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The origin of retrograde shear zones in the Napier Complex: implications for the tectonic evolution of Enderby Land, Antarctica

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Abstract—Retrograde shear zones (RSZs) in granulites at Fyfe Hills in the Napier Complex, East Antarctica, formed during a Late Proterozoic or Early Palaeozoic reactivation event. These RSZs preserve a structural and metamorphic record of excavation from depth equivalents of 6–8 kbar (20–26 km) to depth equivalents of 3–5 kbar (10–17 km). Excavation was essentially isothermal suggesting that the RSZs formed in an allochthonous terrain during crustal thickening by low-angle thrusting. Rehydration of the RSZs was accompanied, in part, by large-ion lithophile element enrichment and reduction in K/Rb, features which are attributed to: (1) the retrograde fluid having originated in continental crust that had not previously undergone granulite–facies metamorphism; and (2) the fluid having been introduced into the RSZs by the intrusion of granitic dykes and pegmatites. The saturation of these RSZ pegmatites in components characteristically depleted in deep-crustal and mantle sources (such as boron and beryllium) supports a low-grade source for the retrograde fluid. Furthermore, a rehydration mechanism involving intrusion of pegmatites suggests that the Fyfe Hills granulites are underlain by a significantly lower-grade, hydrous terrain.

INTRODUCTION

RETROGRADE shear zones (RSZs) in basement complexes have attracted considerable interest because they represent "... natural laboratories for studying deformational and metamorphic processes ..." (Etheridge & Cooper 1981, p. 74). While considerable progress has been made in our understanding of RSZ processes (Vernon & Ransom 1971, Bell & Etheridge 1973, Ramsay & Graham 1970, Beach 1973, 1976, Grocott 1979, Corbett & Phillips 1981), the tectonic significance of basement complex RSZs remains obscure (Beach & Fyfe 1972, Bak *et al.* 1975). RSZs abound in the Archaean granulite-facies gneisses exposed in the Fyfe Hills–Khmara Bay region of the Napier Complex in Enderby Land, East Antarctica (Fig. 1) (Sandiford & Wilson 1983). These RSZs preserve structural and metamorphic evidence for their behaviour during the excavation of the granulites from deep crustal levels, and their chemistry testifies to large-scale metasomatic activity. An understanding of the structural, metamorphic and geochemical character of the RSZs provides constraints on the late tectonic evolution of this ancient deep-seated granulite terrain.

REGIONAL SETTING OF RETROGRADE SHEAR ZONES AT FYFE HILLS

Archaean granulite facies gneisses in Enderby Land were metamorphosed and effectively stabilized by 2500–2400 Ma (Grew & Manton 1979, James & Black 1981, DePaolo *et al.* 1982, Black *et al.* 1983a,b). Subsequent reactivation of these granulites occurred at about 1000 Ma and again at 500 Ma during the 'Rayner' events (Grew 1978, Sheraton *et al.* 1980). The extent of regionally pervasive metamorphism at 1000 Ma delimits the Rayner Complex from the older, somewhat higher grade, Napier Complex (Fig. 1). In the Napier Complex, Late Proterozoic and/or Early Palaeozoic reactivation resulted in the development of numerous amphibolite-grade RSZs.

No supracrustal rocks of Early to mid-Proterozoic age have been recognized in Enderby Land (Sheraton *et al.* 1980). It is probable, therefore, that the currently exposed portions of the Napier Complex remained at deep crustal levels (in the vicinity of the depth equivalent of 6–8 kbar at Fyfe Hills) from 2500 Ma through to the time of RSZ formation. This interpretation is supported by: (1) retrograde reaction coronas on the 2500 Ma granulite–facies assemblages which suggest near-isobaric cooling at depth equivalents in excess of 6–7 kbar (Sandiford 1983); (2) evidence that the 1190 ± 200 Ma Amundsen dykes were intruded into the Fyfe Hills granulites at depth equivalents of up to 6–7 kbar and (3)

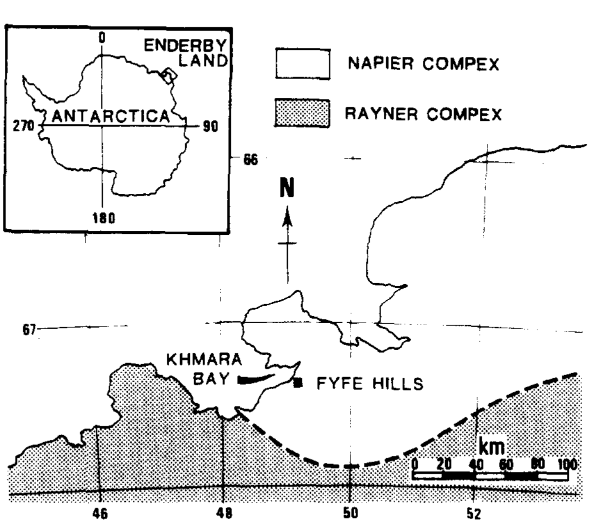

Fig. 1. Geology of Enderby Land, Antarctica, showing localities of Fyfe Hills and Khmara Bay.

evidence (presented here) that the initiation of the RSZs at Fyfe Hills occurred at depth equivalents of 6–8 kbar.

Isobaric cooling following granulite-facies metamorphism (Ellis 1983, Harley 1983, Sandiford 1983) suggests that the Enderby Land crust was in isostatic equilibrium with the underlying mantle during the Early and mid-Proterozoic (Ellis 1980, 1983). By analogy with the 35–40 km thick crusts found in modern-day cratons (Condie 1976), the total crustal thickness of the Napier Complex during Early to mid-Proterozoic is estimated to have been 35–40 km. The crust in the Fyfe Hills–Khmara Bay region is presently 30–35 km thick (Groushinsky & Sazhina 1982). Thus, the interpretation that the crustal level now exposed at Fyfe Hills was at depths of 20–28 km immediately prior to RSZ formation implies that the Fyfe Hills crust was thickened by some 15–30 km during or after RSZ formation.

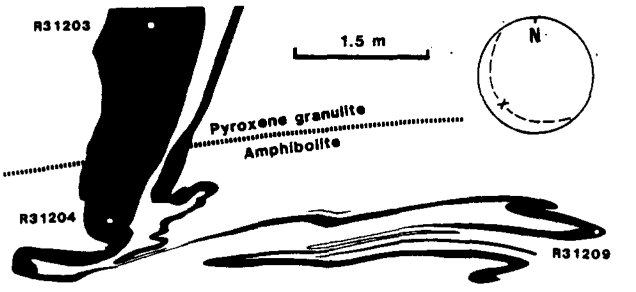

Fig. 2. Retrograde schist zone (tracing from photograph). Black layer is amphibolite retrogressed from pyroxene granulite. Whole-rock analyses of samples R31203, R31204 and R31209 are listed in Table 4. Lower-hemisphere equal-area projection shows orientation of the schist fabric (which parallels the shear zone boundary) and stretching lineation (x).

