Sequence of deformation and metamorphism of granulite facies rocks of south to southwestern Sri Lanka

K. V. Wilbert Kehelpannala
University of Botswana

Yoshikuni Hiroi
Chiba University

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Sequence of Deformation and Metamorphism of Granulites of Sri Lanka*

Masaru YOSHIDA[1], K.V. Wilbert KEHELPANNALA[2], Yoshikuni HIROI[3] and Piyadasa W. VITANAGE

(with 1 Table and 13 Figures)

Abstract

Various L-S and folding structures of mostly granulite facies rocks from central to southwestern-southern Sri Lanka, mainly in the areas around Kandy and Horana were studied from field evidence and geometrical analysis. Metamorphism during the deformations were preliminarily analysed based on microstructures of rocks under the microscope, published geochronological data were discussed, and the following conclusions are obtained.

The earliest D_1-D_2 deformations include more than two deformations, although their differentiation was difficult, such as rootless, isoclinal and close to tight overturned foldings with their hinges plunging generally northwest or southeast but sometimes in various directions. The earlier microstructures during D_1-D_2, formed possibly during ca 1800–2200 Ma, include xenocrystic minerals such as biotite, ilmenite, and sillimanite showing a preferred orientation in helicitic garnet porphyroblasts, and xenocrystic kyanite, staurolite and corundum showing no preferred orientation in the same porphyroblast in the garnet-sillimanite gneiss and in some sillimanite-bearing garnet-biotite gneisses. These microstructures predate the banding and were formed partly under the high shearing tectonics and partly, the high pressure conditions of the kyanite field. The later microstructures during D_1-D_2, formed possibly during ca 1100 Ma, are minerals which parallel the major banding structures of the rock. The breaking down of garnet into orthopyroxene plus plagioclase is the typomorphic change under the lower pressure conditions of the granulite facies. D_3 is the major upright folding generally in the NW-SE direction. Microstructures during D_3, formed possibly during ca 700 Ma, are the recrystallization of biotite and quartz in the area around Kandy, and biotite, quartz, orthopyroxene, or cordierite in the area around Horana along the younger foliation either paralleling the banding or the axial surface of the major upright folds, under the amphibolite to the granulite facies conditions. D_4 is gentle foldings and ductile faultings of various directions often associated with granitic veins. Microstructures associated with D_4, formed possibly during ca 450–600 Ma, are the alteration of garnet or orthopyroxene into biotite plus quartz along the faint schistosity inclined from the pre-existent s-planes belonging the D_1-D_2 or D_3, under the amphibolite facies conditions. The charnockite in the making, found sporadically throughout the survey areas as a result of some local conditions, is considered to belong the D_4 events. The microfractures filled with calii materials and the scanty development of chlorite, sericite, zoisitic

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1. Department of Geosciences, Faculty of Science, Osaka City University, Sugimoto, Sumiyoshi-ku, Osaka 558, Japan
2. Institute of Fundamental Studies, Kandy, Sri Lanka
3. Department of Earth Sciences, Faculty of Science, Chiba University, Yayoi-cho, Chiba, 260, Japan
4. Department of Geology, University of Peradeniya, Peradeniya, Sri Lanka

matter and some other low grade minerals are post D_4 events younger than ca 450 Ma. Whole rock Rb-Sr and Sm-Nd isochron datings published recently are explained to indicate some tectonothermal events of ca 2400 Ma in some Archaean inliners in the Highland Group surrounding Nuwara Eliya.

KEY WORDS: Sri Lanka, Precambrian, Granulite, Deformation, Microstructure

Contents

I. Introduction

An analysis of tectonothermal history is the principal requisite to obtain a realistic conception of the crustal evolution of a metamorphic terrain. A microstructural study of rock combined with a structural analysis is one of the fundamentals to analyse the tectonothermal history as demonstrated by ZWART (1962) and others, although such studies have not been extensively made and sometimes are non-existent in some studies of metamorphic terrains.

Geologic, petrologic, structural, and geochronologic outlines of the Precambrian of Sri Lanka have so far been presented (e.g., HAPUARACHCHI, 1975, BERGER and JAYASINGHE, 1976, COORAY, 1978). In addition, some valuable geochronologic data have also been given recently (e.g., MILISENDA *et al.*, 1988). The present study provides an example of the tectonic and microstructural analysis and presents a preliminary tectonothermal history of the granulite facies complexes of Sri Lanka, field surveys of this study having been made during 1985–1989 (YOSHIDA, 1988).

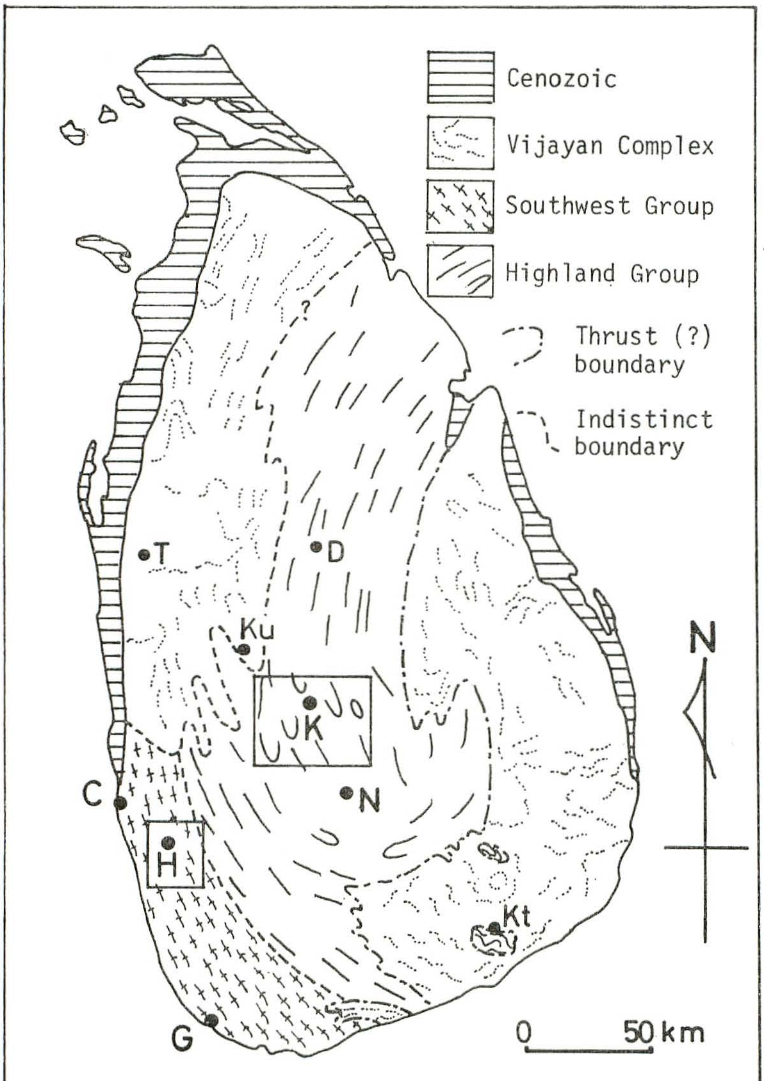


Fig. 1 Geologic outline of Sri Lanka
Frame with K: Area around Kandy. Farme with H: Area around Horana. C: Colombo, D: Dambulla, G: Galle, Ku: Kurunegala, Kt: Kataragama, N: Nuwara Eliya, T: Tonigala.

II. Geologic and Structural Outline of Selected Areas

The Precambrian rocks of Sri Lanka are composed of the amphibolite facies Vijayan Complex and the granulite facies Highland and Southwest Groups, the first being distributed on both the northwestern and eastern coastal low lands and the latter two, on the central highlands and the southwest coast (COORAY, 1978, Geological Survey Department of Sri Lanka, 1982) (Fig. 1).

Study areas include the central, southern and southwestern parts of Sri Lanka where mainly rocks of the granulite facies are distributed. The area around Kandy where the Highland Group is found extensively, and the area around Horana where the Southwest Group is distributed, are selected for study in some detail.

2.1. Area around Kandy

The general structural and geologic outline of the area around Kandy was given by BERGER and JAYASINGHE (1976) and VITANAGE (1980) which is summarized in Fig. 2, along with an interpretative structural profile (Inset, Fig. 2). Granulite facies rocks mainly of interlayered supracrustal sequence origin, composed dominantly of the (sillimanite-) garnet-biotite gneiss, (garnet- and/or biotite-bearing) quartz-feldspathic gneiss, charnockitic rocks (orthopyroxene-bearing rocks with a greasy appearance), marble and quartzite, with some other minor lithologies such as the garnet-sillimanite gneiss (khondalite in a restricted sense) and cordierite-bearing gneisses are distributed zonally throughout the area, although in detail, the zonal distribution of quartzite layers in some places is highly complex. Dominant L and S structures are developed on almost all these rocks (Figs. 3 and 4). Major NW-SE linear foldings of the open to tight type (D_3) with upright to nearly upright axial surfaces and gently plunging hinges affected the whole area. Small folds of various styles with complex chronologic relationships are found sporadically. Migmatitic hornblende-biotite gneiss, granitic biotite gneiss, microcline granites, retrogressed charnockitic rocks, amphibolite and calc gneisses, indicating mostly the amphibolite facies grade of metamorphism occur dominantly in doubly plunging synforms of the major folds with a scale of 10 to 20 km long which are known as 'arenas' (VITANAGE, 1972). VITANAGE (1972) suggested a possible correlation of rocks inside the arenas with the Vijayan rocks judging from petrologic similarities between them, and KRÖNER *et al.* (1987) and MILISENDA *et al.* (1988) pointed out a distinct difference in the radiometric ages of rocks inside the arenas and rocks outside. The mode of occurrence and mass orientations of macroscopic and mesoscopic structures of rocks inside the arenas are somewhat different from rocks outside, although a considerable portion of structures inside appears to have resulted from the D_3 tectonics common to rocks outside (YOSHIDA, 1989 and in preparation). The structure of rocks inside the arenas will be studied elsewhere.

2.2. Area around Horana

The general geologic and structural outline of this area is given in Fig. 5, simplified

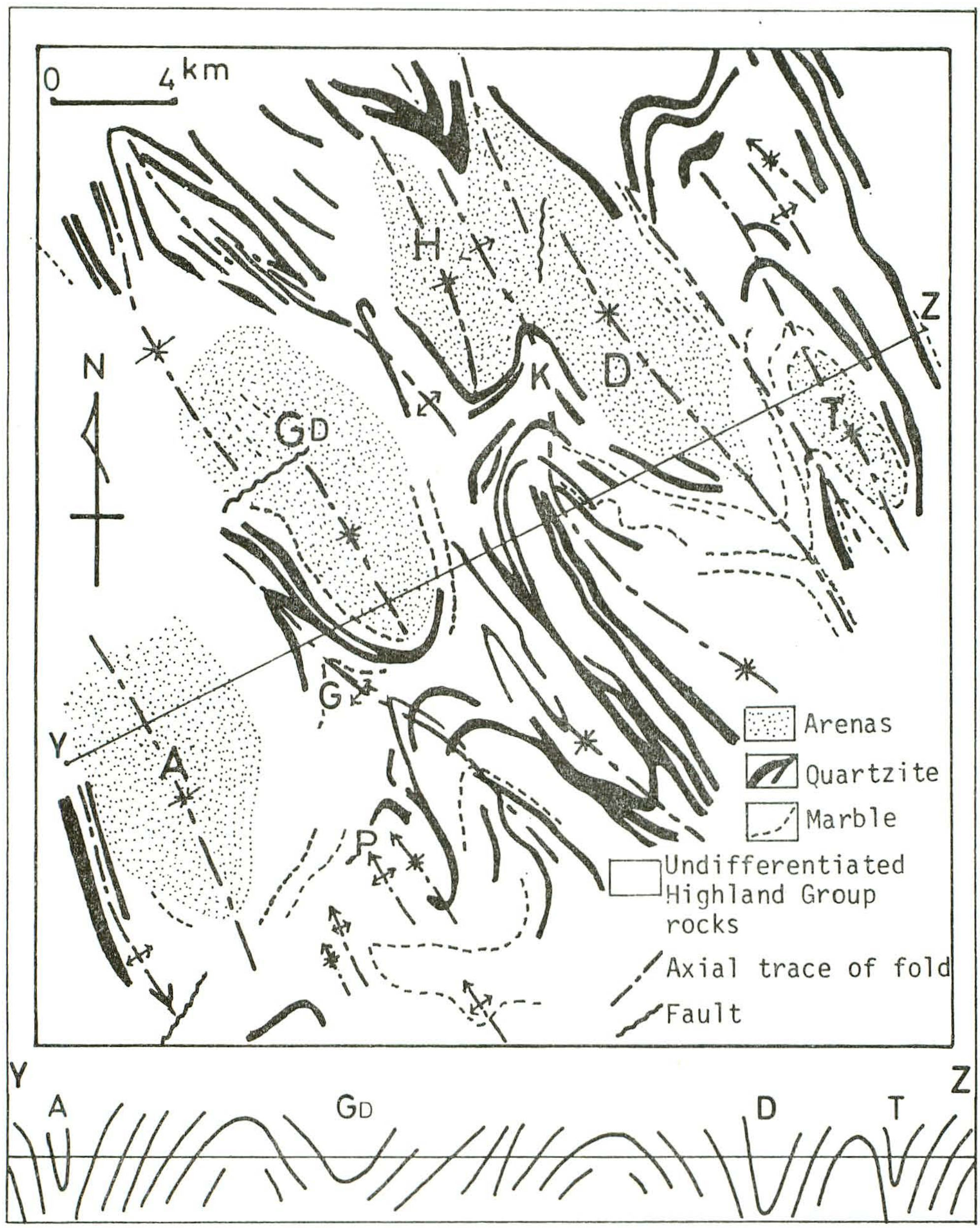


Fig. 2 Geologic map of the area around Kandy (modified after VITANAGE, 1980) with a structural profile (a part of the data is referred to the Survey Department of Ceylon, 1965)
Dotted areas with A, GD, D and T are arenas. K: Kandy, G: Gampola.

