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Interaction between deformation and charnockite emplacement in the Bunger Hills, East Antarctica

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Abstract—The Bunger Hills, East Antarctica, have been metamorphosed at granulite facies and variably deformed by three deformation phases, as well as having been intruded by a number of dyke generations and large pyroxene-bearing intrusive bodies. The multiple intrusion and the conspicuous pattern of the major structural features around the intrusive bodies allows a detailed relative timing history of the events to be established. A layered and a massive gneiss series can be distinguished. The layered gneiss series consists of metapelitic, psammitic, intermediate and meta-basic gneisses that are interlayered on all scales. The massive gneiss series is, in part, identical in bulk composition and has been interpreted as an intrusive equivalent to the layered series. The first deformation phase, D_1, caused recumbent folding of both series and boudinage of an early set of mafic dykes. The metamorphic temperature peak was reached during this deformation. A northern charnockite body (Fishtail Bay body) was intruded during D_1 and was partially deformed by it. D_2 occurred subsequently and is the major shortening deformation. The transition from D_1 to D_2 is marked by intrusion of mafic dykes that are metamorphosed and folded but not boudinaged. The regional orientation of the F_2 axes is extremely variable over the extent of the Bunger Hills. The F_2 axes appear to wrap around the northern charnockite body. This may be explained by a competency contrast between the rigid charnockite and the surrounding partially molten gneiss sequence during deformation in a dextral shear environment. A large southern intrusive body (Lake Figurnoe charnockite) was intruded towards the end of this deformation phase. This body is much coarser grained, is undeformed and has a contact metamorphic halo around it. The metamorphic pressure peak was reached at this time. Strong asymmetric D_3 doming and late brittle fracturing occurred during subsequent cooling of the Bunger Hills.

INTRODUCTION

IN East Antarctica, much of the structural geological interest has been focused on the transition zones between Archaean and Proterozoic terrains. Discussion has been concentrated on reworking criteria and relative timing of events with respect to the superposition of younger events on older granulite terrains (Sandiford & Wilson 1984, Harley 1987, Clarke 1988). The Bunger Hills in East Antarctica (Fig. 1) are isolated from other areas against which their geological history can be evaluated but display several igneous intrusive phases, multiple deformation and a characteristic metamorphic history which can be used to establish a relative history. This paper discusses the multiphase deformation in relation to the emplacement history of the charnockites in an area that has been metamorphosed at high temperatures (800°C) and low pressures (4 kbar).

Limited absolute age data summarized by Grew (1982) suggest that the Bunger Hills (100°E, 66°S) lie at the centre of a mid Proterozoic (approx. 1400 Ma) granulite-facies belt extending west to Mirny station and east as far as the Windmill Islands (Table 1). The belt is bounded by older metamorphics to the east and a younger gneiss series to the west. The mid Proterozoic age for the Bunger Hills, however, is poorly defined and preliminary data by Black (personal communication 1988) suggests that the Bunger Hills have been metamorphosed later. The Windmill Islands and the outcrops around Mirny station (Blight & Oliver 1983) have been suggested to belong to the same belt as the Bunger Hills (Grew 1982). However, the outcrops around Mirny are mainly intrusive rocks of 500 Ma age and are presumed to have intruded the 1400 Ma granulites (Table 1) (Grew 1982).

In the Bunger Hills three major ductile deformation phases took place that are separated by the emplacement of intrusions. The first two deformations, a possibly extensional event (D_1) and subsequent crustal shortening (D_2), are the dominant ductile folding phases. The variable orientation of folds from the same fold generation is a consequence of interaction of D_1 and D_2 with the two large pyroxene-bearing intrusive bodies (henceforth referred to as charnockites). The third deformation formed a strong asymmetrical regional dome and basin structure and caused regionally variable reorientation of the D_2 structures as well as the regional steep dip of most structural elements. Superimposed on the ductile events are later semi-brittle and brittle deformations that are associated with retrograde metamorphism in shear zones.

The early tectonic history described in this paper is in marked contradiction to a tectonic scenario presented by Ding & James (1987) for the same area. They propose thickening of the Proterozoic crust accompanied by deep level thrusting. According to Ding & James (1987), two major pulses of recumbent folding were overprinted

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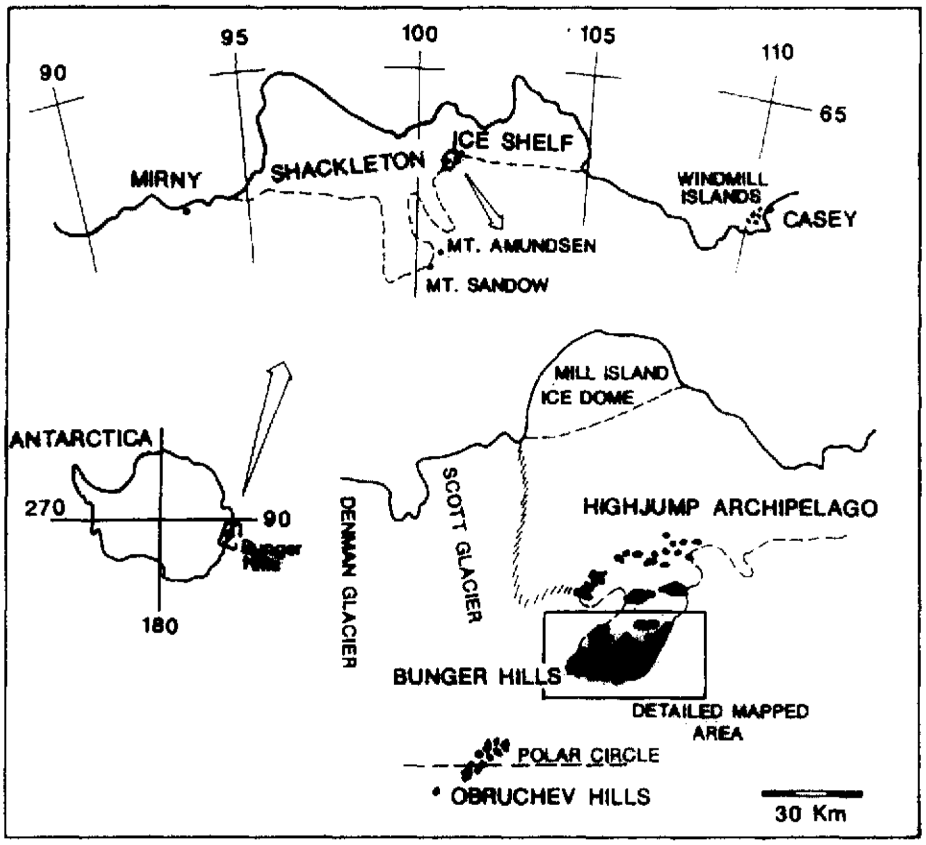


Fig. 1. Location of the Bunger Hills in Antarctica in relation to principal geographical features.

Table 1. Summary of some absolute age data from the Bunger Hills and adjacent areas. Most ages are from pegmatic rocks and may therefore post-date the peak metamorphic events. The date from Mirny is from an intrusion during the 500 Ma event which has been recognized in most parts of East Antarctica. This intrusion is presumed to intrude gneisses equivalent to the Bunger Hills and the Windmill Islands

Area	Age	Method	Mineral–rock	Author
Bunger Hills	1300, 1350	Th–Pb	Allanite in pegmatite	P, T, S
	1520, 1190	U–Pb	Allanite in pegmatite	P, T, S
	1280	K–Ar	Muscovite in pegmatite	P, T
	1330	K–Ar	Biotite in pegmatite	P, T
	1265	K–Ar	Granite (whole rock)	R
Windmill Island	1100–1400	Rb–Sr	Isochron from gneiss	A, W
Mirny	500	Rb–Sr	Isochron from charnockite	M

* Abbreviations of authors are: P = Piciotto & Coppez (1963); T = Tugarinov *et al.* (1959); S = Starik *et al.* (1961); R = Ravich *et al.* (1968); A = Arriens (1975); M = McQueen *et al.* (1972); Williams *et al.* (1983). Note that references P. T and S are very old and may be unreliable.

by an upright folding event and accompanied thrusting, this was then intruded by the charnockites and overprinted by another episode of refolding. The arguments of Ding & James (1987), which appear to be geometrically consistent, are however contradicted by field (Wilson *et al.* 1986), microstructural and metamorphic observations. Ding & James' (1987) first two phases of deformation correspond to the D_1 event described here and occurred during the prograde evolution of the rocks. This event is associated with the intrusion of the Fishtail Bay charnockite body. The D_3 and D_4 events of Ding & James both correspond approximately to the D_2 events described in this paper. The strong D_3 doming described in this paper has no direct equivalent in the paper of Ding & James.

OUTCROP PATTERN AND ROCK TYPES

The Bunger Hills are, after the Vestfold Hills, the second largest outcrop area in East Antarctica. However, despite their enormous size of >300 km^2 previous work has been restricted to two descriptive publications (Ravich *et al.* 1968, Ding & James 1987). Ravich *et al.*

(1968) spent two seasons in the area and also visited the Obruchev Hills, Highjump Archipelago and two outcrops of low-grade metasediments at Mt Amundson and Mt Sandow (Fig. 1). Their publication includes detailed petrography of a large number of rock types but lacks correlations of the units and interpretation of the structure. As a consequence it is necessary to discuss briefly in this section the major rock types and their outcrop patterns.