THE EVOLUTION OF THE RETROGRADE SHEAR ZONES

Structure and chronology

Amphibolite–facies retrograde schists, mylonites and pegmatites occur in zones constituting approximately 10% of exposure in the Fyfe Hills–Khmara Bay region (Sandiford & Wilson 1984). Two stages in the tectonic evolution of the RSZs have been recognized (Sandiford & Wilson in press). Initial RSZ activity resulted in the development of medium- to coarse-grained (4–10 mm) schistose fabrics. These fabrics are preserved only in a few RSZs at Fyfe Hills, typically occurring as isolated relics in younger deformed zones.

Where unaffected by subsequent deformation, the schistose fabric defines a gently, S-dipping foliation with lineations and fold axes plunging down-dip (Fig. 2). Such schist zones are continuous (Burg & Laurent 1978) in the sense that the stratigraphy of the gneissic sequence can be traced into the high-strain zone (Fig. 2). In zones of partial reworking, the schistose fabric is crenulated about a subvertical cleavage (Fig. 3a). This crenulation is parallel to, and increases in intensity towards, nearby mylonite zones with which it is regarded as coeval.

The mylonites occur in both discontinuous and continuous zones. The discontinuous mylonite zones are subvertical, E-trending and up to 300 m wide, and anastomose on the map scale (Fig. 3b) (Sandiford & Wilson in press). The more abundant continuous mylonite zones are also typically vertical. Inclined mylonite zones are rare and are distinct from subvertical mylonite zones in that they contain orthopyroxene-bearing assemblages. The continuous zones are generally less than 3 m wide (Figs. 3c & d), and have variable trends with numerous sets apparent throughout the region (Sandiford & Wilson 1984). In both discontinuous and continuous mylonite zones the stretching lineation is typically subvertical (Figs. 3b–d). Finite displacements across discontinuous mylonite zones are unknown. However, geobarometric studies of the granulites (Sandiford, in prep.) indicate finite vertical displacements must be less than 3–4 km. Shear-sense is variable in these discontinuous mylonite zones. The subvertical lineation implies dominantly vertical movement. However, the asymmetric, anastomosing outcrop pattern of these zones (Fig. 3c) may imply that their early evolution involved strike-slip displacement. Finite displacement in the continuous mylonite zones is generally less than 20–30 m. In such zones, the finite displacement vector is typically discordant to the stretching lineation (by as much as 30°, Figs. 3d and 4). This discordance is believed to reflect late resetting of the lineation (Sandiford & Wilson in press) and suggests that the deformation of the continuous zones comprised numerous, variably directed movements (Fig. 4). Mutual cross-cutting relationships indicate that the 'working' of the continuous and discontinuous mylonite zones was essentially contemporaneous (Sandiford & Wilson in press).

The continuous mylonite zones invariably contain axial granite dykes and pegmatites. These dykes are commonly so deformed that feldspar porphyroclasts are the only recognizable igneous relic. The preservation of the complete range in the sequence pegmatite–protomylonite–mylonite in individual mylonite zones suggests that pegmatites were intruded throughout the

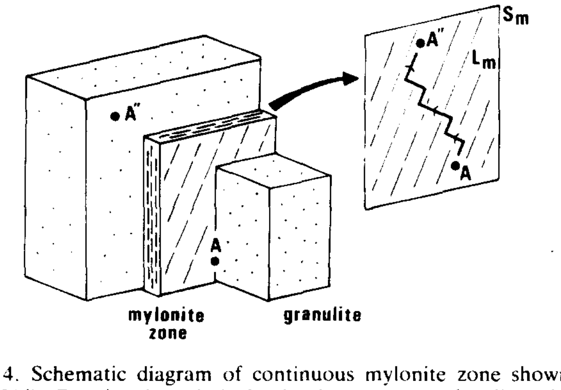

Fig. 4. Schematic diagram of continuous mylonite zone shown in Fig. 3(d). Despite the relatively simple geometry, the discordance between the stretching lineation (L_m) and the finite displacement vector as defined by offset of granulite-facies linear-fabric elements (depicted as A–A″) implies a complex movement history. The movement history is believed to result from numerous variably-directed 'jiggles', with the observed stretching lineation set in the final 'jiggle'. Mylonitic foliation (S_m).

