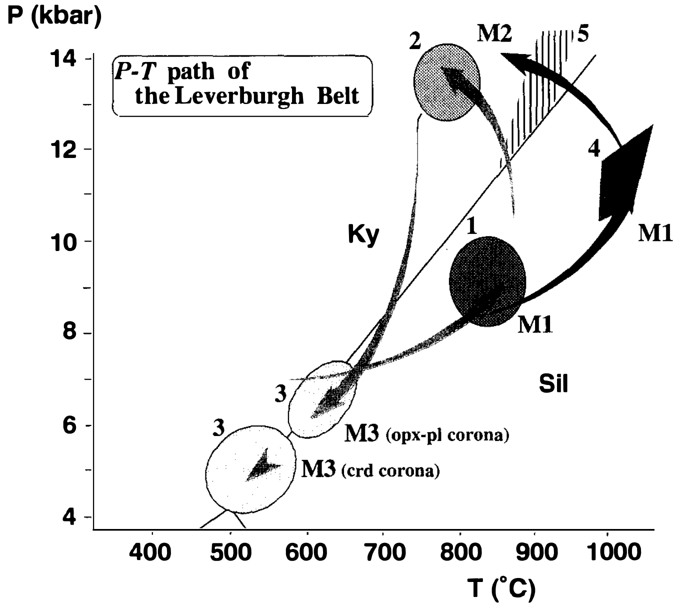

Fig. 7. Inferred P-T path of the Leverburgh Belt. Grey arrows indicate possible P-T path deduced from surrounded gneisses. Black arrows indicate the P-T path deduced from the orthopyroxene-kyanite granulites in this paper. Ornamented fields of metamorphic stages were estimated by using following equilibria; 1, T = two-pyroxene assemblage and P = garnet-spinel-sillimanite-quartz equilibria (inclusion assemblage); 2, T and P = garnet-clinopyroxene-plagioclase-quartz and garnet-kyanite-plagioclase-quartz (for pressure only) equilibria (porphyroblast assemblage); 3, P and T = garnet-orthopyroxene-plagioclase-quartz and garnet-cordierite-sillimanite-quartz equilibria (retrograde corona assemblage); 4, 5, orthopyroxene isopleths (see Fig. 6). Sil-Ky boundaries taken from Holdaway and Mukhopadhyay (1993).

tions of igneous equilibration temperature of 1135–1315°C for the South Harris Igneous Complex, obtained by Witty (in Fettes *et al*., 1992), support the thermal effects for local ultra-high temperature conditions. The pressure-increasing *P-T* path deduced from the opx-ky granulite schematically correspond with those estimated from surrounding gneisses, except for 100–200°C higher temperature (Fig. 7). The Palaeoproterozoic ultra-high temperature metamorphism prior to the high pressure metamorphism in South Harris described here seems an important thermal event for the reconstruction of the Lewisian history at Palaeoproterozoic period.

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