The Bunger Hills are dominated by a generally steeply dipping sequence of meta-sedimentary and meta-igneous rocks that are variably exposed (Figs. 2 and 3). The eastern and northeastern parts of the area around Kinzhal Gulf are excellently exposed (100%), but extensive moraine cover especially in the western half of the Bunger Hills around Edgeworth David, Camp 1, Lake Dolgoe and Dobrovolsky prevent the local resolution of the regional structure. The outcrop pattern of the prominent lithological units (Fig. 2) displays a conspicuous arcuate pattern in which foliations are deflected around, and are subparallel to, the two major charnockite bodies in the mapped area. The northern, 'Fishtail Bay body' covers about 30 km^2 and is exposed in a large synform around Fishtail Bay. The southern, 'Lake Figurnoe body' was intruded southwest of Lake Figurnoe and covers an area of about 15 km^2. The area between these bodies and the iceshelf is dominated by a gneissic sequence that can be divided into a *layered gneiss series* consisting of dominantly meta-sedimentary gneisses with subsidiary felsic orthogneisses and mafic gneisses of probably volcanic origin and a *massive gneiss series* composed of garnet-bearing granite gneisses, charnockitic, intermediate and mafic gneisses. The layered gneiss sequences show high internal strain and any pre-metamorphic features are masked by strong post-D_2 grain growth. The continuity of layering suggests that it is possible to attribute this to bedding. We interpret the massive gneiss series as the intrusive equivalent to the layered gneiss series. The two series overlap in bulk composition (Fig. 2).

Both the layered and the massive gneiss series are intruded by discrete sets of metamorphosed mafic dykes (Fig. 2). Late unmetamorphosed dolerite dykes, hydrous pegmatites and local development of pseudotachylites associated with shear zones are minor components of the terrain. Cambrian sediments occur at Mt Amundson and Mt Sandow south of the Bunger Hills but no contacts with the Precambrian gneiss sequence are exposed. These are the only two outcrops where this cover sequence is preserved and their relationship to the excavation history of the Bunger Hills is not understood.

Layered gneiss series

Within the layered gneiss series it is possible to distinguish three major lithological suites:

(1) migmatized, highly aluminous metapelitic gneisses (QFGA gneiss);

(2) layered high-grade gneisses of probably psammitic origin interlayered with minor garnet quartzites (QG gneiss), cordierite pelites (QFGCo gneiss), garnet-biotite rocks (GB gneiss) and orthopyroxene–garnet rocks; (3) charnockitic, intermediate and mafic layered gneisses of igneous origin.

Individual layers of one bulk composition vary from centimeters up to hundreds of metres in thickness (Fig. 4c) and stratigraphic younging directions are not observed. In the pelitic gneisses of the first and second suite (quartz–feldspar–garnet–sillimanite gneiss (QFGA gneiss) and quartz–feldspar–garnet–cordierite gneiss (QFGCo gneiss)), the peak assemblages of ferromagnesian minerals are usually aligned along discrete S_1 layers indicating a strong early deformation phase (garnet-biotite layers or pure garnet layers in QFG gneiss; cordierite–spinel–garnet layers in QFGCo gneiss). Minerals in these layers and the quartzo-feldspathic matrix are always recrystallized into a coarse-grained granular fabric with recrystallization post-dating the metamorphic peak. This is evidenced in the large ferromagnesian phases that overgrow the early foliation. In sillimanite-rich varieties the post-peak deformation resulted in rotation of garnets within the S_1 layers. Reaction seams may separate individual layers from each other.

The second suite includes foliated garnet-bearing granite gneisses, garnet quartzites and minor orthopyroxene–garnet rocks, garnet–biotite rocks and small calc-silicate lenses. Like the pelitic gneisses, most of these rock types are quartz-rich and the peak assemblages were formed along discrete S_1 bands. The pyroxene-bearing gneiss varieties of the third suite are interlayered with these gneisses. In mafic rocks S_1 foliation development and micro-scale layering is much less common than in the pelitic gneisses. The mafic rocks may be interlayered with quartzo-feldspathic partial melt layers on metre or decimetre scale. It is not clear whether these layers are derived from the mafic rock itself or have their origin in adjacent felsic layers. Pyroxene quartzites are occasionally extremely well layered on centimetre scale into pure pyroxenite and pure quartz–potassium feldspar layers.

Partial melting in the rocks of the layered gneiss series occurred during both early deformation phases. In the QFGA gneiss the D_1 partial melts occur as sausage-shaped layer-parallel melt bodies that have been deformed with the garnet–sillimanite fabric during D_2 (Fig. 4a). In other gneiss varieties D_1 partial melts are essentially layer-parallel leucocratic layers that have been highly deformed with the gneisses (Fig. 4b). D_2 partial melts are little deformed and often intrude locally into surrounding gneissic units.

Massive gneiss series

The mineralogy and bulk composition of the massive gneiss series is equivalent to the second and third suite of the layered series (Fig. 2). Slightly foliated granite gneisses that are pyroxene-free and may be garnet-bearing occur throughout the southeastern part of the Bunger Hills (Fig. 4d). Contacts between the massive

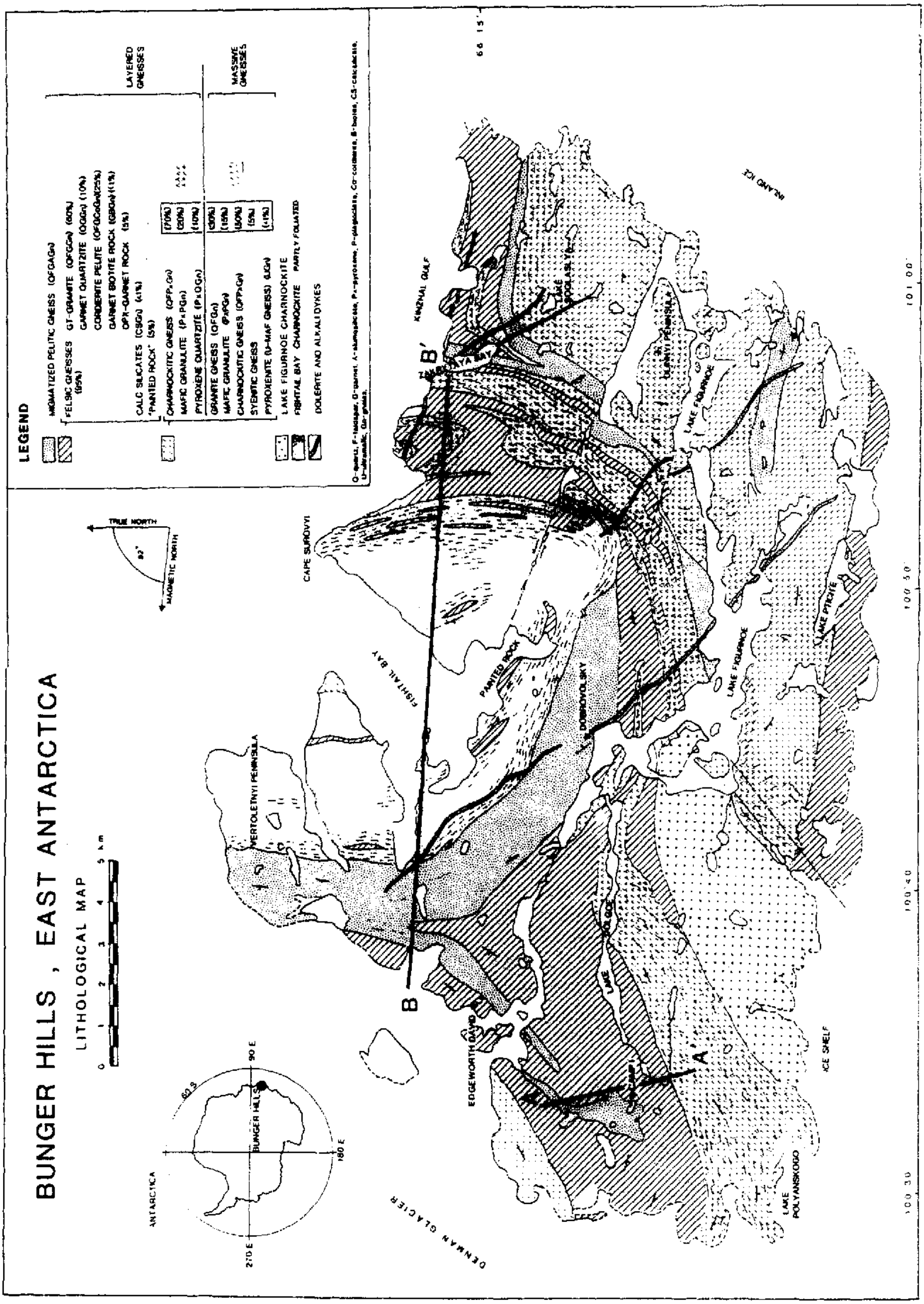


Fig. 2. Rock types identified in the Bunger Hills.

