Earth Evolution Sciences, Vol. 8, pp. 3-12, March, 1, 2014

Field occurrence of high-grade metamorphic rocks at Telen in the Lützow-Holm Complex, East Antarctica

Tatsuya Koizumi[a], Toshiaki Tsunogae[b,c], Daniel J. Dunkley[d], Tomoharu Miyamoto[e], and Mutsumi Kato[f]

[a]*Graduate School of Life and Environmental Sciences, University of Tsukuba, Ibaraki 305-8572, Japan*
[b]*Faculty of Life and Environmental Sciences, University of Tsukuba, Ibaraki 305-8572, Japan*
[c]*Department of Geology, University of Johannesburg, Auckland Park 2006, South Africa*
[d]*Department of Applied Geology, Western Australian School of Mines, Curtin University, GPO Box U1987, Perth, WA 6845, Australia*
[e]*Department of Earth and Planetary Sciences, Faculty of Sciences, Kyushu University, Fukuoka, 812-8581, Japan*
[f]*Department of Earth Sciences, Graduate School of Science, Chiba University, Chiba 263-8522, Japan*

Abstract

We report field occurrence and brief petrographical characters of high-grade metamorphic rocks from Telen in the granulite-facies zone of the Lützow-Holm Complex, East Antarctica, and correlate the dominant lithologies with those in adjacent exposures. The major rock types in Telen are felsic to intermediate orthogneiss, mafic granulite/amphibolite, calc-silicate rocks, felsic garnet gneiss, and pelitic granulite, which are similar to adjacent localities such as Skallen and Skallevikshalsen, although felsic to mafic orthogneisses are dominant in Telen, while calc-silicate rocks and marbles are more abundant in Skallen and Skallevikshalsen. They have monotonous N-S trending foliation dipping gently (about 20–30°) toward the east. Younger granitoids intrude nearly parallel or perpendicular to the metamorphic rocks. Peak metamorphic conditions have been estimated for a garnet-rich mafic granulite as 860–880°C and 10.1–10.5 kbar, which is consistent with the results of adjacent localities. Our study confirmed that Telen-Skallen-Skallevikshalsen region in the central domain of the granulite-facies zone corresponds to a single mass of high-grade metamorphic rocks, which was formed by Late Neoproterozoic to Cambrian high-grade metamorphism possibly related to the final phase of continent-continent collision during the assembly of Gondwana Supercontinent.

Keywords: Granulite; Petrology; *P–T* condition; Neoproterozoic to Cambrian; Gondwana

Introduction

The Lützow-Holm Complex (LHC) of East Antarctica (Fig. 1) is known for its exposures of regionally metamorphosed amphibolite- to granulite-facies rocks formed during the late Neoproterozoic to early Cambrian collisional orogeny, possibly related to the final phase of amalgamation of continental fragments within the Gondwana assembly (~ 0.55 Ga, e.g., Shiraishi et al., 1994, 2003, 2008). The dominant lithologies of this complex are felsic orthogneiss (charnockite and biotite gneiss) and various metasediments and metabasites, which increase in metamorphic grade from amphibolite-facies in the northeast to granulite-facies in the southwest (e.g., Hiroi et al., 1991). Owing to the continuous distribution of low- to high-grade metamorphic rocks, the LHC has been regarded as an excellent example that exposes the crustal cross section of a Neoproterozoic to Cambrian orogenic belt.

Various geological, petrological, and geochronological investigations have been done on the LHC for the last fifty years, but they are mainly focused on large rock exposures (e.g., Skallevikshalsen, Skallen, Rundvågshetta) which are relatively easy to access by a helicopter. In contrast, limited petrological studies have been published on small exposures. Based on geophysical data Nogi et al. (2013) recently traced several geological structures within the LHC, and separated the complex into four blocks possibly bounded by NE-SW-trending right lateral strike-slip faults. They also argued the presence of crustal gaps between the granulite-facies zone and the transitional zone, and also between the transitional zone and the amphibolite-facies zone of the LHC. In order to evaluate the model and to further unravel the complex tectonic history of this region, detailed petrological and geochronological stud-

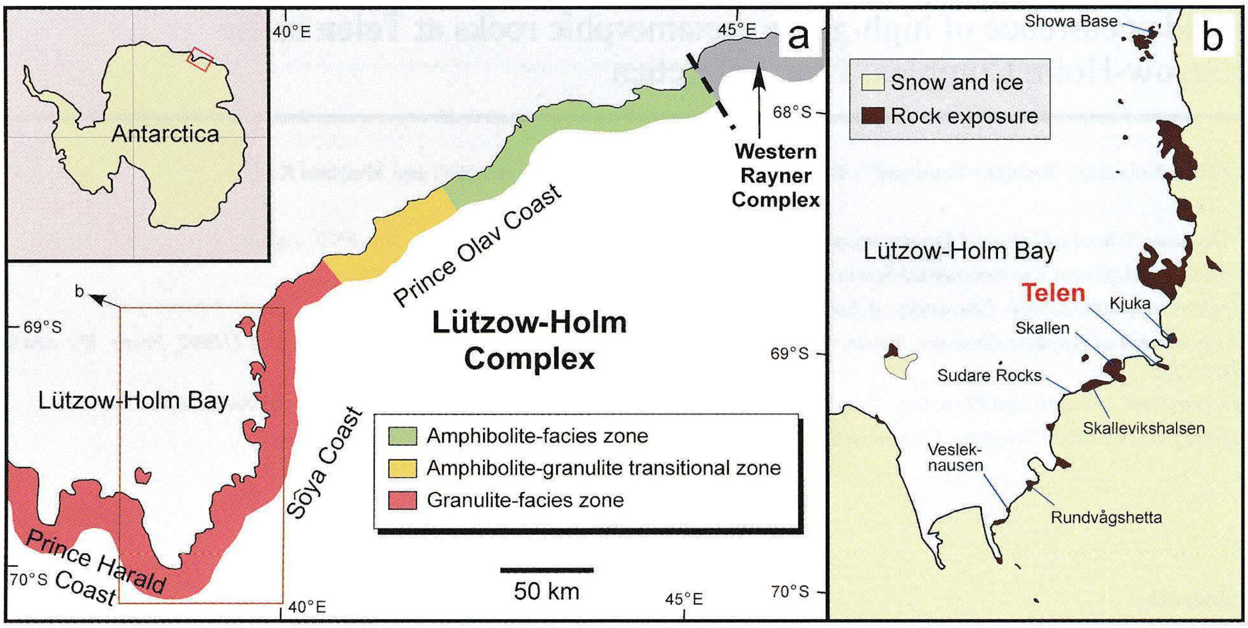

Fig. 1. Simplified geological map of the Lützow-Holm Complex showing the internal subdivision of amphibolite-facies, transitional, and granulite-facies zones (after Hiroi et al., 1991).

ies on various metamorphic/igneous rocks from many localities in the LHC are necessary.