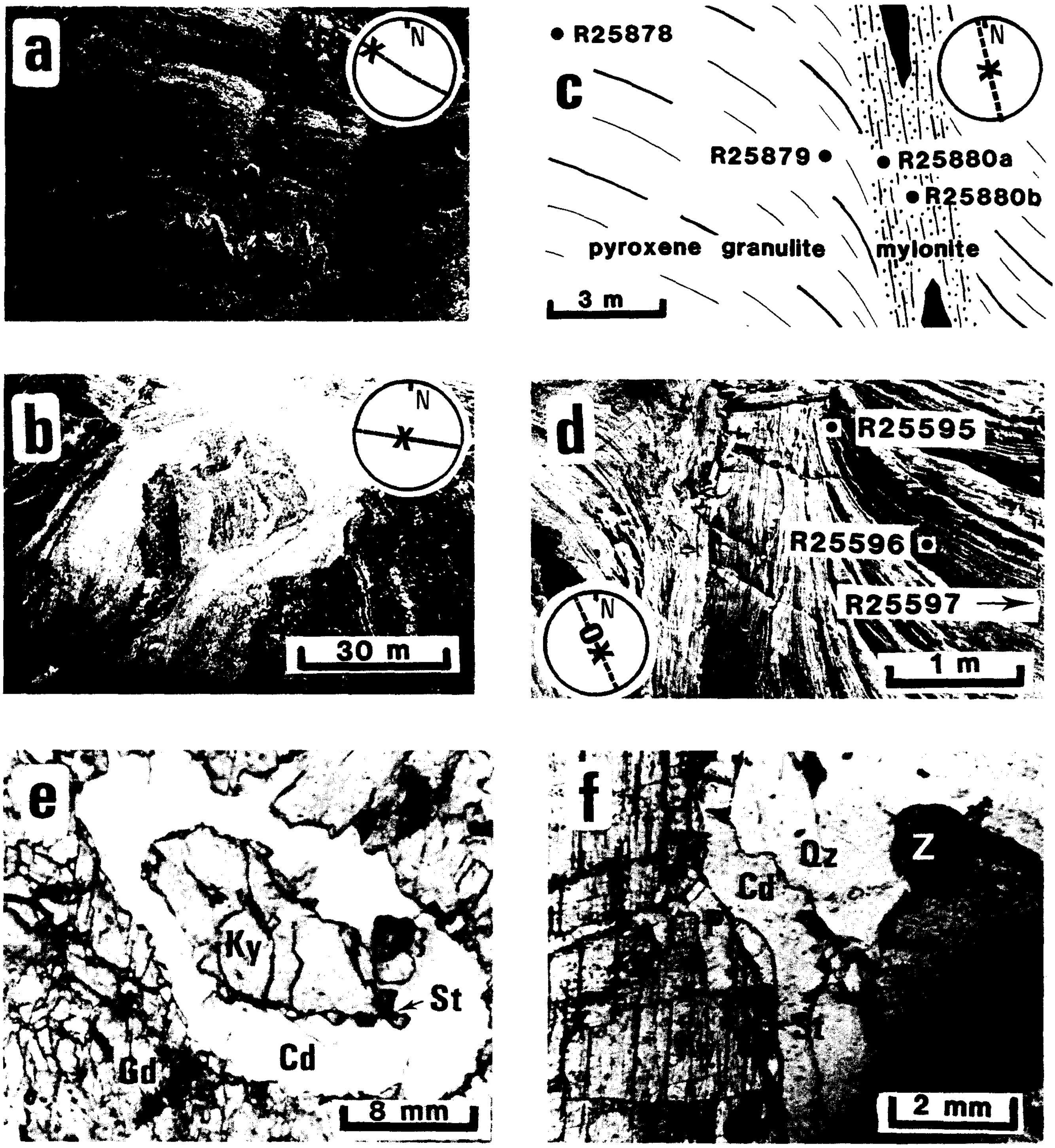

Fig. 3. (a) Crenulated schist fabric. The crenulation cleavage is parallel to, and was formed at the same time as the mylonitic foliation in adjacent mylonite zones. Lower-hemisphere equal-area projection shows orientation of the crenulation cleavage and lineation (x). (b) Anastomosing discontinuous mylonite zone with large isolated blocks of granulite. Lower-hemisphere equal-area projection shows orientation of the mylonite fabric and stretching lineation (x). (c and d) Continuous mylonite zones. Bulk-rock analyses of samples R25878–R25880b (c) and R25595–R25597 (d) are listed in Table 4. The black pods within the mylonite zone in (c) are deformed pegmatites. Lower-hemisphere equal-area projection shows orientation of the mylonite fabric (which parallels the shear zone boundary), stretching lineation (x) and finite-displacement vector (o). (e and f) Reaction developed in schist sample R23497. (e) Cordierite (Cd) and staurolite (St) corona separating kyanite (Ky) and gedrite (Gd). (f) Reaction corona of plagioclase (P) with composition An_{94} on kyanite in kyanite–quartz (Qz)–garnet (Gt) assemblage (cordierite and staurolite also occur possibly due to the subsequent reaction of kyanite and gedrite). Zircon (Z) is accessory.

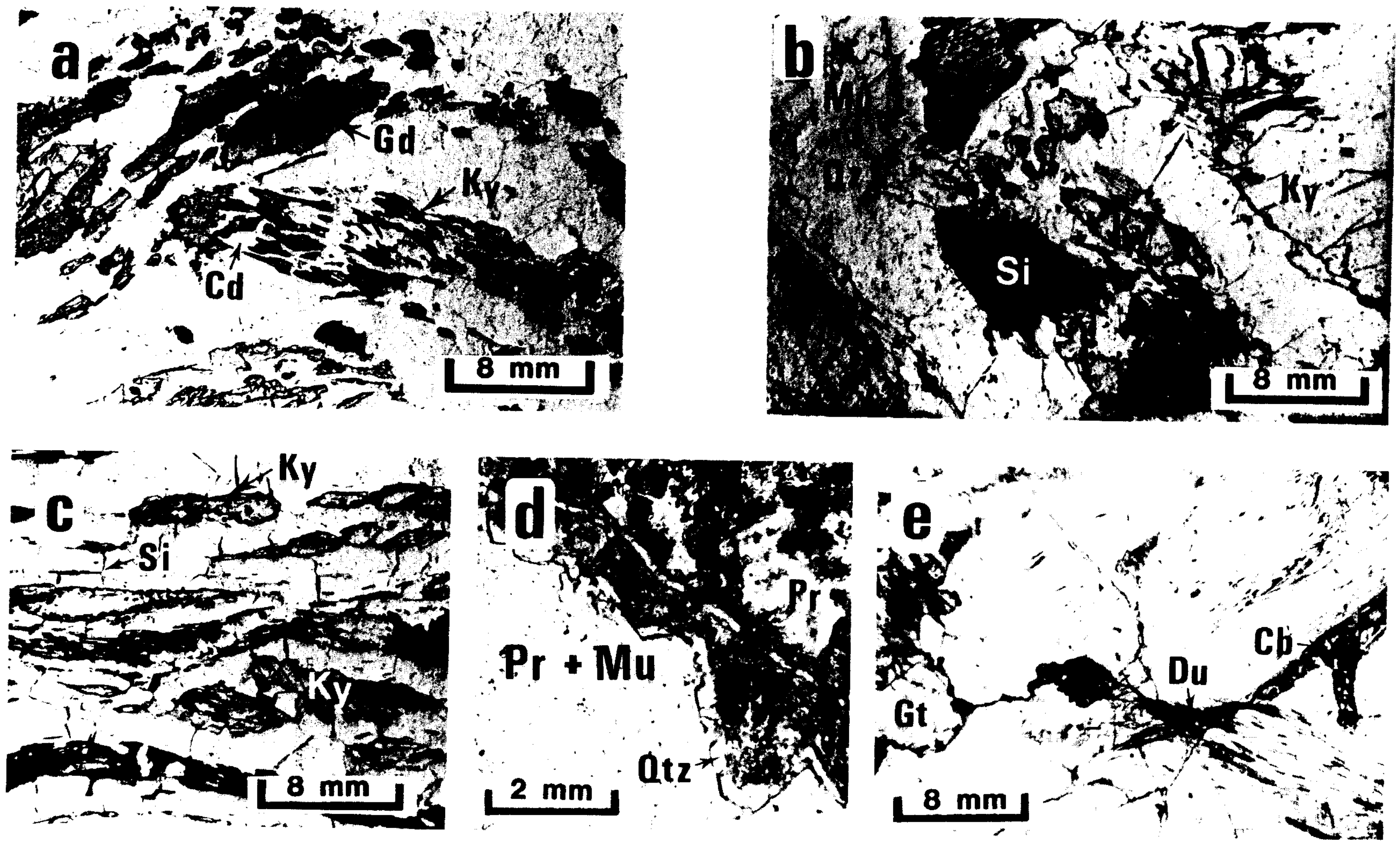

Fig. 5. (a) Reaction corona of cordierite (Cd) developed after crenulation of kyanite (Ky)–quartz–garnet (schist) assemblage. Gd, gedrite. (b) Kyanite, replaced by fibrolitic sillimanite (Si) and muscovite (Mu), in deformed pegmatite in mylonite zone. Qz, quartz; Ky, kyanite. (c) Coexisting kyanite (Ky) and sillimanite (Si) in quartz–biotite–garnet mylonite. (d) Prehnite (Pr)–muscovite (Mu) vein with quartz (Qtz) overgrowths. The vein cross-cuts an earlier retrogressive fabric in which the plagioclase has been pseudomorphed by prehnite. (e) Dumortierite (Du)–chrysoberyl (Cb)–garnet (Gt)-bearing pegmatite. The groundmass consists of quartz and albite.

development of these zones. The youngest, least-deformed pegmatites are distinguished from older, more intensely deformed pegmatites by the occurrence of cordierite and sillimanite and the absence of kyanite.

