Proc. NIPR Symp. Antarct. Geosci., 4, 213–230, 1990

ARRESTED CHARNOCKITE FORMATION IN SRI LANKA: FIELD AND PETROGRAPHICAL EVIDENCE FOR LOW-PRESSURE CONDITIONS

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Abstract: Field data of the arrested charnockite (orthopyroxene-bearing quartzo-feldspathic rock in a broad sense) formation are the striking evidence for CO_2 flushing and resultant subsolidus dehydration reactions and/or partial melting. Such a local phenomenon is, however, distinct from the preceding regional granulite-facies metamorphism, because it took place under much lower-pressure conditions in Sri Lanka. The orthopyroxene+cordierite+K-feldspar as well as orthopyroxene+garnet+K-feldspar±cordierite assemblages are stable in the charnockitized pelitic rocks of the Southwestern Group. In addition, secondary andalusite occurs commonly, though small in amount, together with siderite and cordierite in other pelitic rocks (gneiss and migmatite) of the Southwestern Group.

Secondary andalusite has also been revealed to occur in the Highland Series rocks. This, along with the occurrence of relict kyanite in sillimanite-stable rocks of both the Highland Series and the Southwestern Group establishes that rocks, at least metasediments, of these geological units in Sri Lanka have similar pressure-temperature histories. The later low-pressure metamorphic overprint including arrested charnockite formation was, however, much more extensive in the Southwestern Group than in the Highland Series.

1. Introduction

Sri Lanka as well as South India are famous for the spectacular arrested charnockite formation, or local charnockitization of orthopyroxene-free country rocks. The local charnockite development from hydrous country rocks such as (graphite-garnet-) biotite-hornblende quartzo-feldspathic gneisses has been argued about whether CO_2-flushing takes place so as to enhance subsolidus dehydration reactions (carbonic metamorphism (NEWTON *et al.*, 1980)) and/or partial melting (PETERSON and NEWTON, 1989) and whether it is the major process of granulite formation in the deep continental crust (NEWTON *et al.*, 1980; NEWTON and HANSEN, 1983). Although several lines of evidence have been accumulated for the infiltration of CO_2 along fracture zones (*e.g.*, JACKSON *et al.*, 1988), there is still a debate over the significance of CO_2 influx from the mantle as the major process of regional granulite formation at the bottom of the crust (*e.g.*, MCLELLAND *et al.*, 1988). Thus it is urgent to estimate the *P-T* conditions of local charnockite formation, though some estimation has been done using thermobarometers (HANSEN *et al.*, 1987), and to establish the time relationship between local charnockitization and regional granultie-facies metamorphism in Sri Lanka.

Sri Lanka is a fragment of Gondwanaland, and is generally considered to have been situated next to East Antarctica before the breakup of the supercontinent (*e.g.*, LAWVER and SCOTESE, 1987). Most of the Japanese authors have been concerned with the geology of East Antarctica around Syowa Station, and keen to make up for what they could not observe because of the thick continental ice cover and to check up their interpretations about the tectono-thermal evolution of that portion of East Antarctica in other fragments of Gondwanaland.

In this paper, the authors will present the field and petrographical data on the arrested charnockite formation, especially of pelitic rocks, and describe the mode of occurrence of andalusite in rocks of both the Southwestern Group and the Highland Series, as the first step of the Japan-Sri Lanka joint geological research, in order to suggest that the local charnockite development is distinct from the preceding regional granulite-facies metamorphism and took place under much lower-pressure conditions (not at the bottom of the crust but at shallow to intermediate depths), at least in Sri Lanka.

2. Geological and Petrological Outlines of Sri Lanka

Four-fifths of Sri Lanka is made up of Precambrian high-grade metamorphic rocks, which have been divided into three major units; the Highland Series, the Southwestern Group and the Vijayan Complex on the basis of lithology, structure and age, as shown in Fig. 1 (COORAY, 1978, 1984; GEOLOGICAL SURVEY DEPARTMENT OF SRI LANKA, 1982). The Highland Series is composed of various metasediments and charnockitic rocks metamorphosed, for the most part, under the granulite-facies conditions. The Southwestern Group also consists mainly of granulite-facies metasediments and charnockitic rocks but is somewhat dissimilar to the Highland Series lithologically. The boundary between the Highland Series and the Southwestern Group is diffuse. The Vijayan Complex is a composite unit of metamorphic rocks, migmatites and granites,

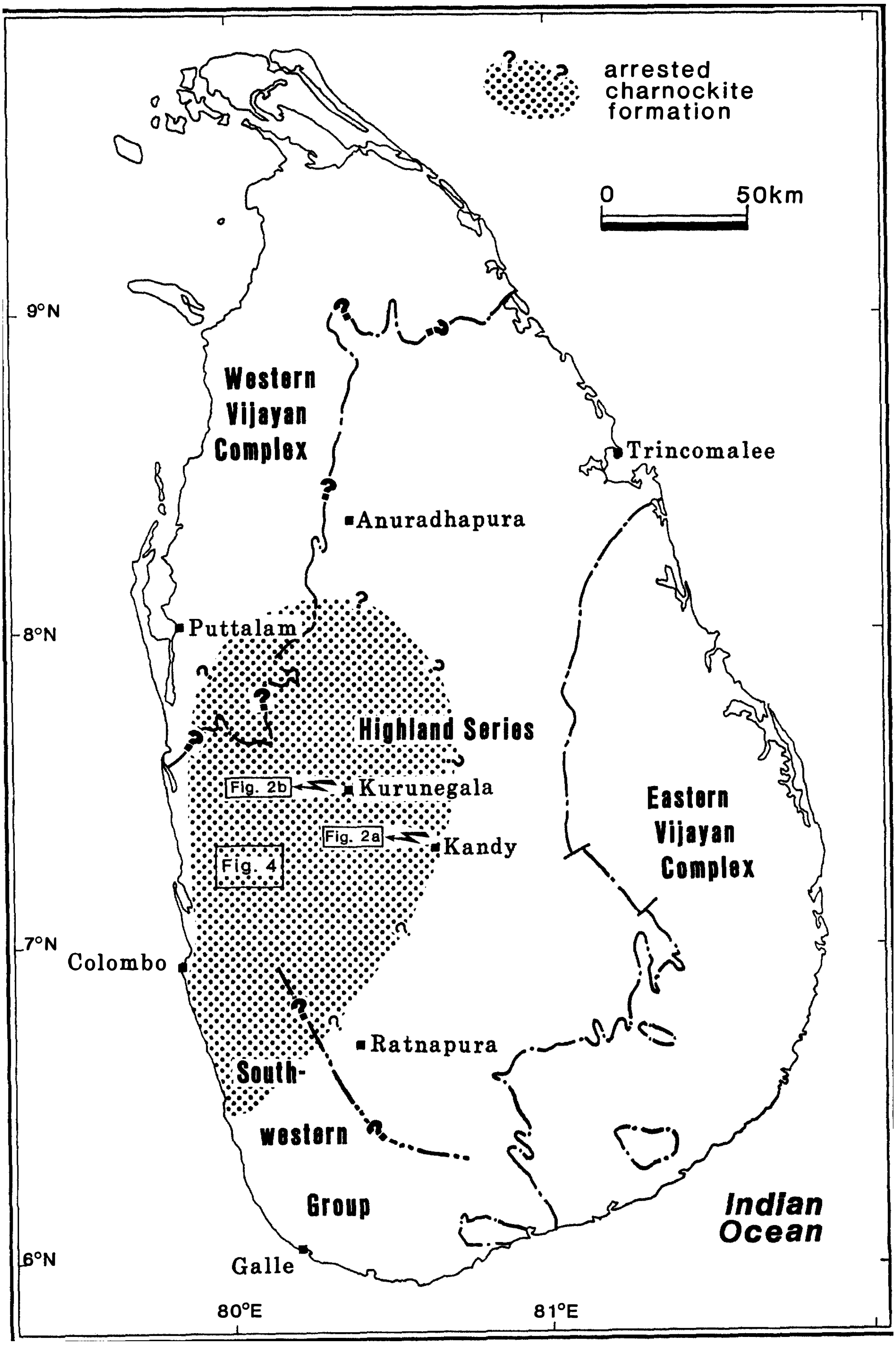


Fig. 1. *Map showing boundaries between three major geological units in Sri Lanka; Highland Series, Southwestern Group and Vijayan Complex, and area where arrested charnockite formation is seen. The boundaries are after* GEOLOGICAL SURVEY DEPARTMENT OF SRI LANKA *(1982). The Vijayan Complex is subdivided into the Western and Eastern Vijayan Complexes.*

which suffered mainly amphibolite-facies metamorphism. It is distributed on both the northwest (the Western Vijayan Complex) and southeast (the Eastern Vijayan Complex) of the centrally situated Highland Series. The boundary between the Highland Series and the Eastern Vijayan Complex is rather definite, though its geological meaning has not been settled, whereas the boundary between the Highland Series and the Western Vijayan Complex is obscure and its position is different from literature to literature.