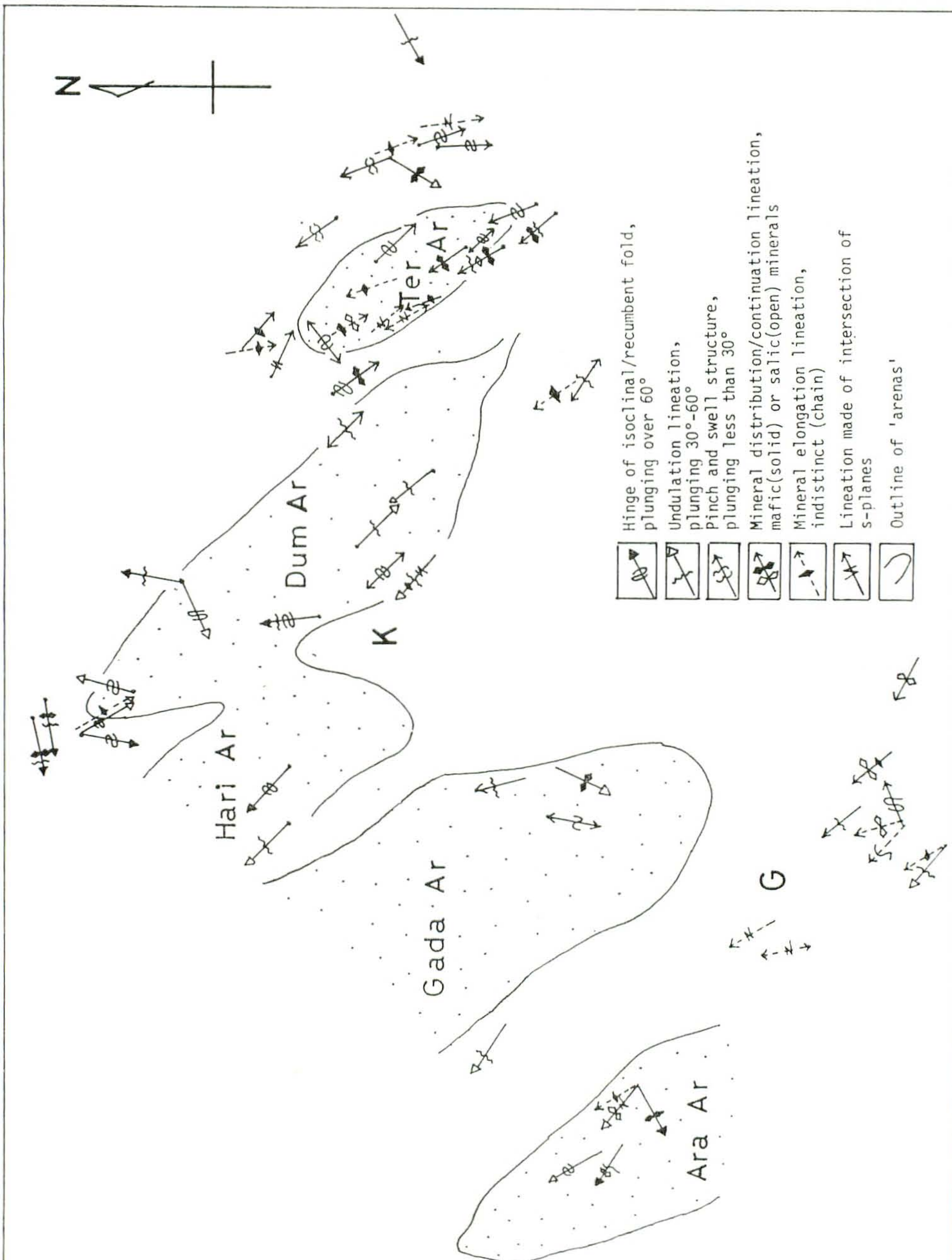


Fig. 3 Distribution of L-S structures mostly belonging to the D_1-D_2 structures in the area around Kandy.
K: Kandy, G: Gampola. Arenas are dotted.

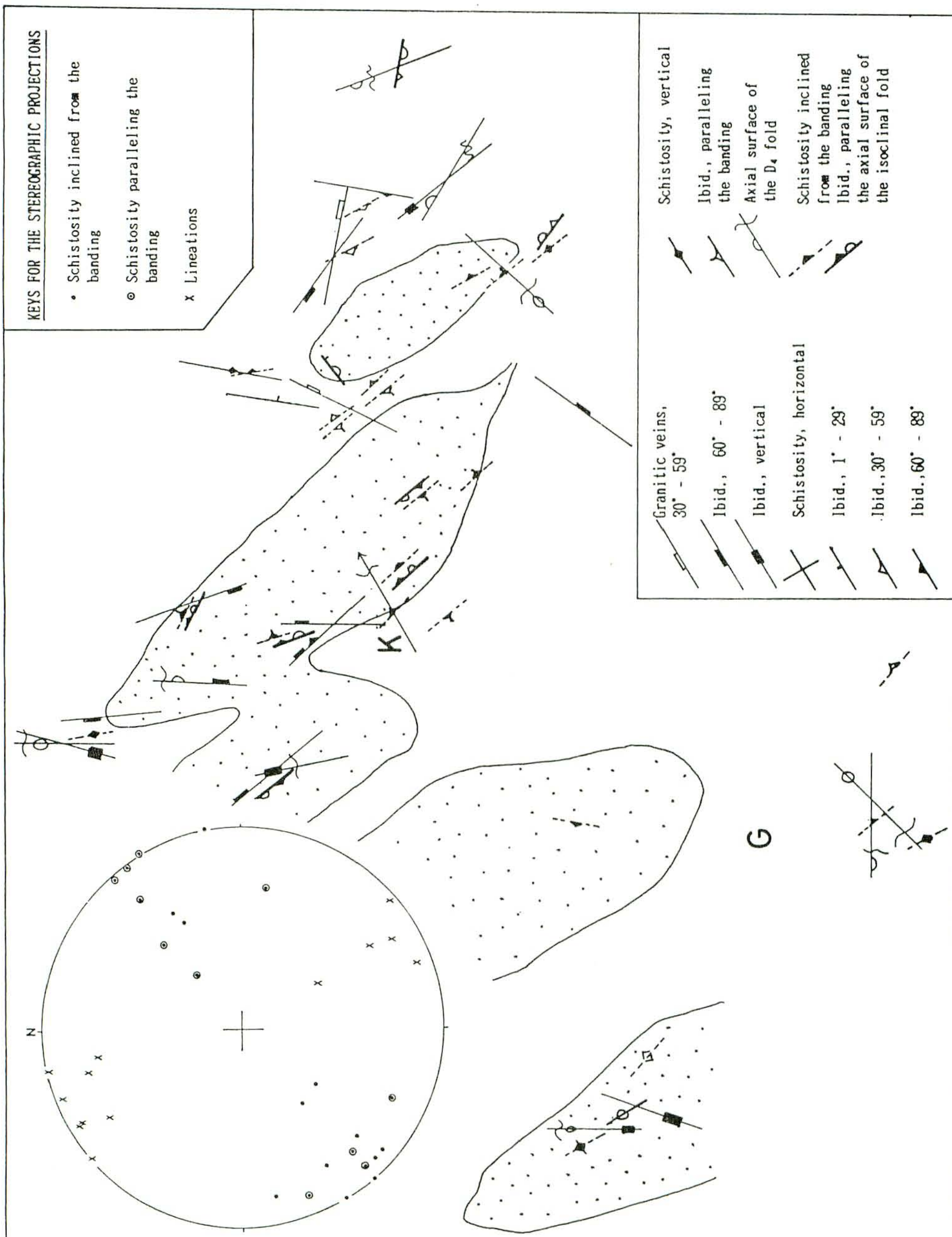


Fig. 4 Distribution of D_3 and D_4 s-structures in the area around Kandy, with an inset showing the equal area stereographic projections of the apparent D_3 structures (cited from YOSHIDA *et al.*, Pers. Comm., 1990).
Arenas are dotted. K: Kandy, G: Gampola

after the one inch - one mile geologic map of South of Panadura and Horana prepared by the Geological Survey Department of Sri Lanka (unpublished), along with an interpretative structural profile (Inset, Fig. 5).

The Southwest Group of this area includes mainly the charnockites and the (cordierite-) garnet-biotite gneiss. Open to isoclinal linear foldings with upright to moderately inclined axial surfaces develop dominantly as the major structures running NW-SE and rocks are distributed zonally paralleling the axial traces of these folds. L and S structures are developed in almost all rocks of the area (cf., Fig. 5) and small folds of open to isoclinal types are not rare. Structural characteristics of the area around Horana as presented above are mostly similar to those of the area around Kandy.

III. Deformational Structures and Events

3.1. Earlier deformations (D_1-D_2)

In the area around Kandy, the distribution pattern of the quartzite layers as seen in the geologic map (cf. Fig. 2) indicates some complex folding structures predating the major D_3 foldings. The banding structures of rocks and its deformational structures such as pinch and swell - lensing out structures, intrafolial isoclinal-rootless small folds, and overturned close to recumbent isoclinal small folds (Fig. 6A, B, and C), are mostly the earlier structures which are affected afterwards by the major linear folding; hence they are termed as the D_1-D_2 structures and the major folds and associated structures, as the D_3 structures following BERGER and JAYASINGHE (1976). Some of the undulation and mineral distribution lineations which are often distinctly inclined from the hinges of the major folds also belong to the D_1-D_2 structures, although some others belong to the D_3 and D_4 structures as mentioned later.

The discrimination of D_1 and D_2 structures are difficult and therefore they are collectively termed as the D_1-D_2 structures following BERGER and JAYASINGHE (1976). There are, however, some instances where we can observe some evidence indicating two folding phases prior to the D_3 deformations. At an outcrop at the Victoria dam, east-southeast of Kandy, the completely isoclinally folded garnet-biotite-quartz-feldspathic gneiss with intercalations of thin mafic layers is refolded by northeasterly trending overturned small open folds, and again is refolded by north-northwesterly microfolds which are associated with the dominant axial plane foliation having a vertical dip (Fig. 7). The intersection of the foliation and banding resulted in a dominant mineral distribution and undulation lineations. The last microfold is referred to the D_3 fold and the earlier two folds, to the D_1-D_2 structures. The disturbance of the dominant foliation (cf., Fig. 7) is considered to be caused by the northeasterly upright fold of the D_4 stage which occurs near by this outcrop.

The stereographic projections of L and S structures of rocks outside the arenas around Kandy are given in Fig. 8A. The distribution of poles of the banding forms a wide great circle girdle with a β maximum plunging gently northwestward. Lineations, hinges

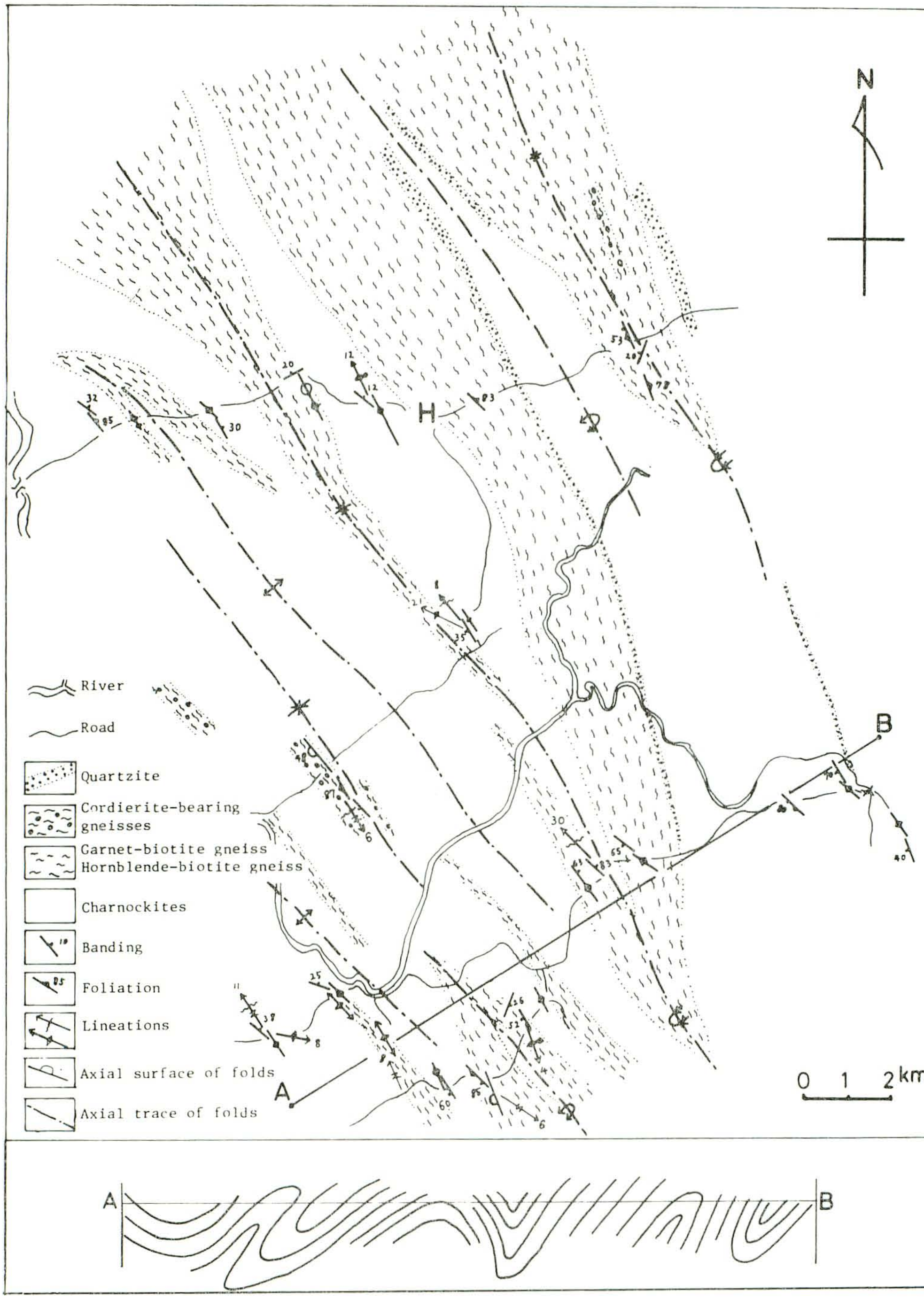


Fig. 5 Geologic map of the area around Horana (modified from the Geological map of South of Panadura and Horana, Geological Survey Department of Sri Lanka, unpublished) and a structural profile (a part of the data is referred to the Survey Department of Ceylon, 1965).