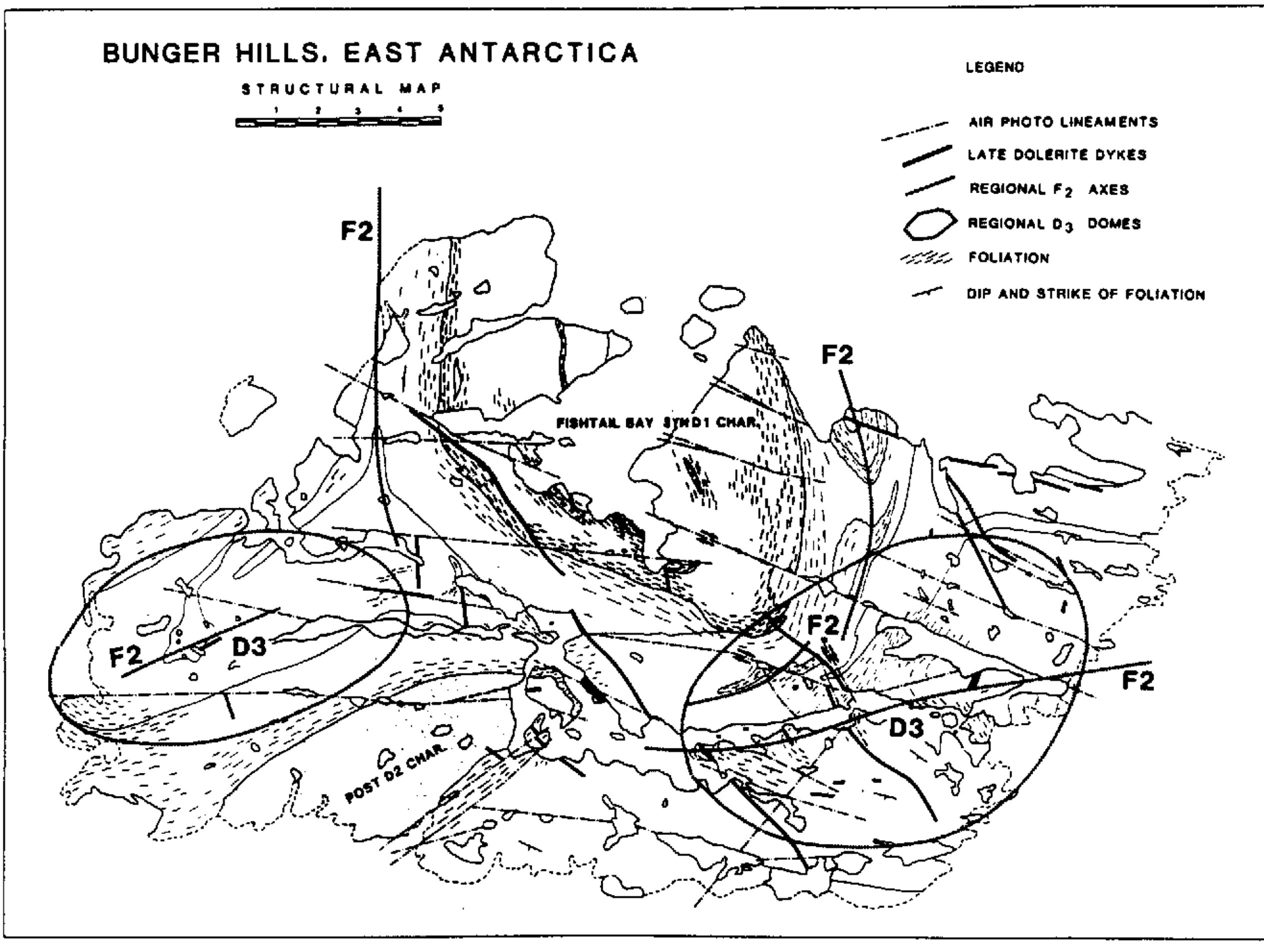


Fig. 3. Structural map of the Bunger Hills.

granite gneisses and the foliated gneisses are generally gradational and difficult to map, but it appears that the massive gneisses intruded the layered sequence prior to all deformation and metamorphism. Subsequent events then deformed and metamorphosed the layered and the massive sequences and the difference in foliation between the two series may be the consequence of strain partitioning. Charnockitic orthogneisses are the dominant lithology in the Obruchev Hills (Fig. 1), outside the mapped area, but occur as part of the massive gneissic sequence within the Bunger Hills.

The Fishtail Bay charnockite

The Fishtail Bay and Figurnoe charnockite bodies are mineralogically and geochemically very similar (Sheraton personal communication 1988) but they have different field appearances and ages relative to the deformation events. Petrographically, both bodies are dominantly hornblende–biotite–pyroxene–quartz gabbros. The Fishtail Bay body is fine-grained, of roughly elliptical shape (Fig. 2) and has steep contacts that are largely parallel to the lithological layering in the enclosing rocks. Only the southern part of the body has clear intrusive relationships. Its outer margins preserve a foliation which is defined by aligned biotite platelets (Fig. 5a) and that follows the contacts throughout the elliptical structure. In thin section, this alignment of biotites is the only obvious foliation that can be recognized. We interpret this foliation to be S_1 and *not* as an intrusive foliation because it is parallel and equivalent to the S_1 foliation in the surrounding gneiss series. The northern closure of the structure is not exposed. The centre of the body is unfoliated (Fig. 6). Small decimetre sized granitic partial melt patches less than 10 cm in diameter are locally developed in foliated parts of the body and are aligned to this foliation (Figs. 5a & b). Garnet is rarely present but may occur in association with minor partial melting (Fig. 5b). Rocks of similar composition to the Fishtail Bay body occur as interlayers in the massive and the layered gneiss series. Because the contacts are generally conformable with the layering in the enclosing gneisses whose mineralogy is also similar to the charnockite, the contact relationships are gradational. Only locally the contacts are intruded by a coarse-grained unfoliated charnockite (Fig. 5c). The most prominent intrusive contacts are associated with the kilometre sized xenoliths at Painted Rock (Fig. 2). The fabric in the charnockite has a strong planar character with a weak steeply plunging lineation defined by biotite, orthopyroxene and feldspar aggregates. Measurements of finite strain intensity using included country rock rafts proved impossible because of the marked inherited planar anisotropy. The foliation trajectories (Figs. 2 and 3) display a general concentric pattern that broadly follows the elliptical shape of the charnockite body. In detail, a perturbation of this trend can be seen at the southern end of the charnockite where the internal foliation cross-cuts the trend of the enclosing country rocks. The strongest foliation and compositional variation are near the outer rim of the body and intensity decreases towards the centre.

The Lake Figurnoe charnockite

This is a sheet like, undeformed intrusive body, sandwiched between charnockitic gneisses belonging to the layered gneiss sequence to the west and migmatitic pelitic and granite gneisses to the south. Mineralogically it is, like the Fishtail Bay body, a quartz-gabbro and quartz-monzogabbro. The convex northeastern end truncates the layered gneiss sequence that contains both F_1 and F_2 folds. The southern end is covered by the ice sheet but there are sufficient islands on the northeast end to ascertain the overall shape and boundary relationships with the enclosing country rocks. The main body is a single-phase intrusion that is coarse-grained (up to 1 cm), unfoliated and has typical igneous textures. Chilled, fine-grained margins may be locally developed that are up to 50 cm wide, indicating that the intrusion of the body occurred at temperatures above ambient conditions. This is also indicated by a narrow contact metamorphic halo of silicified host rock that may be locally developed. Its contacts are layer-parallel but sharp and they dip parallel to the adjacent gneisses. Cross-cutting relationships are indistinct. Adjacent to the contact there are undeformed charnockite apophyses that are injected as subparallel sheets into the quartz–feldspar gneisses. Xenoliths within the charnockite are rare, irregular in shape, up to several metres in size and preserve the earlier S_1 foliation in previously migmatized gneisses (Fig. 5d). A similar cross-cutting charnockite body, outside the area mapped here, has been described by Ravich *et al.* (1968) on the Charnokitovyi Peninsula.

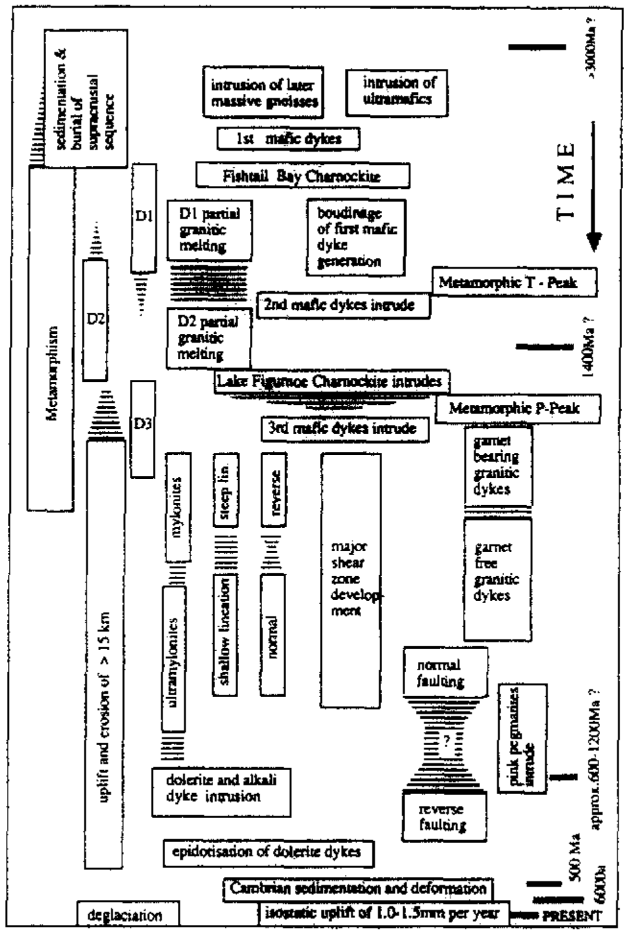
Mafic dykes and pegmatites

Four sets of mafic dykes can be distinguished (Table 2). The earliest dyke set intruded during or prior to D_1 and the peak metamorphic event M_1. These dykes are characterized by two pyroxene plagioclase assemblages and have been extensively stretched and boudinaged during the first deformation (Figs. 7b & c).

The second dyke set has been deformed, folded and metamorphosed at high-grade conditions but has not experienced the high strain the early dykes have undergone. Besides two pyroxenes and plagioclase, hornblende is a common constituent of these dykes. They post-date boudinated D_1 dykes but pre-date the major folding event D_2.

The third and fourth dyke sets post-date all ductile deformation events. The third set was metamorphosed at amphibolite-facies condition and the fourth set is

Table 2. Timetable of events in the Bunger Hills area



contemporaneous with an episode of brittle deformation. This fourth set are the unmetamorphosed dolerite and alkaline dykes that intrude along shear zones and in irregular patterns. The largest of these late dykes is 50 m wide and about 20 km long (Figs. 2 and 3). The dykes are very similar in appearance to dykes in the Vestfold Hills (Collerson & Sheraton 1986) but because of the lack of any absolute dating it is difficult to compare them with each other.

Late felsic intrusives consist of pegmatites made up variably of quartz, feldspars, tourmaline, beryl, garnet, ilmenite and white micas and they may occur as distinct dykes or as irregular pods. Two types of pegmatitic dykes are garnet-bearing and garnet-free; both types are often characterized by distinct biotite haloes in the host gneisses. There are also a number of charnockitic dykes in the area that are texturally and compositionally equivalent to the Lake Figurnoe charnockite body. All of the above described dykes intrude the Bunger Hills in more or less random patterns but are characteristically absent from the two large charnockite bodies.