At least three stages of deformation to form complex folds have been suggested for the Highland Series (BERGER and JAYASINGHE, 1976).

The Highland Series pelitic rocks usually contain the sillimanite+garnet+biotite assemblage with rare cordierite, and there occurs garnet-sillimanite gneiss (khondalite) closely associated with dolomitic marbles. On the contrary, the Southwestern Group pelitic rocks (gneiss and migmatite) are commonly rich in cordierite, the origin of which has been discussed by several authors (*e.g.*, PERERA, 1984). According to them, there was a low-pressure metamorphic overprint on the eariler higher-pressure granulite-facies regional metamorphism to form "secondary" cordierite associated with magnetite from garnet, sillimanite, biotite and others. HIROI *et al.* (1987) found relict kyanite with staurolite and/or spinel as inclusions within garnet in sillimanite-stable rocks of both the Highland Series and the Southwestern Group, and established the clockwise prograde pressure-temperature-time paths on a *P-T* diagram, at least for the metasediments of these geological units. Andalusite has been known to occur in and peculiar to the Southwestern Group (*e.g.*, KATZ, 1972). However, its mode of occurrence and origin have not been clarified yet.

Recent zircon ion microprobe dating has revealed that regional metamorphism took place at *ca.* 1100 Ma and again at *ca.* 500 Ma (KRÖNER *et al.*, 1987). Other geochronological data, however, suggest a more complicated and prolonged history, at least for parts of the Highland Series and Southwestern Group rocks (*e.g.*, CRAWFORD and OLIVER, 1969; KAGAMI *et al.*, in preparation).

3. Field Observation of Arrested Charnockite Formation

Arrested charnockite formation is observed mainly in the central to western parts of Sri Lanka, as shown in Fig. 1, that is in the area where rocks belonging to the Highland Series, the Southwestern Group and the Western Vijayan Complex underlie. In Fig. 2 are shown typical examples of arrested charnockite formation of the Highland Series (graphite-garnet-) biotite-hornblende quartzo-feldspathic rocks in two quarries near Kandy and near Kurunegala. Petrographical and chemical studies of the arrested

Fig. 2 (opposite). Two types of arrested charnockite formation of (graphite-garnet-) biotite-hornblende quartzo-feldspathic gneisses of the Highland Series.

a. Quarry near Kandy (88111103=H89082102), showing local development of charnockite along a fracture, which is represented by the centrally located mafic mineral-poor part (arrow). Note that the foliation of the country biotite-garnet-hornblende gneiss is preserved well in the charnockite. Analyses of rocks A, B and D are given in Appendix.

b. Quarry near Kurunegala (88111852=H89082101), showing irregularly developed charnockite patches. Note that charnockite (Bi-Opx-Kfs-Pl-Qtz with rare Hbl) is more coarse-grained and much less foliated than the original gneiss (Bi-Hbl-Kfs-Pl-Qtz).

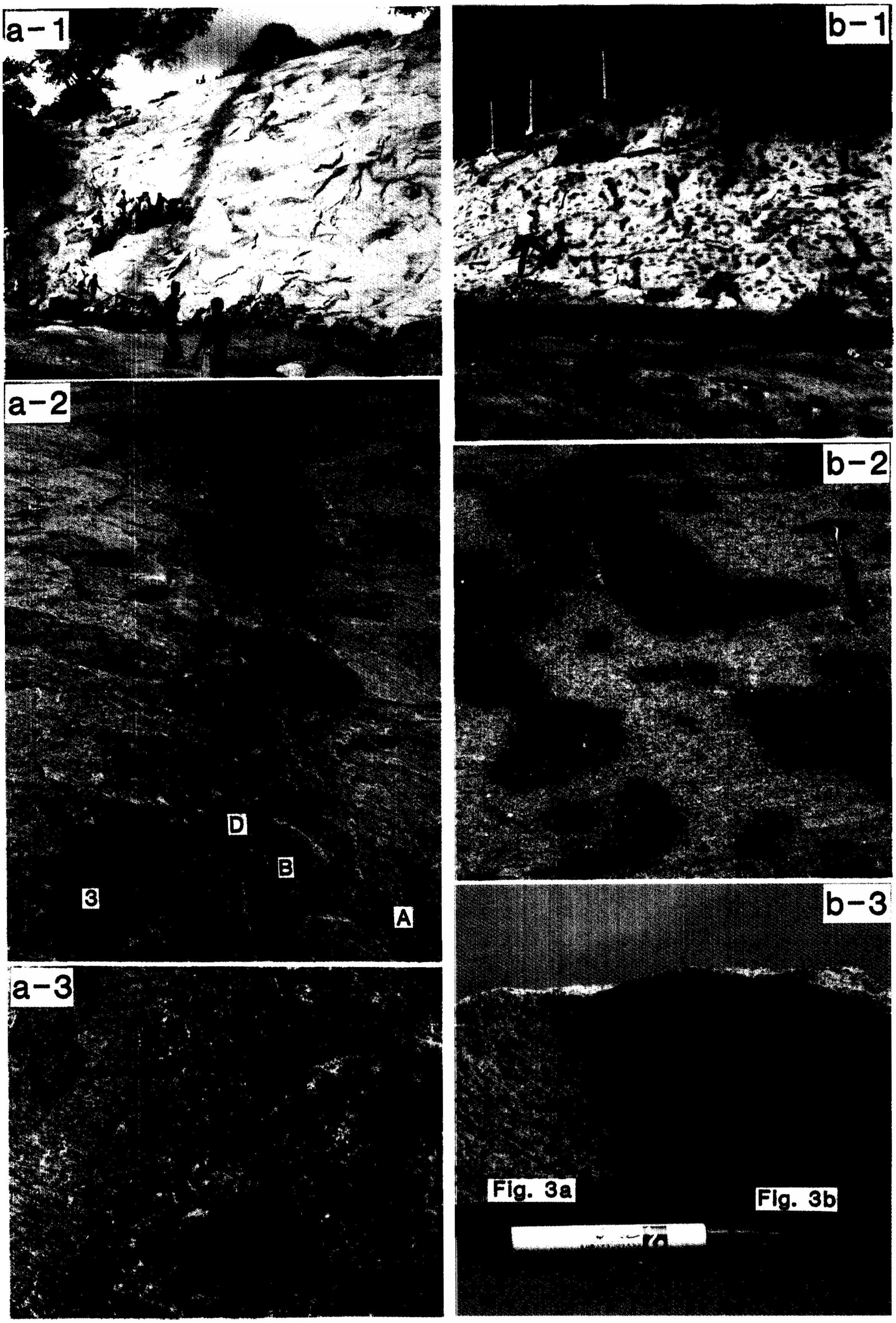
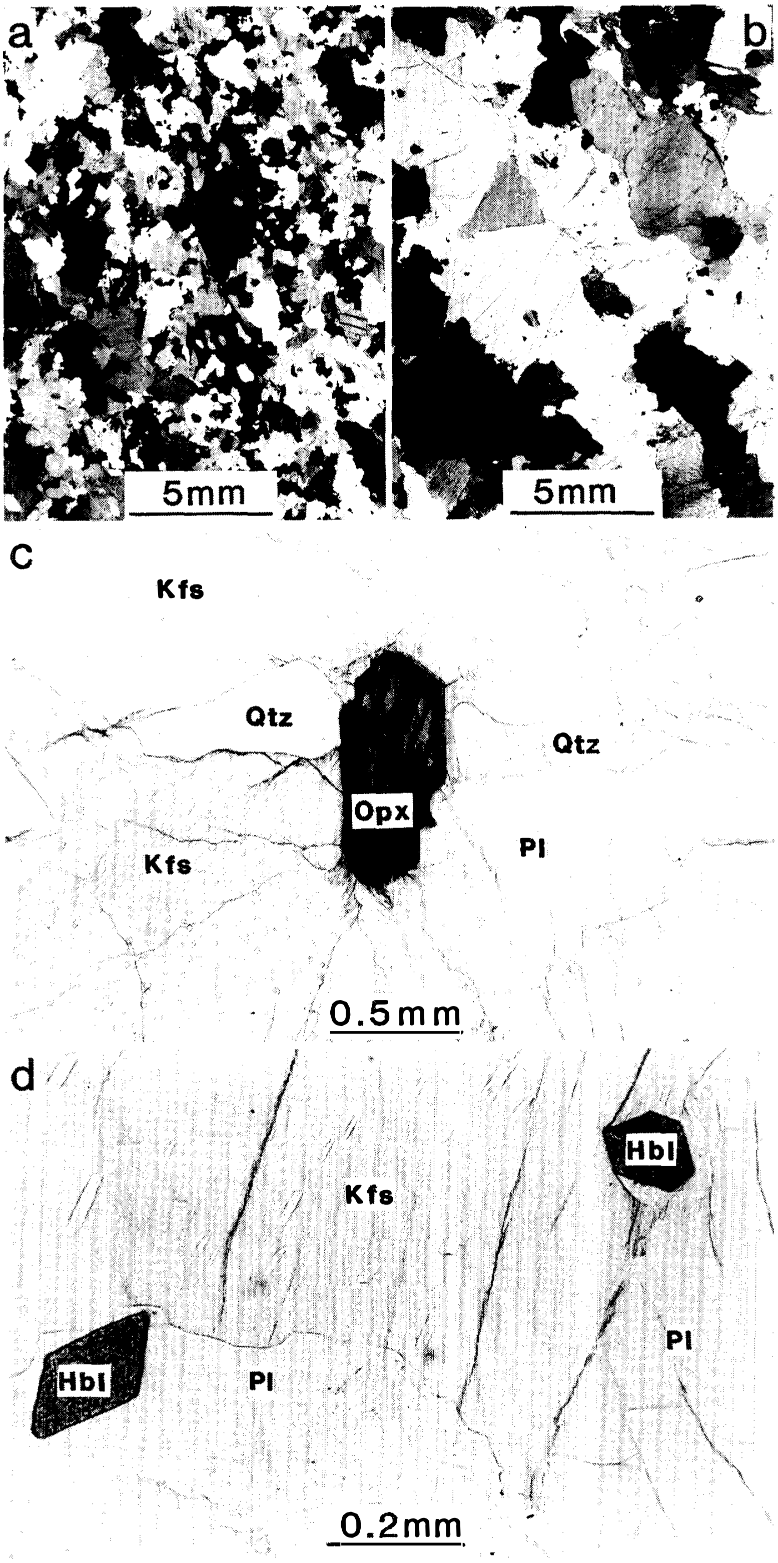


