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The structural evolution of the Fyfe Hills–Khmara Bay region, Enderby Land, East Antarctica

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Five generations of structure (D_1–D_5) have been recognized in the Early Archaean supracrustal gneisses in the Fyfe Hills–Khmara Bay region in Enderby Land, East Antarctica. The D_1, D_2 and D_3 events comprise the Napier structural episode. They resulted in pervasive deformation during Archaean granulite facies metamorphism, and predated the intrusion of the Middle Proterozoic Amundsen dykes. The Napier metamorphic culmination was broadly coeval with, but outlasted both, D_1 and D_2. D_3 occurred during waning granulite facies metamorphism. The D_4 and D_5 events comprise the Rayner structural episode, the effects of which are largely restricted to amphibolite facies retrograde shear zones in which the Amundsen dykes are deformed. The Napier Structural Episode is characterized by: (i) mesoscopic, isoclinal, recumbent, F_1 folds which formed during intense deformation accompanying the prograde burial of the gneissic sequence; (ii) large scale, tight to isoclinal, reclined F_2 folds formed at deep crustal levels; and (iii) large scale, non-cylindrical, asymmetric, upright F_3 folds formed in response to differential vertical movements during the final stages of stabilization of the gneissic sequence. The development of a pervasive mesoscopic gneissic layering associated with the Napier structures is attributed to a variety of processes, only some of which are related to deformation mechanisms. The Rayner structures are restricted to amphibolite grade high strain zones which formed in response to displacements between essentially rigid blocks of granulite. Progressive localization of D_4 and D_5 structures within the retrograde zones, ultimately resulting in the development of pseudotachylite, reflects deformation at successively higher crustal levels during the excavation of the gneissic sequence.

Key words: Antarctica, Archaean, granulite facies, structure, recumbent gneiss terrain, retrograde shear zones.

INTRODUCTION

The Fyfe Hills–Khmara Bay region in Enderby Land, East Antarctica (Fig. 1), occurs near a major tectonic boundary between the Archaean Napier Complex and a region of pervasive Late Proterozoic reworking termed the Rayner Complex (Sheraton *et al* 1980); and is, by virtue of the extensive isotopic research at Fyfe Hills in recent years (Sobotovich *et al* 1976; DePaolo *et al* 1982; Grew *et al* 1982; McCulloch & Black 1983; Black *et al* 1983a, 1983b), one of the critical areas in the Precambrian of East Antarctica. The results of an investigation of the structural geology of the Fyfe Hills–Khmara Bay region are described herein. The principal aims of this research are to elucidate the tectonic behaviour and evolution of this complexly deformed Archaean granulite terrain, and to establish a relative structural chronology as a basis against which the timing of other geological events may be evaluated. The stratigraphy, petrography and chemistry of this region will be described elsewhere (Sandiford & Wilson unpubl. results).

THE STRUCTURAL GEOLOGY OF ENDERBY LAND: BACKGROUND TO THE PRESENT STUDY

In the only detailed studies of the structural geology of Enderby Land, Griffin (1979) and James and Black (1981) identified three phases of folds, broadly contemporaneous with granulite facies metamorphism in the Amundsen Bay area of the Napier Complex. These folds pre-dated the intrusion of a suite of locally abundant dolerite dykes, termed the Amundsen dykes (Sheraton *et al* 1980), which have yielded Rb–Sr whole rock isochron ages of

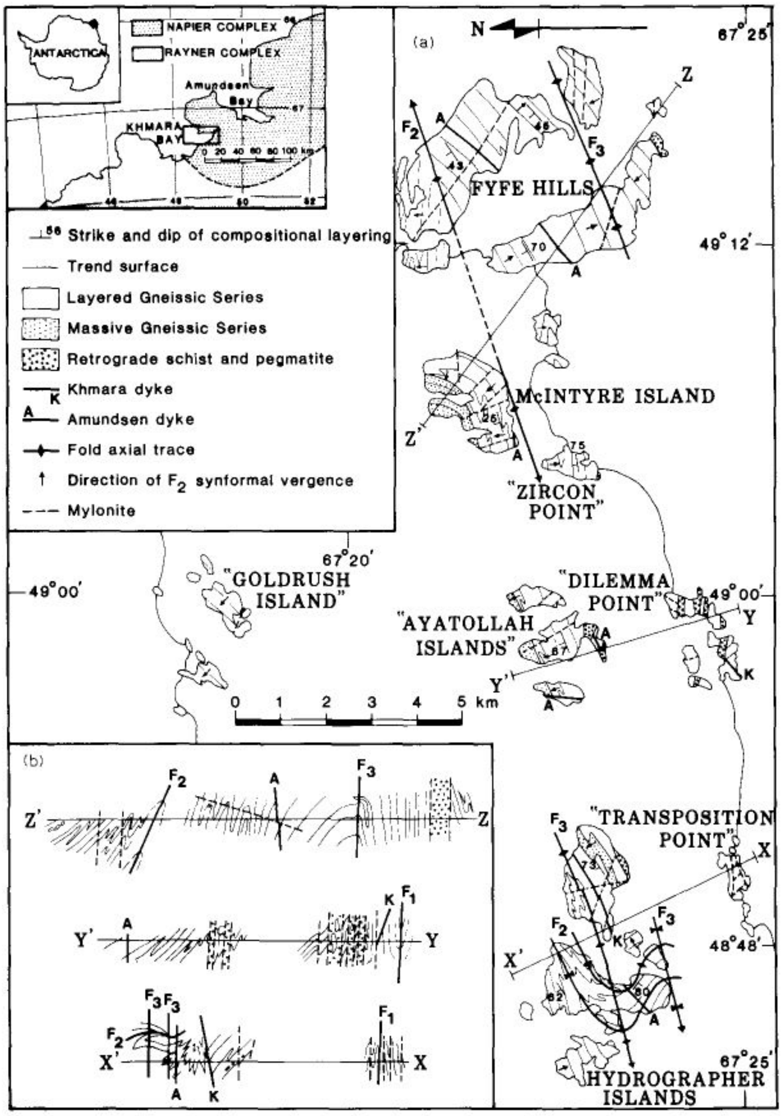

Fig. 1a Structural map of the Fyfe-Hills Khmara Bay region, Enderby Land, East Antarctica. **Fig. 1b** Diagrammatic cross sections through the Fyfe Hills-Khmara Bay region (at the same scale as Fig. 1a).

1190±200 Ma (Sheraton & Black 1981). Furthermore, Sheraton *et al* (1980) suggested that these granulite facies folding events pre-dated the intrusion of a suite of now metamorphosed tholeiitic dykes (the B_2 dykes) in the Amundsen Bay region, which have been dated at 2400±250 Ma (Sheraton & Black 1981); and which are chemically and mineralogically similar, and possibly equivalents of the Khmara dykes of the Fyfe Hills–Khmara Bay region.

The F_1 and F_2 folds in the Amundsen Bay region are large scale, recumbent, isoclinal structures with wavelengths up to (at least) 10 km (Griffin 1979, unpubl. results). Their formation resulted in the development of an essentially horizontal gneissic pile (James & Black 1981). Subsequent folding about large scale, open, non-cylindrical F_3 folds probably resulted in the development of the regional scale dome and basin outcrop pattern distinctive of the Napier Complex (Ravich & Kamenev 1975;

James & Black 1981). Sheraton *et al* (1980), Sandiford and Wilson (1983) and Black *et al* (1983b) described late deformation structures from discrete retrograde shear zones (RSZ). The Amundsen dykes were observed to be deformed and metamorphosed within these zones, but retained their igneous textures elsewhere. Geochronological studies in the Napier Complex, based on Rb–Sr, Nd–Sm, and U–Th–Pb systems (Grew & Manton 1979; Sheraton & Black 1981; James & Black 1981; DePaolo *et al* 1982; Grew *et al* 1982; Black & James 1983; McCulloch & Black 1983; Black *et al* 1983a, 1983b), confirm that the granulite facies deformation events within the Napier Complex occurred during the Mid to Late Archaean (Table 1). However, the precise ages of the deformation events and their relationship to the crystallization of metamorphic assemblages is the subject of varying interpretations (Table 1). Many of the problems associated with chronological studies in the Napier Complex, and in most high grade gneissic terrains, stem from problems in the interpretation of early formed fabrics (Black *et al* 1983a). In particular, the relationship between the formation of the gneissic layering, the evolution of structures and crystallization of metamorphic assemblages is essential to any interpretation of time sequence data, and its elucidation is one of the aims of this contribution.

The structure of the Rayner Complex, which bounds the Napier Complex along its continental margin, is controlled principally by tight upright folds formed during granulite and/or amphibolite facies metamorphism (Sheraton *et al* 1980). The occurrence of highly deformed and metamorphosed basic dykes, believed to be relics of the Amundsen dykes, suggests that the Rayner Complex represents, in part, reworked Napier Complex (Sheraton *et al*1980). Syn-metamorphic charnockites from Molodezhnaya in western Enderby Land have yielded a Rb–Sr isochron age of 987 ± 60 Ma, and provide the best available constraint on the age of the Rayner metamorphism (Grew 1978). Sheraton *et al* (1980) suggested that this metamorphism may correlate with the initiation of RSZ in the Napier Complex; a suggestion for which tentative support is provided by evidence for 1000 Ma old Pb loss in Napier zircons from Khmara Bay (Grew *et al* 1982). Late stage mylonitic RSZ, which are morphologically similar to RSZ in the Napier Complex, also occur in the Rayner Complex (Grew 1978; Sheraton *et al* 1980). Pegmatite minerals from Rayner mylonite zones at Molodezhnaya (Rayner Complex) have yielded U–Th–Pb ages of 500–550 Ma (Grew 1978); an age also recorded from late pegmatites in the Napier Complex (Grew & Manton 1979; Black *et al* 1983a). Reconnaissance studies suggest that the boundary between the Napier and Rayner Complexes is relatively narrow, particularly in western Enderby Land where it is less than 20 km wide (Sheraton *et al* 1980). This boundary may therefore represent a major crustal structure. The present lack of data pertaining to the origin of this structure represents a major deficiency in our understanding of the tectonic evolution of Enderby Land.

Thus, presently the structural evolution of Enderby Land is seen to comprise at least four deformation events extending from the Middle to Late Archaean through to the Late Proterozoic/Early Palaeozoic. At the highest metamorphic grades, during the Archaean granulite facies Napier

Table 1 Sequence of structural, microstructural and metamorphic events described in the Fyfe Hills–Khmara Bay region, together with principal stratigraphic and magmatic events.

	Stratigraphic component	Structural event	Metamorphic event	Age (Ga)
	Layered Gneissic Series			3.5[1]
	Massive Gneissic Series			
Napier		D_1		3.1[2]–2.5[1,3]
Structural	Napier Pegmatites	D_2	M_1	3.1[2]–2.5[1,3]
Episode	Khmara Dykes	D_3	M_2	2.35[4]–2.5[2-4]
	Amundsen dykes			1.2[5]
Rayner		D_4	M_3	0.5[6]–1.0[3,4]
Structural	Rayner pegmatites	D_5	M_4	0.5[4,6]
Episode	Alkaline dykes			0.49[7]

[1] DePaolo *et al* (1982). [2] Black *et al* (1983a). [3] Grew *et al* (1982). [4] Black *et al* (1983b). [5] Sheraton & Black (1981). [6] Grew & Manton (1979). [7] Black & James (1983).

metamorphism, pervasive ductile deformation produced regional folding. Late Proterozoic deformation during retrograde granulite and amphibolite facies conditions resulted in regional folding in the Rayner Complex, and, possibly, the initiation of RSZ in the Napier Complex. The youngest recognized deformation, during the Early Palaeozoic, apparently resulted in the development of mylonite zones in both the Napier and Rayner Complexes (Grew 1978; Sheraton *et al* 1980).