Ultramylonite seams and pseudotachylite veins occur in the discontinuous mylonite zones, as well as in otherwise unaltered granulite. In the mylonite zones, the pseudotachylite invariably cross-cuts the mylonite fabric. Chlorite-, prehnite/muscovite- and calcite/quartz-filled fractures are the youngest structure in the RSZs (Fig. 5d).

The age of the RSZs is constrained by the age of intrusive rocks. An oldest age is provided by the tholeiitic Amundsen dykes which were intruded prior to retrogression (Sandiford & Wilson in press) and which have yielded a 1190 ± 200 Ma Rb/Sr isochron (Sheraton & Black 1981). A youngest age is provided by peralkaline dykes which cross-cut the mylonite zones without displacement (Sandiford & Wilson 1983). These dykes are believed to be coeval with a magmatic episode dated elsewhere in the Napier Complex at 490 ± 3 Ma (Black and James 1983). A late-stage cordierite-bearing pegmatite from Khmara Bay has yielded a 522 ± 10 Ma Rb–Sr isochron age (Black *et al.* 1983b), an age comparable with pegmatites elsewhere in Enderby Land, in both the Napier and Rayner Complexes (Grew 1978, Grew & Manton 1979). Pb-loss in zircons in Khmara Bay granulites at 1000 Ma is correlated with the Rayner reactivation (Grew *et al.* 1982) and may reflect the initiation of RSZs in this region. However, subsequent studies (Black *et al.* 1983b) have failed to produce critical evidence for RSZ activity at this time, and at present the age of initiation of RSZs at Fyfe Hills remains poorly resolved.

In summary, reactivation of the Fyfe Hills granulites involved the production of shallow S-dipping schist zones at some time between 1000 Ma and 500 Ma. Subsequent deformation, either during a continuation of the same regime or in a separate later event, involved the reworking of the early-formed schist zones at about 500 Ma in a regime of dominantly vertical movements. This second-stage mylonitic event was accompanied by the emplacement of significant volumes of pegmatite. Increasing localization of the zone of deformation, together with progressive reduction in the grain size of the associated tectonite fabric (schist–mylonite–ultramylonite–pseudotachylite) is equated with deformation at progressively shallower crustal levels (Bak *et al.* 1975). Eventually, with a transition to a brittle deformation regime, seismic and related fracturing events replaced ductile deformation in the RSZs.

Metamorphic evolution: petrography

The wide range of rock compositions in the granulite-facies sequence at Fyfe Hills (Sandiford & Wilson 1983) has allowed for the development of a diverse suite of RSZ assemblages (Table 1). These assemblages are, in general, indicative of amphibolite–facies metamorphism at $P_{H_2O} = P_{total}$. However, the preservation of ortho-

Table 1. Diagnostic RSZ assemblages, Fyfe Hills

Structural setting	Diagnostic assemblages
Schist	ky–ged–bt–pl–qtz–rut–ilm hb–pl–ilm–qtz–gt–ged
Mylonite	bt–pl–qtz–hb–gt ky–sil–pl–qtz–bt–gt mu–bt–sil–pl–qtz–st opx–gt–pl–bt–qtz
pegmatite	pl–qtz–ky–gt–bt–mu pl–kfs–qtz–mu–bt–ap sil–pl–qtz–gt–st–gt–bt–ilm–crd cb–qtz–pl–du–gt–sil–st–tm

Mineral abbreviations: ap, apatite; bt, biotite; cb, chrysoberyl; du, dumortierite; gt, garnet; ged, gedrite; hb, hornblende; ilm, ilmenite; kfs, k-feldspar; ky, kyanite; mu, muscovite; pl, plagioclase; opx, orthopyroxene; qtz, quartz; sil, sillimanite; st, staurolite; tm, tourmaline; crd, cordierite.

pyroxene-bearing assemblages in some continuous mylonite zones (Table 1) suggests that, at least within these zones, retrograde metamorphism progressed at $P_{H_2O} < P_{total}$.

Aluminous bulk compositions in the schists are characterized by kyanite–gedrite–quartz–rutile assemblages (Figs. 3e & f). Biotite, plagioclase and garnet occur as additional phases, while cordierite, staurolite, ilmenite and plagioclase occur commonly as coronate reaction products in these schists (see below). In more calcic compositions, the two-amphibole assemblage gedrite–hornblende–plagioclase–garnet–ilmenite–quartz is common. Cummingtonite occurs as rims between gedrite and hornblende and as exsolution lamellae in hornblende.

Kyanite–gedrite assemblages are preserved in crenulated schist fabrics (Fig. 5a), but no gedrite has been observed in the mylonitic zones. Fibrolitic sillimanite occurs sporadically in these crenulations, suggesting that crenulation occurred near the kyanite–sillimanite boundary. Indeed, texturally equilibrated kyanite and sillimanite occur in some mylonites (Fig. 5c), although more typically mylonitic kyanite is overgrown by fibrolitic sillimanite (Fig. 5b).

A distinctive assemblage found only in the late-stage, weakly deformed, cordierite-bearing pegmatites is sillimanite–garnet–staurolite–cordierite–plagioclase–biotite. Kyanite has not been observed in these pegmatites. Furthermore, where these pegmatites intrude sillimanite-bearing granulites the coarse-grained granulite-facies sillimanite (Black *et al.* 1983b) is preserved in the retrograde assemblage: sillimanite–biotite–cordierite–plagioclase–quartz–ilmenite. Thus, these late pegmatites are believed to have been intruded and deformed entirely within the stability field of sillimanite.

The assemblage cordierite–staurolite–sillimanite–quartz represents the low-pressure equivalent of kyanite–gedrite–quartz at temperatures of about 600–700°C (Robinson & Jaffe 1969, Bailes & McRitchie 1978) (Fig. 6). Greenwood's petrogenetic grid for the system FMASH ($FeO–MgO–Al_2O_3–SiO_2–H_2O$) (in Bailes & McRitchie 1978) shows that, for the appearance

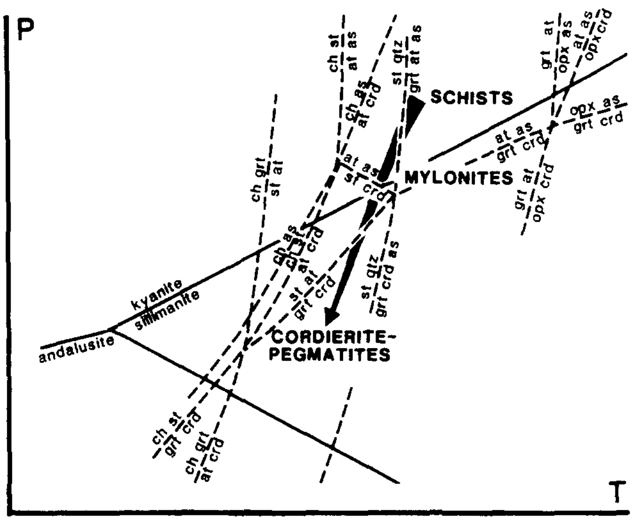

Fig. 6. Petrogenetic grid of the system KFMAS (after Greenwood in Bailes & McRitchie 1978). The approximate *P–T* path defined by the Fyfe Hills RSZ assemblages is illustrated by the arrow. Mineral abbreviations: as, aluminosilicate; at, anthophyllite; crd, cordierite; chl, chlorite; grt, garnet; opx, orthopyroxene; st, staurolite.

of sillimanite–cordierite–staurolite at the expense of kyanite–gedrite in quartz-bearing rocks, decompression must proceed at constant or slightly decreasing, but not increasing temperatures (Fig. 6).