Fig. 2.



a. Well-foliated, medium-grained Bi-Hbl gneiss. Crossed nicols.
b. Massive, coarse-grained charnockite. Crossed nicols.

c. Euhedral orthopyroxene associated with K-feldspar, plagioclase and quartz in the massive charnockite. Plane-polarized light.

d. Fine-grained euhedral hornblende in the charnockite. Hornblende in the country gneiss is usually anhedral to subhedral and much more coarse-grained. Plane-polarized light.

Fig. 3. Photomicrographs of the irregularly developed charnockite and country gneiss from Kurunegala (88111852=H89082101). Hbl; hornblende, Kfs; K-feldspar, Opx; orthopyroxene, Pl; plagioclase, Qtz; quartz.

charnockite formation in the latter quarry have been done repeatedly (Hansen *et al.*, 1987; Glassley *et al.*, 1989). In the Kandy quarry local charnockitization is clearly seen to have taken place along a fracture, which is occasionally represented as a centrally located mafic mineral-poor part, and the original foliation, banding and/or gneissose texture are well preserved even in the charnockitized part (Fig. 2a). On the other hand, the structural control of charnockitization is not always definite and charnockite has been formed as irregular patches in the Kurunegala quarry (Figs. 2b-1 and 2b-2). In addition, the charnockite is more coarse-grained and much less foliated than the country gneiss (Figs. 2b-3, 3a and 3b), suggesting *in situ* partial melting and subsequent crystallization to destroy the original textures. It is noteworthy and may be indirect evidence for partial melting that only in the massive charnockite are present euhedral grains of orthopyroxene, biotite and rare hornblende (Fig. 3).

The local charnockitization of the Southwestern Group pelitic to quartzo-feldspathic rocks may be most significant because of the widespread occurrence of secondary cordierite, as mentioned above. In several quarries, the locality of one of which is shown in Fig. 4, the cordierite-bearing pelitic to quartzo-feldspathic rocks are observed to have been affected irregularly by charnockitization (Fig. 5). Although the original banding structure of the country garnet-biotite gneiss is preserved in places (Fig. 5b), charnockitized parts are usually highly migmatitic (diktyonitic, schlieren and nebulitic structures are seen; Fig. 5a), suggesting that some melts took part in the local charnockitization of pelitic rocks. Orthopyroxene can be seen together with blue-

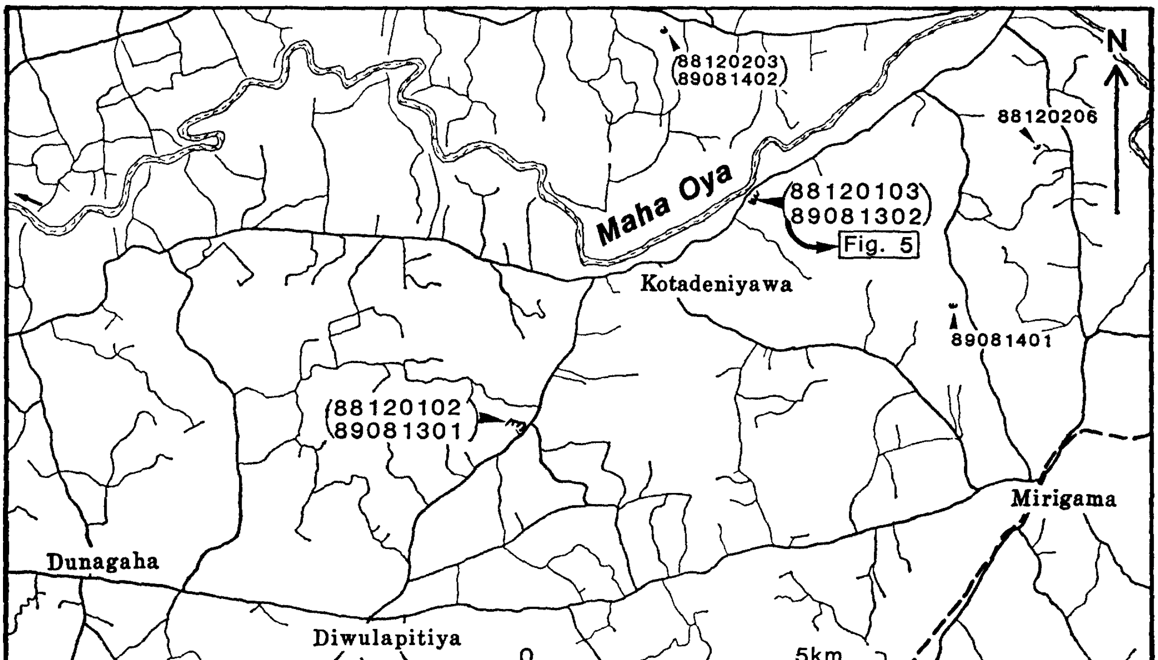


Fig. 4. Map showing localities of quarry 88120103=89081302, where arrested charnockite formation of cordierite-bearing pelitic to quartzo-feldspathic rocks of the Southwestern Group is seen, and quarry 88120102=89081301, where secondary andalusite occurs in pelitic gneiss and migmatite together with siderite and cordierite.