Fig. 6 Mesoscopic structures of the Precambrian rocks of Sri Lanka.

A. Intrafolial rootless folds and lensing-out structures in the cordierite-sillimanite-garnet-biotite gneiss. Locality No. 87082002, 25 km north of Kandy.

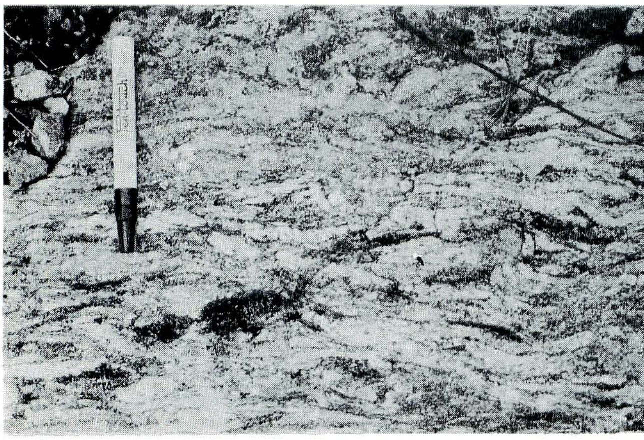
B. Isoclinal folds (D_1-D_2) of a metabasite layer in the charnockite. Locality No. 85101302, 15 km southeast of Kandy.

C. An isoclinal fold of metabasite layers in the garnet-biotite-quartz-feldspathic gneiss. Locality No. 88112201, 17 km east-southeast of Kandy.

D. Upright small folds (D_3) associated with the axial plane foliation. Locality No. 87081903, 9 km east of Kandy.

E. En echeron granitic veins (D_4) in the hornblende-biotite gneiss. Locality No. 85100202, 20 km west-southwest of Kandy.

F. Charnockitization (D_4) in the form of pods and veins in the hornblende-biotite gneiss near Kurunegala.



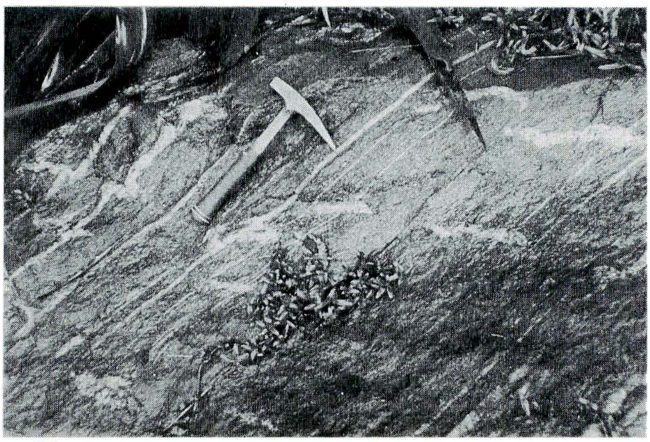
A

B

C

Fig. 6

D



E

F

Fig. 6

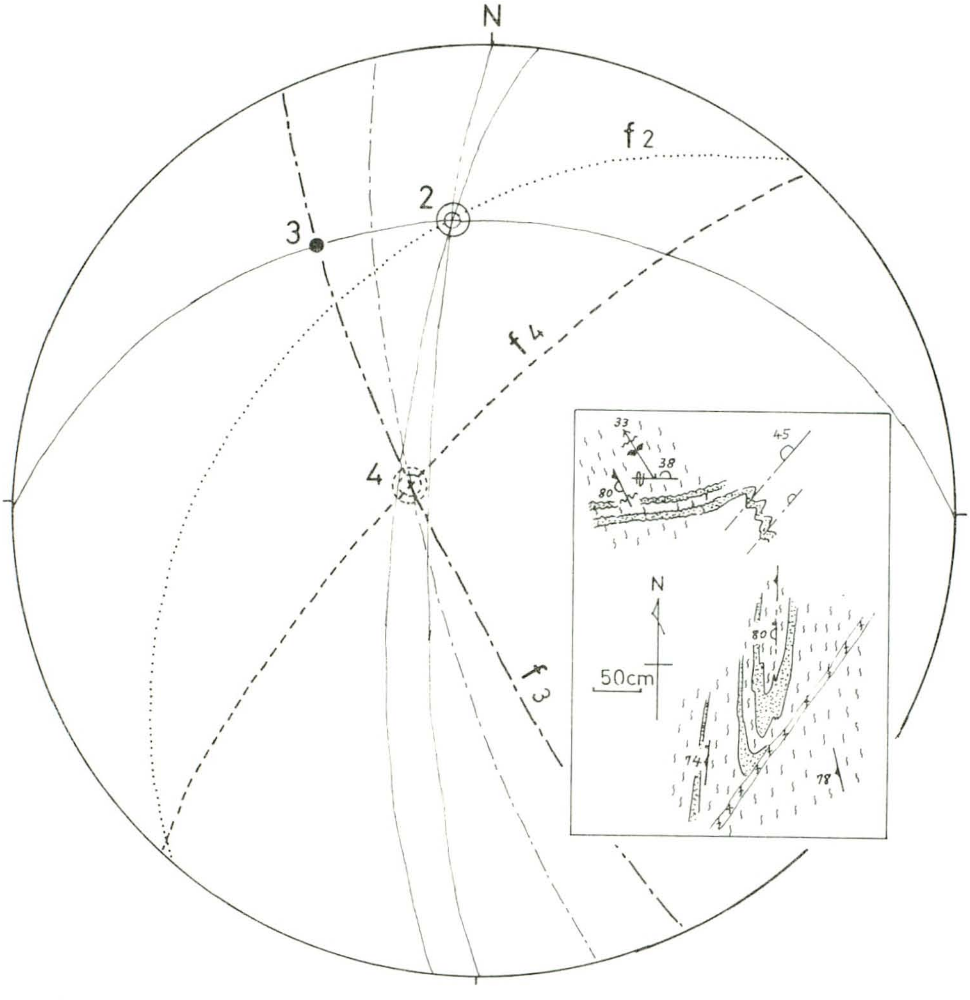


Fig. 7 D_1-D_2, D_3 and D_4 structures observed in the quartz-feldspathic gneiss (wavy mark) with metabasite layers (dotted) at the Victoria dam, east-southeast of Kandy.
Great circle by solid line: Banding. Thin and thick chain: Foliation. f_2, f_3 and f_4 correspond to the folding of each stage. Circles with numbers indicate estimated hinges of folds. Keys for the L and S structures are same as in Figs. 3 and 5.

of small folds and β obtained at each outcrop conform to each other and most of them are distributed on and around the β maximum. Many of the linear structures mentioned above thus belong to the D_3 stage. The poles of the axial surface of the isoclinal and rootless folds with hinges plunging gently, generally in the NW-SE direction, are scattered among the girdle where the poles of the banding structures are distributed. The overturned small folds are randomly oriented, but generally have axial traces

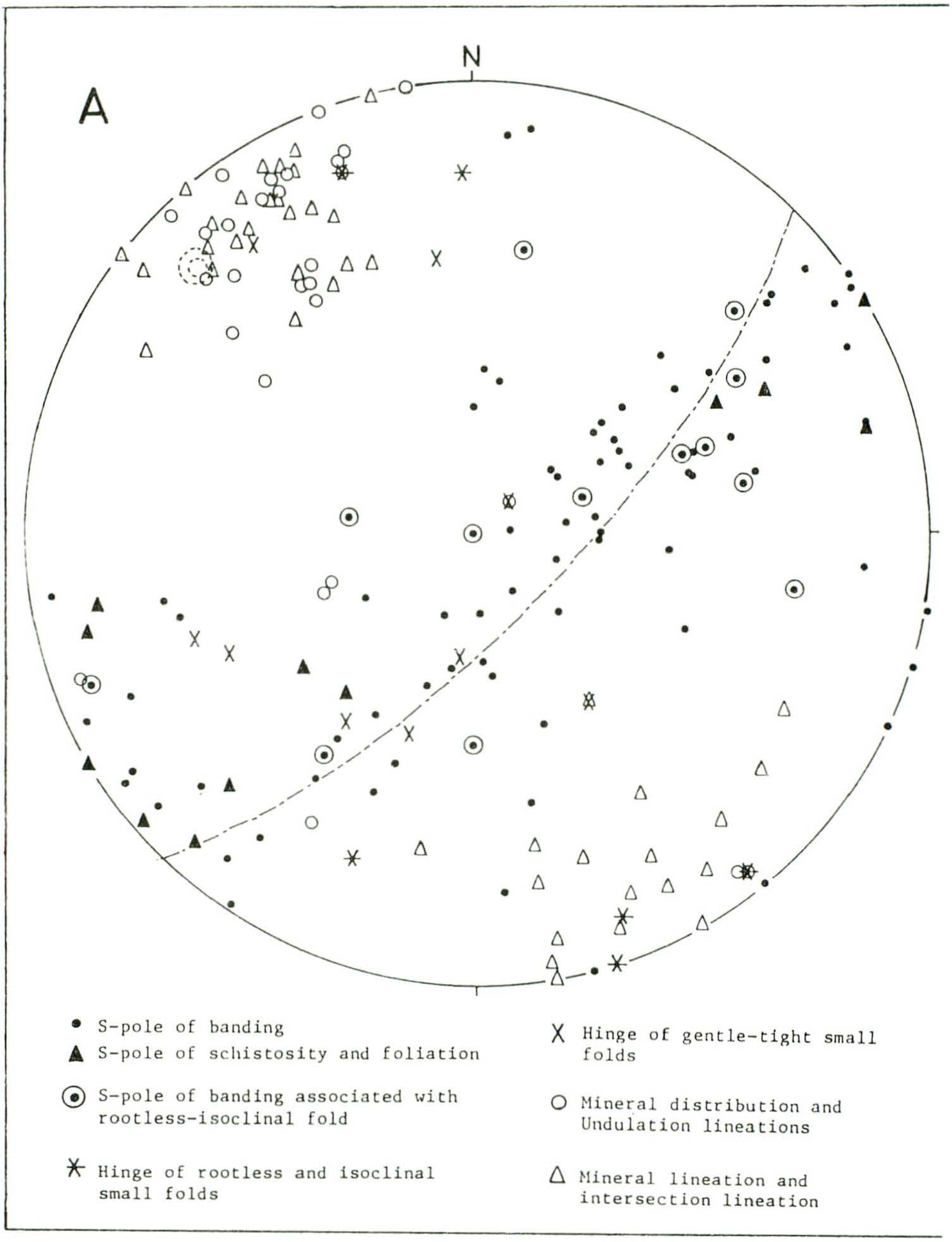
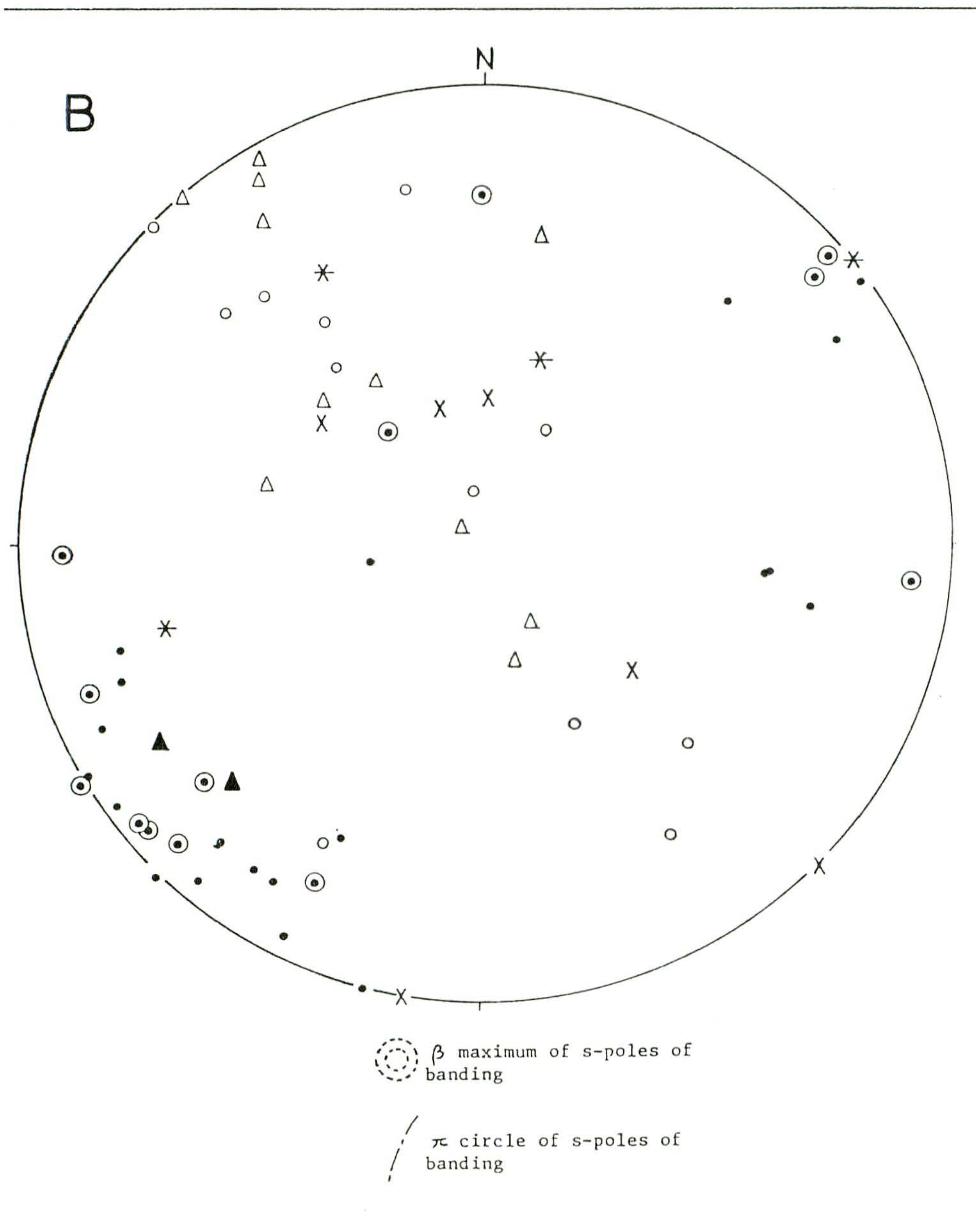


Fig. 8 Equal area stereographic projections (lower hemisphere) of L and S structures of the area around Kandy.
A. L and S structures of rocks outside arenas.
B. L and S structures of rocks inside arenas.



paralleling the major fold (D_3) and have moderately plunging fold hinges in various directions. The stereographic projections of L and S structures of rocks inside the arenas (Fig. 8B) show a distinctly different pattern which will be discussed elsewhere (YOSHIDA, 1989, and in preparation).