A 2 km wide ductile thrust zone has been inferred by Ding & James (1987) to exist in the southwest of the area on the basis of (i) juxtaposition of sequences dominated by supracrustal vs predominantly charnockitic gneisses, (ii) truncation of the structural grain and (iii) a narrow belt of highly strained rocks including mylonites with retrogressive microstructures. Evidence for early mylonites (criterion iii) has not been supported by our obser-

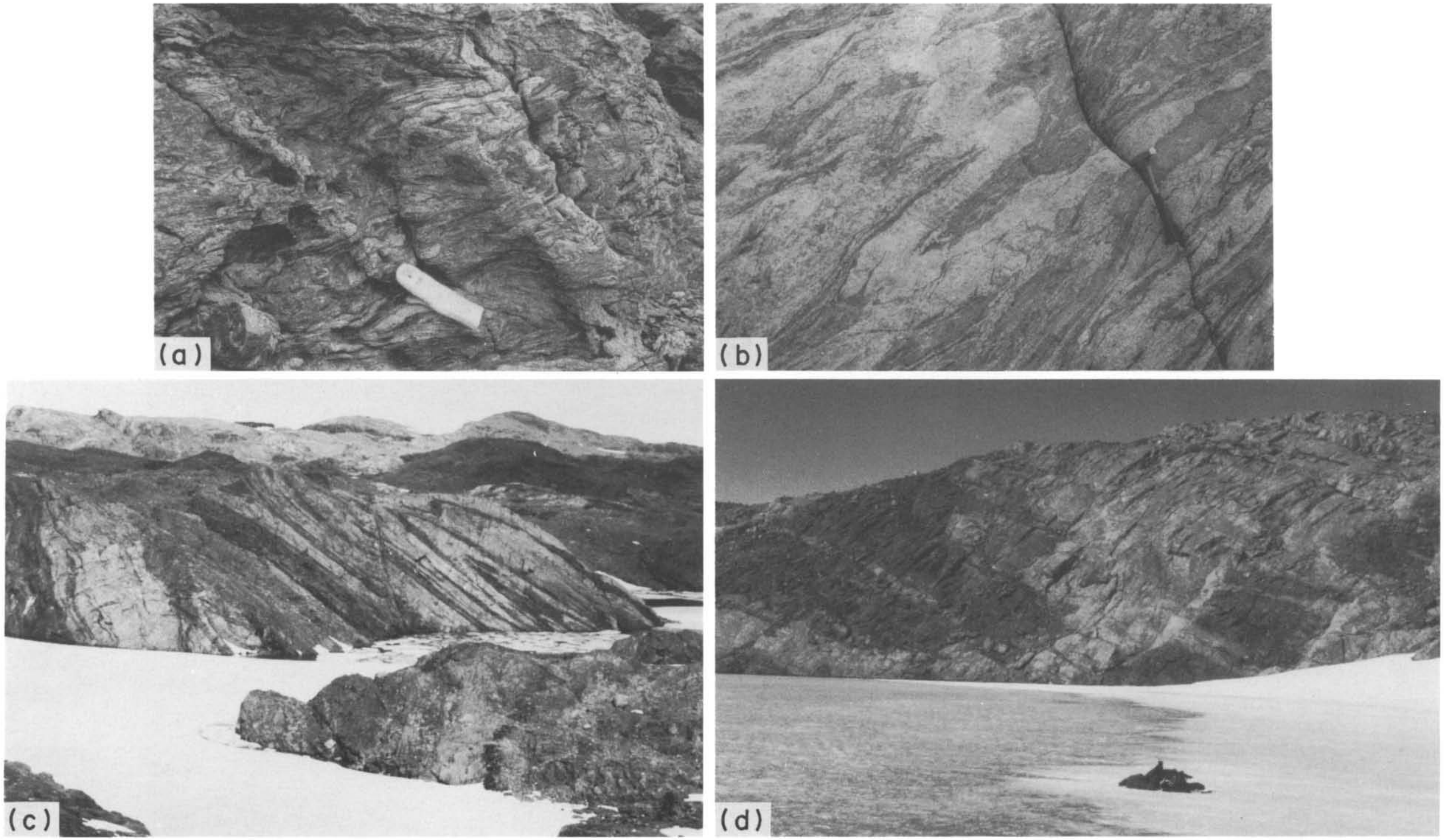


Fig. 4. Features associated with lithological layering and intrusive bodies; (a) migmatized metapelitic gneiss with sausage-shaped partial melt bodies; (b) migmatized felsic gneiss with layer-parallel isoclinally folded partial melt bodies; (c) layered high-grade gneiss sequence near the southeast corner of Lake Figurnoe looking south; (d) massive gneiss series on the south side of Lake Figurnoe.

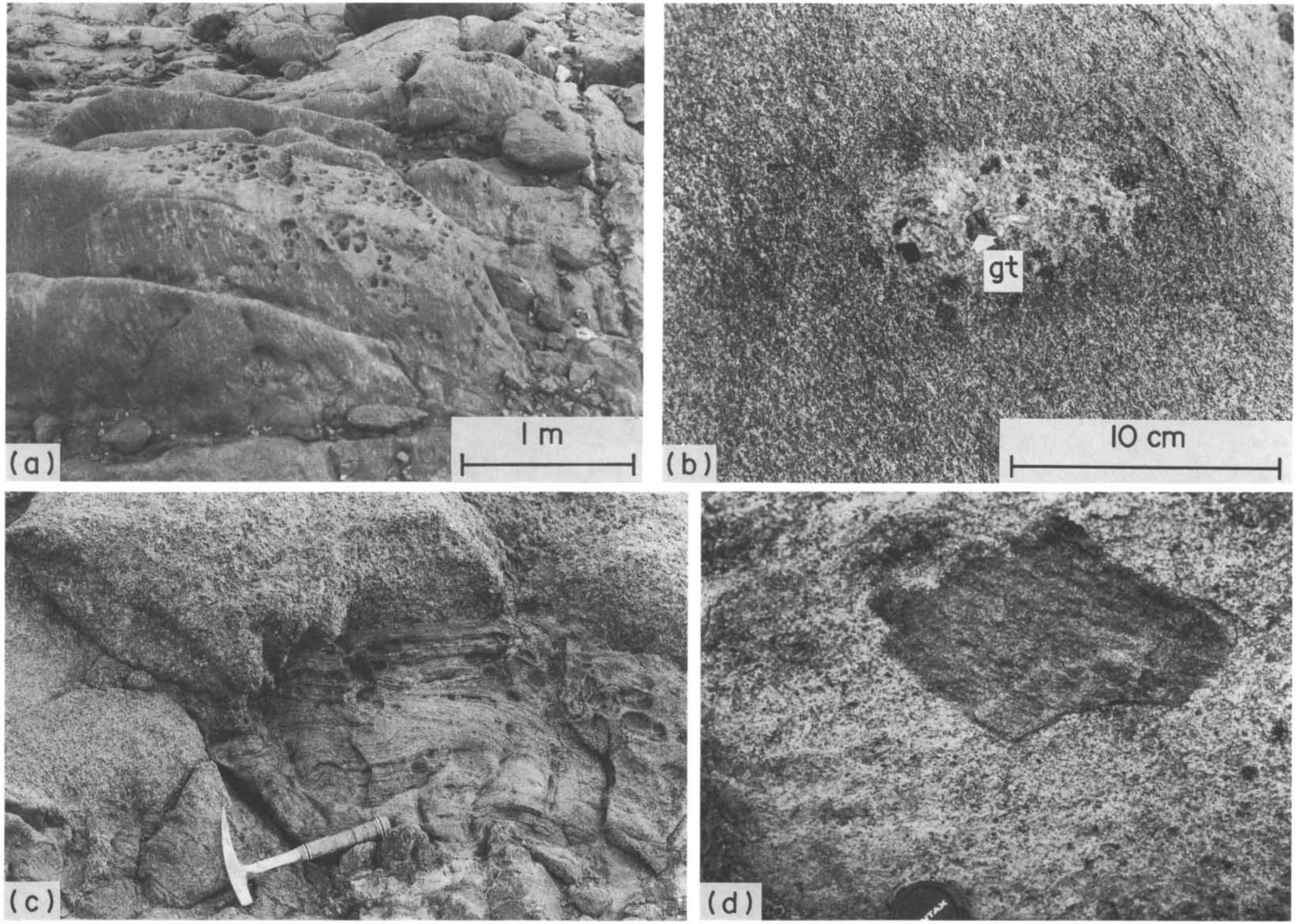


Fig. 5. Features of the charnockites. (a) Biotite-rich Fishtail Bay charnockite with S_1 foliation and small partial melt bodies parallel to the foliation; (b) garnet-bearing granitic partial melt overprinting the S_1 foliation in the Fishtail Bay charnockite; (c) local, intrusive contact between charnockitic gneiss and the Fishtail Bay charnockite on Vertobelnyi Peninsula; (d) xenolith of charnockitic gneiss in the Lake Figurnoe charnockite.