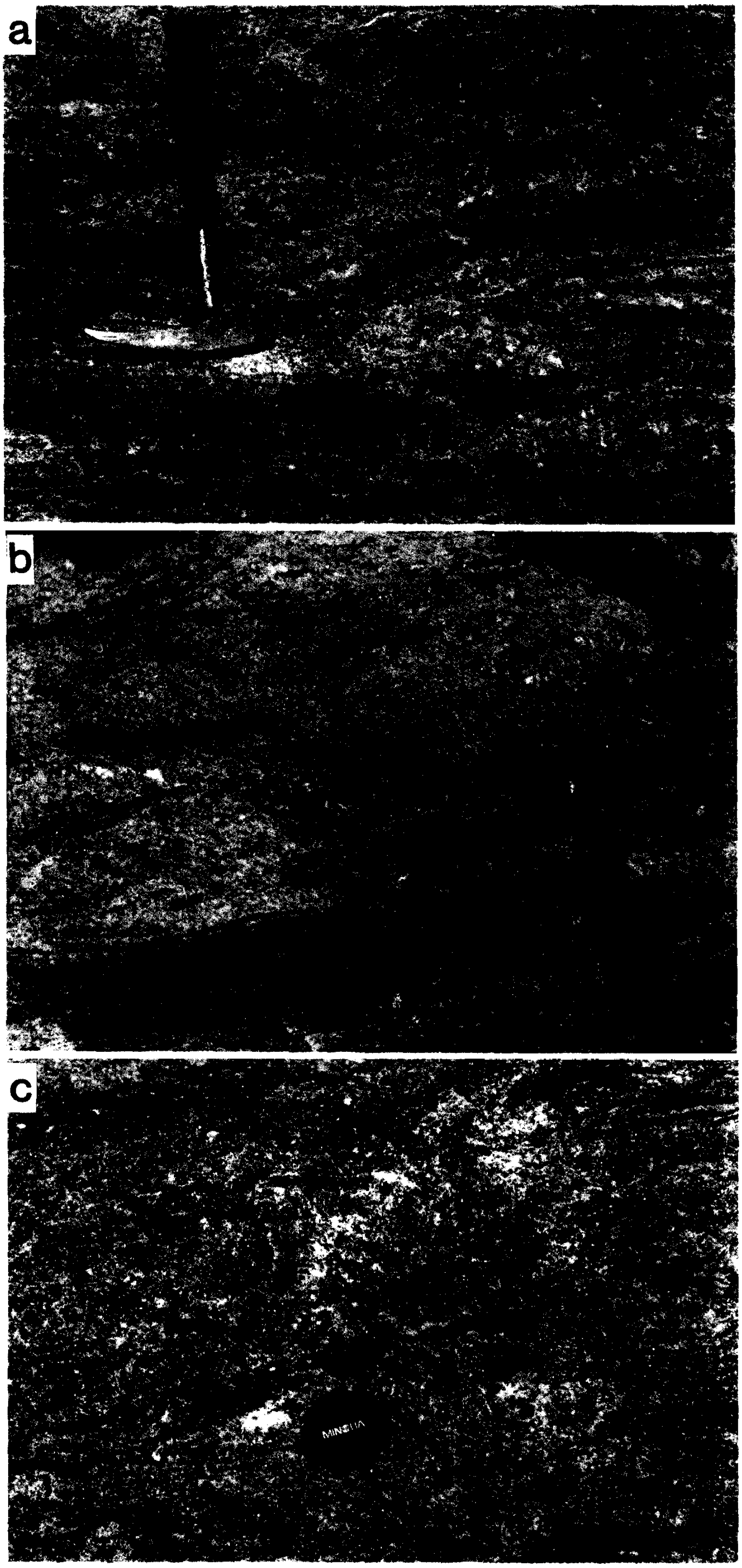


Fig. 5.

violet cordierite and/or reddish garnet with the naked eye (Fig. 5c). It is noteworthy that pink granitic dikes and veins cutting the Southwestern Group rocks are locally charnockitized in some cases.

4. Petrography of Locally Charnockitized and Relevant Pelitic Rocks of the Southwestern Group and the Highland Series

The observed mineral assemblages in the charnockitized pelitic rocks of the Southwestern Group are as follows:

a. cordierite + orthopyroxene + biotite + K-feldspar + plagioclase + quartz + magnetite + spinel + ilmenite
b. garnet + orthopyroxene + biotite + K-feldspar + plagioclase + quartz + magnetite + spinel + ilmenite ($\pm$sillimanite as inclusions in garnet)
c. cordierite + garnet + orthopyroxene + biotite + K-feldspar + plagioclase + quartz + magnetite + spinel + ilmenite ($\pm$sillimanite as inclusions in garnet)

The coexistence of orthopyroxene and cordierite has already been reported by HAPUARACHCHI (1968), COORAY (1978), PERERA (1984) and SANDIFORD *et al.* (1988). Textural relations between orthopyroxene and other minerals in the charnockitized pelitic rocks of the Southwestern Group are shown in Fig. 6. Garnet is usually replaced partially by cordierite and magnetite within as well as outside the charnockitized parts (Fig. 6a). It is noteworthy that sillimanite sometimes occurs as inclusions in garnet coexisting with orthopyroxene, biotite, K-feldspar, plagioclase and quartz (Fig. 6c). The orthopyroxene + sillimanite association, however, has not been found anywhere.

There is a close spatial relationship between the localities of andalusite and the sites of local charnockitization (compare Fig. 7 with Fig. 1). Andalusite commonly occurs, though small in amount, in the cordierite-rich Southwestern Group pelitic rocks cut extensively by pink granitic dikes and veins, which sometimes contain andalusite and/or cordierite and are mylonitic in some cases and granophyric in others. The authors newly found andalusite in the Highland Series pelitic rocks (Figs. 7 and 8c; see Appendix for more detailed localities). The mineral assemblages of andalusite-bearing rocks including pink granitic dikes and veins are as follows:

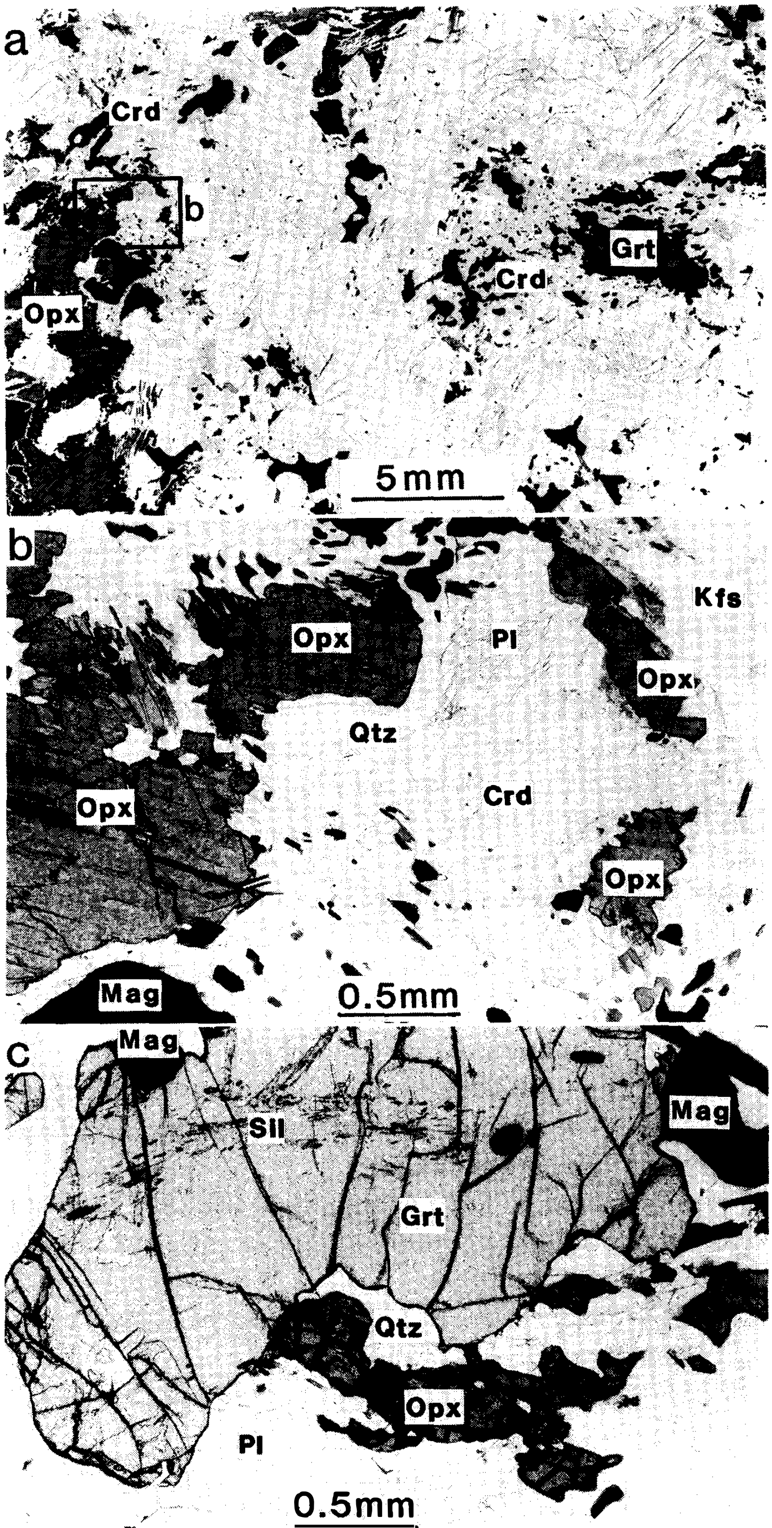
a. andalusite + cordierite + plagioclase + K-feldpsar + quartz + siderite + magnetite + spinel + ilmenite $\pm$ garnet $\pm$ tourmaline ($\pm$ kornerupine as inclusions in cordierite)
b. andalusite + garnet + biotite + plagioclase + K-feldspar + quartz + magnetite + ilmenite + cordierite $\pm$ sillimanite
c. andalusite + garnet + biotite + muscovite + plagioclase + K-feldspar + quartz + siderite + magnetite + ilmenite

Fig. 5 (opposite). Arrested charnockite formation of cordierite-bearing pelitic to quartzo-feldspathic rocks of the Southwestern Group (locality; 88120103=89081302).

a. Irregularly developed migmatitic charnockite.

b. Discordantly charnockitized garnet-biotite quartzo-feldspathic gneiss. Note that original banding structure is preserved in the charnockitized part.

c. Close-up view of migmatitic charnockite. Black orthopyroxene is seen together with blue-violet cordierite and reddish garnet with naked eye.



a. Migmatitic charnockite containing biotite, cordierite, garnet, ilmenite, K-feldspar, magnetite, plagioclase and quartz. Sillimanite is also present as inclusions in garnet. Note that cordierite is associated with abundant magnetite.

b. Orthopyroxene associated with cordierite, K-feldspar and magnetite. Minor amount of biotite is also present. Plane-polarized light.

c. Garnet associated with magnetite, orthopyroxene, plagiocalse and quartz. K-feldspar is also present elsewhere. Note that garnet contains sillimanite inclusions. Plane-polarized light.

Fig. 6. Photomicrographs showing textures of minerals in charnockitized pelitic to quartzo-feldspathic rocks of the Southwestern Group (locality; 88120103=89081302). Bi; biotite, Crd; cordierite, Grt; garnet, Kfs; K-feldspar, Mag; magnetite, Opx; orthopyroxene, Pl; plagioclase, Qtz; quartz, Sil; sillimanite.

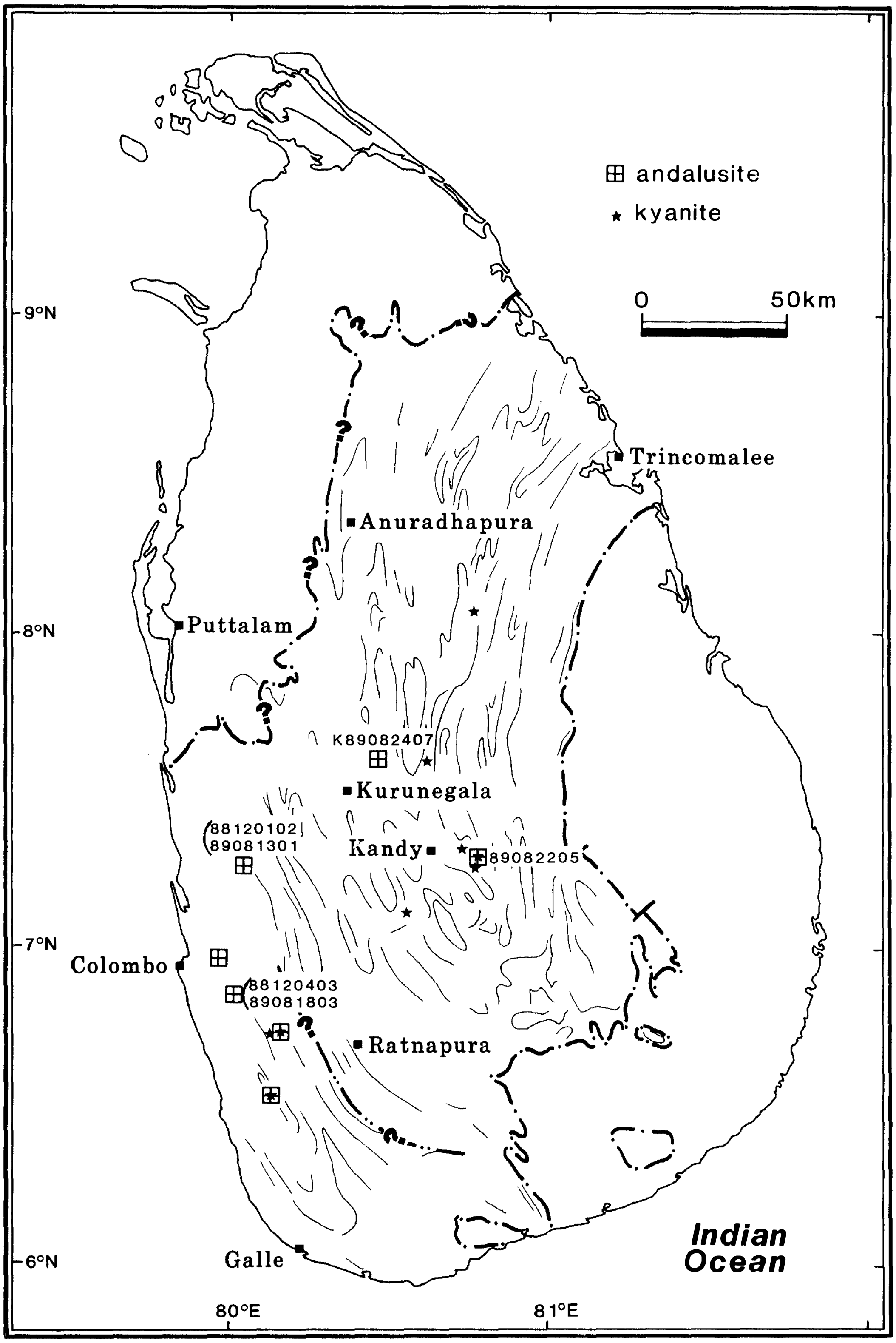
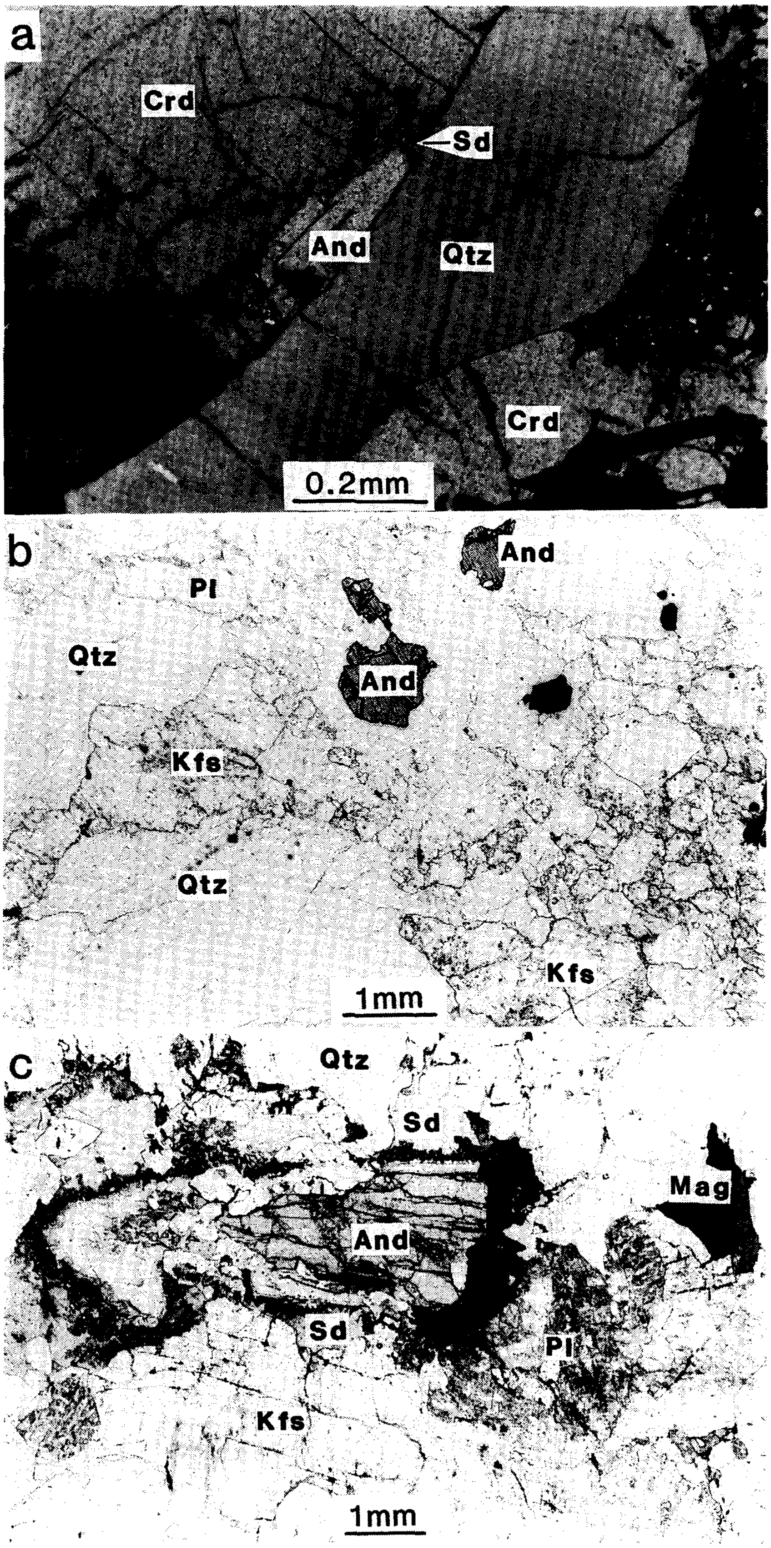