In the area around Horana, two kinds of major folds with their axial traces paralleling each other are developed. The structural profile (cf., inset of Fig. 5) suggests the development of macroscopic isoclinal folds with moderately inclined axial surfaces earlier than macroscopic upright open folds. The upright folds belong to the D_3 stage and the moderately inclined folds, to the earlier stage. The sudden thinning out of some layers of gneisses as seen in the geologic map (cf. Fig. 5) may also be a reflection of isoclinal folds which pre-existed both of the major folds.

Banding structures, its discontinuity perhaps the result of the pinch and swell - lensing out structures, intrafolial isoclinal and rootless folds, and overturned close to tight small folds are structures earlier than the major upright folds and hence are considered to belong the D_1-D_2 structures. Although small overturned folds are found locally to run parallel to the major uprigh folds (D_3), they appear to be earlier than the D_3 structures; an example being mentioned below. At an outcrop about 10 km ENE of Kalutura, small overturned folds develop which range in style from close, tight to isoclinal recumbent. Northwesterly vertical foliation indicated by quartz plates which belong to the D_3 structures develops there, regardless of the folding structures, although the quartz distribution lineation due to these quartz plates is parallel to the hinge of the fold. Thus, the overturned folds are earlier than the D_3 structures.

The equal area stereographic projections of most of L and S structures in the area around Horana are shown in Fig. 9. The distribution of poles of the banding structures forms a great circle girdle indicating the prevalence of the northwest trending major folding structures with NW-SE near horizontal fold hinges which are indicated mostly by dominant lineations. Poles of the axial surface of isoclinal small folds are scattered and appear to spread along the great circle girdle, although observation is not sufficient. The distribution of hinges of both overturned small folds and isoclinal folds mostly coincide with that of the major folds. The coincidence, however, does not necessarily indicate the cogenesis of these structures because discordancies between hinges of the D_1-D_2 folds and mineral lineations are not rare at outcrops in the field. The structural characteristics of D_1-D_2 structures of the area around Horana are thus mostly similar to those of the area around Kandy. The development of overturned folds as a major structure is a noticeable difference. In the area around Kandy, however, the overturned major folds might have been further compressed to reach the isoclinal and are therefore difficult to detect.

The D_1-D_2 structures in the survey areas are thus mostly composed of the banding, its pinch and swell structures and the intrafolial rootless folds of relatively earlier phase, the overturned to isoclinal macroscopic folds, and the overturned small folds of a relatively later phase. However, the concept that the earlier and later folds are included in the D_1 and D_2 stages respectively as mentioned by SANDIFORD *et al.* (1988) can not easily be accepted as discussed later. Some field and microstructural evidence indicates that the structures in the earlier phase are not synchronous and are the result of more than two deformations. Other evidence, as mentioned later, suggests the possibility that some

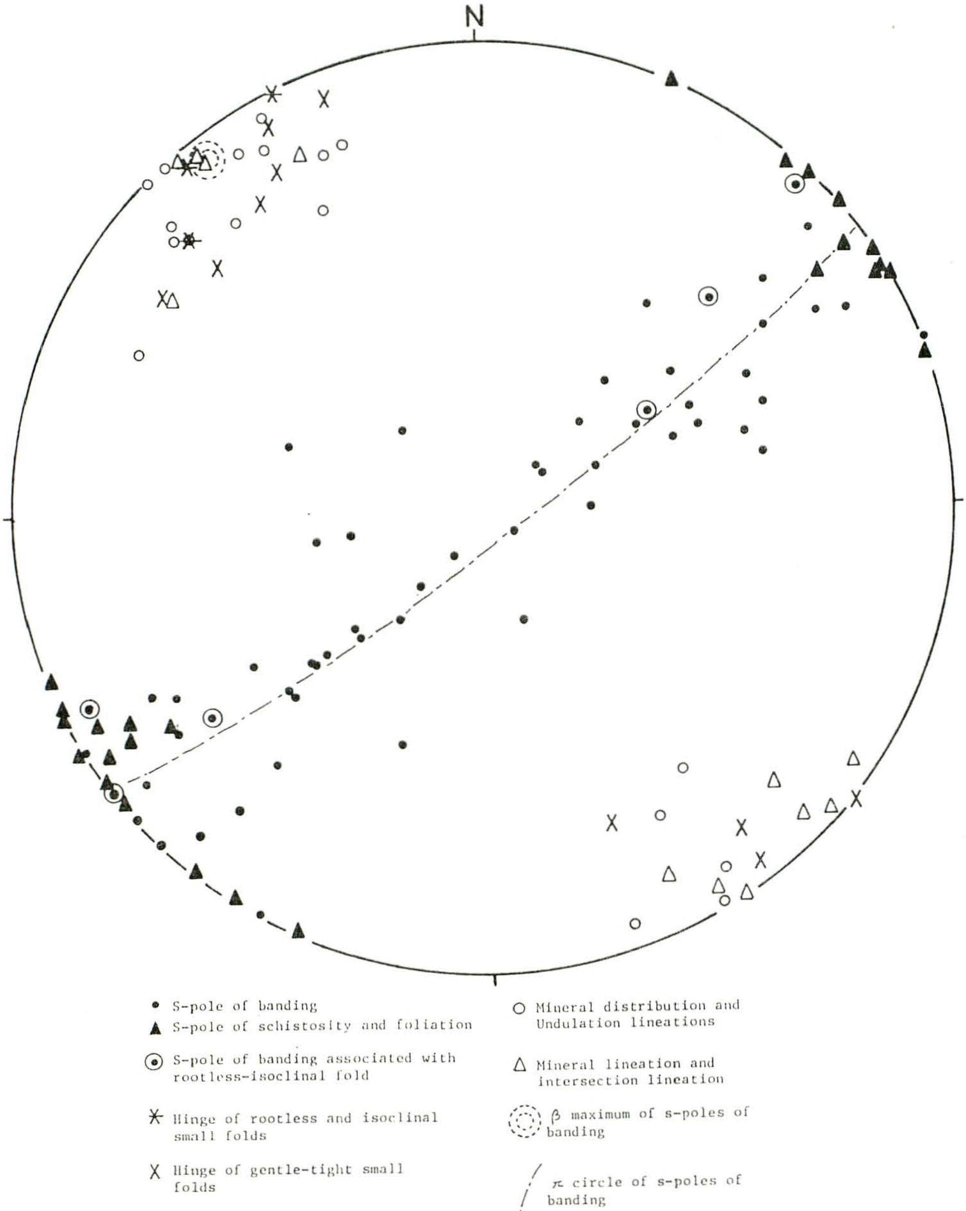


Fig. 9 Equal area stereographic projections of L and S structures of rocks in the area around Horana

structures of the later phase belong to the D_3 stage.

3.2. Deformations related to the major structures (D_3)

In the area around Kandy, the NW-SE major linear folds of the open to tight type mostly with upright axial surfaces, which are well identified on the geologic map and the profile (cf. Figs. 2 and inset) and on the s-pole and lineation diagram (cf. Fig. 8A and inset of Fig. 4), formed during this deformation. BERGER and JAYASINGHE (1976) identified these folds as being mainly the flexural flow folds of the class 1C occasionally approaching the class 2 of Ramsay (1967). The vertical to steep schistosity in various intensities defined generally by either the lattice preferred orientation or continuation of biotite, or the dimensional preferred orientation of quartz which are inclined from the banding, is sporadically found, especially in the hinge area of the major upright folds outside the arenas (YOSHIDA *et al.*, Pers, Comm., 1990) (cf. Fig. 4). In these cases, the strike of the schistosity is generally parallel to that of the axial surface of the major folds

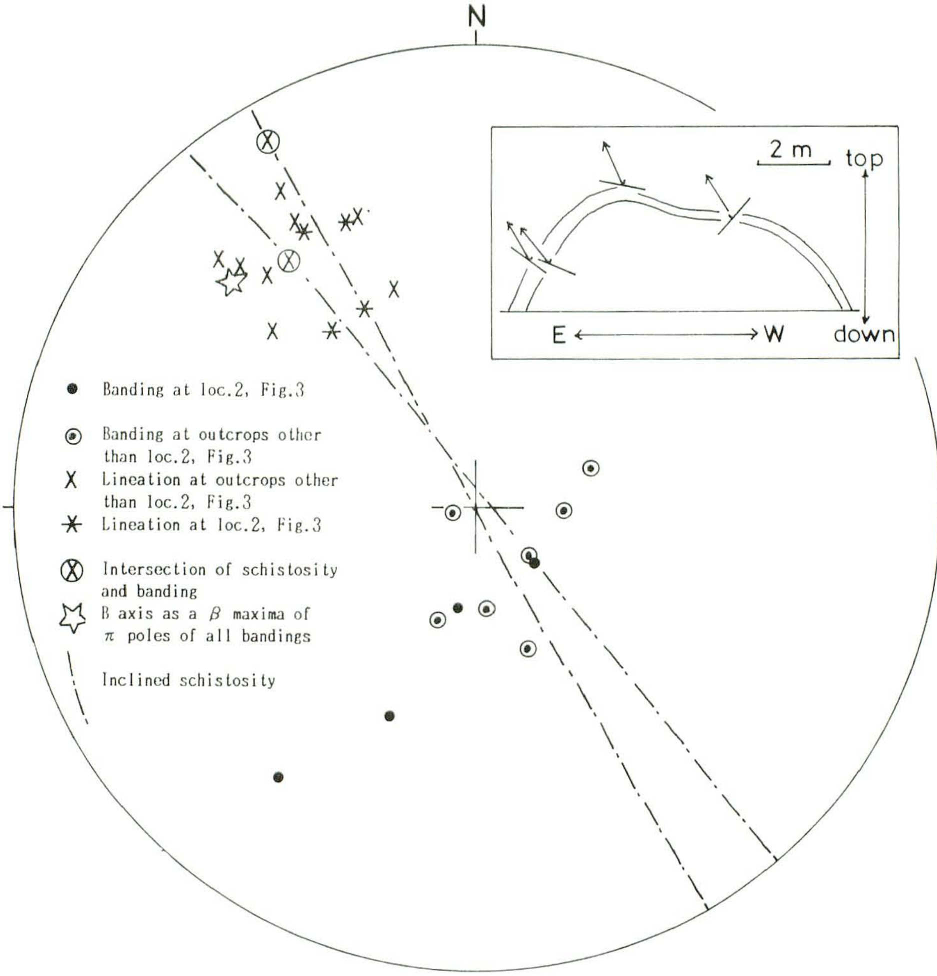


Fig. 10 Equal area stereographic projections of an upright small fold (D_3) and its profile (inset). Locality No. 85101902, south of Gampola. (Cited from YOSHIDA *et al.*, Pers. Comm., 1990).

and the intersection of schistosity with banding represents mineral orientation, mineral distribution, or crenulation lineations which are generally parallel to the estimated axis of the major folds. Mesoscopic open to close folds with upright to near upright axial surfaces which are parallel to those of the major folds are locally observed (e.g., Figs. 6D, 10) where the faint schistosity defined by the lattice preferred orientation of biotite is found paralleling the axial surface of the fold. Mineral lineation occurring as the intersection of the schistosity and the banding coincides with the β maximum of s-poles of the banding structures.

In the area around Horana, NW-SE major upright close folds are the D_3 structures which are associated with other major folds of the D_1-D_2 stages with moderately inclined axial surfaces as mentioned above (cf. Fig. 5). Small folds with upright to nearly up-

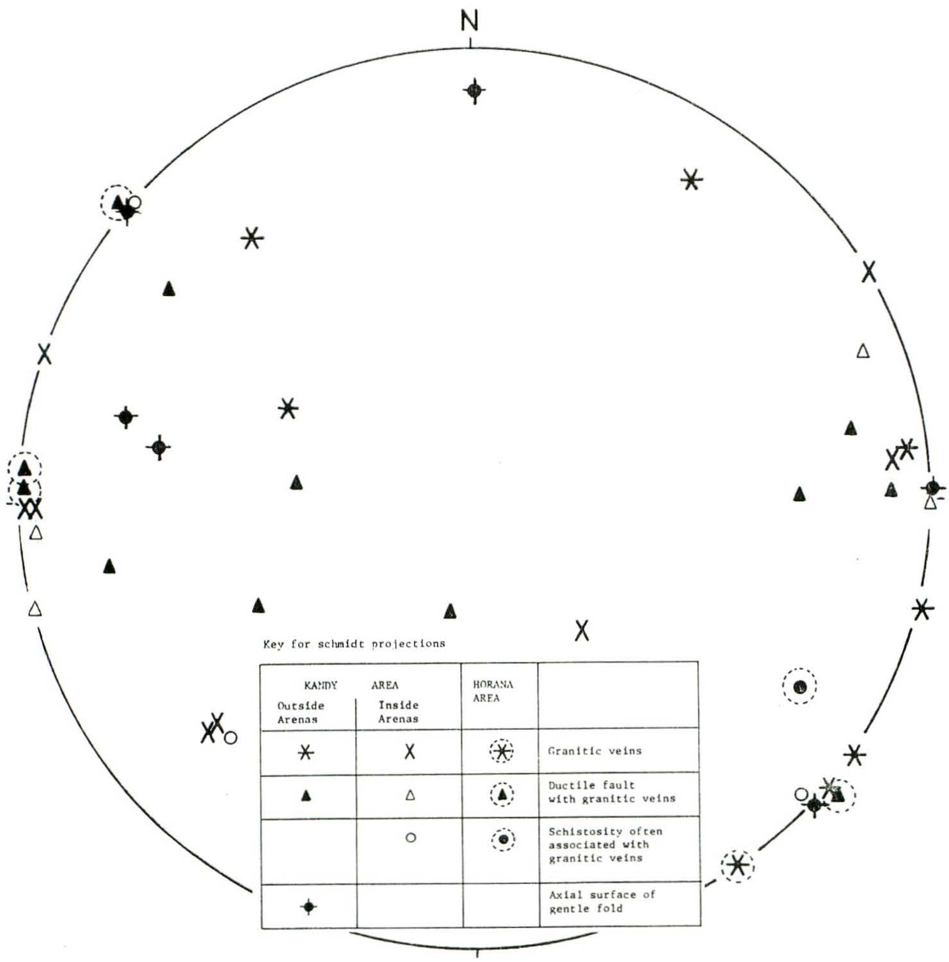


Fig. 11 Equal area stereographic projections of the D_4 structures in the areas around Kandy and around Horana

right axial surfaces paralleling those of the major folds are not rare where the axial plane foliation made mainly of quartz plates develops. Quartz distribution lineation in this case develop paralleling the hinges of the folds.