The near-isothermal decompression *P–T–t* path indicated by the RSZ assemblages is supported by a number of reaction coronas in aluminous schists which formed after the crenulation (and hence after mylonite formation) of the kyanite–gedrite–quartz–rutile assemblage (Fig. 5a). These textures suggest the following reactions:

gedrite + kyanite (+ quartz)
$\Rightarrow$ cordierite + staurolite (Fig. 3e);

garnet + kyanite + quartz (+ gedrite)
$\Rightarrow$ plagioclase + cordierite + staurolite (Fig. 3f)

and

garnet + rutile (+ gedrite)
$\Rightarrow$ ilmenite + aluminosilicate + quartz.

The experimentally investigated end-member equilibria pertaining to these reactions have gentle positive d*P*/d*T* slopes (Green & Vernon 1974, Ghent 1976, Bohlen *et al.* 1983), with the textures indicative of reaction from high-pressure to low-pressure configurations.

Table 2. Geothermometry of Fyfe Hills RSZ assemblages

Rock type	Sample		$X_{gt}^{Mg/Fe}$	$X_{bt}^{Mg/Fe}$	$X_{crd}^{Mg/Fe}$	Ln K^1	Ln K^3	T^1	T^2	T^3
Schist	R25822	c	0.492	1.960*		−1.382		720	665	
		r	0.388			−1.758		575	555	
	R25872	c	0.567	2.299		−1.400		715	660	
		r	0.429	2.272		−1.664		620	590	
	R31168	c	0.540	2.242		−1.503		670	620	
		r	0.402	2.288		−1.737		580	565	
	R31205b	c	0.594	2.033*		−1.582		640	605	
		r	0.312			−1.876		540	530	
	R31213	c	0.323	1.463*		−1.483		680	630	
		r	0.326			−1.501		670	630	
	R25795	c	0.818	3.395*		−1.423		705	645	
		r	0.409			−2.141		465	480	
Mylonite	R25794	c	0.389	1.587		−1.407		710	660	
		r	0.314	1.626		−1.645		615	595	
	R25767	c	0.301	1.313*		−1.475		680	640	
		r	0.250			−1.659		610	590	
	R25774	c	0.201	1.047*		−1.650		610	590	
		r	0.180			−1.747		580	550	
	R25768	c	0.147	0.655*		−1.494		675	630	
		r	0.120			−1.677		595	570	
	R25514	c	0.320	1.409		−1.480		680	635	
		r	0.276	1.607		−1.763		575	555	
	R25867	c	0.444	1.901		−1.456		690	640	
Cordierite Pegmatite	R25528	c	0.423	2.033*	4.228	−1.582	2.293	640	610	580
		r	0.312		3.675	−1.876	2.425	540	530	545
	R25534b	c	0.304		3.036		2.401			550
		r	0.248		3.183		2.552			525

Estimates are provided for both core (c) and rim (r) compositions in adjacent mineral pairs. Minerals in which no significant zoning was detected are marked with an asterisk. Mineral abbreviations: gt, garnet; bt, biotite; crd, cordierite. K^1 = (Fe/Mg)gt/(Fe/Mg)bt. K^3 = (Fe/Mg)gt/(Fe/Mg)crd. Temperature estimates are based on the following geothermometers: T^1 garnet–biotite (Ferry & Spear 1978), T^2 garnet–biotite (Thompson 1976), T^3 garnet–cordierite (Thompson 1976).

Temperature reduction very late in the evolution of the RSZs is indicated by chlorite pseudomorphs after biotite, while late prehnite-filled veins (Fig. 5d) indicate RSZ activity at temperatures <400°C (Liou 1971). The restriction of prehnite to veins indicates this very late-stage, low-temperature RSZ activity occurred while the dominant deformation mode was brittle failure.

Metamorphic evolution: geothermometry and geobarometry

RSZ assemblages suitable for geothermometric and geobarometric analysis (Tables 2 and 3) include: garnet–biotite (Thompson 1976, Ferry & Spear 1978); garnet–cordierite (Thompson 1976); garnet–plagioclase–Al_2SiO_5–quartz (Newton & Haselton 1981); garnet–ilmente–rutile–quartz–Al_2SiO_5 (Bohlen *et al.* 1983) and garnet–orthopyroxene–plagioclase–quartz (Newton & Perkins 1982).

Temperature estimates for all RSZ assemblages fall in the range 550–730°C (Table 2). The schist and mylonite temperatures are indistinguishable, averaging about 660°C for garnet–biotite. These temperatures are consistent with field evidence for the existence of silicate melt throughout the evolution of the RSZs, and with the presence of orthoamphibole with compositions intermediate between anthophyllite and gedrite (Black *et al.* 1983b). The 600°C closure temperature of the anthophyllite–gedrite solvus (Spear 1980) provides a lower limit for the schist assemblages. The cordierite pegmatites yield temperatures of 550–640°C and hence are somewhat cooler than the schists and mylonites.

The Bohlen *et al.* (1983) and Newton & Perkins (1982) barometers define pressures which fall, respectively, in the kyanite stability field for the schists and close to the kyanite–sillimanite boundary for the mylonites (Table 3) (Holdaway 1971). Thus, these barometers appear to provide reasonable pressure estimates for the RSZ assemblages. In contrast, Newton & Haselton's (1981) barometer defines pressures in the sillimanite stability field for all RSZ assemblages, and therefore underestimates the crystallization pressures of the schist and mylonite assemblages (Table 3). Despite inherent underestimation, the Newton & Haselton (1981) barometer provides evidence for decompression during the evolution of the RSZs, as the garnet–sillimanite–plagioclase–quartz assemblages associated with cordierite-bearing pegmatites yield pressures 1.5–2.5 kbar lower than garnet–kyanite–plagioclase–quartz assemblages in the schists (Table 3). The pressures obtained for the cordierite pegmatites are similar to the pressure obtained from the calcic plagioclase (An_{94}) coronas and adjacent garnet rims in schist sample R25497 (Fig. 3f, Table 3).