Fig. 7. *Map showing localities of secondary andalusite and/or relict kyanite (see Appendix for more detailed localities).*



a. Andalusite and siderite embayed by large cordierite in pelitic migmatite of the Southwestern Group (88120403). Crossed nicols.

b. Andalusite in pink granitic vein cutting pelitic gneiss of the Southwestern Group (89090303). Note that the vein shows a granophyric texture. Plane-polarized light.

c. Andalusite and siderite in pelitic gneiss of the Highland Series (K89082407). Plane-polarized light.

Fig. 8. Photomicrographs showing textures of andalusite. And; andalusite, Sd; siderite, other mineral abbreviations as in Fig. 6.

d. andalusite + biotite + plagioclase + K-feldspar + quartz + magnetite + ilmenite

It is significant that andalusite commonly coexists with siderite and is enclosed together with siderite by cordierite (Figs. 8a and 8c).

5. Discussion

The time and space relations among the secondary cordierite formation, pink granite emplacement and local charnockitization are clues to distinguish the local and regional granulite-forming events and to reveal the history of Sri Lankan granulites. As shown in the previous section, charnockitic parts irregularly invade the secondary cordierite-bearing pelitic to quartzo-feldspathic gneiss and migmatite of the Southwestern Group. Such field data clearly evidence that the local charnockitization took place during or after the widespread formation of secondary cordierite in these Southwestern Group rocks.

Mineral textures of the charnockitized pelitic rocks of the Soutwestern Group suggest that some orthopyroxene was formed with cordierite from garnet + quartz (PERERA, 1984; SANDIFORD *et al.*, 1988) and that orthopyroxene is in equilibrium with cordierite, biotite, K-feldspar and quartz. Orthopyroxene may also be in equilibrium with garnet, biotite, K-feldspar and quartz with or without cordierite in other parts of different bulk chemical compositions. According to GRANT (1985) and VIELZEUF and HOLLOWAY (1988) among many, the orthopyroxene + cordierite + K-feldspar assemblage is stable only under low-pressure conditions, probably below 3 kb. This is in good agreement with the occurrence of andalusite together with siderite in pelitic rocks from the area where arrested charnockite formation is observed. Andalusite also occurs in the pink granitic dikes and veins which sometimes show a granophyric texture (Fig. 8b), testifying that andalusite in the country metamorphic rocks is a secondary mineral. The andalusite + siderite assemblage suggests high f_{CO_2} during its formation, because it is chemically equivalent to the CO_2 + garnet and/or cordierite assemblage. In addition, cordierite is known to incorporate CO_2 into its channel (*e.g.*, ARMBRUSTER and BLOSS, 1980). On the basis of field data, it is plausible that CO_2 flushing and resultant local charnockitization took place nearly coevally with the emplacement of the abundant pink granitic dikes and veins of *ca.* 500 Ma.

The occasional occurrence of sillimanite as inclusions in garnet coexisting with orthopyroxene, biotite, K-feldspar and quartz in some charnockitized pelitic rocks suggests modification of original aluminous bulk chemical compositions to less aluminous ones during local charnockitization. This, along with the migmatitic feature, may be most satisfactorily explained by anatexis and mixing of melts of various compositions. As pointed out by HARRIS (1989), the significance of the CO_2 flushing is now being eclipsed by a second argument concerning the effect it has on the minimum melting temperatures of common crustal mineral assemblages. The field and petrographical data of the arrested massive coarse-grained charnockite formation at Kurunegala may also be evidence for partial melting during local charnockitization, as mentioned above. The widespread migmatization of the Southwestern Group pelitic to quartzo-feldspathic rocks, however, may also make it possible to assume that an H_2O-rich fluid moved, ahead of the CO_2-rich one, promoting anatexis which was then arrested by the arrival of the CO_2-rich phase, as suggested by JANARDHAN *et al.* (1982), HOLT and WIGHTMAN (1983) and FRIEND (1983).

The metamorphic ages of *ca.* 1100 Ma and *ca.* 500 Ma have been reported from over a large portion of East Antarctica (*e.g.*, GREW, 1982). The occurrence of relict kyanite and secondary andalusite has been known in the high-grade pelitic rocks around Syowa Station (the Lützow-Holm Complex) (HIROI and SHIRAISHI, 1986; HIROI *et al.*, 1983, 1990), where southwestward progressive metamorphism from the upper amphibolite facies to the granulite facies has been established to characterize the complex (HIROI and SHIRAISHI, 1986; SHIRAISHI *et al.*, 1987; HIROI *et al.*, 1990). Recently relict kyanite and secondary andalusite have also been found in the granulite-facies pelitic rocks of the Sør Rondane Mountains (GREW *et al.*, 1989; ISHIZUKA and KOJIMA, 1987). These features are in common to the high-grade metamorphic rocks from Sri Lanka, as mentioned above, and may be significant in the reconstruction of Gondwanaland. On the other hand, the spectacular phenomena of arrested charnockite formation have not been observed in East Antarctica yet, partly because of the intense weathering of the restricted Antarctic bedrock exposures. More data are needed to establish the exact reconstruction of Gondwanaland.