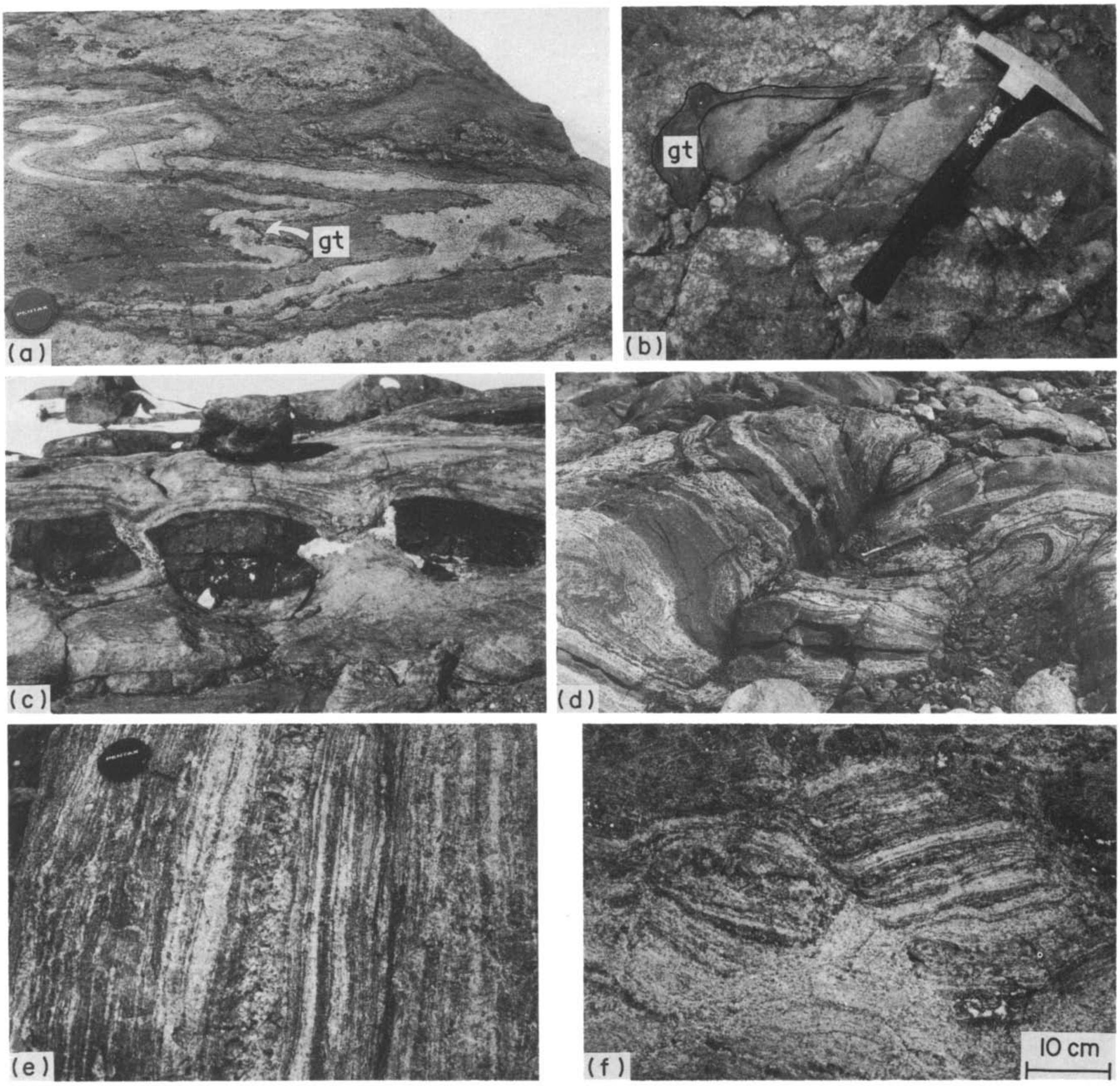


Fig. 7. D_1 deformation features. (a) Oblique section of tight F_1 hinge in QFGC gneiss in a pyroxene-bearing gneiss with garnet reaction crusts along the layer boundaries. There is a prominent S_1 foliation; (b) D_1 mafic boudin circumscribed by garnet reaction crusts and surrounded by QF gneisses that contain D_1 layer-parallel melt segregations; (c) D_1 boudinage of an early mafic dyke with boudin necks infilled with partial melt; (d) isoclinal F_1 folds in QF gneissic layering interbedded with mafic granulites and refolded by F_2. Camp 3 area; (e) D_1 layer-parallel partial melts in pelitic gneiss; (f) D_1 melts forming during boudinage of compositionally intermediate layers and local intrusion of these melts into the boudin necks.

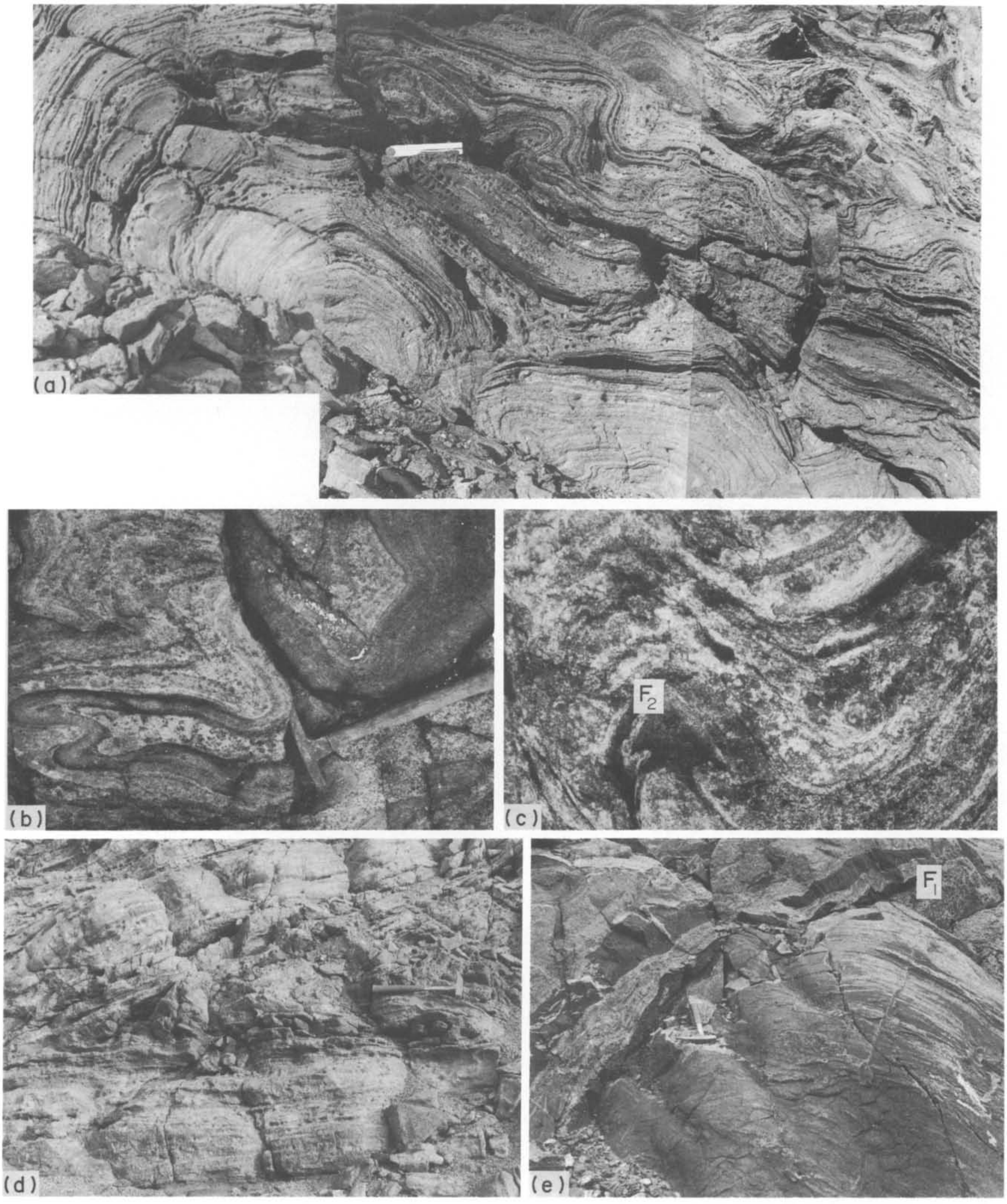


Fig. 10. Interference of D_2 and D_3 with D_1: (a) disharmonic F_2 folds formed in the hinge of a larger scale F_2 fold; (b) type 3 interference pattern; (c) type 2 interference pattern; (d) coaxial interference between an isoclinal F_1 fold and F_2; (e) interference of F_1, F_2 and D_3 doming.

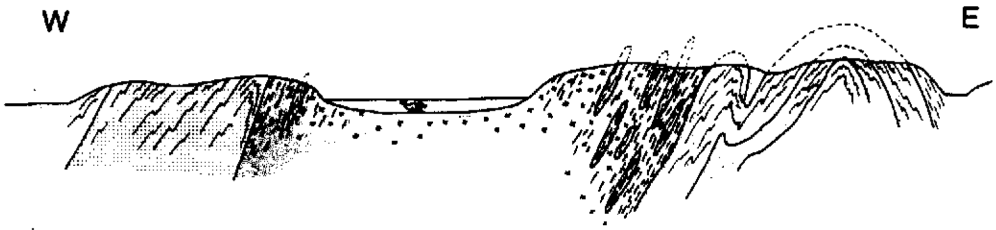


Fig. 6. Structural cross-section B–B′ across the Fishtail Bay charnockite body. See Fig. 2 for location of profile.

vations and the biotite-rich assemblages observed in this area reflect merely more micaceous bulk compositions amongst the QF gneisses. Criteria (i) and (ii) seem to be the only valid arguments, but their validity is in doubt as they could be explained by heterogeneous deformation controlled by the ductility contrasts that exist between a strongly anisotropic supracrustal sequence vs a massive sequence. Moreover, the interpretation of Ding & James would require a tectonic yo-yo, with uplift of the terrain, subsequent reburial and ductile deformation and ultimately excavation to the surface. Such a scenario is strongly contradicted by the metamorphic evolution which involves burial of the terrain after the metamorphic temperature peak (Stüwe & Powell 1989).

D_1 DEFORMATION—CRUSTAL EXTENSION?