Recently, we performed detailed geological field survey of the LHC during the 52nd Japanese Antarctic Research Expedition (JARE52), and examined granulites from Telen, which belongs to the granulite-facies zone (Fig. 1) close to the localities where the highest-grade metamorphic condition (T >950°C) of this complex have been reported. In this study, we report field occurrence of representative lithologies in Telen and describe their preliminary petrographical data, which will be useful for future detailed petrological and geochronological studies of this area, as well as for understanding regional thermal history and tectonic evolution of the LHC.

General geology and petrography

Telen is located at 69°39'S and 39°39–44'E, about 72 km south from Showa Station. It is separated from Kjuka to the northeast by the Telen Glacier and from Skallen to the southwest by the Skallen Glacier. According to the published geological map (Nakai et al., 1979), the dominant lithologies at Telen are garnet-biotite gneiss, garnet-bearing leucocratic gneiss, garnet-bearing felsic gneiss, clinopyroxene gneiss, charnockitic gneiss, two-pyroxene amphibolite, and quartzite (Fig. 2). The rocks show N-S trending foliation dipping gently (about 20–30°) toward the east. SHRIMP zircon U-Pb ages of 1006 ± 21 Ma (protolith magmatic age) and 532 ± 8 Ma (metamorphic age) were obtained from garnet-biotite gneiss (Shiraishi et al., 1994). In this study, we subdivided the lithologies into six types: felsic to intermediate orthogneiss, mafic granulite/amphibolite, calc-silicate rocks, felsic garnet gneiss, pelitic granulite, and intrusive granitoids. General views of exposures in Telen are shown in Figs. 3a to 3c. Field occurrence and mineral assemblage of representative samples are briefly described below.

Felsic to intermediate orthogneiss

Felsic to intermediate orthogneiss is the most dominant lithology in Telen area. It is pale brownish to dark grayish in color, medium grained, and clearly shows foliation defied by alternation of biotite-rich and quartzo-feldspathic layers (Fig. 3d). A representative sample (sample TS1012301307D) is composed mainly of quartz, plagioclase, K-feldspar, garnet, and biotite with accessory apatite and rutile (Figs. 5a,b). Most of the samples collected are garnet bearing, which is probably equivalent to 'garnet-biotite gneiss' as classified by Nakai et al. (1979). The orthogneiss is often brownish in color and contains orthopyroxene as 'charnockite' (orthopyroxene-bearing granitoid). Charnockite is less foliated than orthopyroxene-free orthogneiss probably because of the low modal abundance of biotite (Figs. 5c,d). Grain size of charnockite is slightly coarser than the orthopyroxene-free orthogneiss. Mineral assemblage of a representative sample (TS1012301301A) is quartz + plagioclase + K-feldspar + orthopyroxene + biotite.