6. Conclusion

The spectacular phenomena of arrested charnockite formation are observed well in the central to western parts of Sri Lanka, and may be strong evidence for CO_2 flushing and resultant carbonic metamorphism and/or partial melting (new indirect evidence is given for partial melting during local charnockitization). The field data indicate that the local charnockitization took place during or after the widespread formation of secondary cordierite in pelitic rocks of the Southwestern Group. In the charnockitized pelitic rocks orthopyroxene commonly coexists stably with cordierite, biotite, K-feldspar and quartz, suggesting low-pressure conditions. In harmony with this, secondary andalusite occurs commonly with siderite and cordierite in other pelitic rocks cut extensively by pink granitic dikes and veins, which are also locally charnockitized in some cases. Thus in Sri Lanka, local charnockitization occurred at shallow to intermediate depths (? <3 kb) and is distinct from the preceding regional granulite-facies metamorphism which may have taken place at the bottom of the continental crust.

Acknowledgments

The authors are grateful to Drs. C. PONNAMPERUMA, E.R. JANSZ, C.B. DISSANAYAKE, K. DAHANAYAKE and L.K. SENEVIRATNE for their kind arrangements of the joint research. The authors also thank the staff of the Japan Embassy in Sri Lanka, especially Messrs. S. SHIMAZU and H. KATO, for their help to carry out field survey in 1988 and 1989 under the risky circumstances. This study was financed by the Ministry of Education, Science and Culture, Japan (No. 63041031 to Y.H.).

References

ARMBRUSTER, Th. and BLOSS, F. D. (1980): Channel CO_2 in cordierite. Nature, **286**, 140–141.

BERGER, A. R. and JAYASINGHE, N. R. (1976): Precambrian structure and chronology in the Highland Series of Sri Lanka. Precamb. Res., **3**, 559–576.

COORAY, P. G. (1978): Geology of Sri Lanka Precambrian. Proc. 3rd Region. Conf. Geol. Mineral Res. S-E Asia, Bangkok, 701–710.

COORAY, P. G. (1984): Geology, with special reference to the Precambrian. Ecology and Biogeography in Sri Lanka, ed. by C. H. FERNANDO. The Hague, Dr. W. Junk, 1–34.

CRAWFORD, A. R. and OLIVER, R. L. (1969): The Precambrian geochronology of Ceylon. Geol. Soc. Australia, Spec. Publ., **2**, 283–306.

FRIEND, C. R. L. (1983): The link between charnockite formation and granite production; Evidence from Kabbaldurga, Karnataka, southern India. Migmatites, Melting and Metamorphism, ed. by M. P. ATHERTON and C. D. GRIBBLE. Nantwich, Shiva Publ., 264–275.

GEOLOGICAL SURVEY DEPARTMENT OF SRI LANKA (1982): Geological map of Sri Lanka on a scale of 8 miles to one inch. Colombo, Geological Survey Department.

GLASSLEY, W. E., RYERSON, F. J., SHAW, H. and ABEYSINGHE, P. B. (1989): Chemical changes associated with formation of granulite and migration of complex C-O-H-S fluids, Sri Lanka. Fluid Movement—Element Transport and the Composition of the Deep Crust, ed. by D. BRIDGEWATER. Dordrecht, Kluwer Academic Publ., 39–49.

GRANT, J. A. (1985): Phase equilibria in partial melting of pelitic rocks. Migmatite, ed. by J. R. ASHWORTH. Glasgow, Blackie and Son, 86–144.

GREW, E. S. (1982): The Antarctic Margin. The Indian Ocean, ed. by A. E. M. NAIRN and F. G. STEHLI. New York, Plenum, 697–755 (The Ocean Basins and Margins, Vol. 6).

GREW, E. S., ASAMI, M. and MAKIMOTO, H. (1989): Preliminary petrological studies of the metamorphic rocks of the Eastern Sør Rondane Mountains. Proc. NIPR Symp. Antarct. Geosci., **3**, 100–127.

HANSEN, E. C., JANARDHAN, A. S., NEWTON, R. C., PRAME, W. K. B. N. and RAVINDRA KUMAR, G. R. (1987): Arrested charnockite formation in southern India and Sri Lanka. Contrib. Mineral. Petrol., **96**, 225–244.

HAPUARACHCHI, D. J. A. C. (1968): Cordierite and wollastonite-bearing rocks of Southwestern Ceylon. Geol. Mag., **195**, 317–324.

HARRIS, N. (1989): Carbon dioxide in the deep crust. Nature, **340**, 347–348.

HIROI, Y. and SHIRAISHI, K. (1986): Syowa Kiti shuhen no chishitsu to ganseki (Geology and petrology of the area around Syowa Station). Nankyoku no Kagaku, 5, Chigaku (Sciences in Antarctica, 5. Earth Sciences), ed. by Natl Inst. Polar Res. Tokyo, Kokon Shoin, 45–84.

HIROI, Y., SHIRAISHI, K., YANAI, K. and KIZAKI, K. (1983): Aluminum silicates in the Prince Olav and Sôya Coasts, East Antarctica. Mem. Natl Inst. Polar Res., Spec. Issue, **28**, 115–131.

HIROI, Y., YOSHIDA, M. and VITANAGE, P. W. (1987): Relict kyanite in the Highland and Southwest gneisses in Sri Lanka; Evidence of prograde metamorphism and a characteristic in common with the Lützow-Holm Complex in East Antarctica. Geol. Soc. Sri Lanka, Spec. Publ., **3**, 28.

HIROI, Y., SHIRAISHI, K. and MOTOYOSHI, Y. (1990): Late Proterozoic paired metamorphic complexes in East Antarctica—with special reference to the tectonic significance of ultramafic rocks. Geological Evolution of Antarctica, ed. by M. R. A. THOMSON *et al.* Cambridge, Cambridge Univ. Press (in press).

HOLT, R. W. and WIGHTMAN, R. T. (1983): The role of fluids in the development of a granulite facies transition zone in S India. J. Geol. Soc. London, **140**, 651–656.

ISHIZUKA, H. and KOJIMA, H. (1987): A preliminary report on the geology of the central part of the Sør Rondane Mountains, East Antarctica. Proc. NIPR Symp. Antarct. Geosci., **1**, 113–128.

JACKSON, D. H., MATTEY, D. P. and HARRIS, N. B. W. (1988): Carbon isotope compositions of fluid inclusions in charnockites from southern India. Nature, **333**, 167–170.

JANARDHAN, A. S., NEWTON, R. C. and HANSEN, E. C. (1982): The transformation of amphibolite facies gneiss to charnockite in southern Karnataka and northern Tamil Nadu, India. Contrib. Mineral. Petrol., **79**, 130–149.

KATZ, M. B. (1972): Facies series of the high grade metamorphic rocks of the Ceylon Precambrian. Proc. 24th Int. Geol. Congr., Montreal, **2**, 43–51.

KRÖNER, A., WILLIAMS, I. S., COMPSTON, W., VITANAGE, P. W. and PERERA, L. R. K. (1987): Zircon ion microprobe dating of granulites from Sri Lanka. J. Geol., **95**, 775–792.

LAWVER, L. A. and SCOTESE, C. R. (1987): A revised reconstruction of Gondwanaland. Gondwana Six; Structure, Tectonics, and Geophysics, ed. by G. D. MCKENZIE. Washington, D. C., Am. Geophys. Union, 17–23 (Geophys. Monogr. **40**).

MCLELLAND, J., HUNT, W. M. and HANSEN, E. C. (1988): The relationship between metamorphic charnockite and marble near Speculator, central Adirondack Mountains, New York. J. Geol., **96**, 455–467.