3.3. Later deformations (D_4)

The ductile fault associated with granitic veins and/or mylonitization is a characteristic structure formed during this stage (Fig. 6E). Gentle folds are also not rare. These structures are upright to steep, trending generally NE-SW or N-S and showing mostly the lateral sense of movement; these characteristics are common to both the area around Kandy (both outside and inside the arenas) and the area around Horana (Figs. 4 and 11). The less penetrative nature, sporadic distribution and random orientation of structures of this stage are also common throughout the study areas. An example of the disturbance of the earlier structures by the D_4 structure is seen also in Fig. 7.

In some localities such as near Teldeniya, Kurunegala, and near Pallebadda, the massive charnockite is formed incipiently in situ from some gneisses in such forms as pods or veins cutting the dominant foliation belonging to the D_3 structures (Fig. 6F). HANSEN *et al.* (1987) described and discussed this phenomenon at the Kurunegala outcrop in some detail. Neither folding nor schistosity is found to develop over the charnockite. The charnockite of this type is distinct from the ordinary charnockite. The occurrence and fabric of this charnockite suggest the positioning of this rock after the major D_3 deformation and its possible inclusion in the D_4 stage.

VI. Microstructures and Metamorphism in Relation to Deformations

Most rock in the study areas exibits the banding structure which is made generally of the alternations of mafic-rich and salic-rich layers. Minerals in these layers for the most part suffered the recrystallization of various stages and therefore, identifying which microstructural stage they belong to is somewhat difficult. However, in some rocks having the D_3 microstructures inclined from the banding, we can discriminate the D_1-D_2 microstructures and mineral parageneses which are apparently different from those of the D_3 stage. And in such rocks distinctly lacking the D_3 microstructures, we can discriminate the earlier and later microstructures belonging to the D_1-D_2 stage. Rocks of the study areas exhibit microstructures belonging to the earlier phase of the D_1-D_2, the later phase of the D_1-D_2, the D_3 and the D_4 deformational stages, and to the post D_4 events.

4.1. Earlier microstructures and metamorphism during the D_1-D_2 stage

Microstructures which are considered to have existed before the present banding structure are grouped as the microstructures of the earlier phase of the D_1-D_2 stage. Three examples of microstructures in this stage which are found not only in rocks around Kandy but also in rocks around Horana are mentioned in the following:

i) Very fine-grained and fine-grained xenocryst minerals in garnet porphyroblasts and the relatively Ca-rich core of the garnet itself (Figs. 12A, B and C) of the garnet-

Fig. 12 Photomicrographs of the D_1-D_2 microstructures

A. Garnet-Sillimanite gneiss (khondalite in a restricted sense) containing helicitic porphyroblasts of garnet. A bc section (cut normal to S and parallel to L) of specimen No. 85101511, 9 km east of Kandy. Scale bar: 3 mm

B. A garnet porphyroblast showing the helicitic structure with inclusions of quartz (Q), ilmenite, biotite and sillimanite. Matrix sillimanite (S) wrapping around the porphyroblast is seen. Same thin section as A. Scale bar: 1 mm

C. Xenocrystic minerals in the garnet prophyroblast. Xenocrysts are biotite (brown), staurolite (yellowish, just above the letter T), ilmenite (opaque), and kyanite (just above the letter K). Same specimen as A. Scale bar: 0.3 mm

D. Xenocrystic kyanite (clear grain just above the letter K) and spinnel (green, just above the letter P) in a garnet porphyroblast in a sillimanite (letter S)-garnet-biotite gniess. Specimen No. 85111509, 8 km east of Horana. Scale bar: 0.3 mm

E. Stretched/disrupted garnet (G), decomposing into orthopyroxene, plagioclase and ilmenite in a garnet charnockite (specimen No. 85101703, 10 km east-northeast of Kandy. Section is cut oblique to both S and L). Scale bar: 0.7 mm

F. Same section as E, crossed nicols. Q: quartz, H: Orthopyroxene.

G. Elongated garnet porphyroblast with pressure shadows filled with ilmenite and spinnel. Well elongated ilmenite and sillimanite + ilmenite are also developed, partly altering into biotite at the left side of the figure. G: garnet, S: sillimanite, B: biotite. A bc section of specimen 85101302A, 15 km southeast of Kandy. Scale bar: 0.7 mm

H. Same thin section as G, crossed nicols.

I. Rootless microfolds and lensing-out structures of quartz plates in the quartz-feldspathic gneiss. An ac section (cut normal to both S and L), specimen No. 85092809, 10 km north-northeast of Kandy. Scale bar: 6 mm

J. A bc section of the same specimen.

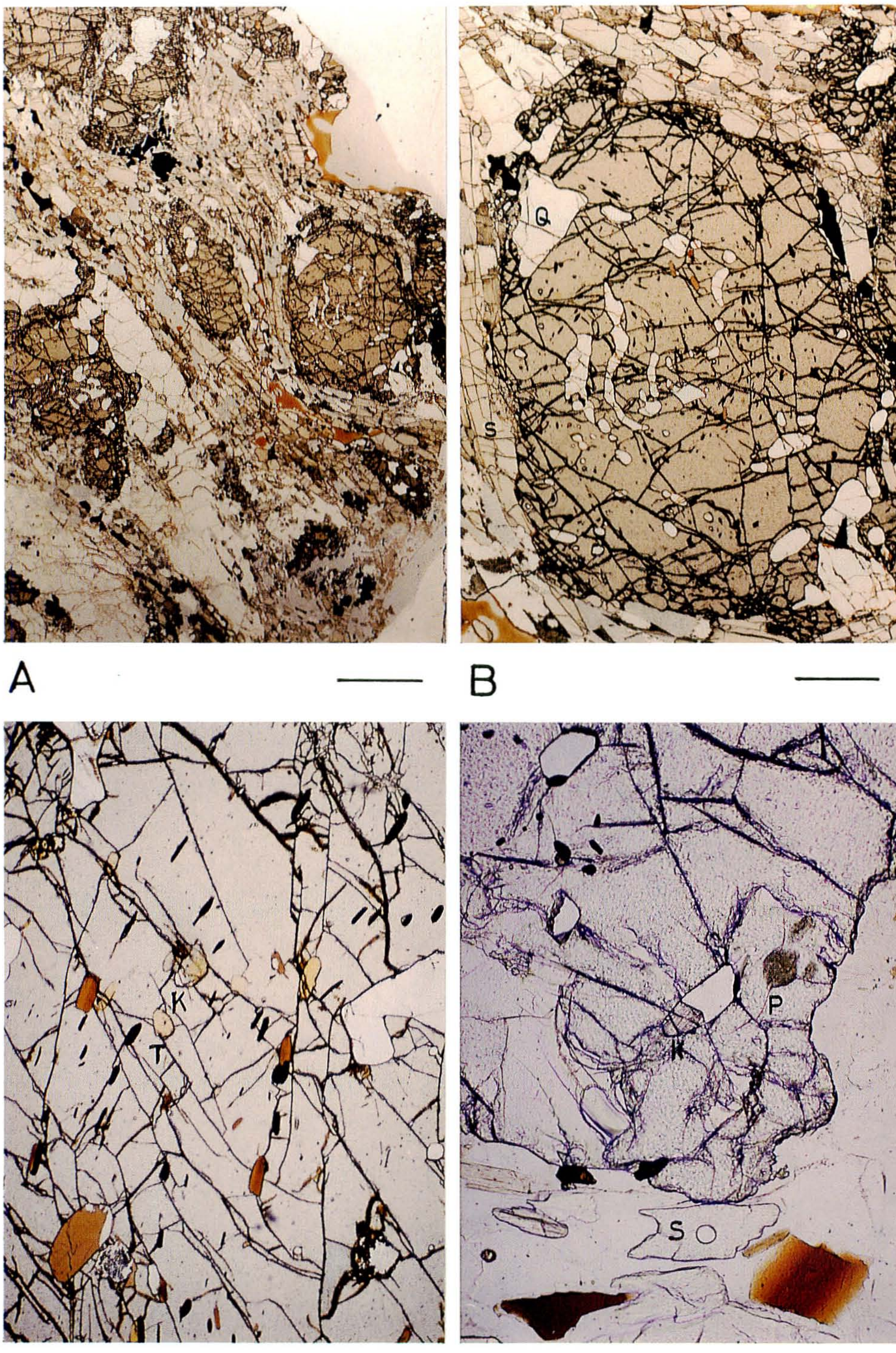
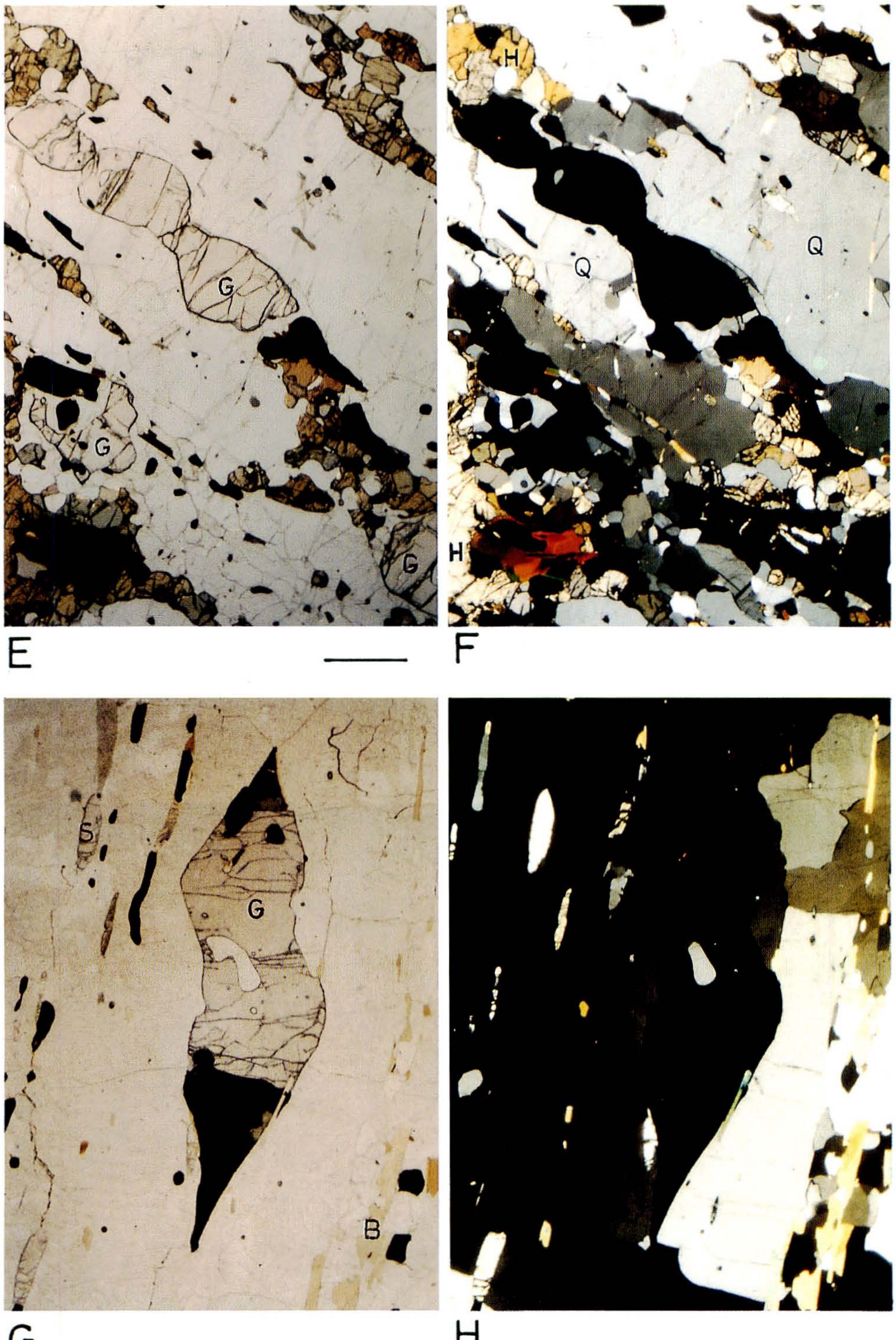