STRUCTURAL ELEMENTS

Detailed structural mapping, with the aid of base maps prepared from low level colour aerial photographs (National Mapping, Simpson Peak, Runs 4-7, CAS/C 8655-CAS/C 8654), was carried out on all major outcrops at Fyfe Hills and in the southern part of Khmara Bay (Fig. 1). The near 100% exposure on individual outcrops allows for excellent structural resolution at the outcrop scale, though the spatial isolation of individual outcrops prohibited stratigraphic correlation across the area, and provides a major limitation to resolution of the macroscopic structure. A further limitation to structural resolution is imposed by the absence of younging criteria within any of the gneisses (Sandiford & Wilson unpubl. results).

The general style of outcrop pattern is illustrated in the structural maps of Ayatollah Island and Dilemma Point (Fig. 3) which, together with the cross-sections (Fig. 1b) and geometric data (Fig. 4) illustrate the geometrical and spatial configuration distinctive of the Fyfe Hills region.

Five temporally distinct generations of tectonic structure (D_1-D_5, Table 1) have been identified on the basis of overprinting criteria. A large variation in style within each generation of structure and a general paucity of tectonite fabrics has rendered the chronological characterization of many individual

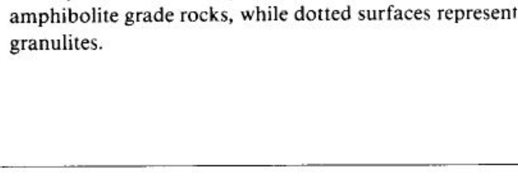

Fig. 2 Diagrammatic block of the Fyfe Hills and McIntyre Island outcrops. Lineated surfaces represent amphibolite grade rocks, while dotted surfaces represent granulites.

structures difficult. However, the structural succession described below is validated by the fact that each structural generation, apart from D_1 and D_2, is associated with distinct sets of mineral assemblages (Table 2) (Sandiford, in press and unpubl. results).

The structure of the Fyfe Hills-Khmara Bay region is dominated by macroscopic, shallow plunging, predominantly east trending F_2 and F_3 antiforms (Figs 1, 2). The F_2 folds overprint a set of earlier (D_1) mesoscopic, isoclinal structures, which, in turn, deform the primary compositional layering. The orientation of D_1 and D_2 fabric elements are controlled principally by F_3 structures (Fig. 4), although the near coaxial nature of the first three generations of folds indicates that, in general, only minimal reorientation of F_1 and F_2 axes occurred during D_3. The Hydrographer Islands provide an exception to this rule (Fig. 1). Khmara dykes are typically located in zones of high D_3 strain suggesting an association between their intrusion and deformation. Limbs of F_3 folds are cut by undeformed Amundsen dykes, which in turn are deformed and metamorphosed within a set of variably striking, generally steeply dipping RSZ. Two distinct generations of structure (D_4 and D_5) have been identified in the largest RSZ characterized by schistose and mylonitic fabrics, respectively. Metamorphic foliations, defined by gneissose, schistose and mylonitic fabrics, are associated with each of the five deformation 'events'. D_1 and D_2 structures frequently exhibit uniform, medium grained (3-6 mm), granoblastic microstructures. These microstructures characterize a pervasive mesoscopic gneissic layering developed throughout the Fyfe Hills region.

D_1 structures are observed in virtually all lithological components of the high grade gneissic pile including both the Layered and Massive Gneissic Series (Sandiford & Wilson unpubl. results); the only exceptions being rare, sill-like pyroxene gneisses on McIntyre Island which show discordant intrusive contacts in the hinge regions of F_2 folds (Sandiford & Wilson unpubl. results). There observations imply that the processes of crustal formation by magmatic addition in the Fyfe Hills region (Black *et al* 1983a; Sandiford & Wilson unpubl. results), were essentially complete by the onset of D_1. However, there is evidence from other parts of the Napier Complex (Griffin unpubl. results; Sheraton & Black 1983) that the intrusion of the felsic magmas which comprise the Massive Gneissic Series (Sandiford & Wilson unpubl. results) was, on

Table 2 Diagnostic mineral associations for each rock type (Sandiford & Wilson unpubl. results) and each fabric element and microstructural/metamorphic association recognised in the Fyfe Hills region. Abbreviations: op orthopyroxene; mp mesoperthite; qz quartz; kf K-feldspar; pl plagioclase; il ilmenite; bt biotite; cp clinopyroxene; gt garnet; hb hornblende; sh sphene; gd gedrite; cu cummingtonite; ol olivine; kt kaersutite; sp spinel; sa sapphirine; si sillimanite; ky kyanite; st staurolite; mu muscovite; mg magnetite; gr grunerite; bf Ba-feldspar; sc scapolite; wo wollastonite; cc calcite. Minerals and assemblages for which there is only poor evidence for existence during the designated event are placed in parentheses.

Structural event Microstructural/ metamorphic association	D_1 M_1	D_2 (Napier assemblages)	D_3 M_2	D_4 M_3	D_5 M_4
Gneiss type					
Quartz–feldspar pyroxene gneiss	op–mp–qz–il op–pl–qz–il	op–mp–qz–il op–pl–qz–il	op–pl–kt–qz–il	bt–pl–kf–qz	bt–pl–kf–qz–gt
Pyroxene gneiss	op–cp–pl–il	op–cp–pl–il	op–cp–pl–gt–hb–il	hb–gt–pl–il hb–gd–pl–il	hb–pl–sh hb–cu–pl–ilm
Ultramafic gneiss		ol–op–cp–kt–mg sa–op–sp			
Garnet–feldspar gneiss		gt–mp–sa–op–qz op–si–qz	kf–si–gt–qz	gt–ky–pl–bt–gd–(st)	gt–cd–si–pl–qt–(st) si–qz–mu–bt
Meta-ironstone		mg–op–cp–qz gt–cp–mg–bf		(mg–gr–qz)	
Calc-silicate		gt–cp–pl–sc wo–cc–qz			
Khmara dyke			cp–gt–pl–op–hb–il	hb–pl–gt–il	hb–pl–il
Amundsen dyke				hb–pl–gt–il	hb–pl–il

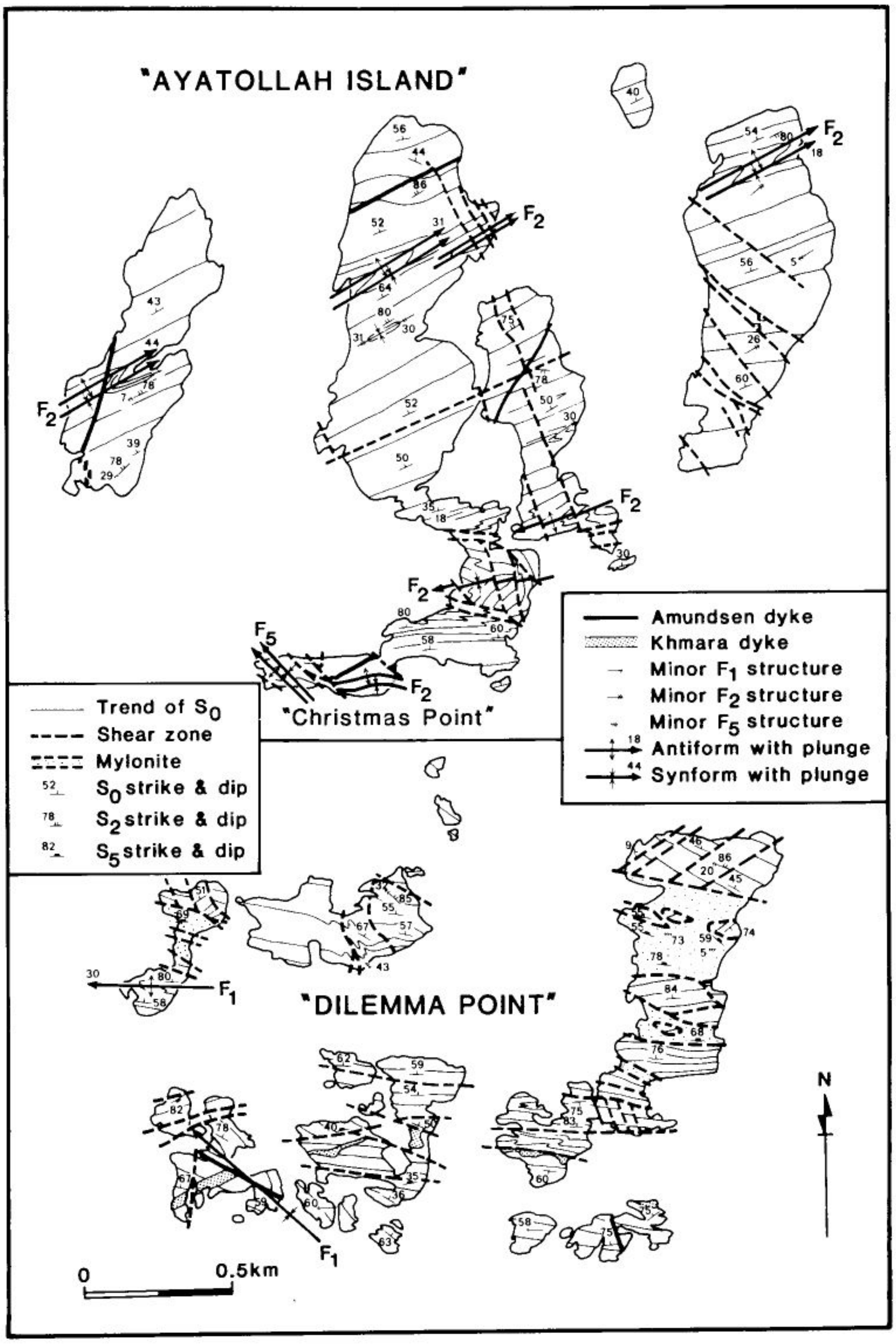

Fig. 3 Detailed structural maps of Ayatollah Islands and Dilemma Point illustrating the typical outcrop pattern in Khmara Bay.