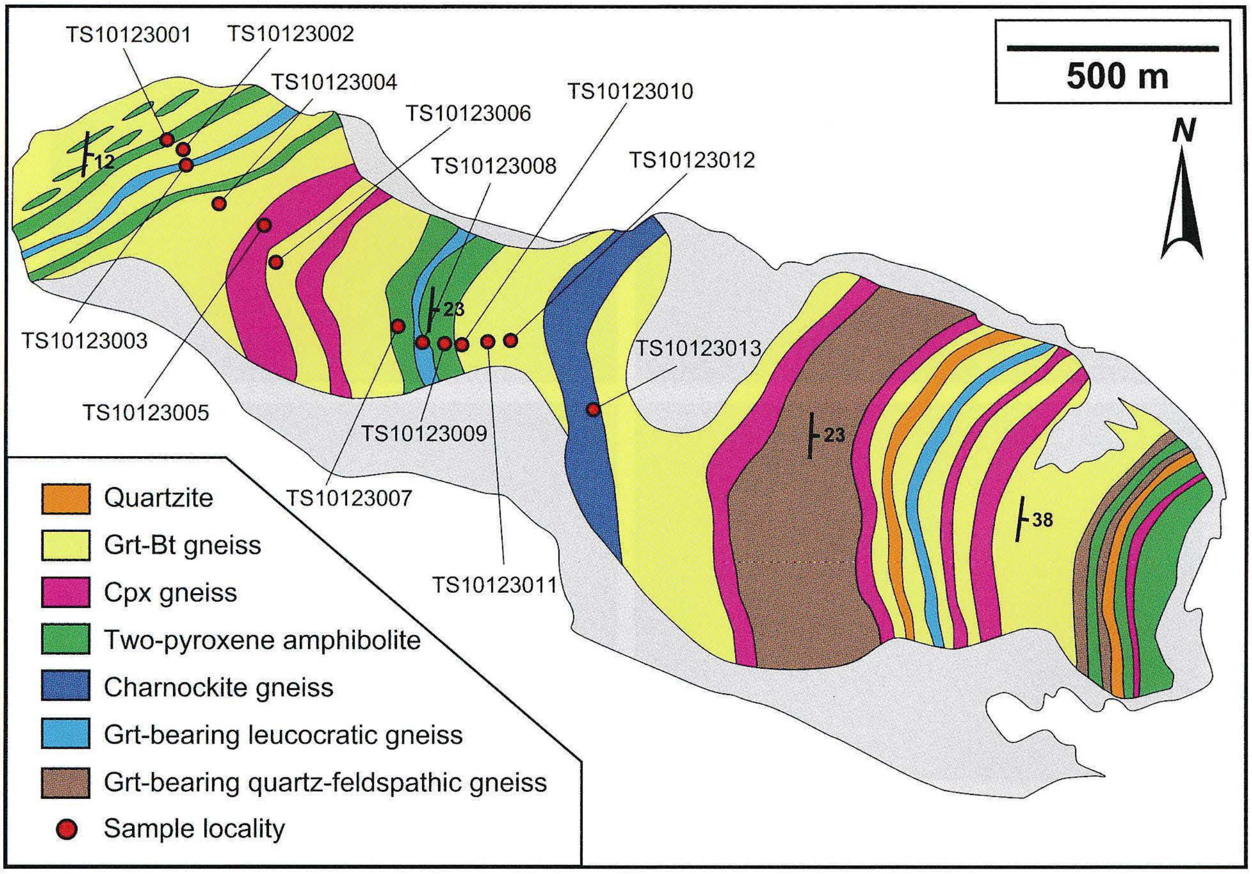

Fig. 2. Geological map of Telen (after Nakai et al., 1979) with the localities of samples discussed in this study.

Mafic granulite/amphibolite

Mafic granulite is a coarse-grained melanocratic rock that occurs as lenses, layers, or boudins parallel to the foliation of matrix orthogneiss (Fig. 3e). It is composed mainly of orthopyroxene, clinopyroxene, hornblende, and plagioclase with or without quartz (e.g., sample TS1012301313G). The rock often shows partial melting texture (Fig. 3f), suggesting H_2O-satulated condition during the high-grade metamorphism. Garnet is rarely present, and, it present, it is usually surrounded by orthopyroxene + plagioclase corona (Fig. 3f) as an indicator of decompression after the peak metamorphism. Such corona texture has been reported from many mafic granulites that underwent clockwise *P–T* evolution (e.g., Nishimiya et al., 2009; Saitoh et al., 2011). A representative hand specimen is composed of clinopyroxene, orthopyroxene, garnet, plagioclase, quartz, and biotite (sample TS1012301313G, Figs. 5e,f). Amphibolite (hornblende + plagioclase) layers are also present locally, and its field occurrence is similar to that of mafic granulite.

Garnet-rich mafic granulite also occurs as a block of up to 1 m within pelitic granulite (Fig. 3h). It is coarse grained, homogeneous (metagabbroic), and composed mainly of garnet, clinopyroxene, plagioclase, quartz, and biotite (Figs. 5g,h), suggesting relatively high-pressure metamorphism because of the stability of quartz. Similar blocks of high-pressure garnet + clinopyroxene rocks have been reported throughout the granulite-facies zone of the LHC (e.g., Hiroi et al., 1986)

Calc-silicate rock

Calc-silicate rock is a minor lithology in Telen, although it is abundant in adjacent localities such as Skallen, Skallevikshalsen, and Sudare Rocks (Yoshida et al., 1976; Osanai et al., 2004; Satish-Kumar et al., 2006). It is greenish to dark greenish, and occurs as ovoidal or rounded blocks of about 20 cm to 1 m in felsic to intermediate orthogneiss (Fig. 4a). The blocks are distributed parallel to the foliation of the matrix orthogneiss as boudins probably due to E-W compression or N-S extension. The dominant mineralogy of the rock is fine-grained clinopyroxene, sphene, plagioclase, and quartz (Figs. 6a,b). Relict carbonates are absent as they were probably completely metasomatized to silicates, although thick layers of pure marble occur in Skallen and Skallevikshalsen.