The first ductile deformation event (D_1) was an intense flattening event with the local directions of maximum compressive strain throughout the area having a subvertical orientation. As has been demonstrated in many other granulite terrains on the East Antarctic Shield (e.g. Sandiford & Wilson 1984, Stüwe *et al.* 1989) this type of regional strain pattern has generally been regarded as evidence of crustal extension; however, in the Bunger Hills, the evidence is ambiguous. This deformation produced the dominant foliation S_1 and isolated isoclinal, mesoscopic F_1 fold hinges (Fig. 7a) in the layered sequences. S_1 is generally defined by a microscopic layering and planar mineral alignment within the M_1 fabric. A lineation L_1 may be present on S_1 planes as either an intersection lineation between S_0 and S_1 or as linear mineral or partial melt alignment as layer-parallel segregations on the bedding and S_1 foliation surfaces. This L_1 lineation in pelitic and highly migmatized felsic gneisses is defined by oriented sillimanite needles and by small elongate sausage-shaped melt bodies (Fig. 4a), parallel to fold hinges, with dimensional ratios of approximately $X:Y:Z = 10:3:1$ (where $X > Y > Z$ are the principal longitudinal strains). Isolation of these bodies from thinned layer-parallel segregations indicates continued flattening and stretching during and post-dating the D_1 melting. Local sheath folding accompanied by an isolation of F_1 fold hinges from their limbs and the variable presence of S_1 and L_1 suggests that the strain during the first deformation phase was very inhomogeneously distributed.

Recognition of F_1 folds is restricted to intrafolial isoclinal folds in which the S_1 surfaces have been rotated by later deformations. In the southwest one reclined F_1 fold of regional significance was mapped (Fig. 8). This fold is delineated by sillimanite-rich quartz–feldspar–garnet (QFG) gneisses within a quartz–pyroxene gneiss sequence and is characterized by near planar N-dipping limbs and a rounded closure that is flat-lying near the centre of a major D_3 dome around the Camp 1 area, but increasingly W-plunging on the west side of this dome and increasingly steep E-plunging on its east side (Fig. 8).

Boudinage associated with D_1 occurs to an extremely variable degree (Figs. 7b & c). Small mafic layers and ultramafic pods show only weak boudinage by 'necking in' in repeated intervals (Fig. 7c). Boudins of distinct rock types such as pre-D_1 mafic dykes can be seen to be separated from each other for up to hundreds of metres (Fig. 7c). Pre-D_1 mafic dykes display prograde reaction crusts developed between the boudin and the surrounding felsic gneisses (Fig. 7b). These crusts composed of garnet circumscribe individual boudins and therefore suggest substantial pressure increase after the D_1 boudinage.

D_1 under granulite-facies conditions was accompanied by partial melting (Figs. 5a & b). Partial melt segregation is best preserved in metapelitic gneisses. Bodies of partial melt occur as layer-parallel segregations and as small sausage-shaped bodies in fold hinges. Isolation of these bodies from thinned layer-parallel segregations indicate continued flattening and stretching during and after D_1 melting. In intermediate and mafic rocks D_1 partial melts formed during boudinage (Fig. 7f). Major bodies of D_1 partial melt remained only partially *in situ* but also locally intruded the surrounding gneisses (Fig. 7d). Such leucocratic rocks sometimes contain garnet, they are characteristically deformed but unfoliated by S_1 and produce features that resemble extensional crenulation cleavages (Fig. 7f).

Local felsic intrusions and intrusion of mafic dykes mark the transition from D_1 to D_2. These mafic dykes are deformed by D_2 structures but major boudinage is absent. Good examples of mesoscopic, deformed and metamorphosed but unboudinaged dykes occur between Dobrovolsky and Edgeworth David. Although these dykes are lithologically similar to the D_1 dykes, garnet reaction coronas are absent indicating that intrusion post-dated the peak metamorphic event.

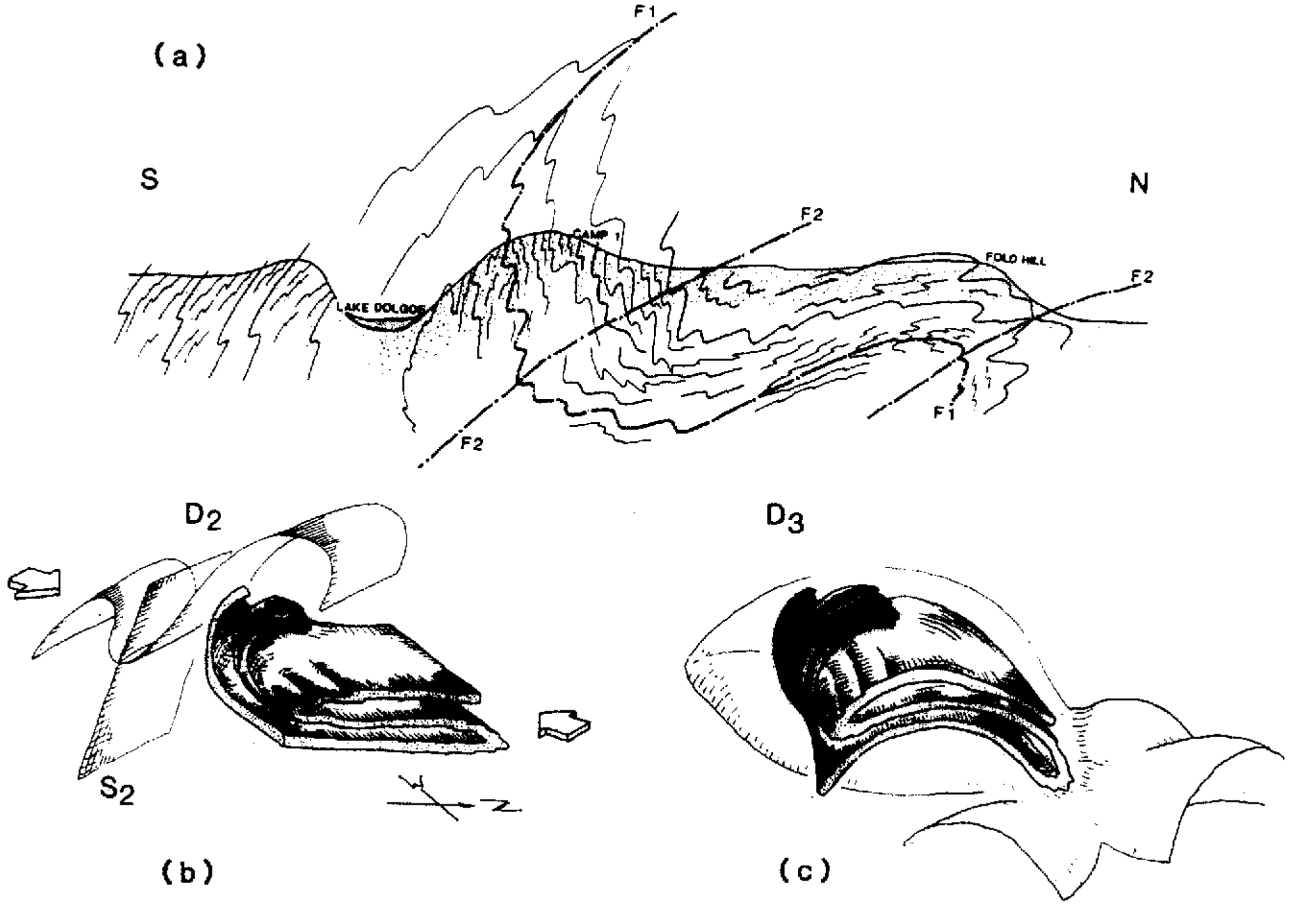


Fig. 8. Schematic structural cross-section and D_1–D_2–D_3 interference in the Camp 1 area. (a) Geological cross-section A–A' across subarea 1 (see Fig. 2) showing the interference between the D_1 and D_2 structures. Thick interrupted lines are axial planes of F_1 and F_2; medium solid lines are F_2 folds; thin solid lines are F_1 folds. Note that F_1 and F_2 folds on the south side of Lake Dolgoe have opposite vergences; same vergences in the Camp 1 area and opposing vergences around Fold Hill. (b) Schematic block diagram showing the not quite coaxial nature of D_1 and D_2. (c) D_3 doming around the Camp 1 area. The section in (a) goes through the middle of the dome.

INTERFERENCE BETWEEN D_1 AND D_2

It is possible to define areas dominated by gently dipping pre-D_2 fabrics and orientations (Fig. 9) and areas reoriented by superimposed F_2 folds (Figs. 8 and 9). It is the relationship between D_1, D_2 and the charnockite emplacement that allows a regional interpretation of the Bunger Hills to be made. Generally, D_2 is the major shortening deformation and most of the outcrop sized cylindrical folds observed in the field are F_2 folds. F_2 folds can be observed on regional scale, and axial traces connecting the outcrops of regional F_2 hinges can be followed for tens of kilometres through the Bunger Hills. Critical areas that display the nature of D_1 and D_2 are subarea 1 and north of the Edgeworth Davis Base. In these areas mesoscopic D_2 structures are abundant, particularly as first-order asymmetrical parasitic folds on the limbs of the major structures. They are typically tight to isoclinal and fold the earlier S_0/S_1 foliation and partial melts (Fig. 10). In major D_2 hinges the F_2 folds are open, but can be disharmonic with variably dipping axial surfaces (Fig. 10a). Tectonic fabrics crystallized during D_2 are typically granoblastic and medium grained (3–6 mm) and there is generally a lack of a distinct axial-planar foliation. A new axial-planar fabric, generally defined by aligned sillimanite is only developed within the QFGA gneiss. L_2 tectonite fabrics defined by the preferred alignment of biotite, pyroxene and melt aggregates are occasionally developed as a weak elongation fabric.

The geometries of superimposed folds are displayed as two-dimensional fold interference patterns on glacial pavements. The shapes of mesoscopic interference patterns depend on the orientation of the section through a three-dimensional interference pattern (Thiessen 1986). Because of the near coaxial nature of most fold structures (Figs. 8b and 10b) the majority of the patterns are type 3 (Ramsay & Huber 1987) but there are type 2–3 transitional patterns (Fig. 10c) due to slightly different attitudes of F_1 with respect to F_2. On a regional scale the dip of S_2 (Fig. 9) is to the southwest with a northward-vergence of the major F_2 folds.