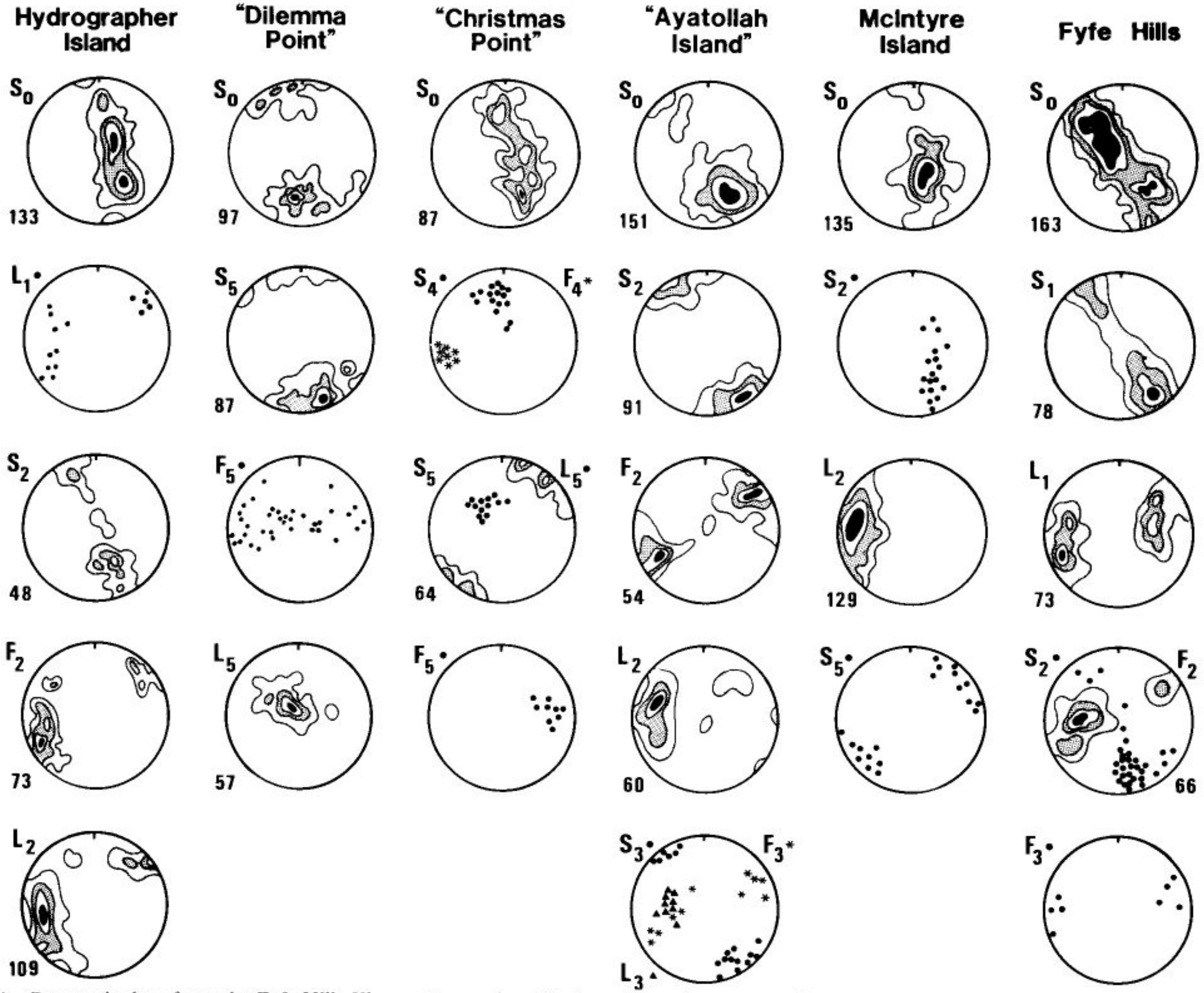

Fig. 4 Geometric data from the Fyfe Hills-Khmara Bay region. Contour intervals are approximately 1, 3, 6 and 10% per 1% area. All S-surfaces are plotted as poles.

a regional scale, broadly coeval with this early recumbent deformation.

THE NAPIER STRUCTURAL EPISODE

D_1, D_2 and D_3 structures formed prior to the intrusion of the Middle Proterozoic Amundsen dykes (Fig. 1), and thus distinguish the Napier structural episode. Both D_1 and D_2 resulted in the development of mesoscopic layered gneissic fabrics which contain assemblages indicative of unusually high grade granulite facies metamorphism (Table 2) (Sandiford unpubl. results). D_3 structures contain retrograde garnet-granulite assemblages.

The macroscopic gneissic layering

The Fyfe Hills region is characterized by a pronounced compositional layering developed on all scales from 0.1 m to 50 m thick (Sandiford & Wilson unpubl. results), and thus resembles many other parts of the Napier Complex (James & Black 1981). James and Black (1981) concluded that this distinctive macroscopic lithological layering results largely from tectonic interleaving during a regime of intense subhorizontal shortening. While recognizing that deformation has profoundly affected the nature of the lithological relationships in the Fyfe Hills region (Fig. 7d), there is considerable field and geochemical evidence that, on its largest scale, this compositional layering results primarily from the intrusion of felsic gneiss (charnockite and enderbite) into a pre-existing supracrustal sequence (Sandiford & Wilson unpubl. results).

The mesoscopic gneissic layering

A high grade gneissic layering, distinct from the macroscopic gneissic layering, is defined by cm-scale variations in mineral distribution (Fig. 5). The principal microstructure in this layering is a medium to coarse grained (2–10 mm) granoblastic microstructure defined by the highest grade (Napier) assemblages (Table 2). The formation of this layering may be attributed to a number of processes, namely: (i) transposition, flattening and attenuation of pre-existing compositional variations (Figs 5a–c); (ii) segregation and localization of melt (Fig. 5d), particularly within garnet–feldspar and quartz–feldspar–pyroxene gneisses; (iii) palimpsest crystallization along pre-granulite metamorphism chemical anisotropies (Fig. 5e); and (iv) reaction zoning between adjacent compositional layers of contrasting composition (Fig. 5f). In some cases, the mesoscopic gneissic fabric apparently results from the interaction of a number of these processes (Figs 5a, d). Some of these processes allowed for preservation of structures formed prior to the Napier structural episode (Fig. 5e), while others postdate the formation of F_2 folds (Fig. 5f). In the light of these observations, the value of this layering in providing unequivocal timing relationships and overprinting criteria must be doubted. Of particular importance to geochronological studies is the recognition that this layering preserves pre-D_1 structures, either tectonic or sedimentary in nature, which involved the production of a cm-scale chemically differentiated layering (Fig. 5e).

The D_1 structural event

The earliest recognizable structural event is characterized by: (i) mesoscopic, isoclinal, subsimilar folds marked by extreme limb attenuation and hinge thickening (Figs 6a–c); (ii) a transposed gneissic layering (Fig. 5c); (iii) an axial schistosity defined by quartz-flaser textures (Fig. 6d); and (iv) boudins (Fig. 7). A stretching lineation (L_1) defined by elongation of platy quartz grains in S_1 is locally well developed. The only recognized macroscopic F_1 folds occur at Dilemma Point (Fig. 3), and thus bulk stratigraphic repetitions due to large recumbent folds appear to be uncommon, although local stratigraphic repetitions due to tectonic slides may be common (Fig. 7f). The typical exposure of mesoscopic F_1 folds on flat pavements prohibited collection of sufficient geometric data to document regional variations in F_1 orientation. However, the characteristic Type 3 interference patterns (Ramsay 1967) between F_1 and F_2 folds suggest that F_1 and F_2 are nearly coaxial with axial planes inclined at 23–50° (Fig. 6c). F_1 axes always parallel L_1. The geometry and style of D_1 structures, together with the inferred sub-horizontal attitude of the enveloping surfaces of subsequent fold generations, imply that the D_1 folds were initially recumbent (James & Black 1981).

D_1 boudins have been identified where they are overprinted by S_2 fabrics (Fig. 7a). The boudins are composed predominantly of ultramafic, and to a lesser extent pyroxene–feldspar gneisses where they are bounded by quartzo–feldspathic gneiss. Diopsidite and pyroxene–feldspar boudins are typically medium grained, oblate discs with length at least

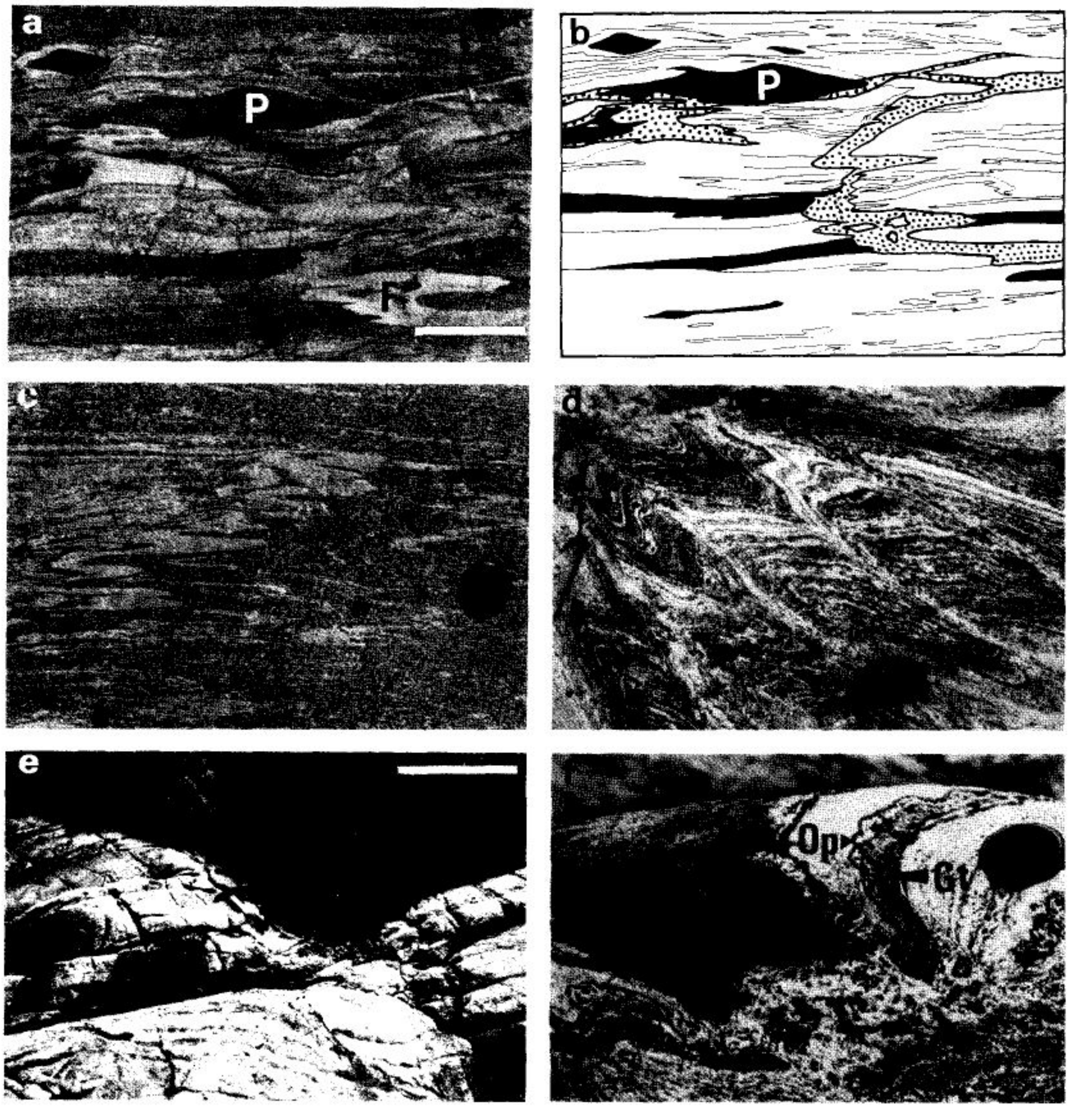

Fig. 5 Variations in the style of the mesoscopic gneissic layering. **Fig. 5a, b** Gneissic layering developed as result of transposition and attenuation of pyroxene gneiss (P), and anatexis and mobilization of felsic gneiss (F) in a composite quartz-feldspar-pyroxene and pyroxene-feldspar gneiss, Fyfe Hills. Bar scale is 10 cm. **Fig. 5c** Mesoscopic layering developed in quartz-feldspar leucosomes as the result of transposition in the hinge region of mesoscopic F_1 fold, Transposition Point. **Fig. 5d** Anatectic leucosome in garnet-feldspar gneiss defines a new gneissic layering parallel to the axial plane of F_2 folds, and truncates an early formed gneissic fabric which is folded about F_2, McIntyre Island. **Fig. 5e** Gneissic layering in raft of garnet-feldspar gneiss represents palimpsest crystallization of a pre-Napier structure, either sedimentary or tectonic in origin, as it is truncated by an intrusive charnockite which itself contains D_1 structures, McIntyre Island. Bar scale is 50 cm. **Fig. 5f** Reaction zoning in garnet (Gt)–orthopyroxene (Op)–plagioclase gneiss resulting in a palimpsest gneissic layering, McIntyre Island. The orthopyroxene–plagioclase reaction zone completely circumscribes, and thus postdates, D_2 boudins.