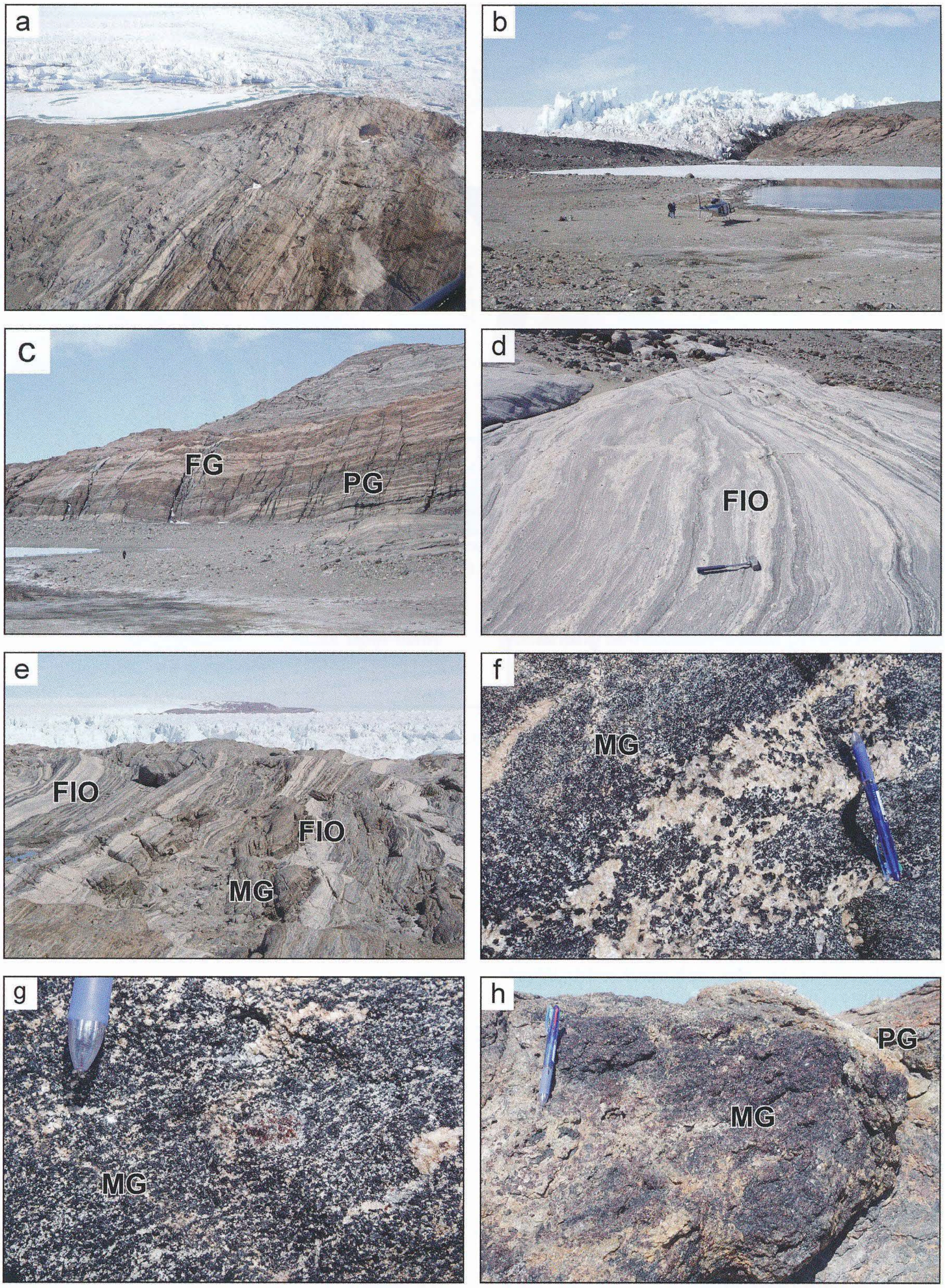

Fig. 3. Field occurrence of high-grade metamorphic rocks in Telen. (a) An overview of the geology of the western part of Telen where felsic to mafic orthogneiss are dominant. (b) An overview of the central part of Telen with the deployment position of helicopter. (c) Thick package of pelitic granulite (PG) and felsic garnet gneiss (FG) in the central part of Telen. (d) Felsic to intermediate orthogneiss (FIO) with obvious foliations defined by biotite-rich and quartzo-feldspathic layers. (e) Layers and lenses of mafic granulite (MG) within felsic to intermediate orthogneiss. (f) Coarse-grained mafic granulite with partially-molten patches. (g) Porphyroblastic garnet in mafic granulite showing a corona texture. (h) A block of metagabbroic garnet-clinopyroxene rock in pelitic granulite.

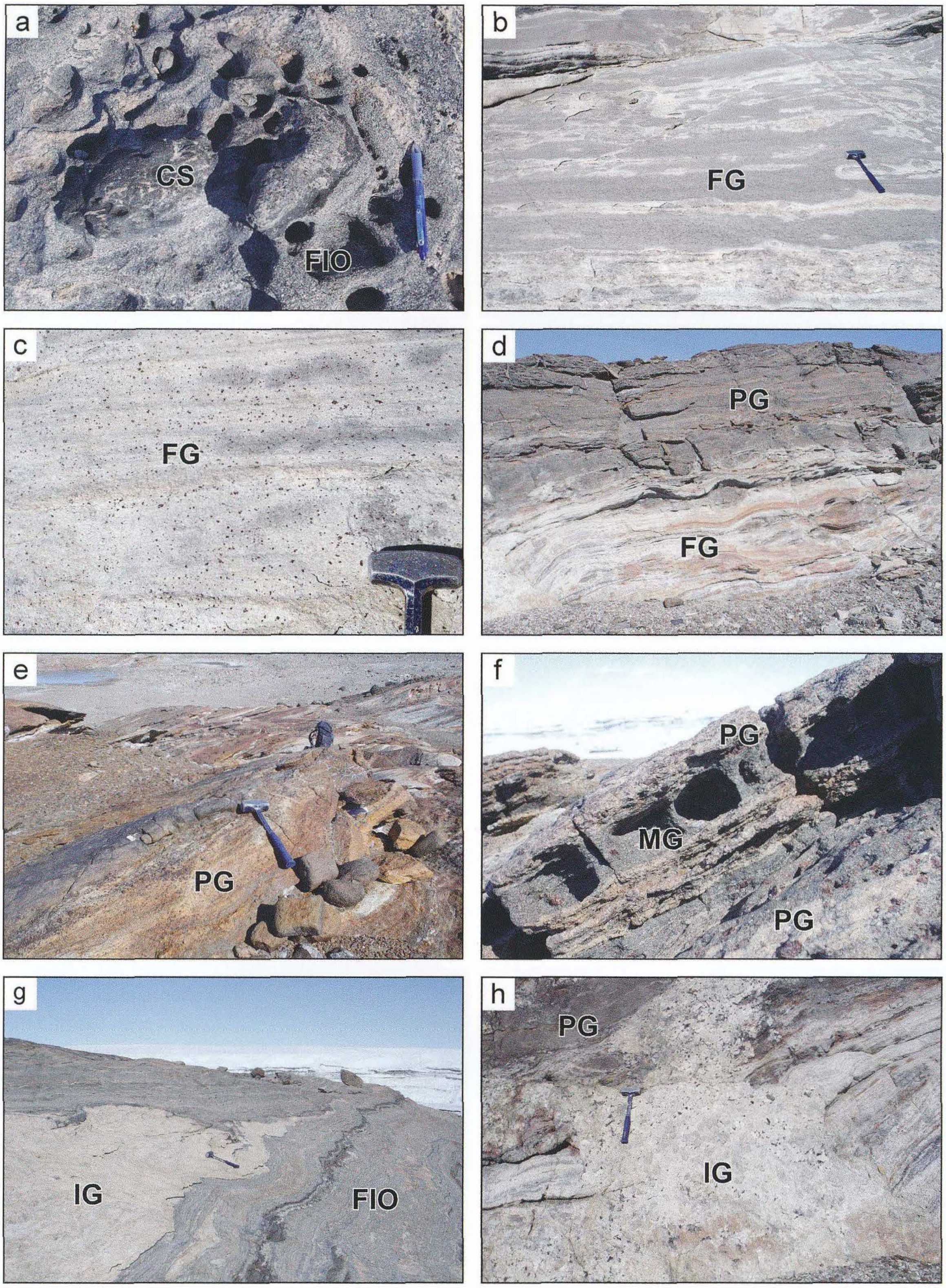

Fig. 4. Field occurrence of high-grade metamorphic rocks in Telen. (a) A lens of calc-silicate rock (CS) in felsic to intermediate orthogneiss. (b) A thick layer of felsic garnet gneiss. (c) Porphyroblastic garnets in felsic garnet gneiss. (d) Compositional layering of pelitic granulite and felsic garnet gneiss. (e) Slightly weathered brownish surface of pelitic granulite. (f) Compositional layering of pelitic and mafic granulites. (g) Post-tectonic granitoid (IG) intruding parallel to the foliation of matrix orthogneiss. (h) Post-tectonic granitoid intruding perpendicular to the foliation of matrix pelitic granulite.