D_2 is the dominant folding event with F_2 folds occurring on all scales in most parts of the Bunger Hills. The general style of D_2 interference on D_1 is illustrated in Fig. 8(b). D_2 is approximately coplanar, but not colinear with the recumbent D_1 deformation. D_1 folds of regional scale are rare in the Bunger Hills and this type 3

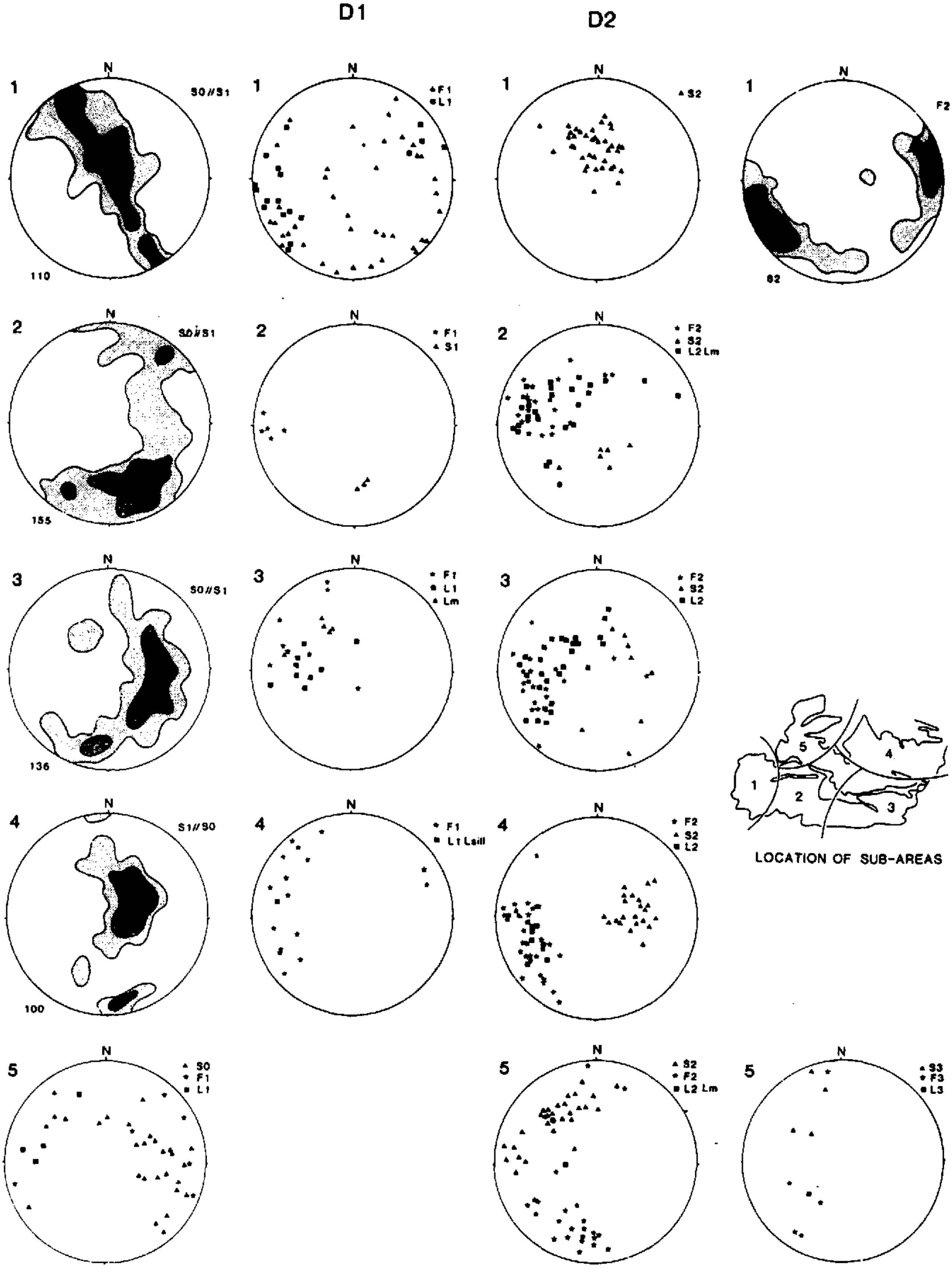


Fig. 9. Lower-hemisphere, equal-area stereographic projections of the structural data from five different sub-areas collected in the Bunger Hills.

interference pattern is associated with a crescent-shaped outcrop pattern within a pelitic gneiss unit (Fig. 2) that defines an asymmetrical, reclined, antiformal F_2 fold that continues north through the Edgeworth David Base and then east to Dobrovolsky (Fig. 3). The Fishtail Bay charnockite truncates this sequence and is in part conformable with another large, asymmetrical F_2 hinge east of Cape Surovyi (Fig. 3).

The orientation of the F_2 folds is highly variable depending on the position of the fold relative to the Fishtail Bay charnockite body (Fig. 3). East of this body (subarea 4) the F_2 fold axes are plunging to the south. South of the body (subareas 2 and 3) they plunge west and on the west side of the body (subarea 5) their dominant directions are north and south. Because of this systematic geometrical arrangement of the regional F_2 axes around the Fishtail Bay body there must be a close association between the second deformation phase and the charnockite body. The best exposed macroscopic F_2 fold crops out in the northeast of the area adjacent to the charnockite body in Fishtail Bay as a reclined anticline. Its axial plane trends N–S and the fold axis is plunging 30–50° to the south. The regional asymmetry of this and the associated folds indicates that it formed after the intrusion of the early charnockite body.

Because of the general subparallelism of F_1 and F_2 fold axes, L_1 is generally preserved in its trend but locally affected in plunge by D_2 (Fig. 8). This similarity in trend of the F_1 and F_2 axes (Figs. 7 and 9) is consistent with continued movement of the sequence to the northeast during both deformations. It seems simplest to consider the D_1 and D_2 events as having developed progressively during the same orogenic event, which suggests that the time span between them could be small.

Most gneisses lack the undeformed reference state required for judging the level of total D_1 and D_2 strain. If markers were present, their existence appears to have been masked by the metamorphic overprint. The only idea of this strain can be obtained from the deformed boudins. Individual D_2 boudins are elongated parallel to F_2 and the separation between boudins in the X or Y direction is always less than the length of the boudin in the XZ or YZ plane. The lack of large separations between D_2 boudins and a small flattening component where $X:Y:Z = 1.5:1:0.7$ suggests that the D_2 finite strain was substantially less than the D_1 finite strain. This D_2 strain is also reflected in features like flattening around and deformation of M_1 porphyroblasts, shear bands and pegmatitic veining in extensional crenulation cleavages. None of these features can be used on a regional scale to delineate zones of high incremental strain as was suggested by Ding & James (1987) as their development is very dependent on the rock type. Within the Fishtail Bay charnockite the D_2 features are only very weakly developed.

D_3—DOMING

The third recognized deformation phase is a strong regional asymmetrical updoming of the area and is accompanied by local ductile folding (F_3) with no penetrative planar fabric development. Two major domes are recognized that are about 15 km apart. The centre of one is located northwest of Lake Dolgoe, the other is near the east margin of the Bunger Hills on Dinniy Peninsula. At both centres S_0 and S_1 are essentially horizontal (Fig. 3, 7). The asymmetry of the domes is shown in Fig. 8. The dome structures are defined by the change in plunge direction of L_1, L_2 and F_2 from a westerly to an easterly direction. This is because prior to the doming event F_2 axes and the lineations were the only horizontal features. Compositional layering is refolded by two fold generations and is therefore steeply dipping. Doming of these bedding planes causes no symmetric interference.

Although D_3 occurs on regional scale only as a doming event, periclinal warps and small folds (Fig. 10e) can be observed on outcrop scale. These folds were found in association with the eastern dome structure. D_3 is of a ductile nature but it is not a folding event in the sense of having a well defined stress field. D_3 occurred probably in response to an initiation of uplift and thus marks the beginning transition towards a brittle regime.

A third set of mafic dykes was emplaced during D_3. These dykes are undeformed but have been metamorphosed at amphibolite-facies conditions. They must therefore have intruded during still relatively high-grade conditions but post-date the major ductile folding events. Initiation of the shear zones started at the end of D_3 and proceeded through much of the cooling history of the rocks.

CHARNOCKITE EMPLACEMENT

One of the prominent structural features of the Bunger Hills is the distribution of the regional structures in a near helicoidal patterns around the two major charnockite bodies. In this section we will show that this cannot be explained by interference of cylindrical folding events but can be attributed to the relative timing of intrusion and deformation and the interaction between intrusion and deformation.

In summary from above, an interpretation of the emplacement history must be consistent with following features: in the Fishtail Bay charnockite it must explain (i) contact-parallel foliation of regionally elliptic shape and a weak lineation, (ii) contacts parallel to lithological layering and an unfoliated centre of the body, (iii) igneous geochemical signature (Sheraton personal communication 1987) and minor partial melting within the body and (iv) orientation of the regional F_2 axes around the body. For the Lake Figurnoe charnockite the model must explain (i) undeformed, coarse-grained, typically igneous textures with stoped, deformed country rock fragments, (ii) intrusion temperatures near 1000°C and (iii) narrow contact metamorphic halo at cross-cutting contacts.

For the Lake Figurnoe charnockite body these features indicate that this body was intruded after the dominant shortening deformation D_2. The layer-parallel contacts and regional shape of the body suggest that intrusion occurred parallel to the steeply dipping layering, pushing aside the layered gneiss sequence, possibly during late ballooning prior to crystallization. This interpretation of the timing of intrusion is consistent with the P–T history of the Bunger Hills. Stüwe & Powell (1989) showed that D_2 occurred during a period of substantial compression with the major textural equilibration occurring towards the end of this compression period. The charnockite body intruded at the end or after this period and no metamorphic textures are present.