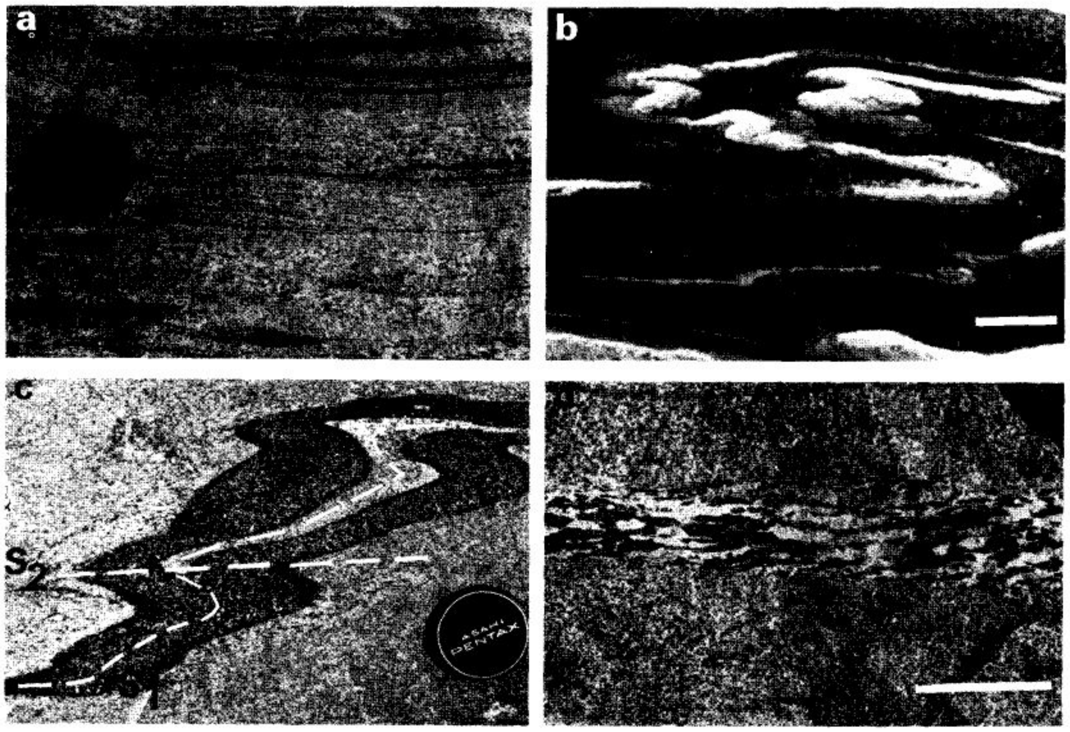

Fig. 6 D_1 structures. **Fig. 6a** S_1 fabric in transposed gneissic sequence, with relict isoclinal F_1 hinges, Mount Novogodnaya. **Fig. 6b** F_1 isoclines in felsic layers, showing hinge thickening and limb attenuation, Ayatollah Islands, Bar scale is 30 cm. **Fig. 6c** F_1 isocline refolded about F_2 folds giving rise to a Type 3 interference pattern, Hydrographer Islands. S_1 and S_2 schistosities are indicated. **Fig. 6d** S_1 quartz–flaser texture in thin quartz–feldspar gneiss within pyroxene–feldspar gneiss, Mount Novogodnaya. Bar scale is 5 cm.

twice their breadth; they are generally less than 2 m long and are flattened in the plane of the S_1 foliation (Fig. 7a). In comparison, orthopyroxene boudins often form coarse to very coarse grained (up to 15 cm) irregular spheroids up to 10 m long which show no systematic orientation with respect to the enclosing foliation (Fig. 7b). Large orthopyroxene boudins commonly contain anorthositic veins possibly resulting from anatexis during the initial rupture of the boudin (Figs 7c, 7d). D_1 boudins, typically, show large separations from neighbouring boudins in all directions in the plane of the enclosing (S_1) foliation. Most importantly boudins show large separations in profile planes perpendicular to L_1; that is in planes which approximate Y-Z of the finite strain ellipse (where X, Y and Z represent the maximum, intermediate and minimum axes of finite strain, respectively). This observation implies that finite D_1 involved flattening strains with $K < 1$ [where $K = (X/Y)/(Y/Z)$ after Flinn (1962)]. Interboudin distances are typically 20–30 times the length of individual boudins. Assuming disruption from an originally continuous layer, interboudin distances imply both X/Z and $Y/Z > 20$. Even larger strains are implied if the strain accumulated internally within individual boudins is taken into account [cf. boudin morphology with the boudin necking model proposed by Ramsay (1967 p. 106)]. The locally strong stretching lineation implies that $X/Y > 1$, with a maximum $X/Y = 20$ implied by the assumption of constant volume deformation at $K < 1$. The resultant finite strain of $X : Y : Z = 400 : 20 : 1$ is exceptional for pervasive crustal deformations (Pfiffner & Ramsay 1982), and it is therefore suggested that $X/Z < 400$. This implies that D_1 involved finite strains with $K < 1$, and is noteworthy as most previous workers [reviewed by Park (1981)] have regarded that recumbent folding in granulite terrains was produced by large simple shear strains; that is in plane strain where $K=1$. The recognition that folding was accompanied by extension in all directions on a sub-

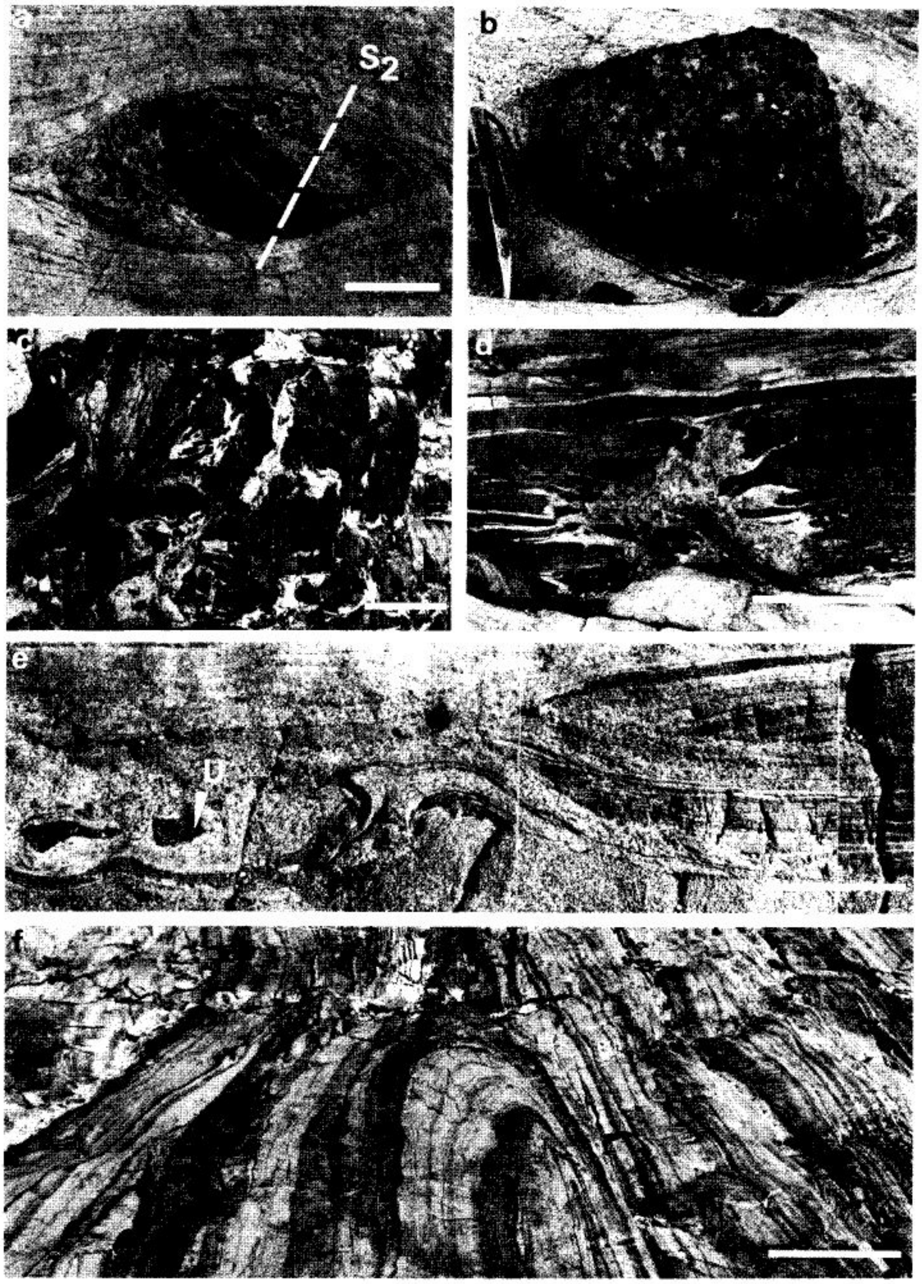

Fig. 7 D_1 structures. **Fig. 7a** Discoidal clinopyroxene boudin, Ayatollah Island. A poorly developed S_2 fabric cross cuts the boudin from top-right to bottom-left. The fold axis in the boudin is parallel to L_1 and thus the outcrop plane approximates the Y-Z plane of the finite strain ellipse. Boudin separation in Y-Z implies D_1 flattening strains. Bar scale is 20 cm. **Fig. 7b** Bronzitite boudin, Hydrographer Island. Hammer head is 20 cm. **Fig. 7c** Bronzitite boudins net veined by anorthosite, Hydrographer Island. Intensification of deformation at boudin termination results in development of strongly flattened S_1 fabrics. Bar scale is 1 m. **Fig. 7d** Anorthosite leucosome development at incipient boudin neck in pyroxene gneiss, Mount Novogodnaya. Bar scale is 50 cm. **Fig. 7e** Sliding and disruption of felsic layers is attributed to boudinage of ultramafic (U) pod, Goldrush Island. Bar scale is 15 cm. **Fig. 7f** Fold at Ayatollah Island. There appears to be no stratigraphic continuity across this fold, suggesting that the attenuated limb results from thrust-like sliding. Bar scale is 2 m.

horizontal (X-Y) plane has importance in the tectonic significance of large scale recumbent folds in the Napier Complex (see Discussion).

The D_2 structural event

D_2 structures are abundant, particularly as first order parasitic folds to a major E trending antiform passing through the southern part of Khmara Bay (Fig. 1). Such folds are common within the layered gnessic series but are rarely observed in the massive gneissic series (Figs 8a–c). They are typically tight to isoclinal and overturned with shallow to steep N dipping axial surfaces, which steepen towards Fyfe Hills due to near co-axial reorientation about F_3. Initially, F_2 folds are believed to have been reclined, and may have been recumbent; their present orientation being due largely to the effects of F_3 refolding. F_2 axes are generally shallow E or W plunging (Fig. 4). Some F_2 folds are markedly non-cylindrical. [See northern part of Ayatollah Island (Fig. 3)]. Most F_2 folds in felsic gneisses are subsimilar (Fig. 8b). More open, subparallel folds occur in pyroxenites (Fig. 8c).

Tectonic fabrics crystallized during D_2 are occasionally preserved (Fig. 6c): more typically D_2 fabrics are medium grained (3–6 mm) and granoblastic. L_2 tectonic fabrics defined by the preferred orientation of sillimanite prisms parallel to F_2, frequently occur in textural equilibrium with sapphirine and quartz, an assemblage distinctive of the Napier metamorphic culmination (Ellis 1980). Axial planar fabrics in garnet–feldspar gneisses are commonly defined by anatectic leucosomes (Fig. 5d).