Felsic garnet gneiss

Felsic garnet gneiss is a leucocratic rock with coarse-grained (2–8 mm) spots of dark reddish porphyroblastic garnet (Fig. 4b). Foliation of the rock is not obvious but alternation of biotite-free and biotite-bearing layers parallel to the regional N-S-trending foliation can be seen in hand specimen (Fig. 4c). This is a dominant lithology in the western part of Telen, and occurs as thick layers of up to 5 m. The rock is composed dominantly of garnet, K-feldspar, quartz, and minor plagioclase (e.g., sample TS1012301302A; Figs. 6c,d). Similar leucocratic garnet-bearing rocks have been reported from many granulite terranes as a product of partial melting of pelitic rocks (e.g., Stevens and van Reenen, 1992). However, lack of thick metasedimentary units adjacent to the felsic gneiss suggests that the rock might correspond to a metamorphosed psammitic rock. Occurrence of many fine-grained (detrital?) rounded zircons in the rock might also suggest its sedimentary protolith.

Pelitic granulite

Pelitic granulite occurs in the central part of Telen. It is brownish in color due to surface weathering (Fig. 4e), and often intercalate with felsic garnet gneiss and mafic granulite (Figs. 4d,f). N-S trending foliation of the rock is defined by alternation of quartzo-feldspathic and garnet-rich layers, which probably corresponds to protolith sandstone-siltstone association in a thick (>10 m) sedimentary package. Coarse-grained (~ 2 cm) poikiloblastic garnet, which is obvious in hand specimen, is surrounded by medium-grained quartz, K-feldspar, plagioclase, and biotite in the matrix (e.g., sample TS1012301307H). Sillimanite is rare but present around or as inclusions in the garnet (Figs. 6e,f). Similar metasediments are present in Skallevikshalsen, although it is more aluminous in Skallevikshalsen and contains abundant spinel and sillimanite. No reaction texture can be seen in the Telen metasediments.

Intrusive granitoids

The high-grade metamorphic rocks in Telen are intruded by undeformed felsic granitic rocks that occur nearly parallel or perpendicular to the foliation of the matrix orthogneiss and pelitic granulite (Figs. 4g,h), clearly suggesting post-metamorphic magmatic activity. It is coarse grained (pegmatitic), leucocratic, and holocrystalline. A representative sample (TS1012301307F, which occurs parallel to the foliation) is composed of coarse-grained and semi-equigranular K-feldspar, quartz, plagioclase, and biotite (Figs. 6g,h).

Geothermobarometry

In order to evaluate metamorphic conditions of Telen area, garnet-clinopyroxene geothermometer was applied to porphyroblastic garnet and clinopyroxene in metagabbroic mafic granulite (Fig. 3h). The estimated temperature range for the pairs is 860–880°C for sample TS10123013H2 based on the method of Ellis and Green (1979) which relies on experimental calibration of Fe–Mg fractionation between garnet and clinopyroxene at 750°C to 1350°C and 24 to 30 kbar, and is a widely applied thermometer for granulite terranes. The temperatures were calculated at 10 kbar, a reference pressure inferred from the peak pressure condition of the samples estimated by garnet-clinopyroxene-plagioclase-quartz geobarometer of Moecher et al. (1988) as discussed below.

Metamorphic pressure for the sample was calculated using garnet-clinopyroxene-plagioclase-quartz assemblages based on experimental calibration of Perkins and Newton (1981). The estimated results are 7.0–7.3 kbar at 900°C. We also adopted the method of Moecher et al. (1988), which is based on improved garnet-clinopyroxene-plagioclase-quartz geobarometer using new thermodynamic and experimental data. Application of this method yielded a pressure range of 10.1–10.5 kbar (at 900°C) suggesting high-pressure conditions.

Discussion

This is the first report on the occurrence and petrography of dominant lithologies as well as preliminary *P–T* conditions of Telen in the central part of the granulite-facies zone of the LHC. The major lithologies in Telen are felsic to intermediate orthogneiss, mafic granulite/amphibolite, calc-silicate rock, felsic garnet gneiss, and pelitic granulite, which are similar to adjacent localities such as Skallen and Skallevikshalsen (e.g., Yoshida et al., 1976; Osanai et al., 2004), although felsic to mafic orthogneisses are dominant in Telen, while calc-silicate rocks and marbles are more abundant in Skallen and Skallevikshalsen. Younger granitoids intruded nearly parallel or perpendicular to the surrounding metamorphic rocks. The dominant mineral assemblages of the lithologies are quartz + plagioclase + K-feldspar + biotite ± garnet (felsic to intermediate orthogneiss), orthopyroxene + clinopyroxene + plagioclase ± garnet ± quartz ± hornblende (mafic granulite), hornblende + plagioclase (amphibolite), clinopyroxene + sphene + plagioclase + quartz (calc-silicate rock), garnet + K-feldspar + quartz + plagioclase (felsic garnet gneiss), garnet + sillimanite + K-feldspar + plagioclase + biotite (pelitic granulite), and K-feldspar + quartz + plagioclase (intrusive granitoid). Common