Fig. 12



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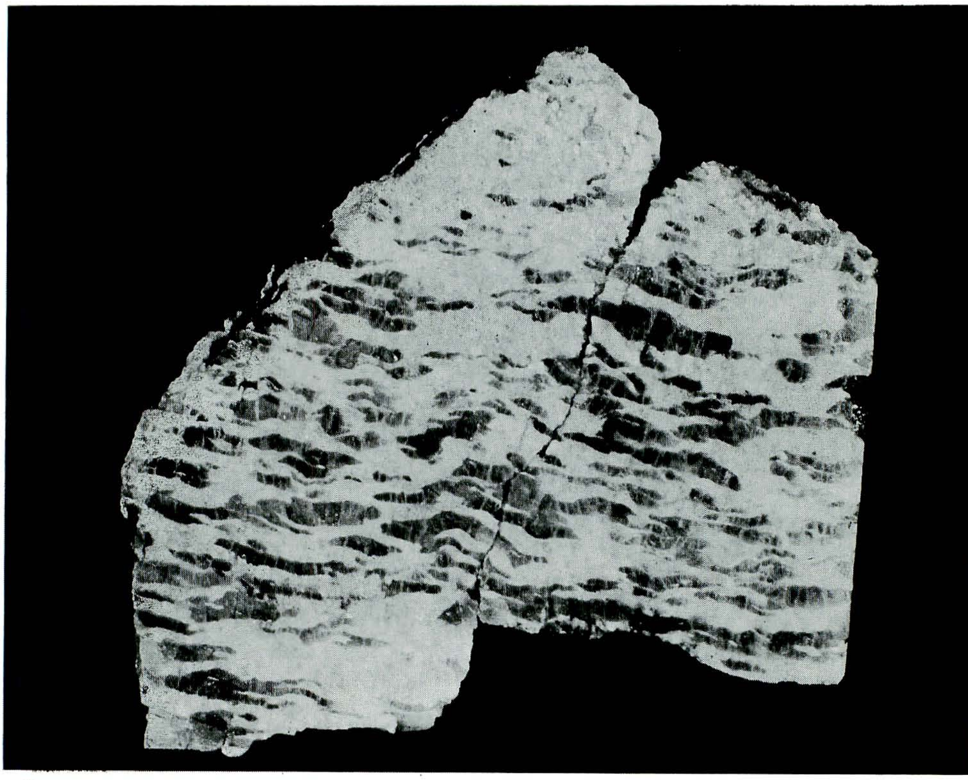

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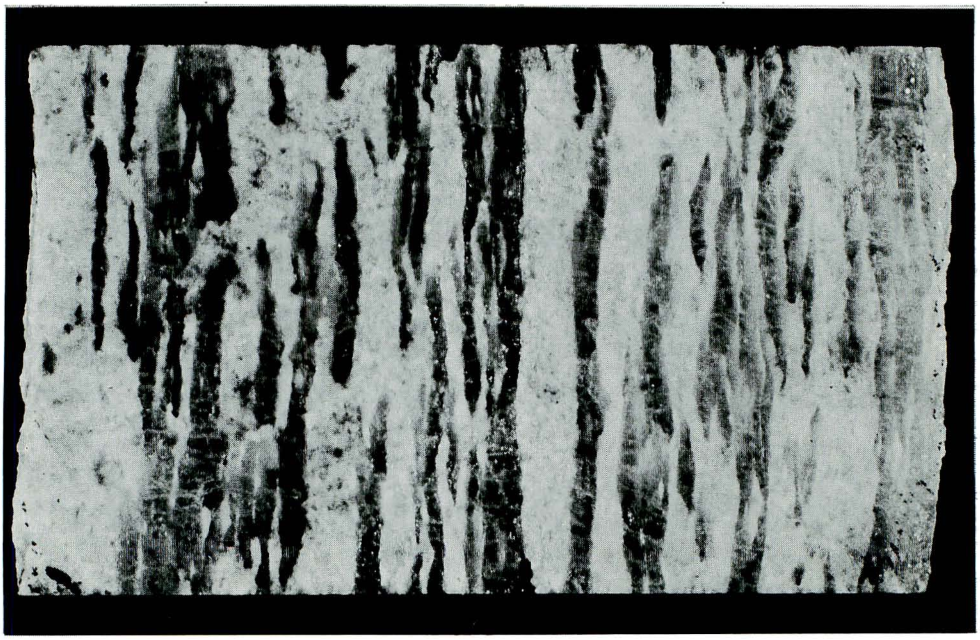

J

Fig. 12

sillimanite gneiss (HIROI *et al.*, 1987 and in preparation) from east of Kandy represent a good example of microstructures of this stage. The porphyroblasts are wrapped by medium- to coarse-grained sillimanite which is parallel to the banding and belongs to the microstructure of the later phase of the D_1-D_2 stage. Very fine-grained inclusions in the core are elongated grains of sillimanite, ilmenite and biotite showing generally the preferred orientation which sometimes show folded structures, giving rise to the helicitic structure of the host garnet. It is worthy of note that the helicitic structure is detected in all thin sections cut parallel or normal to the major lineation of the rock, and therefore, the rotational axes of the helicitic structure of the porphyroblasts appear not to be parallel to each other among the porphyroblasts and that many of them are considered to be highly inclined from the major lineation of the rock. Fine-grained xenocrystic biotite, staurolite, kyanite, corundum and hercynite showing no preferred orientation sometimes occur also in the garnet. Fine- to coarse-grained quartz and medium- to coarse-grained sillimanite inclusions occur also in the porphyroblast; the quartz is often parallel to the helicitic structure. Some of these two minerals continue to the sillimanite and quartz outside garnet. Thus, the very fine-grained xenocrystic minerals in the garnet are the earliest, and the core portion of the garnet itself, and possibly, the fine-grained xenocrystic minerals are the next formation, all of them being earlier minerals than the banding structures. Garnet porphyroblasts with similar inclusions are also found in some gneisses throughout the survey areas including the area around Horana (Fig. 12D) (HIROI *et al.*, 1987 and in preparation).

ii) Garnet and/or clinopyroxene which are now disrupted along the banding structures in some charnockitic rocks and garnet-biotite gneisses (Figs. 12 E-H) from both areas around Kandy and Horana are considered to have formed prior to their distruption. Minerals belonging to the later phase of the D_1-D_2 stage wrap around or fill pressure shadows of the disrupted garnet and clinopyroxene as mentioned later. In some cases, these garnet and clinopyroxene include fine-grained xenocrysts such as quartz, biotite, ilmenite or sillimanite. Some of these xenocrystic minerals may have formed earlier than or simultaneous to the host minerals and therefore are considered to belong also to the earlier phase of the D_1-D_2 stage.

iii) Flattened quartz plates with lensing out and rootless folding structures develop dominantly in the quartz-feldspathic gneiss north-northeast of Kandy. The quartz plates are well folded and elongated paralleling the banding, showing the dominant quartz distribution lineation. On the ac section (cut normal to both the s-plane and lineation), many rootless folds and pinch and swell and lensing-out structures are detected. Quartz plates in the bc section (cut normal to the s-plane and parallel to the lineation) are generally very flat and elongate, although some rootless folds are also found to develop. The geometric shape of some quartz plates is complex and indicates that it is caused by some interference of more than two folds (Figs. 12 I, J). These geometric characteristics of the quartz plate can not be explained by only such a single compressional tectonics as the tectonics during the later phase of the D_1-D_2 stage, and therefore, are regarded to have formed under the tectonics of the earlier phase of the D_1-D_2 stage.

Mineral parageneses of the earlier microstructures during the D_1-D_2 stage mentioned above indicate the amphibolite to the granulite facies conditions of metamorphism at least partly in the kyanite field. This is apparently incompatible with the dominant mineral parageneses of the rocks as discussed by HIROI *et al.* (1987 and in preparation) who have given the mineral chemistry and discussed in some detail the petrology of some of the xenocrystic minerals and mineral parageneses mentioned above. The metamorphism mentioned above is comparable to the first phase of the first period of metamorphism by HAPUARACHCHI (1975) and the peak metamorphism by SANDIFORD *et al.* (1989).

Some of the inclusion minerals and a part of the core portion of the host garnet of the garnet-sillimanite gneiss of the area around Kandy mentioned above are considered to have formed under some stress conditions of the monoclinic symmetry including the earlier non-rotational tectonics which formed the distribution of oriented needrous xenocrystic minerals and the later rotational tectonics which formed the helicitic structure of the host garnet. The rootless folding, as exemplified by the completely rootless-folded quartz plates in the quartz-feldspathic gneiss north-northeast of Kandy, was also possibly formed under the same rotational tectonics.

4.2. Later microstructures and metamorphism during the D_1-D_2 stage

Microstructures which are considered to have formed simultaneously with the formation of the banding and to bo cut by the microstructures during the D_3 stage are considered to have formed during a relatively later phase of the D_1-D_2 stage. These microstructures develop most dominantly throughout rocks of the study areas, some examples being given below.

i) Matrix sillimanite of the garnet-sillimanite gneiss from east of Kandy mentioned above (cf., Figs. 12A and B) along with some portions of the garnet porphyroblast which are associated with the matrix sillimanite. The sillimanite is medium- to coarse-grained, arranged parallel to the banded structure of the rock with a distinct linear fabric and wraps the garnet porphyroblast. Associated minerals with the matrix sillimanite are garnet, potash feldspar and quartz, sometimes with rutile and ilmenite.

ii) Orthopyroxene which fringes or fills the pressure shadows of the disrupted garnet or clinopyroxene and is distributed paralleling the banding (cf. Fig. 12E) in the charnockitic rock represents also the typomorphic microstructure of this phase. Plagioclase, quartz, and sometimes ilmenite are associated with the orthopyroxene. The similar microstructure is found in some charnockitic rock in the areas around Kandy and around Horana.

iii) Ilmenite sometimes associated with sillimanite and/or spinnel also occurs paralleling the banding, either at pressure shadows of garnet or as elongate fine grains paralleling the banding in a sillimanite-biotite-garnet gneiss occurring southeast of Kandy (cf. Fig. 12G).

Mineral parageneses during this phase as mentioned above indicate the granulite facies conditions of metamorphism of relatively lower pressure and indicate decompression from the previous microstructural events. Data on mineralogy and discussions on the petrology of part of the microstructures mentioned above are given by HIROI *et al.* (1987 and in preparation). The metamorphism of this phase is comparable with the second phase of the first period of metamorphism by HAPUARACHCHI (1975) and the symprectic intergrowth of hypersthene and plagioclase by SANDIFORD *et al.* (1989). Microstructures of this phase along with mesoscopic structures mentioned in the previous section appear to indicate that the metamorphism of this phase took place under the layer normal compressional stress conditions of the monoclinic symmetry without the rotational element; however, observations are not sufficient.

4.3. Microstructures and metamorphism during the D_3 stage

The microstructures of this stage include the schistosity and foliation generally paralleling the axial surface of the major D_3 linear foldings and those paralleling the banding. Including some already reported by YOSHIDA *et al.* (Pers. Comm., 1990), they are described in the followings:

i) The faint schistosity-foliation made of the elongation of biotite and quartz which is generally parallel to the axial surface of the major folds but is inclined from the banding (Figs. 13A, B and C). This structure is found in the garnet-biotite gneiss occurring in the hinge area of the southern outside margin of the Teldeniya arena in the area around Kandy and in some gneisses and charnockitic rocks occurring also in the hinge area of the major D_3 folds in not only the area around Kandy but also the area around Horana. Some biotites with similar features are arranged parallel to the banding in these rocks, indicating their simultaneous formation with the biotite which form the inclined schistosity. Orthopyroxene, when present, is generally more or less altered to these biotites. Some grains of the associated garnet in the garnet-biotite gneiss, which are distributed (during the D_1-D_2 stage) parallel to the banding are not altered into biotite and hence are considered to have been stable during this stage, possibly having their chemical composition re-arranged.

ii) Dominant biotite schistosity and/or foliation being mostly parallel to the banding and either parallel to or inclined from the axial surface of the major folds develop more or less in some gneisses and charnockitic gneisses in areas around Kandy and Horana. The biotite of this microstructure is generally thick, does not generally show a good lattice preferred orientation, and forms the decussate aggregate with basal planes of each flake being more or less parallel, resulting in the development of the rough but dominant schistosity of the rock. These biotites are optically similar to the biotite that forms the inclined schistosity mentioned above, and surround or fill pressure shadows of garnet, or alter orthopyroxene.

In the garnet-biotite gneiss southwest of Kandy, a shear band composed of aggregate of thin biotites showing a relatively good lattice-preferred orientation paralleling the banding cuts the dominant D_3 schistosity made of the rough orientation of biotites. The shear band is parallel to the dominant schistosity and the two kinds of biotite are similar

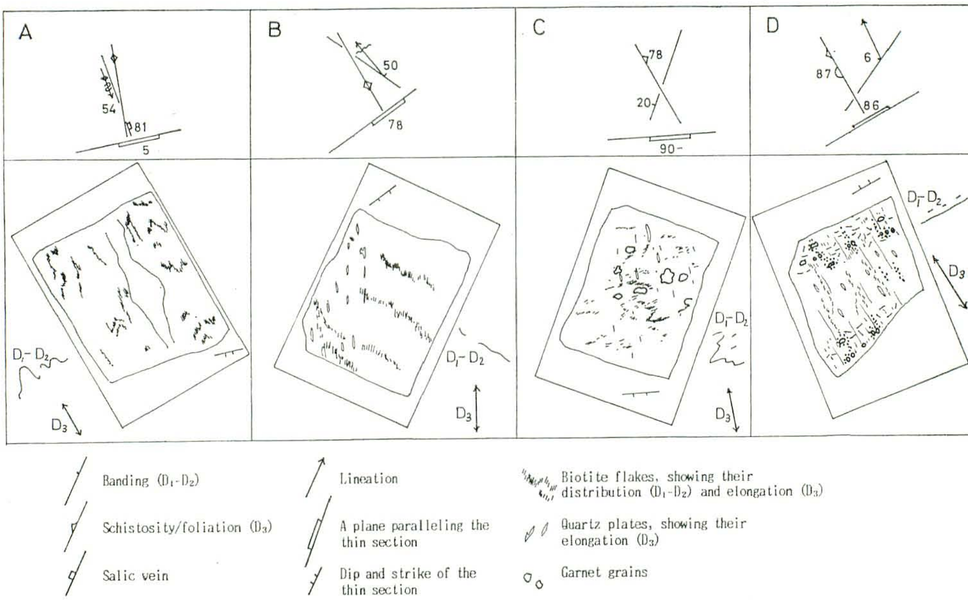

Fig. 13 D_3 microstructures cutting the D_1-D_2 structures
A. Schistosity and microfolds of the D_3 stage made of the lattice preferred orientation of biotite (thin bars) mostly paralleling the apparent banding made of veins of aggregate of quartz and feldspars (outlined with the thin solid line). The D_1-D_2 structure is indicated by the incomplete continuation of biotite. Specimen No. 85101505, 13 Km north-northwest of Kandy.
B. Schistosity (D_3) made of the elongated clots of quartz (pods outlined with thin solid line) and the lattice preferred orientation of biotite (short bars, their distribution indicating the D_1–D_2 banding) in the biotite gneiss. Specimen No. 85100502A, 17 km east-southeast of Kandy.
C. Schistosity (D_3) made of scattered dimensional preferred orientation of quartz and lattice preferred orientation of biotite in the garnet-biotite gneiss. The D_1-D_2 structures are indicated by the indistinct continuation and folded structures of garnet (amoeboed grains outlined with thick solid line) and biotite. Specimen No. 85111511, 5 km east of Horana.
D. Foliation (D_3) made of blastomylonitic pods (indicated by discontinuous wave lines) accompanied with cordierite in the cordierite-garnet-biotite gneiss. Specimen No. 85112106A, 10 km southwest of Horana. The D_1–D_2 structure is indicated as the wide banding.