D_2 boudins occur commonly within garnet–feldspar gneiss (Figs 8b, d). Individual boudins are elongated parallel to F_2 (Fig. 8b), and, in contrast to D_1 boudins, D_2 boudin separation is always less than the profile length of the boudin. The lack of large separations between D_2 boudins suggests that D_2 finite strain was substantially less than D_1 finite strain.

Coarse grained peraluminous pegmatites, containing assemblages indicative of crystallization at the peak conditions (Table 2), are commonly developed in the inter-boudin spaces. The relative ductility of rock types indicated by D_2 boudinage increases from sillimanite bearing garnet–feldspar gneiss through more felsic types to charnockites, and is roughly proportional to the amount of D_2 melt [as indicated by leucosome development (Fig. 5d)] in these rock types. Discordant dyke-like pegmatites at Ayatollah Island form conjugate sets intersecting perpendicular to F_2 within S_2 and thus presumably represent D_2 anatectic melts.

The D_3 structural event

Large scale, open to tight, subparallel, asymmetric, non-cylindrical folds with wavelengths in excess of 5 km are the dominant expression of D_3. At Fyfe Hills (Fig. 9a) and at Hydrographer Islands they are characterized by steep dipping southern limbs and shallower north limbs. D_3 strain is most intense in these steeper S dipping limbs which are occasionally overturned (Fig. 9a) and boudinaged (Fig. 9b). F_3 synforms are generally tighter than corresponding antiforms of the same scale (Figs 9a, 10). As the southern limbs of the F_3 folds are markedly shorter than the northern limbs the overall enveloping surface of the F_3 fold train is subhorizontal. The non-cylindrical nature of F_3 folds is indicated by large amplitude variations. At Hydrographer Islands amplitude diminishes eastwards along strike from greater than 200 m to less than 50 m over a distance of approximately 3 km. As S_3 and L_3 have essentially constant orientations along the length of this fold, the fold axis curvature is attributed to heterogeneous non-coaxial deformation rather than the interference of two distinct generations of structure. Thus it is probable, as first suggested by James and Black (1981), that the D_3 deformation is responsible for the regional scale dome and basin outcrop pattern observed throughout the Napier Complex.

Mesoscopic F_3 folds exhibit variable morphology and geometry. The typical Type 3 (Ramsay 1967) F_2/F_3 interference pattern (Fig. 9c) indicates near coaxial folding with axial surfaces intersecting at a moderate angle. Many of the mesoscopic F_3 folds are non-cylindrical. This is particularly the case in magnetite-quartz bearing gneisses where D_3 strain appears to have been strongly localized (Figs 9d–f). In these gneisses, S_3 is often refolded into markedly non-cylindrical sheath folds (Figs 9d-f). The formation of sheath folds is attributed to markedly non-coaxial deformation (Minnigh 1979). In less deformed settings, S_3 fabrics are defined by the elongation of fine grained recrystallized mineral aggregates which, in basic and acidic gneisses, are distinguished from both S_1 and S_2 fabrics by the occurrence of garnet, biotite and hornblende (Table 2). A pronounced, near vertical stretching lineation (L_3), lying at a high angle to the fold axes and contained within the S_3 plane, is defined by the elon-

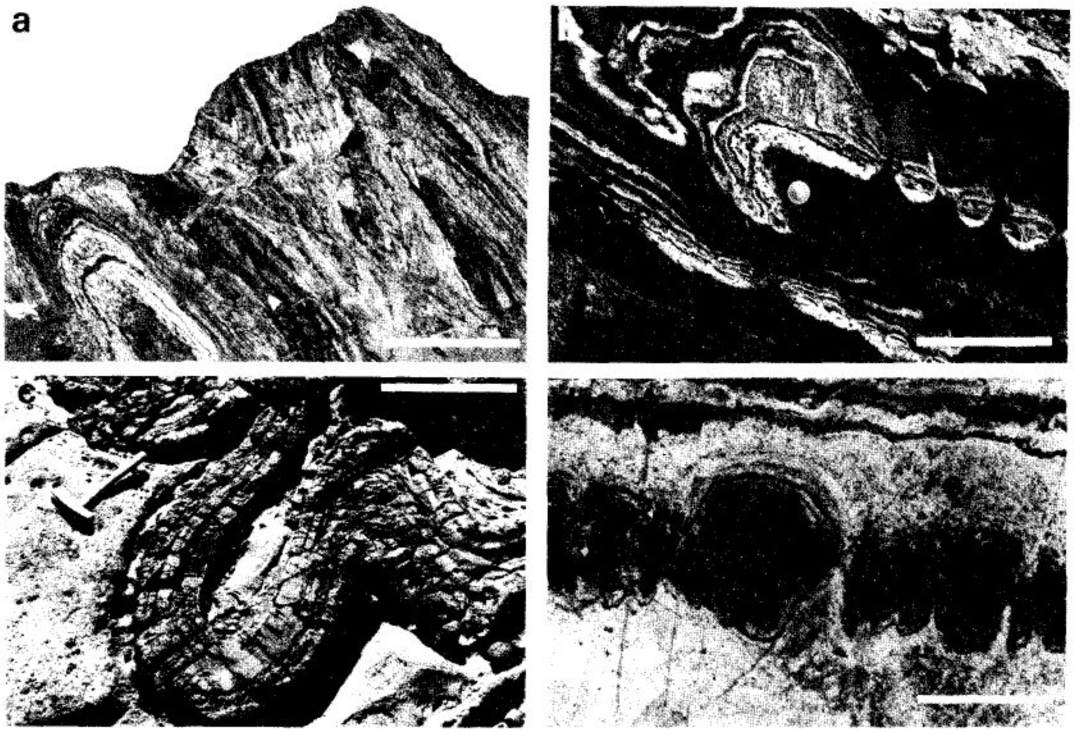

Fig. 8 D_2 structures. **Fig. 8a** F_2 folds in Layered Gneissic Series, Fyfe Hills. The upright nature of these folds is largely due to reorientation during F_3 folding. Cliff face is approximately 200 m high. **Fig. 8b** Mesoscopic asymmetric F_2 fold seen in both profile and in plan, McIntyre Island. Boudinage and attenuation of limbs is apparent, while a lineation defined by garnet-sillimanite aggregates parallels the F_2 fold axis as well as the principal elongation of the boudins. **Fig. 8c** Sub-parallel F_2 folds in pyroxene gneiss, McIntyre Island. **Fig. 8d** D_2 boudins in garnet-sillimanite gneiss enclosed within quartz-feldspar gneiss. Bar scale is 10 cm.

gation of mineral aggregates. This lineation is locally very well developed.

D_3 boudins (Fig. 9b) are morphologically distinct from D_1 and D_2 boudins as they: (i) form large tabular blocks with only slight terminal thickening; (ii) show only minimal boudin separation; and (iii) do not have pegmatite developed in the interboudin spaces. Indeed, contrary to Black *et al* (1983b), we have observed no pegmatites that can, unequivocally, be established as syn-D_3 in the Khmara Bay region.

Syn-D_3 intrusion of Khmara dykes is suggested by the fact that these dykes (Fig. 10); (i) are typically sub-parallel to F_3 axial planes (Fig. 10); (ii) have folded apophyses; and (iii) contain fine grained (0.5–2 mm), granoblastic fabrics and garnet-bearing assemblages. The intrusion of dykes parallel to an axial planes of developing folds provides important constraints on the nature of folding, as the dilation implied by dyke intrusion can only be achieved by markedly non-coaxial deformation. This interpretation is in agreement with the development of markedly non-cylindrical folds on both macroscopic and mesosopic scales.

THE RAYNER STRUCTURAL EPISODE

Amphibolite facies schists and mylonites occur in RSZ on all outcrops in the Fyfe Hills region. As the Amundsen dyke are deformed within these zones, RSZ deformation is attributed to Late Proterozoic or Early Palaeozoic activity. [A minimum age is provided by early Palaeozoic alkaline dykes which crosscut RSZ on Hydrographer Island without apparent displacement (Sandiford & Wilson unpubl. results)]. The RSZ vary from a few centimetres wide to 300 m wide (Figs 3, 11). The structure of the large zones is complex (Sandiford in press), with two distinct stages in the develop-

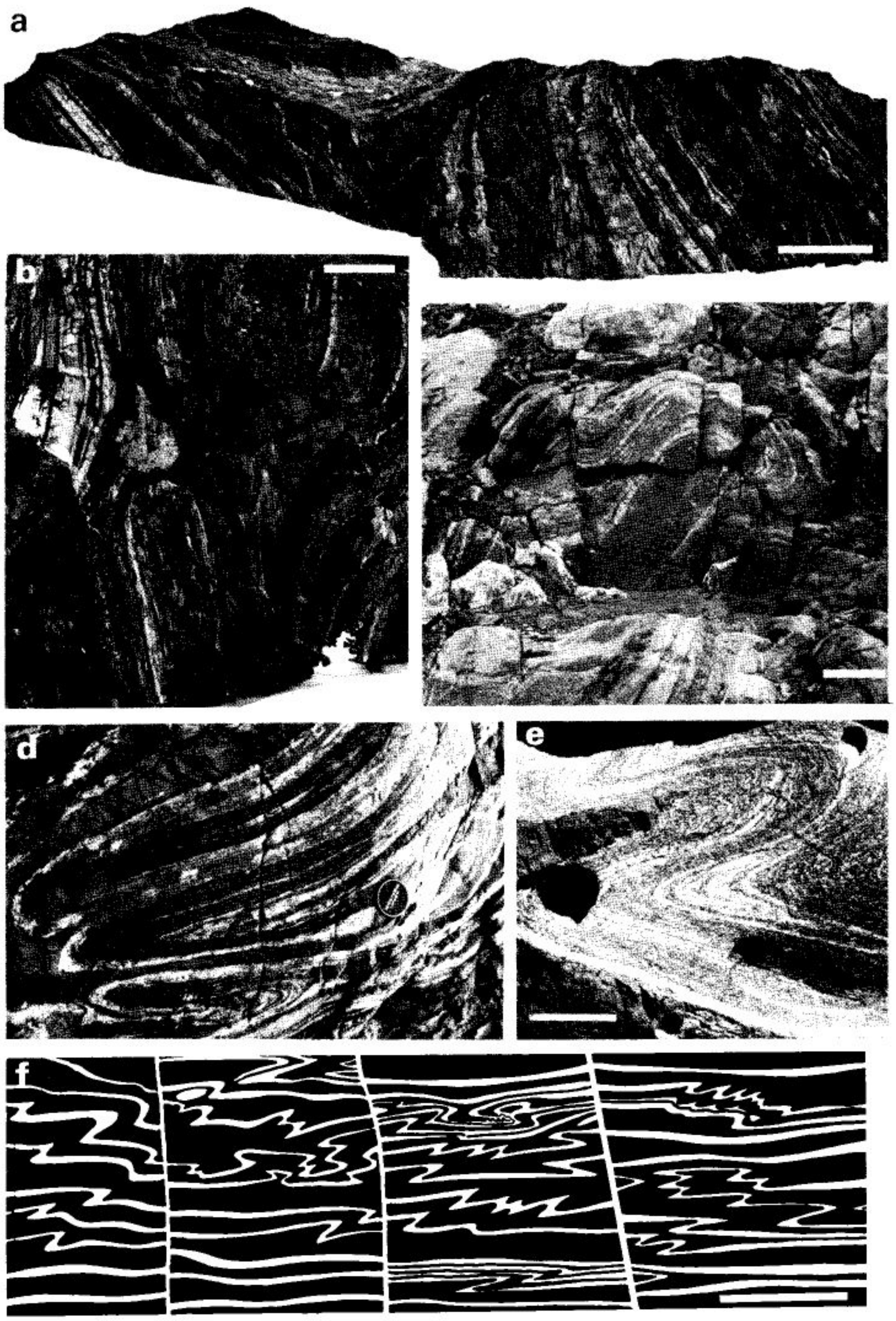

Fig. 9 D_3 structures. **Fig. 9a** Macroscopic F_3 synform at Fyfe Hills. Bar scale is 10 m. **Fig. 9b** D_3 boudins in garnet-sillimanite gneiss on southern side of the Fyfe Hills antiform (Fig. 10a). Bar scale is 2 m. **Fig. 9c** Type 3 interference pattern produced by F_3 refolding of an F_2 fold, which, in turn, folds the mesoscopic gneissic layering in quartz-feldspar-pyroxene gneisses, McIntyre Island. Bar scale is 1 m. **Figs 9d-f** Non-coaxial D_3 structures in interlayered magnetite-rich gneisses are attributed to inhomogenous non-coaxial D_3 strain. **Fig. 9d** F_3 sheath folds, McIntyre Island. **Fig. 9e** Sheath-folds in S_3 fabric, McIntyre Island. Bar scale is 5 cm. **Fig. 9f** Outcrop pattern, Ayatollah Island. Bar scale is 4 m.