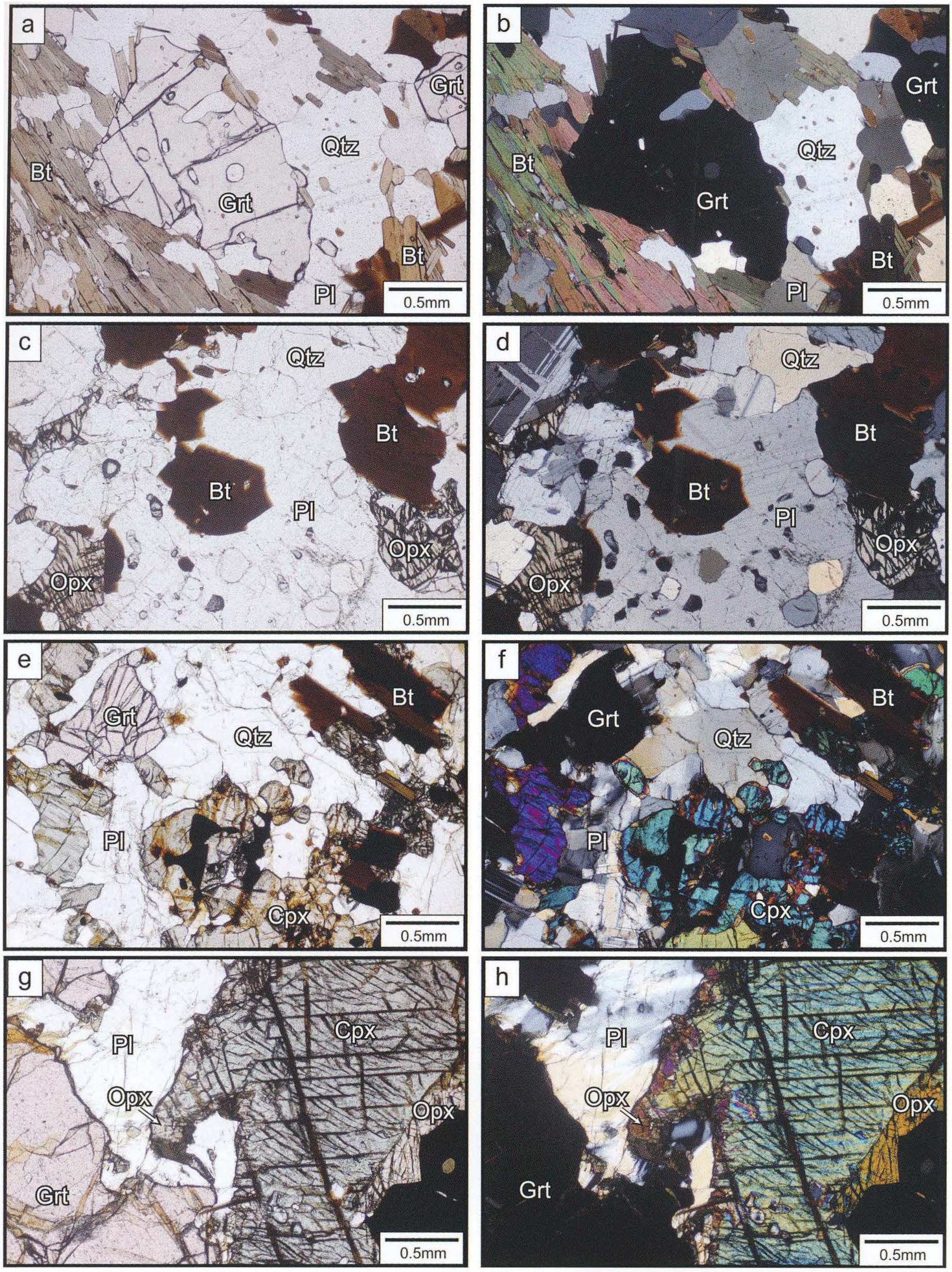

Fig. 5. Photomicrographs of representative high-grade metamorphic rocks in Telen. (a), (c), (e), and (g) are polarized light photographs, while others are crossed polars. (a) and (b) Garnet + biotite + plagioclase + quartz assemblage in felsic to intermediate orthogneiss with obvious foliation defined by aligned biotite (sample TS1012301307D). (c) and (d) Plagioclase + quartz + orthopyroxene + biotite in felsic orthogneiss (charnockite) (sample TS1012301301A). (e) and (f) Garnet + clinopyroxene + biotite + plagioclase + quartz assemblage in mafic granulite (sample TS1012301313G). (g) and (h) Coarse-grained garnet, clinopyroxene and plagioclase in garnet-rich mafic granulite (sample TS10123013H2).