The relationship between deformation and the intrusion of the Fishtail Bay body is not as easily explained. Ravich *et al.* (1968) described the charnockite and the arrangement of the gneissic sequence around it as a syncline implying isoclinal folding of the charnockite in its centre. Similarly, Ding & James (1987) interpreted the form as a late isoclinal fold and, for consistency, attribute different folding events to very similar regional F_2 folds in different regions of the Bunger Hills because of their different regional orientation. However, the core of the Fishtail Bay charnockite body is essentially undeformed and strongest deformation features (e.g. foliation) are along the margins. This is consistent with an interpretation as an isoclinal fold in which strongest deformation would be expected in the core. Moreover, we have shown that D_2 and D_3 do not form isoclinal folds on regional scale. The Fishtail Bay body can therefore not be a late fold. Analogously, it cannot be an early F_1 fold because the S_1 foliation curves around the contacts and arrangement of the regional F_2 axes cannot be reconciled with the Fishtail Bay body being a large fold. The elliptic shape of the body and the accompanying foliation must therefore be explained by a different mechanism. Now we will show that the similar F_2 folds of different regional orientation can be explained by interaction between D_2 with the charnockites.

Interference between intrusion and D_1 stress fields is such a mechanism. Ballooning of the charnockite following diapir-like intrusion (Ramberg 1970) and occurring synkinematically with the foliation-forming D_1 event will cause an elliptic shape of the foliation in and around the body. The generally gradational conformable contacts and the coincidence of the early S_1 foliation inside and outside the body suggest that the body intruded syntectonically either prior to or during the first deformation phase. It is suggested that the intrusion direction was inclined upwards towards the northeast without any great truncation of the enclosing foliations (Fig. 3). Brun & Pons (1981) suggested a similar mechanism to account for equivalent structural features associated with granitoid intrusions in Spain. The suggested timing relation is constrained by the absence of pre-D_1 mafic dykes within the body and by the presence of small partial melts. These partial melts may have formed during continued high-grade metamorphism during D_2.

Whereas an interpretation of the interference between intrusion and D_1 is satisfactory in explaining the regional shape of the foliation in and around the body, it remains to explain the absence of D_2 features within the body and the arrangement of the regional F_2 axes in a near helicoidal pattern around the Fishtail Bay charnockite (Fig. 3). We suggest that this can be attributed to the competence contrast between the little deformed homogeneous Fishtail Bay charnockite and the highly migmatised surrounding gneiss sequence. The body may have been disconnected from its root during the first stages of the shortening deformation D_2 and then rotated in a dextral shear environment to cause the asymmetrical arrangement of the regional F_2 axes around the body (Fig. 3). Similar behaviour during post-intrusive deformation phases has been observed by Brun & Pons (1981) and by Zhensheng *et al.* (1988). The interpretation of a substantial competence contrast is supported by following observations. (i) Partial melts, which are very common in the layered gneisses, are practically absent in the Fishtail Bay body. It is therefore possible that D_1 partial melts were present in the rocks throughout the D_1 and D_2 history and enlarged the competence contrast necessary for this interpretation. (ii) The regional variability of the F_2 axes can best be explained by wrapping of the structure around the charnockite body. The nature of the third deformation phase enhances the irregular distribution of the regional F_2 axes. D_3 is an asymmetric doming event with radial periclinal fold axes and the reorientation of F_2 axes did therefore not occur in systematic interference patterns. They were reoriented relative to their position to the centre of the dome structures.

MICROSTRUCTURES AND METAMORPHISM

Two metamorphic events can be recognized in the Bunger Hills. The early M_1 event occurred at about 4 kbar and 800°C, probably towards the end of D_1. These conditions are indicated by the peak assemblages garnet–cordierite–spinel–ilmenite or garnet–sillimanite–spinel–ilmenite–rutile in quartz- and feldspar-bearing pelitic gneisses. The ferro-magnesian M_1 peak assemblages are concentrated along S_1 foliation planes and mineral grains may be strongly elongated parallel to an early L_1 lineation. In sillimanite-bearing gneisses, the sillimanite may be wrapped around strongly flattened garnet grains. Because of the strong association of the mineral alignment parallel to the L_1 stretching lineation and the microlayering we believe that this layering formed during D_1. Later metamorphic events caused coarse-grained overgrowth of most of the early microstructures, erasing most of the early fabrics. For example, the spinel–cordierite–garnet–quartz bands are overgrown by massive, undeformed cordierite and garnet coronas which indicate pervasive textural equilibration at much higher pressures and towards the end of the pervasive ductile deformation phases.

The substantial compression (M_2) that caused the growth of the coronas occurred during minimal cooling.

It was accompanied by the major shortening deformation D_2. M_1 assemblages are folded by D_2, but no new pervasive axial-planar cleavage was formed. Complete textural and compositional equilibration of the assemblages occurred during and up towards the end of the D_2 period. The peak of M_2 occurred at about 6.5 ± 1.2 kbar and 750°C (Stüwe & Powell 1989). The coarse-grained, undeformed fabric crystallized during this event leaving most of the spinel-bearing M_1 assemblages only as relicts. Because of this late coarsening of the fabrics during D_2 there are few corona textures and earlier M_1 assemblages form only small inclusions in the M_2 grains. No microstructures are associated with the late D_3 event.

The microstructures of the Lake Figurnoe and Fishtail Bay charnockite bodies are different and support the interpretation of their different age relative to the deformation phases as presented in this paper. The Lake Figurnoe body bears typically igneous textures with pyroxenes containing abundant exsolution lamaellae that indicate crystallization temperatures of up to 1000°C. Alkali-feldspars in the body crystallized late, filling intergranular spaces and containing wavy inclusion trails that follow the growth lines between other grains. The Fishtail Bay charnockite is finer grained and may have a weak fabric defined by aligned biotite and plagioclase laths (see above). In the Fishtail Bay body the igneous textures are not as obvious and individual grains appear to have recrystallized together with the gneissic sequence. Pyroxene thermometry indicates crystallization temperatures much lower than those of the Lake Figurnoe body and more similar to those of the surrounding gneissic sequence.

BRITTLE DEFORMATION

Towards the end of the ductile deformation events in the Bunger Hills, a complicated history of brittle and semi-brittle deformation commenced that formed shear zones and faults and was associated with the late dolerite dyke emplacement in all parts of the Bunger Hills. The shear zone-forming events and the subsequent brittle fracturing are summarized as D_4. In general, two sets of shear zones can be recognized that strike 110° and 160°, respectively, and most of them dip steeply. The regional sense of displacement along both sets is dextral and individual shear zones may be up to 15 km long and 50 m wide (Fig. 3). The 110° striking set dominates. On outcrop scale, the displacement history of the shear zones is complicated but similar for the two major regional sets. The respective orientations of the two sets and their similar displacement histories might suggest that they form parts of a conjugate shear zone set, however, the same regional displacement along both sets precludes such an interpretation.

The shear zones contain mylonitic fabrics with a strong reduction of the grain size. Competent grains such as garnets may be rolled and rounded within mylonitic fabrics of quartz and feldspar. Retrograde assemblages of hornblende, mica and chlorite are associated with the mylonitization. The asymmetry of the fabrics and an associated steep lineation indicate that displacement along these early mylonites was a reverse thrusting motion. These fabrics may be overprinted by later ultramylonites that are associated with a shallow lineation and account for the strike-slip displacement observed in the field. The relative timing of the steep reverse and the shallow dextral displacement is often difficult to recognize in the fabrics but can be demonstrated with a number of generations of pegmatites that cut the shear zones in the various stages and are displaced by them. A set of pink orthoclase-rich extremely coarse-grained pegmatites cuts the shear zones after their vertical motion but before the lateral displacement along them. Pseudotachylites are often spatially associated with the shear zones. However, as their generation during frictional faulting is inconsistent with the ductile nature of the shear zones, they must have formed during an independent and possibly later event. In fact, we found pseudotachylites that occur along reverse faults that cross cut the earlier shear zones. Nevertheless, pseudotachylites are generally associated with the shear zones, possibly indicating a reactivation of these zones in the brittle field.

REGIONAL INTERPRETATION AND A TECTONIC MODEL FOR THE CHARNOCKITES

From the above presented evidence for multiphase deformation and charnockite emplacement it is possible to establish an integrated picture of the structural evolution of the area (Table 2). This history involves an initial precursor sequence of sedimentary, volcanic and intrusive rocks of possibly Archaean age that were cross cut by mafic dykes. An intense early deformation formed recumbent folds that are only in some areas of regional extent and caused intense boudinage of the mafic dykes. The northern Fishtail Bay charnockite body intruded during this early deformation. The interference of the intrusion with the still acting D_1 deformation allowed the S_1 foliation to penetrate the margins of the intrusive body. D_2, which followed this event was the major shortening deformation and occurred in a compressive simple shear environment.

The time break and transition between D_1 and D_2 is difficult to evaluate. If D_1 was in fact extensional, it is difficult to explain the change into a compressive regime (during D_2) in a continuous evolution. Houseman & England (1986) have shown that crust undergoing extension due to thermal perturbation in the mantle will generally not be self-limiting and will consequently continue until rifting occurs. Moreover, Stüwe & Powell (1989) have shown that the thermal perturbation that is responsible for regional metamorphism in the Bunger Hills occurred during a period of thickening of previously thinned crust rather than in a period of thinning. It is therefore likely that the thermal perturbation weakened the thin crust to a degree where gravitational collapse occurred (Stüwe & Powell 1989). Consequently, an *extensional* D_1 would have to have occurred essentially separate from D_2. For this, however, there is no field or microstructural evidence.

Alternatively, if D_1 was a compressional event, immediately preceding the D_2 deformation, it is difficult to account for the intense boudinage of the dykes, the recumbent nature of the F_1 folds and, most of all, the intense flattening fabric associated with this early deformation. The intense fabric is especially difficult to explain as the compression would have the characteristics of a passive collapse rather than active compression.

D_2 occurred after the intrusion and crystallization of the northern charnockite body in a dextral shear environment. This is indicated by the arrangement of the regional F_2 axes around the Fishtail Bay body. The intrusion of the Lake Figurnoe charnockite body occurred at the end of D_2 and therefore after the intrusion of the Fishtail Bay charnockite. This interpretation contradicts the interpretations of Ding & James (1987). The structural evidence precludes the interpretation of a same age for the two bodies, as at least the period of D_2 was free of any major charnockite intrusion.

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