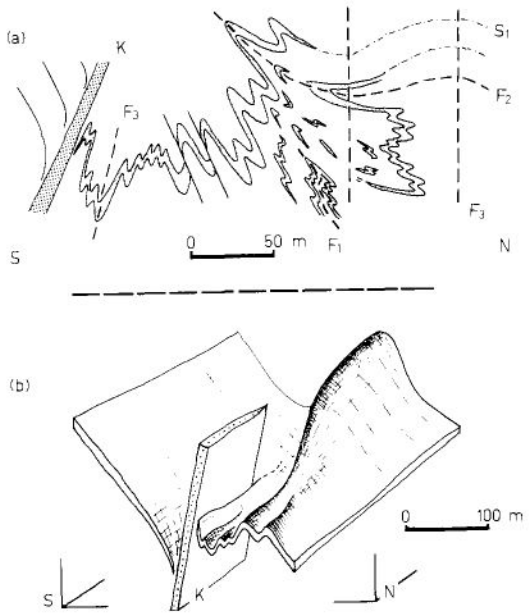

Fig. 10 Khmara dyke-D_3 relations, Hydrographer Island. **Fig. 10a** Diagrammatic section through south dipping Khmara dyke (K). Intensification of deformation adjacent to the dykes is indicated by the rotation of the F_3 structures on the N side of the dyke. **Fig. 10b** Diagrammatic block of Khmara dyke and the macroscopic F_3 folds, the Khmara dyke is axial to an asymmetric and markedly non-cylindrical F_3 fold train.

ment of the larger RSZ evident (Fig. 11). The relationships between these two stages are best exposed at Christmas Point where the oldest retrograde structures (D_4) are progressively deformed and reoriented towards zones of younger structural (D_5) reworking (Figs 3, 11a, b). At most other localities RSZ contain only the D_5 structures, although microstructural evidence of D_4 activity is locally preserved at Fyfe Hills, Dilemma Point and Hydrographer Islands. Pseudotachylite which is frequently associated with, but often truncates D_5 structures, while very late chlorite and prehnite filled fractures occur in some RSZ (Sandiford in press). The structural and metamorphic evolution of these RSZ, and in particular the nature of the temporal and tectonic relationship between the two deformation events observed in these RSZ, are discussed in more detail by Sandiford (in press).

The D_4 structural event

Foliations (S_4) in medium to coarse grained (5–10 mm) schists are the oldest recognized structure preserved within the RSZ and are the principal manifestation of the D_4 event. S_4 occurs in deformed relics of the Amundsen dykes at Christmas Point, where it is E trending and shallow dipping (Fig. 4). Subsimilar F_4 folds are preserved within an intensely deformed RSZ at Christmas Point (Fig. 11a). A lineation (L_4) defined by the preferred dimensional orientation of amphiboles, parallels F_4, and plunges down dip within S_4 (Fig. 4). Finite displacements due to D_4 RSZ deformation have not been determined. The lack of apparent displacement across the RSZ in Fig. 4 is most probably due to the inappropriate orientation of the outcrop section, as the strong localization of deformation in such planar sharply bounded zones implies markedly non-coaxial deformation. It is believed therefore that these RSZ formed in response to large simple shear strains in response to low angle (? thrusting) movements between essentially rigid blocks of granulite.

S_4 frequently contains assemblages indicative of crystallization at deep levels, such as kyanite–gedrite–quartz (Green & Vernon 1974). Indeed, kyanite is a diagnostic mineral of the D_4 structural episode. Kyanite-bearing felsic segregations and quartz veins are commonly associated with D_4 structures. Discordant intrusive contacts between kyanite-bearing pegmatites and country rock have not been observed. However, the occurrence of intensely deformed kyanite-bearing pegmatites in RSZ at Fyfe Hills suggests that the pegmatites may have been intruded during D_4.

The D_5 structural event

At a number of localities at Christmas Point the S_4 fabric is strongly crenulated (Fig. 11b). The ultimate stage in the development of the crenulation cleavage (S_5) is represented by mylonitic fabrics. Two morphologically distinct types of mylonite RSZ have been recognized; and are termed discontinuous and continuous mylonites, respectively (Burg & Laurent 1978).

Discontinuous mylonites typically form large, E-trending, sub-vertical RSZ up to 300 m wide, and are best-developed at Dilemma Point (Figs 3, 11c). The mylonites are fine to very fine grained (0.1–10 mm) amphibolite grade rocks, with fabrics defined by finely interlayered leucocratic and melanocratic domains, and by the preferred dimensional orientation of biotite. They generally lack the feldspar porphyroclasts typical of the continuous

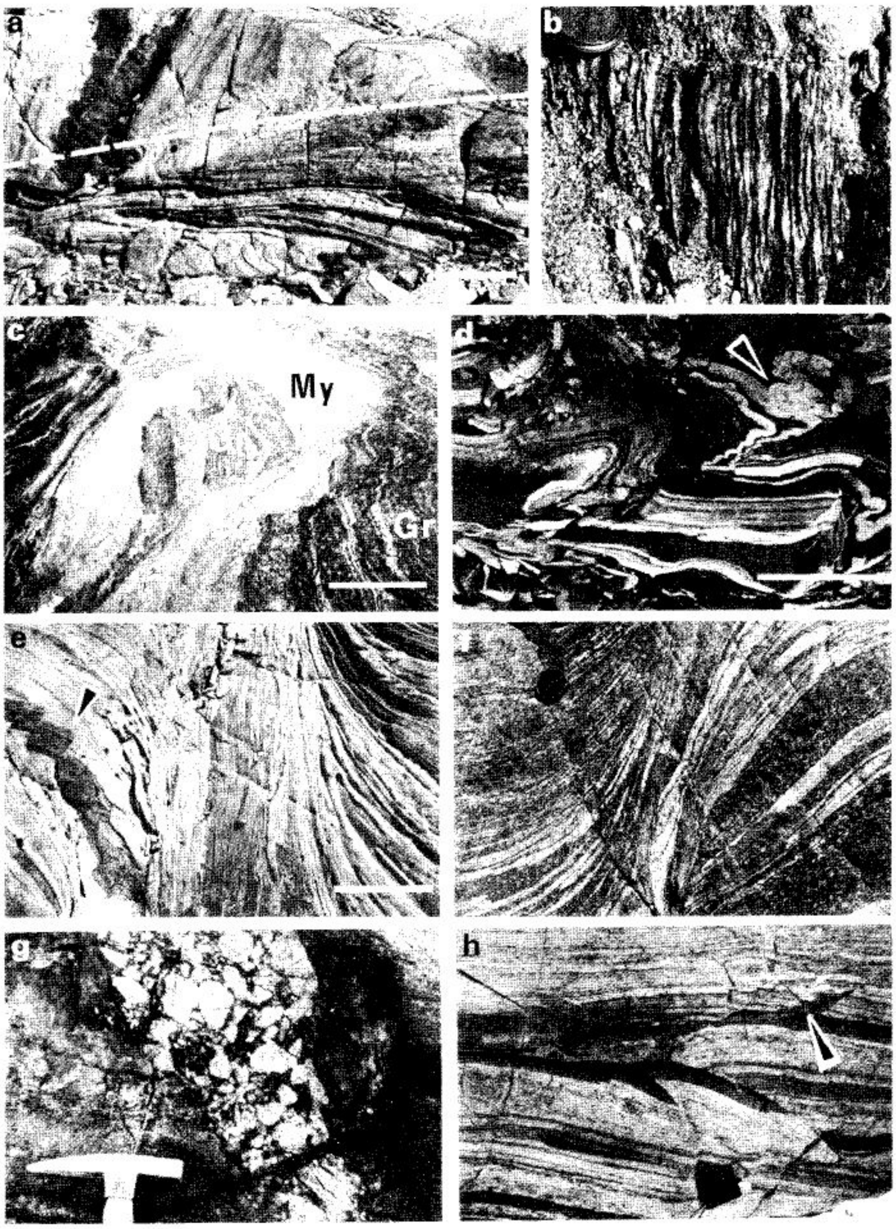

Fig. 11 Structures in retrograde shear zones. **Fig. 11a** F_4 folds in amphibolite (dark) and garnet-feldspar (light) layers. The retrograde transition (dashed line) from primary granulite facies assemblages to amphibolite facies assemblages is sharp and corresponds to the zone of intense D_4 strain. Bar scale is 1 m. **Fig. 11b** S_5 crenulations in S_4 schistosity from hinge of F_5 fold, Christmas Point. **Fig. 11c** Discontinuous mylonite zones (My) surrounding a block of unretrogressed granulite (Gr), Dilemma Point. Bar scale is 20 m. **Fig. 11d** Sheath folds (arrowed) from discontinuous mylonite zones, Dilemma Point. Bar scale is 25 cm. **Fig. 11e** Continuous mylonitic shear zone, McIntyre Island. Relict pegmatitic feldspar porphyroclasts occur within the mylonite. Note brittle rupture of pyroxene gneiss (arrowed) outside the zone of ductile deformation. Bar scale is 1 m. **Fig. 11f** Continuous mylonite zone in quartz-feldspar-pyroxene gneiss, Dilemma Point. **Fig. 11g** Pseudotachylite-breccia dyke in charnockitic gneiss, McIntyre Island. The light coloured breccia clasts consist of garnet-feldspar gneiss, presumably derived from a nearby horizon prior to intrusion during pseudotachylite development. **Fig. 11h** Pseudotachylite (arrowed) associated with small thrusts in unretrogressed pyroxene-feldspar and quartz-feldspar-pyroxene gneisses, Zircon Point.

mylonites. S_5 is commonly refolded into non-cylindrical sheath folds (Fig. 11d) with the consequence that F_5 defines a girdle contained within S_5 (Fig. 4). Sheath fold axes are subvertical and parallel L_5 which is defined by the elongation of mineral aggregates within S_5. Thus movement in discontinuous mylonites was essentially vertical. No field constraints on finite displacements in discontinuous mylonites have been identified, but geobarometric determinations of granulites from the Fyfe Hills region suggest that differential vertical displacements due to these RSZ cannot have exceeded 3–5 km (Sandiford unpubl. results). The formation of sheath folds is attributed to inhomogeneous (non-coaxial) extension during progressive deformation (Minnigh 1979).

The discontinuous D_5 mylonite zones at Dilemma Point form anastomosing arrays (Fig. 11c). The boundary between granulite and the mylonite tends to be abrupt, and there is little evidence of retrogression more than a few metres into the granulite. The typical aluminosilicate found within the mylonites is sillimanite, though kyanite occurs occasionally along the margins of mylonites. On the basis of observations at Christmas Point where the development of S_5 is marked by the appearance of sillimanite at the expense of, or together with kyanite, it is suggested that discontinuous D_5 mylonites were initiated during D_4 (Sandiford in press). The preservation of S_4 as a relic fabric at the margins of, and as pods within, sub-vertical, east-trending D_5 mylonite zones at Dilemma Point, Hydrographer Islands and Fyfe Hills, confirms earlier D_4 'working' of these zones.