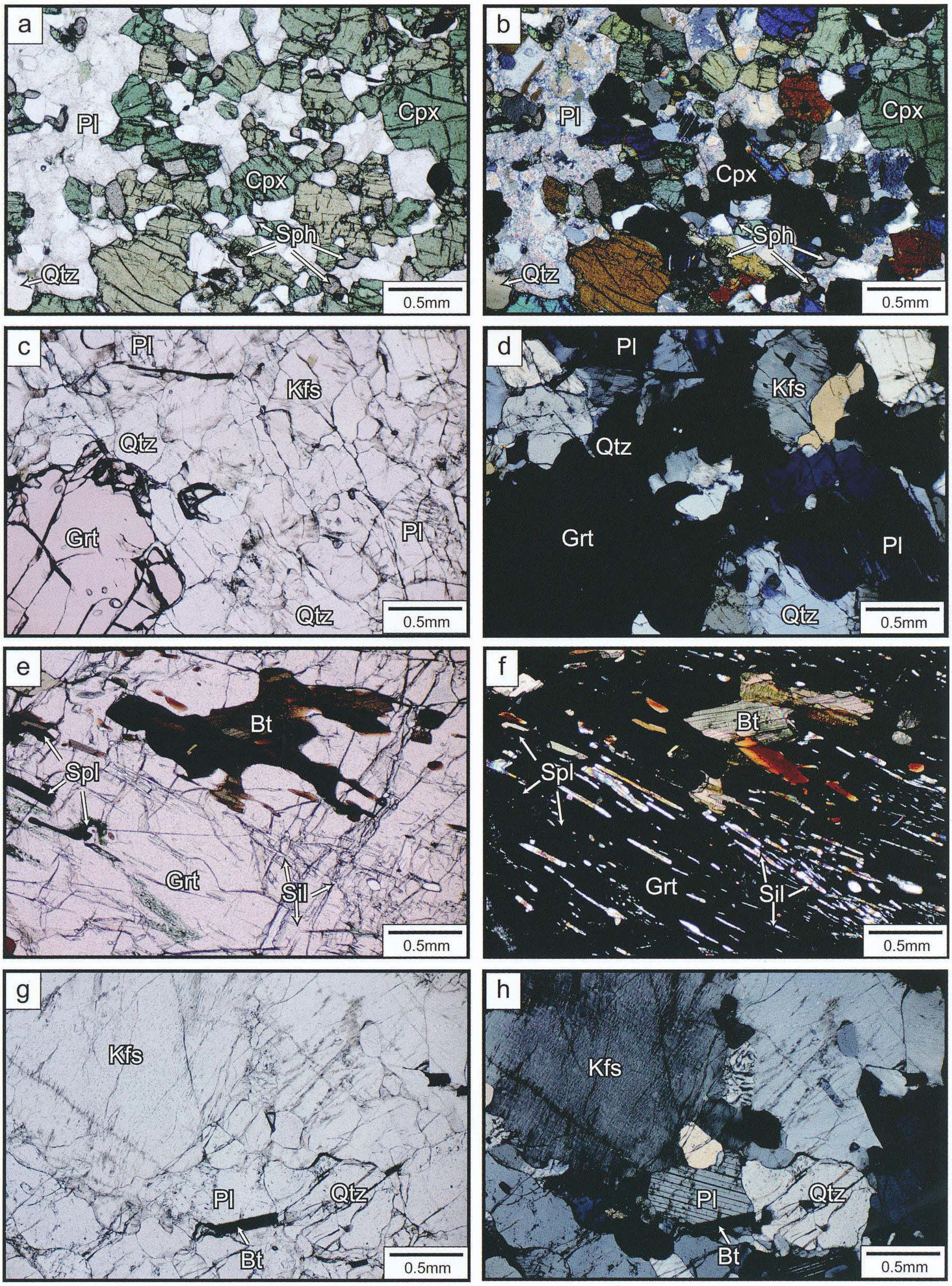

Fig. 6. Photomicrographs of representative high-grade metamorphic rocks in Telen. (a), (c), (e), and (g) are polarized light photographs, while others are crossed polars. (a) and (b) Fine-grained clinopyroxene + sphene + plagioclase + quartz assemblage in calc-silicate (sample TS10123009). (c) and (d) Medium-grained garnet + quartz + K-feldspar + plagioclase association in felsic garnet gneiss (sample TS1012301302A). (e) and (f) Coarse-grained porphyroblastic and garnet with inclusions of sillimanite, spinel, and biotite in pelitic granulite (sample TS1012301307H). (g) and (h) Coarse-grained K-feldspar, quartz, and plagioclase in intrusive granitoid (sample TS1012301307F).

occurrences of orthopyroxene in felsic to mafic orthogneiss and K-feldspar in metasediments suggest that this region underwent granulite-facies metamorphism, which is consistent with the results of previous studies that the southwestern region of the LHC along the Soya Coast underwent regional granulite-facies metamorphism. *P–T* conditions estimated for metagabbroic garnet-clinopyroxene (mafic) granulite (860–880°C) also confirmed peak granulite-facies condition. Although higher metamorphic conditions of T >950°C have been reported from several localities in the LHC (e.g., Yoshimura et al., 2008a,b; Kawasaki et al., 2011; Motoyoshi et al., 1997), Tsunogae et al. (2014) argued that, based on pseudosection analysis of massive charnockite from Vesleknausen and Rundvågshetta, such ultrahigh-temperature conditions are related to local events, while common rocks in the granulite-facies region of the LHC underwent ordinary granulite-facies metamorphism of 800–900°C. Therefore, the peak metamorphic conditions obtained from Telen are consistent with their results, although we cannot neglect a possibility that the temperature range (860–880°C) obtained in this study corresponds to a retrograde stage after a T>950°C peak metamorphism. Our ongoing detailed petrological studies including phase equilibrium modeling will give us some ideas on the maximum *P–T* conditions recorded in the rocks.

Previous geological studies inferred that orthogneiss is abundant in Telen (Nakai et al., 1979), while metasediments are more abundant in adjacent localities such as Skallen and Skallevikshalsen. However, dominant occurrences of metasedimentary rocks such as felsic garnet gneiss and pelitic granulite suggest the principal lithologies of Telen are similar to those of surrounding regions. This is also consistent with N-S-trending foliation of Telen region, which is nearly equivalent to the foliation at Kjuka, located about 6 km NNE from Telen. The foliation trend is, however, perpendicular to E-W- or ENE-WSW-trending foliation at Skallen and Skallevikshalsen, about 8 km west from Telen (Fig. 1b), suggesting large-scale folding. The results of this study therefore confirm Telen-Skallen-Skallevikshalsen region in the central domain of the granulite-facies zone corresponds to a single mass of granulites formed by Late Neoproterozoic to Cambrian high-grade metamorphism possibly related to the final phase of continent-continent collision during the assembly of Gondwana Supercontinent.

Acknowledgements

We express our sincere thanks to the members of JARE-52 and the crew of the icebreaker Shirase for giving us the opportunity for geological field investigation of the Lützow-Holm Complex, and for their helpful support. Especially we thank Dr. T. Hokada, Professors K. Kawasaki, K. Shiraishi, and Y. Motoyoshi for their support and discussion. We thank Prof. Y. Arakawa for his editorial handling. Partial funding for this project was produced by a Grant-in-Aid for Scientific Research (B) from Japan Society for the Promotion of Science (JSPS) to Tsunogae (No. 22403017).

References

Ellis, D.J., Green, D.D., 1979. An experimental study of the effect of Ca upon garnet-clinopyroxene Fe-Mg exchange equilibria. *Contributions to Mineralogy and Petrology* **71**, 13-22.