In summary, the RSZ assemblages provide evidence for the excavation of the Fyfe Hills granulites from depth equivalents of about 6–8 kbar to 3–5 kbar (Fig. 7). This excavation occurred at constant or slightly decreasing temperatures (Fig. 7). The resulting increase in the 'apparent geotherm' cannot be attributed to heating of the metamorphic pile. Rather, it must be due to the excavation proceeding more rapidly than thermal relaxation. The RSZ pressure estimates suggest that the transition from ductile to brittle deformation modes in the Fyfe Hills RSZs occurred at depth equivalents of less than 3–5 kbars and temperatures lower than 550°C.

Table 3. RSZ geobarometry, Fyfe Hills

Event	Sample			$a_{An,pl}$	$a_{Fe,gt}$	$a_{Mg,gt}$	$a_{Gr,gt}$	$a_{En,opx}$	$X_{ru}^{TiO_2}$	$X_{il}^{FeTiO_3}$	Log K[1]	Ln K[2]	Ln K[3]	P[1]	P[2]	P[3]
Schists	R25497				0.708				0.991	0.884	0.301			7.8		
	R25823			0.365	0.710		0.050		0.988	0.934	0.372	−6.298		6.7	5.9	
	R31212				0.728				0.987	0.885	0.271			8.0		
	R31168	c	k	0.635			0.074					−6.467			5.7	
	R31213	c	k	0.520			0.060						−6.472			5.7
		r		0.520			0.070					−6.035				
	R25872	r	k	0.661			0.072					−6.430			5.8	
Mylonite	R31114	c		0.580		0.217	0.184	0.284					−2.914			6.6
		r				0.187	0.203	0.281					−3.139			
	R31115	c		0.564		0.236	0.236	0.305					−2.959			6.5
	R25867	c		0.445		0.435	0.057	0.385					−2.776			7.0
	R25514	c	s/k	0.425			0.045					−6.748			5.1/5.4	
		r		0.386			0.046					−6.399				
	R25794	c	s	0.395			0.041					−6.766			5.0	
		r		0.351			0.031					−7.313				
Cordierite Pegmatite	R25534	c	s	0.805			0.069					−7.369			3.3	
	R25528	c	s	0.760			0.081					−6.721			4.4	
		r		0.783			0.091					−6.742				
Corona	R25497		s	0.908			0.058					−7.347			3.6	

Estimates are provided for both core (c) and rim (r) compositions in adjacent mineral pairs. Mineral abbreviations: gt, garnet; bt, biotite; opx, orthopyroxene; pl, plagioclase; s, sillimanite; k, kyanite, ru, rutile; il, ilmenite. Component abbreviations: An, anorthite; Py, pyrope; Gr, grossular; En, enstatite. $K^1 = (a_{Al,gt} \cdot a_{TiO_2,ru})/(a_{FeTiO_3,il})$. $K^2 = (a_{Gr,grt}/a_{An,pl})^3$. $K^3 = (a_{Gr,gt} \cdot (a_{Py,gt})^2)/(a_{An,pl} \cdot a_{En,opx})$. Pressure estimates derived from: P[1], Bohlen *et al.* (1983a); P[2], Newton & Haselton (1981); P[3], Newton & Perkins (1982).

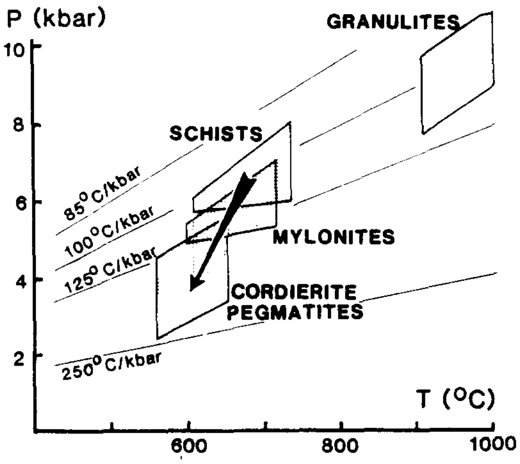

Fig. 7. Preferred P–T fields for RSZ assemblages at Fyfe Hills. P–T estimates are based on the barometers of Newton & Perkins (1982), Newton & Haselton (1981) and Bohlen *et al.* (1983) and the thermometers of Thompson (1976) and Ferry & Spear (1978), see Tables 2 and 3. The P–T conditions for the granulite–facies assemblages are based on Sandiford & Wilson (1983).

Geochemistry and origin of pegmatites

In view of the extremely 'dry' nature of granulite facies assemblages in the Napier Complex (Sandiford, in prep.), the fluid reponsible for the hydration during RSZ formation must ultimately have originated from an external source. Geochemical changes accompanying the formation of the RSZs at Fyfe Hills are briefly described below in an attempt to identify the source of this retrograde fluid.

While the chemical changes accompanying RSZ formation are readily documented, the interpretation of these chemical changes is problematic (Beach 1976). In particular, the extent to which source character of a retrograde fluid is maintained in the RSZ environment is fundamental to interpretation of the geochemistry of these fluids. While an external fluid source is commonly implied by theoretical considerations, it is possible, if not probable, that modification of fluid chemistry by interaction with the host rock effectively prohibits the identification of a 'source character'. RSZs in basement complexes show extremely variable chemistry (Burwash & Krupicka 1969, Beach 1976, Beach & Fyfe 1972, Etheridge & Cooper 1981). Such zones may be either enriched or depleted in K, Rb and Ba. They are typically enriched in Na and depleted in Si. Such metasomatism has been attributed to the introduction of fluids derived from: (1) the mantle (Burwash & Kupricka 1969), (2) underthrust continental material (Beach & Fyfe 1973); (3) higher crustal levels (Etheridge & Cooper 1973) and (4) crystallization of anatectic melts within the basement complex (Corbett & Phillips 1981).

The distinctive chemical signature of the Fyfe Hills granulites (Sandiford, in prep.) provides a useful basis for evaluation of the chemical effects of retrogression. In particular, chemical changes can be related to K/Rb as the Fyfe Hills granulites have, in common with many granulites, unusually high K/Rb ratios. This approach has been used, for instance, by Burwash *et al.* (1973) who argued that the increased K/Rb resulting from regional retrogression in the Canadian shield was due to the