Continuous mylonites are relatively narrow, variably trending and generally sub-vertical. They typically consist of a core of mylonite or ultramylonite rarely more than 3 m wide, bounded by partially retrogressed gneiss grading into unaltered gneiss over a distance of 2–5 m (Fig. 11e). Smaller scale, cm-wide zones are locally abundant (Fig. 11f). Folds are generally absent within continuous mylonites, although small intrafolial rootless hinges, defined by the refolded S_5 fabrics, are locally preserved. Pegmatites are common in the continuous mylonites and are often extremely deformed (Fig. 11e). All stages in the petrogenetic sequence from pegmatite through protomylonite and blastomylonite to mylonite are preserved [terminology after White (1982)]. In zones where pegmatites occur as undeformed dykes there is generally evidence of earlier stages of pegmatite activity in the form of relic feldspar blasts in the bounding mylonite.

In all continuous mylonite zones, S_5 contains a pronounced subvertical stretching lineation (L_5) defined by the elongation of component minerals and/or mineral aggregates. In a continuous mylonite zone at McIntyre Island, finite D_5 displacement, which totals 20 m (as indicated by the displacement of earlier linear fabric elements), is towards the S, plunging at 70° (left lateral strike slip component), and defines 30° angle to the N plunging lineation (Sandiford in press). The discordance between finite displacement and L_5 is believed to result from a deformation history involving a number of variably directed movements, with L_5 being reset during the last increment of movement. The ease with which the lineation resets, even within these structurally simple mylonite zones, cautions against the use of such lineations as the sole basis for the determination of the finite displacement vector in mylonites. L_5 is generally constant within individual sets of mylonites, but varies appreciably from one set to another (Fig. 4).

At Dilemma Point, pegmatites associated with NW trending continuous mylonites intersect and penetrate some 5–10 m before being smeared out in the E-trending discontinuous mylonites. The mutually cross-cutting relationships between the two types of mylonites indicate contemporaneous movement.

Pseudotachylite breccias and veins (Fig. 11g) occur in the mylonite zones and in unretrogressed gneisses, particularly at the contacts between gneiss and Amundsen dyke. Glass is not preserved within the pseudotachylite, but spherulitic textures are commonly preserved and indicate the former presence of melt. The common association of pseudotachylite with D_5 mylonite zones suggests a temporal association, though it is possible that more than one pseudotachylite producing event occurred. Pseudotachylite is often associated with faults in unretrogresed granulite (Fig. 11h) which may represent the generation sites of much of the pseudotachylite (Sibson 1975). Breccia fragments, consisting of garnet–feldspar gneiss, within a pseudotachylite dyke have been intruded at least 5 m into the overlying charnockitic gneiss at McIntyre Island (Fig. 11g). The occurrence of brittle deformation features associated with pseudotachylite (Fig. 11h) outside the RSZ indicates that the unretrogressed granulite blocks between the RSZ remained effectively rigid while deformation progressed in a ductile manner within these RSZ. At Christmas Point, pseudotachylite has been metamorphosed by late pegmatites (Sandiford & Wilson unpubl. results), which crystallized in the muscovite-quartz-melt stability field [>3.5 kbar (Kerrich 1972)]; indicating that the pseudotachylite has probably formed at depths in excess of 12 km.

MICROSTRUCTURE AND THE TIMING OF METAMORPHIC CRYSTALLIZATION

The essential microstructural criteria for the correlation of metamorphic and structural events are those that indicate whether grains or grain aggregates crystallized prior to, during, or after, a given tectonic event (Spry 1969; Vernon 1976). Unfortunately many textures are ambiguous (Vernon 1978), and a common problem in granulite facies terrains is how to interpret the ubiquitous granoblastic equigranular polygonal microstructures [terminology after Moore (1970)]. Such microstructures most probably arise by continued grain boundary adjustment (annealing) following the cessation of the tectonic stresses associated with dynamic recrystallization (Vernon 1976).

The microstructural character of the Fyfe Hills gneisses varies with the composition and structural and metamorphic setting of the gneiss, and the microstructural diversity is large, particularly in aluminous garnet–feldspar gneisses. However, the great proportion of gneisses exhibit microstructures which reflect the predominance of one pervasive tectonothermal event (M_1, Table 1). This is typified by medium grained, granoblastic, polygonal textures (Fig. 12a). Secondary microstructural components are invariably present as disequilibrium textures. These are largely restricted to grain boundaries (e.g. recrystallization and replacement) and, to a lesser extent, grain interiors, as exsolution and recovery features. The M_1 microstructural association is observed in both D_1 and D_2 structures and is diagnostic of the high grade gneissic fabric. It is recrystallized in S_3, and thus is considered to represent the microstructural state attained at the end of the D_2 event. Contained within this micro structure are parageneses, such as mesoperthite–orthopyroxene–quartz and sapphirine–quartz, indicative of the Napier metamorphic culmination (Table 2) (Sheraton *et al* 1980; Grew 1980; Sandiford unpubl. results).

Rare S_1 quartz–flaser fabrics in two-pyroxene gneisses indicates that D_1 occurred during granulite facies conditions. These assemblages are identical to the assemblages preserved in the M_1 microstructure (Table 2), and thus it is inferred that the Napier metamorphism (M_1 in Table 1) was initiated prior to D_1. In light of the evidence that the Napier metamorphism occurred during a perturbed geothermal regime (Ellis 1980; Sandiford & Wilson 1983; Sandiford unpubl. results), it is considered probably that both D_1 and D_2 are closely related in time. That the highest metamorphic grade was attained after the D_2 event is indicated by the fact that boudinaged garnet layers in some quartz-bearing metapelitic gneisses are completely circumscribed by hypersthene–plagioclase coronas (Fig. 5f).

Progressive recrystallization of M_1 microstructures in pyroxene-plagioclase gneisses during the development of S_3 [which defines the M_2 microstructural association (Tables 1, 2)] occurs in the sequence (Fig. 12): (i) recrystallization of plagioclase; (ii) recrystallization of clinopyroxene accompanied by some conversion to hornblende; (iii) recrystallization of orthopyroxene; and, finally, (iv) crystallization of garnet. The equilibrium S_3 fabric is a fine grained, equigranular, polygonal, granoblastic microstructure which contains garnet-granulite assemblages (Table 2). Biotite forms a common component of the S_3 fabric in metapelitic and charnockitic gneisses (Sandiford unpubl. results).

Some F_2 folds, which preserve M_1 microstructures in their hinges, have highly deformed limbs characterized by marked grain-size reduction. Typical retrograde minerals occurring in this fine grained fabric include biotite or phlogopite, garnet and hornblende, minerals characteristic of M_2 assemblages. Thus, the recrystallization of these F_2 limbs is believed to be the product of D_3 reworking of suitably oriented F_2 structures rather than a late-stage retrogressive D_2 phase. The evidence for increasing grade during and after D_2, based on the occurrence of post-D_2 orthopyroxene–plagioclase reaction coronas on M_1 garnet assemblages (Fig. 5f), lends support to this interpretation.

Microstructures associated with D_4 are typically nematoblastic within a medium to coarse-grained schistosity defined by biotite, amphibole and/or kyanite. The transition from anhydrous assemblages to these hydrous M_3 assemblages (Table 1) is typically sharp (Fig. 11a). An envelope, in which coronate garnet forms around pyroxenes, extends no greater than a few metres out from the

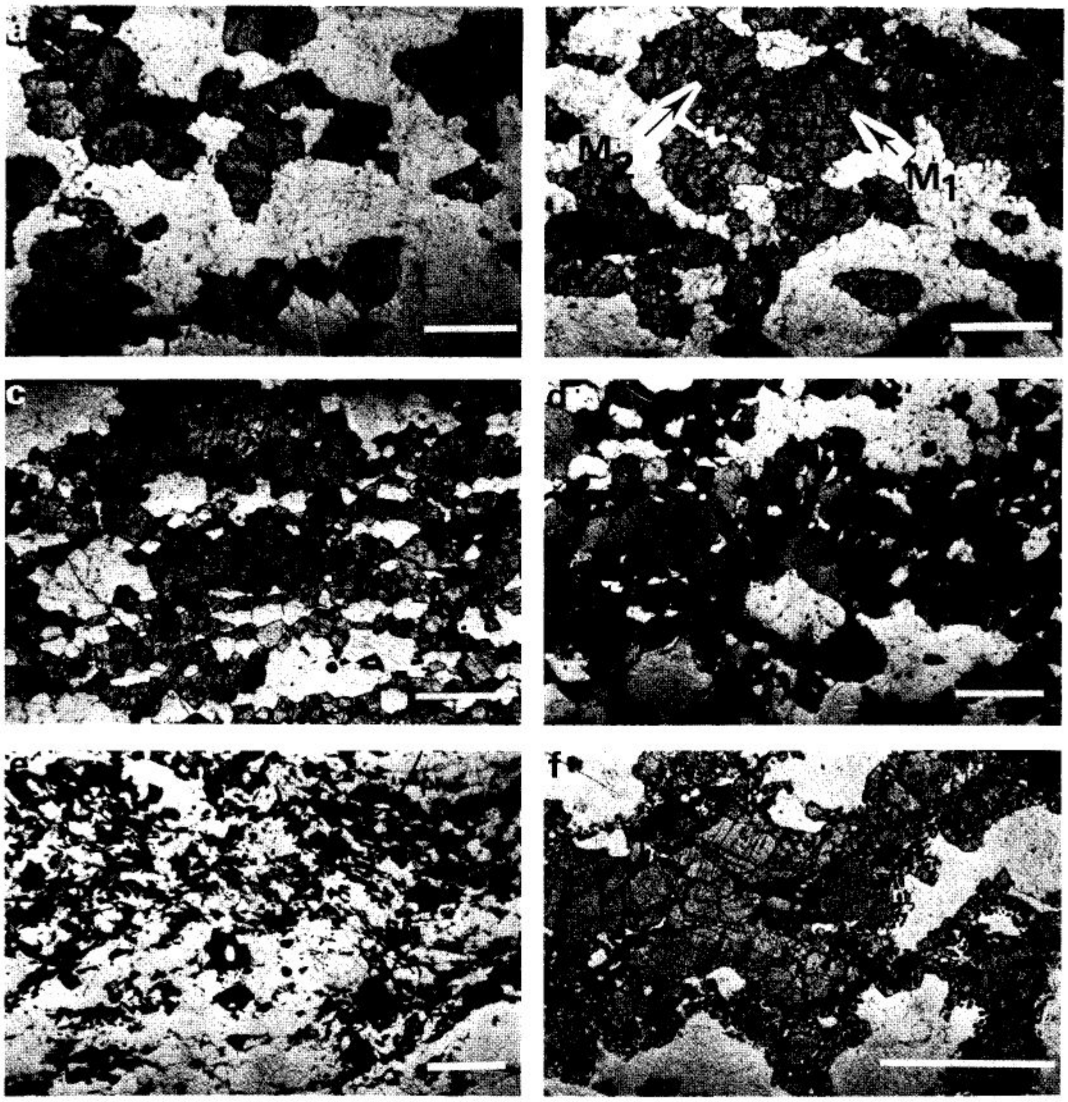

Fig. 12 Microstructural evolution of pyroxene–feldspar gneisses. Bar scale is 5 mm in all photographs. **Fig. 12a** High grade (M_1) granoblastic fabric. **Fig. 12b** Incipient development of S_3/M_2 fabric. Relict M_1 clinopyroxene porphyroclasts are mantled by finer grained M_2 clinopyroxenes. M_1 orthopyroxene is not recrystallized in this section. **Fig. 12c** S_3 fabric containing retrograde (M_2) garnet and hornblende, as well as clinopyroxene and plagioclase. **Fig. 12d** S_4 fabric in M_3 amphibolite. **Fig. 12e** S_5 fabric with retrograde (M_4) biotite. **Fig. 12f** Coronate growth of garnet and hornblende between pyroxene and plagioclase in pyroxene–plagioclase gneiss adjacent to the retrograde zone from which Fig. 12d was taken.

rehydrated zone, and demarcates the limit of D_4 mineralogical re-equilibration.