NEWTON, R. C. and HANSEN, E. C. (1983): The origin of Proterozoic and late Archean charnockites—evidence from field relations and experimental petrology. Proterozoic Geology: Selected papers from an International Proterozoic Symposium, ed. by L. G. MEDARIS, Jr. *et al.* Boulder, Geol. Soc. Am., 167–178 (Geol. Soc. Am. Memoir **161**).

NEWTON, R. C., SMITH, J. V. and WINDLEY, B. F. (1980): Carbonic metamorphism, granulites and crustal growth. Nature, **288**, 45–50.

PERERA, L. R. K. (1984): Co-existing cordierite-almandine—a key to the metamorphic history of Sri Lanka. Precamb. Res., **25**, 349–364.

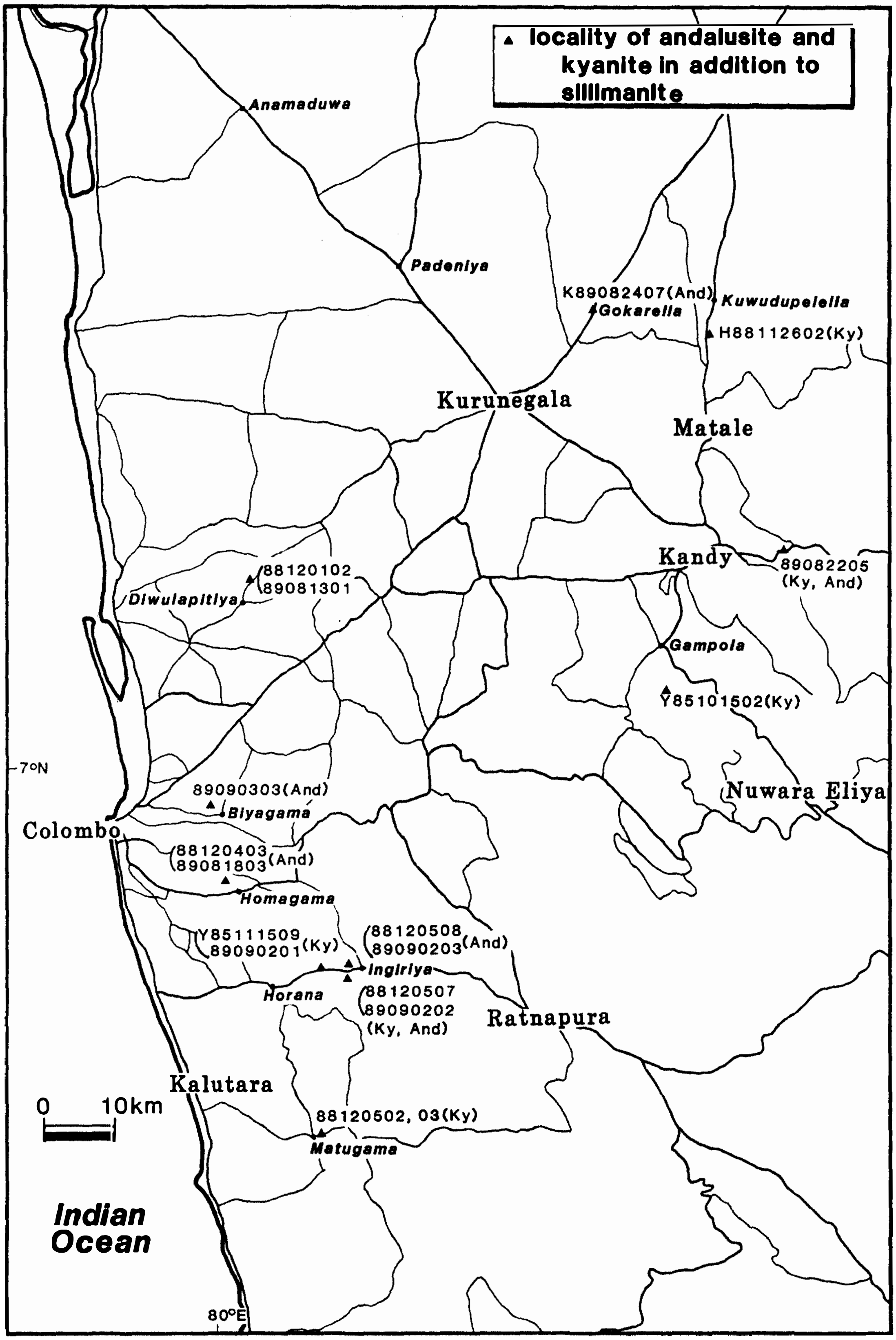
PETERSON, J. W. and NEWTON, R. C. (1989): CO_2-enhanced melting of biotite-bearing rocks at deep-crustal pressure-temperature conditions. Nature, **340**, 378–380.

SANDIFORD, M., POWELL, R., MARTIN, S. F. and PERERA, L. R. K. (1988): Thermal and baric evolution of garnet granulites from Sri Lanka. J. Metamorph. Geol., **5**, 351–364.

SHIRAISHI, K., HIROI, Y., MOTOYOSHI, Y. and YANAI, K. (1987): Plate tectonic development of Late Proterozoic paired metamorphic complexes in Eastern Queen Maud Land, East Antarctica. Gondwana Six; Structure, Tectonics, and Geophysics, ed. by G. D. MCKENZIE. Washington, D. C., Am. Geophys. Union, 309–318 (Geophys. Monogr., **40**).

VIELZEUF, D. and HOLLOWAY, J. R. (1988): Experimental determination of the fluid-absent melting relations in the pelitic system. Contrib. Mineral. Petrol., **98**, 257–276.

(Received March 12, 1990; Revised manuscript received April 24, 1990)



Appendix 1. Detailed map showing localities of secondary andalusite and/or relict kyanite in addition to sillimanite.

Appendix 2. Analyses of charnockites and nearby gneiss from Kandy (88111103=H89082102). See Fig. 2a-2 for their positions.

Locality	88111103		
Specimen	A	B	D
(wt%)			
SiO_2	69.70 (70.16)	70.48 (70.44)	69.18 (69.80)
TiO_2	0.53 (0.53)	0.53 (0.53)	0.59 (0.60)
Al_2O_3	14.35 (14.44)	14.18 (14.17)	14.03 (14.16)
Fe_2O_3 (FeO)*	4.74 (4.29)	5.04 (4.53)	5.65 (5.13)
MnO	0.05 (0.05)	0.05 (0.05)	0.06 (0.06)
MgO	0.22 (0.22)	0.28 (0.28)	0.22 (0.22)
CaO	2.22 (2.23)	2.27 (2.27)	2.43 (2.45)
Na_2O	2.04 (2.05)	2.04 (2.04)	2.11 (2.13)
K_2O	5.84 (5.88)	5.58 (5.58)	5.29 (5.34)
P_2O_5	0.13 (0.13)	0.11 (0.11)	0.12 (0.12)
Total	99.82 (100.00)	100.56 (100.00)	99.68 (100.00)
(ppm)			
Ba	1255	1178	1141
Cr	3	10	8
Ga	16	15	23
Nb	25	26	25
Ni	11	22	26
Pb	42	40	33
Rb	252	246	237
Sr	274	265	257
Th	16	14	21
V	33	16	35
Y	49	51	57
Zn	91	89	104
Zr	463	442	590

* Total Fe as Fe_2O_3 or FeO.

XRF analysis (Analysts; Y. OSANAI, M. OWADA and H. KAGAMI).

A. Gray Gr-Ilm-Spn-Bt-Grt-Hbl-Kfs-Pl-Qtz gneiss.

B. Light grayish brown foliated Gr-Ilm-Spn-Bt-Opx-Hbl-Grt-Kfs-Pl-Qtz charnockite.

D. Grayish brown foliated Gr-Ilm-Spn-Bt-Hbl-Opx-Cpx-Grt-Kfs-Pl-Qtz charnockite (Carbonate and sulfide minerals are also present).

Gr; graphite, Spn; sphene, Cpx; clinopyroxene. Others as in Fig. 6.