Table 4. Geochemistry of retrogression, Fyfe Hills–Khmara Bay region

	Schist zone				Mylonite zone					Mylonite zone				Pegmatite
Sample No.	R31203	R31204	R31209	( )	R25878	R25879	R25880a	R25880b	( )	R25597	R25596	R25595	( )	
SiO_2	46.40	45.69	45.11	–	50.46	51.72	52.30	60.87	+	62.61	58.31	67.01	+	74.39
TiO_2	1.20	1.18	1.84	+	1.84	1.82	1.52	1.55	–	1.07	0.98	0.41	–	0.12
Al_2O_3	14.70	14.90	13.77		13.99	14.11	13.79	12.36		14.84	15.14	14.99		13.17
Fe_2O_3	13.95	12.80	16.17	+	13.52	15.22	13.58	11.02	–	7.61	8.68	4.57	–	2.02
MnO	0.20	0.19	0.19		0.01	0.01	0.02	0.03		—	0.14	—		0.02
MgO	9.03	9.31	9.33		6.24	5.36	5.67	3.65	–	3.47	4.45	1.72	–	0.52
CaO	13.04	12.59	10.28	–	8.77	8.69	7.52	5.24	–	5.58	5.94	4.27	–	0.90
Na_2O	0.48	0.92	1.10	+	2.43	1.97	2.14	2.43		2.99	3.16	3.78	+	3.79
K_2O	0.13	0.16	0.23		0.67	0.78	1.83	1.49	+	0.53	1.28	1.38	+	4.65
P_2O_5	0.06	0.09	0.28		0.40	0.39	0.32	0.35		0.19	0.19	0.08		0.03
SO_3	0.06	0.09	0.54	+	0.34	0.38	0.47	0.14		0.29	0.18	0.07		0.05
Loss	−0.12	0.77	.0.31	+	−0.37	−0.31	−0.07	0.24	+	0.15	0.47	0.59	+	0.48
Rb	7	4	7		13	15	97	46	+	3	32	29	+	147
Sr	141	162	83		154	162	128	128		155	171	164		103
Ba	81	30	73		353	491	313	918	+	219	265	436	+	645
Total	99.19	98.99	99.47		99.30	100.19	99.09	99.37		99.33	98.22	98.88		100.1
K/Rb	150	330	270	+	430	430	160	268	–	1400	330	390	–	260
Mineral						Mode								
Orthopyroxene	22	—	—		15	10	—	—		20	5	—		
Clinopyroxene	16	—	—		18	14	—	—		—	—	—		
Plagioclase	40	32	28		43	45	33	32		45	40	42		
Quartz	—	—	—		2	4	8	23		15	15	28		
Ilmenite	3	5	10		10	9	5	10		5	5	2		
Garnet	7	—	—		6	10	—	—		3	5	tr		
Hornblende	12	63	68		4	7	39	14		7	10	4		
Biotite	—	—	—		3	8	25	18		5	20	25		
Zircon	—	tr	—		—	—	tr	3		tr	tr	tr		
Apatite	—	—	tr		—	—	3	—		—	—	—		

Significant chemical changes accompanying increasing retrogression in individual RSZs are listed under ( ). Pegmatite is the average of six pegmatite and granite dyke analyses.

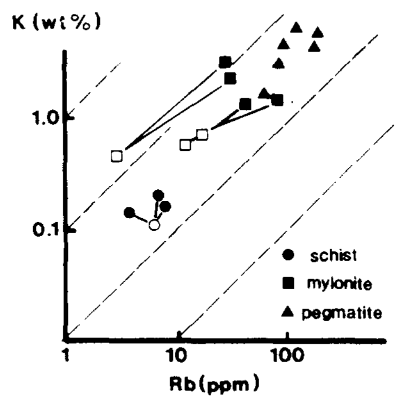

Fig. 8. Log/log plot of K vs Rb. Open symbols represent gneisses not retrogressed with tielines connecting retrogressed (solid symbols) equivalents (see Table 4 for complete analyses). Retrogression during the formation of the schist zones resulted in little change in total K and Rb and a slight increase in K/Rb. In contrast, mylonite formation resulted in significant enrichment in K and Rb and a decrease in K/Rb. These mylonites have Rb and K contents intermediate between the host granulite and the RSZ pegmatites and granite dykes (triangles).

introduction of a retrograde fluid with a high K/Rb derived from the mantle.

Only one schist-zone suite has been analysed (Table 4, Fig. 2). The schists are depleted in Si and Ca and enriched (variably) in Na, Fe (total) and Ti with respect to equivalents not retrogressed. No significant introduction of K and Rb occurred during retrogression. The K/Rb ratio of these schists is higher than in the host granulite (Fig. 8). However, as the mafic–granulite host gneiss has an unusually low K/Rb ratio (150 as compared with the average value of 850 for eight mafic granulites at Fyfe Hills). I doubt that the relative changes in K/Rb in this shear zone can be regarded as significant.

The mylonite zones are enriched in Si and K, Rb and Ba (large-ion lithophile elements) with respect to equivalents not retrogressed (Table 4). These chemical changes (in particular, the substantial introduction of SiO_2) are most unusual for basement-complex RSZs (Etheridge & Cooper 1981) and indicate that significant metasomatism accompanied retrogression of the mylonites. The mylonites have significantly lower K/Rb ratios than their equivalents not retrogressed (Fig. 8). The implied low K/Rb ratio and the silica saturation of the retrograde fluid suggests that it originated in a terrain which had not previously been 'depleted' by granulite-facies metamorphic processes (Heier 1973).

The mylonites have K and Rb contents, as well as major element chemistry, which fall close to a mixing line between the granulite–facies host gneiss and the RSZ pegmatites and granite dykes (Fig. 8). This suggests that the retrograde fluid had equilibrated with the pegmatites. It seems likely, therefore, that the fluid was introduced into the granulite terrain by the intrusion of these pegmatites. Indeed, I suggest that the intrusion of pegmatites provided a principal rehydration mechanism during mylonite formation at Fyfe Hills. Additional support for a comparatively low-grade source for the pegmatites is suggested by boron and beryllium saturation of these pegmatites, as evidenced by the occurrence of beryl, chrysoberyl, dumortierite and tourmaline (Fig. 5e). The low concentrations of boron and beryllium in granulite-facies rocks (Horman 1969, Harder 1974) implies that melting of granulites is unlikely to give rise to melts saturated in these elements. Similarly, as mantle-derived rocks are characteristically depleted in boron and beryllium (Horman 1969, Harder 1974) mantle-derived fluids are likely to be also depleted. Thus, beryllium- and boron-saturated pegmatites are most likely to form as a result of melting of continental crust that has not previously undergone granulite–facies metamorphism.

The geochemistry of RSZ formation at Fyfe Hills provides two important constraints for models of the origin of the RSZs. First, the retrograde fluid responsible for rehydration of mylonites derives from an 'undepleted' (low-grade) continental source. This is based on the evidence for: (1) the comparatively low K/Rb ratio implied for the source of the retrograde fluid and (2) the boron and beryllium saturation of pegmatites. Secondly, a rehydration mechanism involving the intrusion of pegmatites implies that the 'undepleted' source of the retrograde fluid was beneath Fyfe Hills at the time of retrogression.

DISCUSSION

Any reasonable hypothesis for the origin of the RSZs at Fyfe Hills must account for the following geological constraints: (1) bulk thickening of the Enderby Land crust; (2) deformation during a predominantly vertical tectonic regime involving near-isothermal decompression and (3) infiltration of a retrograde fluid derived from an 'undepleted' continental source beneath the Fyfe Hills.