Hiroi, Y., Shiraishi, K., Motoyoshi, Y., Kanisawa, S., Yanai, K. and Kizaki, K., 1986. Mode of occurrence, bulk chemical compositions, and mineral textures of ultramafic rocks in the Lützow-Holm Complex, East Antarctica. *Memoirs of National Institute of Polar Research, Special Issue*, **43**, 62–84.

Hiroi, Y., Shiraishi, K. and Motoyoshi, Y., 1991. Late Proterozoic paired metamorphic complexes in East Antarctica, with special reference to the tectonic significance of ultramafic rocks. In: *Geological Evolution of Antarctica (Thomson, M.R.A., Crame, J.A. and Thomson, J.W. Eds.), Cambridge University Press, Cambridge,* 83–87.

Kawasaki, T., Nakano, N., and Osanai, Y., 2011. Osumilite and a spinel + quartz association in garnet-sillimanite gneiss from Rundvågshetta, Lützow-Holm Complex, East Antarctica. *Gondwana Research*, **19**, 430–445.

Moecher, D.P., Essene, E.J., Anovitz, L.M., 1988. Calculation and application of clinopyroxene-garnet-plagioclase-quartz geobarometers. *Contributions to Mineralogy and Petrology* **100**, 92–106.

Motoyoshi, Y. and Ishikawa, M., 1997. Metamorphic and structural evolution of granulites from Rundvågshetta, Lützow-Holm Complex, East Antarctica. In: *The Antarctic Region: Geological Evolution and Processes (Ricci C.A. Ed.) Terra Antarctica, Siena,* 65–72.

Nakai, Y., Kano, T., Yoshikura, S., Ishikawa, T., and Yanai, K., 1979. Explanatory text of geological map of Kjuka and Telen, Antarctica. *Antarctic Geological Map Series, Sheet 8 (Kjuka and Telen), National Institute of Polar Research,* 5pp.

Nishimiya, Y., Tsunogae, T., and Santosh, M., 2008.

Petrology and fluid inclusions of garnet-clinopyroxene rocks from Paramati in the Palghat-Cauvery Shear Zone System, southern India. *Journal of Mineralogical and Petrological Sciences*, **103**, 354-360.

Nogi, Y., Jokat, W., Kitada, K., and Steinhage, D., 2013. Geological structures inferred from airborne geophysical surveys around Lützow-Holm Bay, East Antarctica. *Precambrian Research*, **234**, 279-287.

Osanai, Y., Toyoshima, T., Owada, M., Tsunogae, T., Hokada, T., Crowe, W.A., Ikeda, T., Kawakami, T., Kawano, Y., Kawasaki, T., Ishikawa, M., Motoyoshi, Y., and Shiraishi, K., 2004. Explanatory text of geological map of Skallen, Antarctica (revised edition). *Antarctic Geological Map Series, Sheet 39 Skallen (revised edition), National Institute of Polar Research,* 23pp.

Perkins, D., Newton, R.C., 1981. Charnockite geobarometers based on coexistence garnet-pyroxene-plagioclase-quartz. *Nature*, **292**, 144–146.

Saitoh, Y., Tsunogae, T., Santosh, M., Chetty, T.R.K., and Horie, K., 2011. Neoarchean high-pressure metamorphism from the northern margin of the Palghat-Cauvery Suture Zone, southern India: petrology and zircon SHRIMP geochronology. *Journal of Asian Earth Sciences*, **42**, 268-285.

Satish-Kumar, M., Hermann, J., Tsunogae, T., and Osanai, Y., 2006. Carbonation of Cl-rich scapolite boudins in Skallen, East Antarctica: Evidence for changing fluid condition in the continental crust. *Journal of Metamorphic Geology*, **24**, 241-261.

Shiraishi, K., Ellis, D.J, Hiroi, Y., Fanning, C.M., Motoyoshi, Y., and Nakai, Y., 1994. Cambrian orogenic belt in East Antarctica and Sri Lanka: Implications for Gondwana assembly. *Journal of Geology*, **102**, 47-65.

Shiraishi, K., Hokada, T., Fanning, C. M., Misawa, K., and Motoyoshi, Y., 2003. Timing of thermal events in eastern Dronning Maud Land, East Antarctica. *Polar Geoscience*, **16**, 76–99.

Shiraishi, K., Dunkley, D.J., Hokada, T., Fanning, C.M., Kagami, H., and Hamamoto, T., 2008. Geochronological constraints on the Late Proterozoic to Cambrian crustal evolution of eastern Dronning Maud Land, East Antarctica: a synthesis of SHRIMP U-Pb age and Nd model age data. *Geological Society, London, Special Publications*, **308**, 21–67.

Stevens, G. and van Reenen, D.D., 1992. Partial melting and the origin of metapelitic granulites in the Southern Marginal Zone of the Limpopo Belt, South Africa. *Precambrian Research*, **55**, 303-319.

Tsunogae, T., Dunkley, D.J., Horie, K., Endo, T., Miyamoto, T., and Kato, M., 2014. Petrology and SHRIMP zircon geochronology of granulites from Vesleknausen, Lützow-Holm Complex, East Antarctica: Neoarchean magmatism and Neoproterozoic high-grade metamorphism. *Geoscience Frontiers*, **5**, 167-182.

Yoshida, M., Yoshida, T., Ando, H., Ishikawa, T., and Tatsumi, T., 1976. Explanatory text of geological map of Skallen, Antarctica. *Antarctic Geological Map Series, Sheet 9 (Skallen), National Institute of Polar Research*, 16pp.

Yoshimura, Y., Motoyoshi, Y., and Miyamoto, T., 2008a. Sapphirine + quartz association in garnet: implication for ultrahigh-temperature metamorphism at Rundvågshetta, Lützow-Holm Complex, East Antarctica. *Geological Society, London, Special Publications*, **308**, 377–390.

Yoshimura, Y., Motoyoshi, M., and Miyamoto, T., 2008b. High-grade metamorphic rocks from Skallevikshalsen in the Lützow-Holm Complex, East Antarctica: metamorphic conditions and possibility of partial melting. *Polar Geoscience*, **17**, 57-87.