in their optical features. This shear band may indicate the differential movement paralleling the banding which took place during the D_3 stage.

iii) The foliation of the D_3 stage made of elongated clots of orthopyroxene and quartz is found in some charnockites in the area around Horana. These rocks are located in about the hinge area of the major fold. The foliation is nearly vertical, being generally parallel to the axial surface of the major fold, and is inclined from the banding. An inclined schistosity from the banding structure, the schistosity being composed of the elongation of pyroxenes and ilmenite, is found also in some charnockitic rock from Nuwara Eliya.

iv) A characteristic D_3 microstructure found in the cordierite-sillimanite-garnet-biotite gneiss near Horana is the distribution of cordierite, associated with elongate aggregates of fine-grained quartz, polash feldspar and plagioclase, the elongation being highly inclined from the banding (Fig. 13D) and nearly parallel to the axial surface of the major fold. Garnet and sillimanite in this rock is partly altering to the cordierite. PERERA (1984) mentioned the stable occurrence of cordierite with garnet along the banding in granulitic rocks from both the Southwest and Highland Groups. Many of his examples appear to be correspondable to the metamorphism during the D_1-D_2 stage.

In the area around Kandy, decomposition of pre-existent unhydrous minerals into biotite is characteristic, indicating the amphibolite facies conditions; whereas in the area around Horana, the re-arrangement of orthopyroxene and quartz and the decomposition of garnet into cordierite took place, along with the general development of the biotite schistosity altering pyroxenes and garnet. The mineralogy and petrology of the secondary formation of cordierite in the cordierite-sillimanite-garnet gneiss of the area around Horana are discussed by HIROI *et al.* (1987 and in preparation). The metamorphism during the D_3 stage is comparable to the second period of metamorphism of HAPUARACHCHI (1975), who concluded that the conditions of the metamorphism to be the hornblende granulite subfacies to the amphibolite facies. The recrystallization during the D_3 stage is considered to have taken place under the compressional stress normal to the axial surface of the major folds, mostly with a monoclinic symmetry. However, the associated differential movement in rocks of the study areas is considered to have differed from place to place and portion to portion of rocks, either parallel or near parallel to the axial surface of the major folds or to the pre-existent banding, even when the banding is more or less inclined from the axial surface of the major folds.

4.4. Microstructures and metamorphism during the D_4 stage

Microstructures during the D_4 stage are sporadically found only where the mesoscopic D_4 structures develop. They are detected as the faint schistosity shown by very small amounts of biotite inclining from the dominant banding and/or foliation which belong to the D_1-D_2 and D_3 microstructures. In the biotite-hornblende gneiss about 8 km north-northeast of Kandy, NNW-SSE small drag folds of the D_4 stage develop, their axial surfaces paralleling the granitic veins. The dominant and uniform foliation belonging to the D_3 microstructures made of the elongation and continuation of biotite and hornblende also develops in WNW-ESE direction, paralleling the banding of the rock. Some biotite grains run parallel to the granitic veins and thus form the faint schistosity belonging to the D_4 microstructures. Biotite grains constituting the faint schistosity are very thin relative to the other biotite grains, although they are optically simillar under the microscope. The biotite of the D_4 stage in some rocks cuts hornblende and is fringed by the thin film of quartz. When the rock contains orthopyroxene or garnet, the biotite of the D_4 microstructure cuts them, forming a symprectic structure with quartz. Analogous D_4 structures as mentioned above develop in some other rocks of both the areas around Kandy and Horana where the mesoscopic D_4 structures are found.

The D_4 microstructures described above indicate that the metamorphic conditions during this stage is generally the amphibolite facies.

4.5. Microstructures and metamorphism after the D_4 stage

Microfractures develop in various intensities over many rocks throughout the survey

Table 1 Microstructures of the granulite facies rocks of Sri Lanka in reference with tectonic stages.

TECTONIC STAGES	CHARNOCKITES	PELITIC GNEISSES
D_1-D_2 Relict structures earlier than the banding	Disrupted garnet and/or clinopyroxene along the banding	Xenocrystic minerals in garnet porphyroblasts, some of which show helicitic structure (quartz, biotite, ilmenite, sillimanite, corundum, kyanite and staurolite) in garnet-sillimanite gneisses Rootless microfold in a quartz-feldspathic gneiss
Foliation paralleling the banding	Orthopyroxene, ilmenite and plagioclase at pressure shadows of clinopyroxene and/or garnet	Distribution of sillimanite and garnet along the banding Sillimanite and ilmenite at pressure shadows of garnet
D_3 Foliation and schistosity paralleling either the banding or the axial surface of the D_3 folds	Wide and dominant growth of biotite mostly paralleling the banding, and altering pyroxenes and garnet Recrystallization and branching of quartz plates along the axial surface of the D_3 folds	
	Branching of the distribution of orthopyroxene along the axial surface of the D_3 folds	Schistosity composed of roughly oriented biotites paralleling the axial surface of the D_3 folds Formation of cordierite surrounding garnet associated with recrystallization of salic crystals, paralleling the axial surface of the D_3 folds
D_4 Schistosity paralleling granitic veins	Lattice preferred orientation of biotite which is generally very thin. Orthopyroxene and/or garnet alter into this biotite	
Post D_4 Microfractures	Sporadic and small amounts of chlorite, green biotite, sericite, zoisitic matter, calcite, smectite and claii matter, some of which fill the microfractures	

areas and are filled with claii materials. Orthopyroxene in some charnockitic gneisses throughout the survey areas is partly altered into smectite along network fractures in the crystal grain. The smectite, in some cases, is found to continue to the microfractures and to fill them. Plagioclase is generally fresh, but less dominantly is altered by minute grains of sericite, zoisitic matter and calcite. Biotite is also generally fresh, but a very small part of biotite in some rocks is changed into green biotite, muscovite, chlorite or claii matter.

The chronological relationships among the different alterations mentioned above are not clear. But all of them show no preferred orientation to the rock and develop over almost all crystals in rocks, and therefore, are considered to be grouped in the post D_4 events. Metamorphic conditions during these events are considered to be the green-schist facies or slightly lower. The wide development of microfractures in rocks indicates that most of these rocks suffered some tectonics under relatively low confining pressures.

A simplified reference of the microstructural events to the tectonic stages for the granulite facies rocks in the study areas are shown in Table 1.

V. Discussion and Conclusion

5.1. Nature and sequence of deformations

Nature of lineations formed during the D_1-D_2 stage BERGER and JAYASINGHE (1976) pointed out that most of the lineations in Precambrian rocks of Sri Lanka belong to the D_1-D_2 deformations and that the D_3 folds took place coaxially with the pre-existing tectonites controlled by their structural inhomogeneity. A considerable portion of the major lineations in rocks of the present area, however, is considered to have formed or been intensely re-arranged during the D_3 deformations as mentioned above. The overall development of coaxial folds due to the structural inhomogeneity of pre-existent tectonites is considered unlikely, since the rocks are considered to have been totally recrystallized into the granulite facies metablastic rocks before the D_3 folds and are expected to have acted as somewhat homogeneous bodies with regard to the widespread D_3 tectonics. Some instances, however, are seen where the major lineation of a rock is explained by the D_1-D_2 deformations.

The development of a dominant lineation on the banding plane, the lineation being inclined from the axis of the D_3 folds and refolded by these folds, was found locally in the field. The lineation in this case is regarded to belong to an earlier phase than the D_3 folds and therefore, apparently to the D_1-D_2 stage. The detection of the rootless folds of the quartz plates in a thin section cut parallel to the quartz-distribution lineation of the quartz-feldspathic gneiss is an additional example. The lineation, in this case, is nearly parallel to the hinge of the D_3 fold.

From the volume considerations based on observations and discussions presented in the foregoing pages, the lineations earlier than the D_3 structures include possibly the followings: Lineations related to the preferred oriention of sillimanite, biotite and ilmenite in the helicitic garnet porphyroblasts of the garnet-sillimanite gneiss (cf., Fig. 12 B); those related to the distribution lineation of quartz on the s-plane of the quartz-feldspathic gneiss (cf., Figs. 12I, J), reflecting strong shearing and rotational tectonics in the direction of the lineation; those related to the elongation-lineation of the matrix sillimanite in the same garnet-sillimanite gneiss mentioned above, having formed under the layer normal compressional tectonics; eastward stretching lineations related to some overturned small folds with an eastery vergent, indicating the thrusting tectonics of the Highland Group over the East Vijayan Complex. The last example mentioned above is cited from SANDIFORD *et al.* (1989).

The superposition of the D_3 tectonics over these lineations might have caused various modifications as discussed below.

The possibility of superposition of more than two different structures during the D_1-D_2 stage BERGER and JAYASINGHE (1976) considered the D_1-D_2 structures as the superposed isoclinal and rootless folds prior to the D_3 structures, and SANDIFORD *et al.* (1989) discriminated the D_1 isoclinal and rootless folds from the D_2 overturned small folds. We found also that some overturned small folds predate the D_3 major folds and post-date the isoclinal and rootless folds. However, we also consider the possibility, as BERGER and JAYASINGHE (1976) pointed out, that the isoclinal and rootless folds are composed of more than one structural phase. We consider that some part of the complex patterns of the distribution of quartzite layers of the area around Kandy (cf. Fig. 2), which is difficult to be explained by the superposition pattern given by RAMSEY (1967), may be the result of the interference of more than one isoclinal fold and the later upright fold. As a suppliment to the above data, we observed two chronologically different isoclinal folds being developed over the calcareous gneiss on the Galle coast. The detection of two different tectonics for the earlier microstructures of the D_1-D_2 stage as described in the foregoing pages is another support. Although the detection of these older events is quite difficult, further detailed study may contribute to the unravelling of this problem.

D_3 events Major foldings, axial plane schistosity and assosiated recrystallization of the D_3 events as discussed by YOSHIDA *et al.* (Pers. Comm., 1990) are relatively clear compared to the earlier events. Problems to be discussed here are lineations and expected mesoscopic folds associated with the D_3 major folds, because the exclusion of most lineations from the D_3 structures has often been stressed by earlier studies (.e.g., BERGER and JAYASINGHE, 1976, SANDIFORD *et al.*, 1989). In some rocks occurring in the area around Kandy, some mineral distribution lineations are found to be inclined from hinges of the D_3 folds and are traversed by another mineral lineation which is considered to belong to the D_3 structures; these observations are partly consistant with the earlier views. However, in many cases where only one dominant lineation develops nearly paralleling the hinge of the major folds, the association of most of these lineations with the D_3 structures is generally possible as already mentioned. It is possible that many of the pre-existent D_1-D_2 lineations which had been inclined from the hinges of the D_3 folds either disappeared or were transposed during the dominant penetrative tectonics during the D_3

stage, and that some earlier major lineations which had been parallel to the D_3 lineations more or less survived during the D_3 deformations.

The D_3 folding might have formed in total as the flexural flow fold as BERGER and JAYASINGHE (1976) pointed out; but, judging from the mode of development of the schistosity related to the D_3 tectonics as mentioned below, mesoscopic and microscopic structural observations indicate that the differential movement of rock might have differed according to physical characteristics and location of the rock with regard to the D_3 fold. The faint schistosity paralleling the axial surface of the upright D_3 fold is not so commonly found. Schistosity paralleling the banding is sometimes met with, even though the banding is highly inclined from the axial surface of the D_3 fold. And in some rocks, no schistosity develops. Such evidence strongly suggests that layer parallel movement to the banding in some rock, no remarkable tectonics in some other rock, and layer parallel movement to the axial surface of the major folds in still other limited rock took place during the D_3 folding.

D_4 events and the heterogeneous formation of the charnockite D_4 structures found as sporadic ductile faults, granitic veins and gentle folds in the field are distinctive from other structures in that they are less penetrative and less ductile. Although the postposition of the D_4 events to the D_3 events is apparent, they appear to be in some genetic familiarity because of the following reasons: i) They are both related to the activity of granitic rocks such as the migmatization in the D_3 stage and granitic veins in the D_4 stage. ii) Biotite schistosity is characteristically common to both events especially in the area around Kandy, and iii) Change of structural characteristics from the D_3 to the D_4 structures is gradational as to decrease the homogeneity and ductility.

The incipient charnockitization is considered to have occurred during either the later phase of the D_3 stage or the D_4 stage under localized unusual physicochemical conditions. The formation of the charnockitic rock from gneissic rock is in pods or veins having inhomogeneous, less penetrative and less ductile characteristics, and therefore, is considered to belong to the D_4 structures. A Rb-Sr whole-rock isochron age of 430 Ma (KAGAMI *et al.*, in press) is favourable to the above consideration, although the ca 746 Ma U-Pb age for zircon from the charnockite of the Kurunegala outcrop (German-Sri-Lankan Consortium, 1987) appears to be favourable to the reference of the charnockitization with the D_3 stage as mentioned later.

5.2. Highland Group/Southwest Group interrelationship

The distinction between the Highland Group and the Southwest Group (e.g., COORAY, 1978) is based mainly on the occurrence of cordierite commonly in the Southwest Group and rarely in the Highland Group; the occurrence being considered to reflect the difference in the nature of the metamorphism concerned. The difference in the lithological characteristics has also been pointed out.