Progressive reduction of grain-size in both the granulite and earlier formed amphibolite assemblages occurs during the development of S_5. The equilibrium S_5 microstructures is mylonitic with a nemoblastic fabric imparted by the preferred dimensional orientation of biotite. The amphibolite grade assemblages preserved within the S_5 microstructure (Table 2), both in mylonites and deformed pegmatites, define the fourth (M_4) microstructural/metamorphic association in the Fyfe Hills region (Tables 1, 2).

In addition to the tectonite components indicative of syn-kinematic metamorphic crystallization, microstructures indicative of post-kinematic crystallization are abundant in the Fyfe Hills region. These microstructures occur as coronas, symplectites, and exsolution lamellae. Their description and interpretation is beyond the scope of this paper. Suffice to say that the correlation of disequilibrium microstructures with a structural chronology is extremely difficult. Only in a few cases, such as the coronate growth of garnet adjacent to D_4 retrograde zones, it is possible to deduce a unique temporal relationship between structure and coronate texture.

DISCUSSION

The structural and metamorphic evolution, and the sequence of intrusive events, observed in the Fyfe Hills region (Table 1) are comparable with, but somewhat more complex than those previously recorded in the Napier Complex (Griffin 1979, Sheraton *et al* 1980; James & Black 1981). The additional complexities at Fyfe Hills are largely due to the influence of the retrogressive Rayner structural episode; reflecting the proximity of Fyfe Hills to the Napier–Rayner boundary (Fig. 1). The Napier structures in the Fyfe Hills region are similar to those observed in the Amundsen Bay area (Griffin in prep.), with the only apparent difference being the paucity of large scale recumbent isoclinical F_1 folds at Fyfe Hills. Estimates of the age of the five deformation events, as deduced from isotopic determinations by independent workers, are listed in Table 1.

A substantial body of isotopic data, collected from the Fyfe Hills region (Table 2), has direct relevance to the structural evolution of this region. The interpretation of this data in terms of the structural evolution of the Fyfe Hills region has proved problematic and there is some controversy over the age of deformation events associated with the granulite facies metamorphic events at Fyfe Hills (DePaolo *et al* 1982; Grew *et al* 1982; Black *et al* 1983a; 1983b). The work presented herein does not contribute any specific age constraints for these events. The interpretation of the high grade mesoscopic gneissic layering, which has an extremely complex history in the Fyfe Hills region, is essential to the interpretation of isotopic data (Black *et al* 1983a). Many aspects of this layering cannot easily be related to the observed deformation history and therefore this layering may lead to erroneous interpretations when used to constrain the timing relationships between the high grade deformation events. Some of the difficulties encountered in dating the high grade deformation events in the Fyfe Hills region are overcome by the use of diffusive pegmatites formed in boudin necks (Grew *et al* 1982), as these structures provide unequivocal timing relationships.

Park (1981), in a review of the origin of recumbent structures in gneiss terrains, considered the origin of these structures in terms of four models: (i) subduction; (ii) gravity spreading; (iii) mantle decoupling and (iv) thinned-crust collision. While recognizing that there was little compelling evidence to favour any one of these four models, Park (1981) regarded the 'mantle decoupling' and 'thin-crust collision' models as the most convincing. A major consideration in the arguments presented by Park (1981) concern the nature of strain in these recumbent terrains. Based largely on strain estimates deduced by Escher and Watterson (1974) and Watterson (1968), Park (1981) concluded that the intense strain in recumbent gneiss terrains results from simple shear, and dismissed ". . . the alternative of flattening due to crustal load as an explanation of these (recumbent) structures . . . in view of the space problem posed by accommodating large strains . . ." (p. 482). Qualitative strain estimates based on boudin morphology at Fyfe Hills, preclude plane strain models for the generation of the recumbent F_1 folds. Indeed the extreme separations of these boudins suggest that D_1 accompanied bulk sub-horizontal extension. The metamorphic evolution of the Napier Complex also precludes significant tectonic thickening of crust by sub-horizontal crustal shortening during D_1 and D_2 (Sandiford unpubl. results) and suggests magmatic overaccretion was the principal burial mechanism. This interpretation is consistent with a number of field observations (Sandiford & Wilson unpubl. results). It is suggested that D_1 structures in the Fyfe Hills region result from gravitational instability generated through this magmatic accretion (Ramberg 1981; Gastil 1979). As such the F_1 folds are considered to be a consequence rather than a cause of burial of the supracrustal gneisses at Fyfe Hills. This is contrary to many previous structural interpretations of recumbent gneiss terrains (Bridgwater *et al* 1974; Hobbs *et al* in press) which have assumed that the burial of the supracrustal component of these ancient gneissic terrains was achieved by recumbent folding or by thrusting during a regime of sub-horizontal crustal shortening.

Deep level crustal shortening perpendicular to the reclined (or recumbent) F_2 axial plane is indicated by the concertina-like shape of the F_2 fold train, and the sub-similar morphology of F_2 folds. However, without any details of D_2 finite strain it is difficult to evaluate the geodynamic significance of these folds. That extensive crustal thickening did not occur during D_2 is indicated by the fact that the granulite metamorphism accompanying their formation was followed by a period of near isobaric cooling (Ellis 1980; Sandiford unpubl. results) and by the fact that D_1 granulite facies assemblages imply that deep crustal levels had been attained prior to D_2.

Large scale F_3 folds record bulk crustal shortening of about 15–20% assuming a buckle deformation mechanism. Additional sub-horizontal shortening would be implied by D_3 boudinage and the near-vertical stretching lineation if D_3 involved significant pure shear. However, the intrusion of dykes along steeply dipping high strain zones characterized by subvertical lineations suggests that the D_3 deformation was strongly partitioned into ductile zones between rigid blocks of granulite undergoing relative vertical displacements and thus was strongly non-coaxial. Moreover, geobarometric studies (Sandiford unpubl. results) suggest that isostatic responses produced uplift of 5–10 km between D_2 and D_3 and hence preclude substantial crustal thickening during D_3. The driving force for the F_3 folds is thought, therefore, to be related to differential vertical movements within the granulite terrain. Further constraints on the nature of the F_3 folds are implied by the necessity for a source of retrograde fluid as substantial biotite and hornblende crystallized during D_3. The crystallization of anatectic melts generated during earlier (syn-D_1 and D_2) granulite facies metamorphism may have provided the source of this retrogressive fluid. In light of this possibility it is interesting to note that Wells (1980) has suggested that the typically non-cylindrical upright structures characterizing the late mobile stages of deformation in many Archaean gneissic terrains may result primarily from the gravitational rise of such melts, prior to their freezing. Such a deformation mechanism implies that the F_3 folds do not result from buckling, and therefore do not necessarily imply substantial crustal thickening. The strongly 'pinched' nature of F_3 synforms at Fyfe Hills resembles Laxfordian folds in the Outer Hebrides granulites which Coward *et al* (1970) ascribed to instabilities generated through the superposition of relatively viscous crustal layers upon a less viscous crust. Such conditions may have attained at Fyfe Hills if anatectic melts were largely restricted to crustal levels beneath those presently exposed at Fyfe Hills. The freezing of such melts would mark the end of the 'permobile' deformation in this granulite terrain. As D_3 represents the last pervasive folding event recognized in the Fyfe Hills region it accompanied the effective stabilization of the Napier Complex. Indeed, the intrusion of Khmara dykes during F_3 folding suggests that quasi-brittle conditions were already attained during D_3.

The Rayner structural episode is characterized by extreme localization of strain in discrete retrogressive zones. A number of observations suggest that the observed change in style of deformation from D_4 through D_5 results largely from changes in the rheological response of the rock body to deformation at successively higher crustal levels (Sandiford in press). Reworking of D_4 zones by D_5 structures at Christmas Point and, to a lesser extent, at Dilemma Point , was accompanied by a reduction in the size of the active shear zone. Consequently, structures produced early in the retrograde episode are preserved only at the margins of zones of younger structures. The reduction in the working volume is accompanied by a pronounced grain size reduction from D_4 'schists' to D_5 'mylonites', which in a qualitative fashion reflects the operative stresses within the shear zone. [Grain size is, to the first approximation, inversely proportional to stress (Edward *et al* 1982)]. The reduction in the working volume and the decrease in the grain size in the RSZ ultimately resulted in ultramylonite and pseudotachylites. Finally, the rock body passed the ductile-brittle transition after which deformation was inhibited and the structural record effectively ceased. Such a deformation path can be achieved either by systematically increasing the stress at constant temperature, or by decreasing pressure at constant stress. In light of the evidence that the metamorphic events record prograde, rather than retrograde, reactions from D_4 to D_5 (D_4 kyanite is replaced by D_5 sillimanite), and that the movement on the retrograde zones, especially during D_5, was essentially vertical, the changing structural response is believed to reflect changes in the crustal depth (Sandiford in press). Initiation at the deepest levels occurred in broad E trending zones. With progressive working due to essentially vertical displacement between rigid blocks of granulite these zones narrowed to the extent that operative stresses exceeded the yield strength of the rock. These observations are consistent with, although do not provide conclusive evidence for, the interpretation that deformation occurred in more or less continuous fashion from D_4 through D_5 during the excavation of the gneissic sequence from deep crustal levels.

The structural succession observed at Fyfe Hills is remarkable in its similarity to the structural succession observed in many other Arcnaean gneissic terrains. The generalized succession, defined by the development of tight reclined structures, non-cylindrical upright structures and, finally, retrograde shear structures, has been documented from a great many Precambrian gneissic terrains including: the Scourian (Sheraton *et al* 1973) and Laxfordian (Graham & Coward 1973) in Scotland; the Willyama Complex in Australia (Hobbs *et al* in press), and presumably reflects processes characteristic of the Precambrian and/or processes characteristic of deformation at deep crustal levels and high metamorphic grades. The surface exposure of these terrains is believed to be a consequence of a composite tectonic regime which requires firstly burial and stabilization of a supracrustal succession at deep levels, and secondly excavation of the previously stabilized deep level crustal segment.

CONCLUSIONS

The Fyfe Hills gneisses have suffered a complex deformation history involving the generation of five phases of folds over a period of at least 2.0 Ga, from the Mid to Late Archaean through to the earliest Palaeozoic.

The first three deformation events (D_1–D_3) accompanied the granulite facies Napier metamorphism, with the metamorphic culmination broadly coeval with but outlasting both D_1 and D_2. D_3 occurred during the retrograde phase of this unusually high grade granulite facies event.

The D_1, D_2 and D_3 deformation events occurred at deep crustal levels. Morphology and style of individual structures suggests that crustal thinning occurred during D_1.

A mesoscopic gneissic layering is associated with the Napier structures in almost all rock types. Its development is complex and cannot always be related to specific deformation events or mechanisms. Of particular importance is the recognition that, in some cases, the gneissic fabric preserves structures which formed prior to the Napier events, either as primary sedimentary structures or as earlier tectonic structures.

The effects of the post-Amundsen dyke deformation events (D_4 and D_5), termed the Rayner structural episode, are spatially restricted to discrete, generally sub-vertical zones of amphibolite facies retrogression. These zones preserve a structural and metamorphic record of excavation from deep crustal levels.

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