No mantle-derived magmas of appropriate age are known from Enderby Land. Therefore, magma addition can be excluded as a mechanism of crustal thickening during RSZ formation. Rather, crustal thickening must have involved crustal shortening. This may have been achieved by thrusting or by autochthonous shortening of the crust. From the metamorphic and geochemical point of view, the essential difference between these two processes is that thrusting may result in transient inversion of metamorphic profiles, while a normal metamorphic profile will be maintained during autochthonous shortening of the crust. It is arguable that both mechanisms are consistent with the observed geometry of the RSZs (Fig. 4), although the preponderance of vertical structures in the RSZs is difficult to reconcile with thrusting (see below). However, the evidence of a low-grade 'undepleted' source beneath the Fyfe Hills granulites implies that RSZ formation accompanied inversion of the metamorphic profile of the crust. Therefore, an allochthonous thickening mechanism is favoured for the origin of the Fyfe Hills RSZs.

Further support for an allochthonous crustal-thickening mechanism is provided by consideration of the metamorphic evolution of the RSZs (Fig. 9). The salient

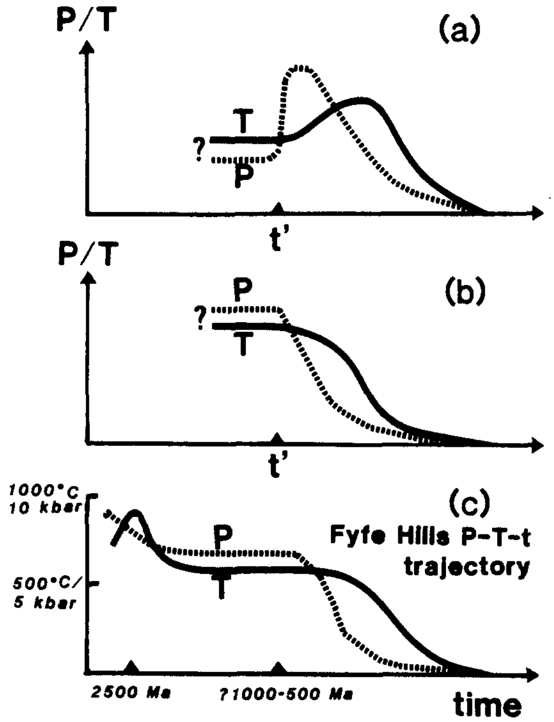

Fig. 9. (a) Pressure–time ($P-t$) and temperature–time ($T-t$) trajectories for bulk crustal thickening at time t' by autochthonous crustal shortening. (b) $P-t$ and $T-t$ trajectories for an allochthonous (overthrust) terrain during crustal thickening by thrusting. (c) $P-t$ and $T-t$ trajectories for Fyfe Hills gneisses.

features of a P–T–t path of a segment of crust undergoing autochthonous crustal shortening are burial during the initial stages followed by an increase in temperature during decompression (Fig. 9a) (England & Richardson 1977). A similar P–T–t trajectory will be experienced by an underthrust terrain. In contrast, an overthrust terrain will undergo rapid decompression which will be, initially, at constant or slightly decreasing, but not increasing, temperature (Fig. 9b). The absence of evidence for progressive burial at any stage during the development of the RSZs at Fyfe Hills (Fig. 9c), and the evidence for slight thermal relaxation during the RSZ formation suggest that the Fyfe Hills gneisses formed part of an overthrust terrain during allochthonous thickening of the crust.

The interpretation that the RSZs formed due to crustal-scale thrusting processes is difficult to reconcile with the typically vertical orientation of the stretching lineation. I have argued that the continuous mylonite zones formed after the intrusion of pegmatites. Thus, mylonite deformation was localized along zones which had been previously weakened and hydrated by the intrusion of dykes. In contrast, the localization of the rare, non-vertical continuous mylonite zones, which contain orthopyroxene (implying relatively low a_{H_2O}) and do not contain relict igneous feldspar porphyroclasts, is unlikely to have been controlled by pegmatite intrusions.

While the origin of most continuous mylonite zones can be related to the intrusion of pegmatites, the principal controls on the formation of the schist zones and discontinuous mylonite zones are poorly constrained. The paucity of schist-zone exposures in original orientation at Fyfe Hills precludes definitive interpretations, although the initial gentle orientations of the schist foliation (Fig. 2) are consistent with a thrust origin.

The fact that discontinuous and continuous mylonite zones are coeval suggests some genetic link. The continuous mylonite zones record 'jiggling' motions between adjacent rigid blocks of granulite (Fig. 4). That such 'jiggles' accompanied the excavation of the granulites from deep levels is indicated by the fact that the youngest and least-deformed pegmatites in these zones contain mineral assemblages of lower pressure than the older more-deformed pegmatites. Therefore, the 'jiggling' motion recorded by the continuous mylonite zones is attributed to deformation induced by slight differences in the rate of excavation of adjacent blocks of granulite. This style of deformation can be attributed to the interplay of isostatic compensation and erosion in an actively thickening crust. Such an interpretation is compatible with the observation that maximum present-day uplift and erosion rates are similar (within an order of magnitude) to rates of thrusting in the continental crust (1–10 mm a^{-1}, Wyllie 1971). Thus, in any tectonic setting in which thrusting is operative on a continental scale (as proposed for the Fyfe Hills RSZs), erosion and uplift will significantly affect the P–T–t trajectory in the allochthonous terrain (England & Richardson 1977). The effects of erosion should be particularly important at the leading edge of the thrust, where the rate of crustal thickening is most pronounced. Because of the similarities in thrust rates and erosion rates, large differential subvertical crustal displacements may be contemporaneous with the thrust-induced subhorizontal displacements. It is interesting, therefore, that large subvertical normal faults, with throws in excess of 10 km, have been documented from Tibet (Burg *et al.* 1984), in an archetypal example of the continental-scale allochthon (Hirn *et al.* 1984). These faults are parallel to the structural trend of the Himalayas and occur between the Main Central Thrust and the Tsangpo suture zone. Therefore, I suggest that the vertical motions recorded by the discontinuous mylonite zones at Fyfe Hills may be consistent with formation in an allochthonous sheet formed by subhorizontal crustal shortening in an extensively thickened crust.

Excavation of ancient high-grade gneissic terrains by crustal duplication along low-angle thrusts has been proposed by a number of workers (O'Hara 1978, Ellis 1983, Schenk 1983). However, while the geometry of younger orogenic belts commonly involves the development of large allochthonous terrains (Bally 1981), there are few Precambrian gneissic terrains which are demonstrably allochthonous (Lobato *et al.* 1983). In this paper, I have presented evidence that the excavation of the Fyfe Hills granulites occurred during a regime of tectonic thickening during the Late Proterozoic or Early Palaeozoic. Three lines of evidence suggest that excavation accompanied the thrusting of the Fyfe Hills granulites over lower-grade continental rocks. (1) RSZs formed during an event in which the Enderby Land crust was thickened by some 15–30 km. (2) Retrogression accompanied near-isothermal excavation from deep-crustal levels (20–28 km), with excavation being rapid enough to prevent substantial thermal relaxation. (3) Rehydration during retrogression was achieved in part by the emplacement of pegmatites derived from an 'undepleted' continental source.

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