Petrological study of the cordierite-bearing rocks of both the Southwest and Highland Groups by PERERA (1984), however, clarified that the occurrence of cordierite is not rare in rocks of the Highland Group, although still relatively uncommon. From the petrological study, he pointed out that the difference in the occurrence of cordierite in rocks of both the Southwest and Highland Groups is not due to the conditions of metamorphism but is due mainly to the difference in the chemical composition of the rock. He raised doubt concerning the differentiation of the two groups based on the nature of metamorphism. HIROI *et al.* (1987 and in preparation) pointed out the general post-position of cordierite to the major granulite facies mineral parageneses, a similar view being partly mentioned in the present article (cf., Fig. 13D). Such evidence is also in disagreement as to the discrimination of the two groups based on the occurrence of cordierite. The result of the present study revealed that there are many similarities in tectonic and microstructural features of rocks in both the Highland Group in the area around Kandy and the Southwest Group in the area around Horana. The characteristics and sequence of deformations of the D_1-D_2, D_3, D_4 and post D_4 stages are analogous. Associated microstructures with the D_1-D_2, D_3, D_4 and post D_4 stages are also similar between rocks of the two groups, although the D_3 microstructures of rocks in the Southwest Group in the area around Horana appear to have formed under relatively higher temperature conditions than those of the rocks in the Highland Group in the area around Kandy. The similar occurrence of xenocrystic minerals including kyanite in the garnet porphyroblast of a garnet-biotite gneiss in the Southwest Group as in the rocks of the Highland Group (HIROI *et al.*, 1987 and in preparation) critically supports the similarity in the metamorphic history of the two groups. These similarities may suggest that the Highland Group and the Southwest Group can not principally be separated with regard to tectonic-metamorphic characteristics. This conclusion is in agreement with the similar geochronologic features of rocks of the two groups pointed out by MILISENDA *et al.* (1988).

Some differences, however, in structural and metamorphic characteristics as mentioned in the foregoing sections are pointed out between the Highland Group and the Southwest Group. It should be noted that the stereographic lineation projections of the rocks in the Southwest Group around Horana are mostly fringed surrounding the B axis of the major folds, not so much scattered as those of the rocks of the Highland Group in the area around Kandy. P-T conditions of the peak metamorphism estimated for a sillimanite-garnet-biotite gneiss of the Southwest Group is considerably lower than those obtained for the similar gneisses of the Highland Group (HIROI *et al.*, 1987 and in preparation). The difference in lithologic characteristics as already mentioned by COORAY (1978) is inevitable evidence. These are problems to be further studied in the future.

5.3. Commentary on geochronology

Not so much geochronological work has been done until recently on the Precambrian rocks of Sri Lanka (CRAWFORD and OLIVER, 1969; WICKREMANSINGHE, Pers. Comm., 1969), although the recent ion microprobe analysis of zircon by KRÖNER *et al.* (1987) and BAUR *et al.* (1987), Sm-Nd model age mapping by MILISENDA *et al.* (1988), U-Pb zircon and Sm-Nd garnet geochronology by HÖLZL and KÖHLER (Pers. Comm., 1989), and whole-rock Rb-Sr and Sm-Nd isochron dating by KAGAMI *et al.* (in press) added a considerable amount of valuable data. Including these recent data, all radiometric ages scatter from 430 to 4271 Ma; these are grouped into six age groups of ca 450–600 Ma, ca 700 Ma, ca 1100 Ma, ca 1800–2200 Ma, ca 2400 Ma, and even older ages.

Ca 450–600 Ma ages include U-Pb ion microprobe zircon ages (BAUR *et al.*, 1987), Rb-Sr whole-rock, Rb-Sr biotite, and K-Ar hornblende ages (WICKREMANSINGHE, Pers. Comm., 1969, CRAWFORD and OLIVER, 1969 and HÖLZL and KÖHLER, Pers. Comm., 1989), and a Rb-Sr whole-rock isochron age (570±15 Ma with an initial $^{87}Sr/^{86}Sr$ ration of nearly 0.71) for gneissic rocks and amphibolites from the Vijayan Complex by WICHREMANSINGHE (Pers. Comm., 1969). KAGAMI *et al.* (in press) recently presented Rb-Sr and Sm-Nd isochron ages ranging from 430 to 490 Ma for rocks of the Highland Group. Most of these ages, younger than ca 550 Ma, are considered to reflect the emplacement of the post-tectonic granites and associated thermal events as also pointed out by German-Sri Lankan Consortium (1987). The D_4 events of the present study are considered comparable to these ages, since the D_4 events are found throughout the survey areas as the youngest events almost always associated with the intrusion of granitic veins. WICKREMANSINGHE (Pers. Comm., 1969) considered that the Rb-Sr isochron age of ca 570 Ma indicated the last metamorphic episode of the Vijayan metamorphism, and HÖLZL and KÖHLER (Pers. Comm., 1989) considered that ca 600 Ma ages mainly of U-Pb zircon and Sm-Nd garnet pointed to the only one high grade regional metamorphism of the Highland Group. KAGAMI *et al.* (in press) also gave the analogous interpretation. The authors, at present, consider that ca 600 Ma ages may either reflect the D_3 events, because these events are developed intensely throughout rocks of the Highland Group, or be erraneous ages caused by the intereference between the ca 500 Ma and ca 1100 Ma events. We arbitrarily prefer the latter interpretation, although the former possibility can not be eliminated.

The local and incipient formation of charnockite, which is considered to belong to the D_4 events from its tectonic characteristics, is dated as ca 430 Ma with the initial $^{87}Sr/^{86}Sr$ ratio of 0.7150 by the Rb-Sr whole-rock isochron method by KAGAMI *et al.* (in press). They concluded, from the initial strontium ratio, that the original rocks of the Kurunegala charnockite might have a ca 1000 Ma history and not so much older than that. The same rock is dated as ca 746 Ma by German-Sri Lankan Consortium (1987); but BAUR *et al.* (1987) appear not to be confident on this age as the age of the charnockitization. The present writers prefer, therefore, to give superiority to the structural characteristics than to the zircon age.

Ca 700 Ma ages form a minor group including both Rb/Sr whole rock model ages mostly of the amphibolite facies metamorphic or granitic rocks (CRAWFORD and OLIVER, 1969) and U-Pb ion microprobe zircon ages from the charnockite 'in the making' from Kurunegala (746±25 Ma, German-Sri Lankan Consortium, 1987) and from the pink gneissose granite in one of the arenas in the area around Kandy (768±100 Ma, German-Sri Lankan Consortium, 1987). Excepting for the problematic (as mentioned above) age for the Kurunegala charnockite, these ages are considered to reflect the D_3 events of the present study, since the arena structure is concordant with the D_3 structures. However, as mentioned above, we can not eliminate a possibility of the reference of the D_3 events with the ca 600 Ma age group. Future work on this point is expected.

Ca 1100 Ma ages include Rb-Sr whole-rock ages of various rocks throughout Sri Lanka and three Rb/Sr whole-rock isochron ages of a granite mass (986±28 Ma) or gneisses (1150±60 Ma) of the Vijayan Complex (CRAWFORD and OLIVER, 1969) and of the Highland Group rocks (1000 Ma with the initial $^{87}Sr/^{86}Sr$ ratio of 0.702, KAGAMI *et al.*, in press), as well as the dominant ion microprobe zircon ages of some rocks throughout Sri Lanka (KRÖNER *et al.*, 1987, German-Sri Lankan Consortium, 1987, and BAUR *et al.*, 1987). The granulite facies metamorphism represented by the later microstructures of the D_1-D_2 stage of the Highland and Southwest Groups severely affected most rocks and concealed mostly the previous metamorphic fabrics. Therefore, ca 1100 Ma ages are considered to be comparable to the later metamorphism of the D_1-D_2 stage, i.e., the major granulite facies metamorphism, as considered also by German-Sri Lankan Consortium (1987) and KRÖNER *et al.* (1987), although HÖLZL and KÖHLER (Pers. Comm., 1989) and KAGAMI *et al.* (in press) considered these ages to indicate the formation of original rocks. One of the authors (Y.H.), is in the opinion that the ealier tectonothermal episodes of the D_1-D_2 events might also have taken place in about this time.

Ca 1800 to 2200 Ma ages include three Rb/Sr whole-rock isochron ages of the rocks of the Highland Group. They are 2055±55 Ma with the initial $^{87}Sr/^{86}Sr$ ratio of 0.7093 for garnet-bearing gneisses from the Kataragama complex (CRAWFORD and OLIVER, 1969), 2170±18 Ma with the initial $^{87}Sr/^{86}Sr$ ratio of 0.7038 for charnockitic rocks surrounding Gampaha (WICHREMANSINGHE, Pers. Comm., 1969), and 1790±170 Ma with the initial $^{87}Sr/^{86}Sr$ ratio of near 0.72 for biotite-bearing rocks surrounding Nuwara Eliya (KAGAMI *et al.*, in press). These ages were regarded to reflect the high grade metamorphic events by CRAWFORD and OLIVER (1969), WICKREMANSINGHE (Pers. Comm., 1969), and COORAY (1978). Many Rb-Sr whole rock model ages ranging from about 2000 to 2300 Ma are grouped into this age group, if they are re-calculated with appropriate initial strontium ratios. HÖLZL and KÖHLER (Pers. Comm., 1989) obtained U-Pb zircon ages of 1982±290 Ma from a paragneiss and 1851±28 Ma from an orthogneiss from the Highland Group, and German-Sri Lankan Consortium (1987) also reported a U-Pb zircon age of 1830±8 Ma for an orthogneiss of the Highland Group. An older group of these ages may point to the age of a strong tectonothermal event considering relatively high initial $^{87}Sr/^{86}Sr$ ratios, and a younger group may indicate the age of the post tectonic intrusion. The earlier tectonothermal episodes of the D_1-D_2 events are considered to be comparable to the older isochron ages within this age group. KRÖNER *et al.* (1987) and HÖLZL and KÖHLER (Pers. Comm., 1989) suspected the existence of any meaningful tectonothermal event of this age based on their zircon studies. There are two points of view with regard to our reference of the metamorphism with these ages. First, the pressure conditions of the metamorphism of this episode is distinctly higher than the later metamorphism of the D_1-D_2 stage; such rapid upheaval and denudation may be unlikely (one of the authors, Y.H., considers it to be likely) to have taken place within a short period surrounding the ca 1100 Ma age. Second, the Highland Group is not necessarily a homogeneous one geologic unit. Zircon ages are sometimes contradictory to the Rb/Sr isochron ages (e.g., BLACK *et al.*, 1987), so we have to depend on the geology in such cases.

Three whole-rock isochron ages of ca 2400 Ma have been obtained. They include a Rb-Sr whole-rock isochron age of 2411±3 Ma with the initial $^{87}Sr/^{86}Sr$ ratio of near 0.72, and a Sm-Nd whole-rock isochron age of 2328±21 Ma with the initial $^{143}Nd/^{144}Nd$ ratio of 0.50960 for charnockitic rocks from around Nuwara Eliya (KAGAMI *et al.*, in press), and a Rb-Sr whole-rock isochron age of 2480±60 Ma with the initial $^{87}Sr/^{86}Sr$ ratio of 0.7045, for unmodified charnockites from south of Nuwara Eliya (HOLLAND, 1985, based on the data of CRAWFORD and OLIVER, 1969). These ages are considered to reflect some tectonothermal events, because of their high initial $^{87}Sr/^{86}Sr$ ratios (HOLLAND, 1985, KAGAMI *et al.*, in press). HOLLAND (1985) considered the crustal residence time to be about 300 Ma, and KAGAMI *et al.* (in press) suggested, based on their Sm-Nd isotope studies, that the age of the original rocks derived from mantle source may be 2500–2600 Ma. Ages of 2450–3170 Ma of detrital zircons from the quartzite from the central part of the Highland Group (KRÖNER *et al.*, 1987) are considered to reflect the ages of the source rocks that supplied material to the quartzite, and the youngest age may limit the maximum age of the sedimentation of the quartzite as KRÖNER *et al.* mentioned. A considerable amount of apparent Rb/Sr whole rock ages ranging from 3251 to 4271 Ma were reported by CRAWFORD and OLIVER (1969). Some of these ages may be meaningless because of incorrectly setting the initial $^{87}Sr/^{86}Sr$ ratio, the disturbance by the later metamorphism, and so on. There may be a possibility, however, that some are reliable, and thus, reflect the remanent rocks of the Archaean. Ca 2400 Ma Rb-Sr and Sm-Nd isochron ages and high initial $^{87}Sr/^{86}Sr$ ratios as mentioned above are suggestive of the existance of Archaean inliners surrounding Nuwara Eliya, analyses of deformations and microstructures of rocks of the inliners being left for future studies.

5.4. Tectonothermal history

Summarizing descriptions and discussions in the foregoing sections, a possible and preliminary figure of the tectonothermal history of the study areas is summarized as follows.

Older than ca 2400 Ma: Formation of original rocks of the Archaean inliners now occurring surrounding Nuwara Eliya.

Ca 2400 Ma: Some tectonothermal events in the Archaean inliners.

Older than ca 2200 Ma and younger than ca 2400 Ma: The sedimentation of supracrustal material including pelitic-psamitic rocks, quartzite and marble associated with the igneous activity of various compositions, comprising most of the Highland Group.

Ca 1800–2200 Ma: The earlier episodes of the D_1-D_2 stage (ca 2100 Ma) (Y.H. is not in agreement with this as mentioned above) and the later intrusion of the original rocks of some charnockite (ca 1850 Ma).

Ca 1100 Ma: The later episodes of the D_1-D_2 stage, i.e., the major granulite facies metamorphism.

Ca 700 Ma: The amphibolite-granulite facies metamorphism associated with the D_3 Deformations.

Ca 450–600 Ma: The amphibolite facies metamorphism associated with the D_4 deformations. The progressive charnockitization as the result of some local conditions might have occurred during this period.

Younger than ca 450 Ma: Alteration under the greenschist facies or slightly lower metamorphic conditions, locally associated with the microfracturing of rocks.

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