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Environment and Structural Controls on the Intrusion of the Giant Rare Metal Greenbushes Pegmatite, Western Australia

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Abstract

The Greenbushes pegmatite district has been the main center of production of alluvial tin in Western Australia since the beginning of this century, and more recently, for the production of tin, tantalum, and lithium from one of the largest rare metal pegmatite deposits in the world. The intrusive rocks in the Greenbushes pegmatite district are concentrated along the ancient crustal-scale, Donnybrook-Bridgetown shear zone, analogous to the present San Andreas fault system, and are characterized by steeply dipping planar mylonitic fabrics with horizontal stretching lineations, asymmetric folds, asymmetric pressure shadows, and shear bands suggesting sinistral strike-slip movement. The Greenbushes pegmatite occurs in a higher temperature and higher pressure metamorphic terraine than would be expected for pegmatites containing rare element mineralization. The pegmatite contains the same shear fabrics as its host rocks and has evidence for syntectonic crystallization of minerals such as tourmaline, tantalite, garnet, and cassiterite.

It is proposed that intrusion of the Greenbushes pegmatite magma was controlled by the Donnybrook-Bridgetown shear zone. Any melts or fluids present during movement along the shear zone would have been channeled into it, leading to intrusion of the pegmatite. The fluid pressure in the pegmatite magma may then have increased causing further failure, zones of structural weakness, and further intrusion of pegmatite generally parallel to the mylonitic fabric in the shear zone.

According to present models and classifications, the Greenbushes pegmatite group should be unmineralized. However, it is apparent from this study that giant rare metal pegmatites can occur in higher grade metamorphic terranes and that these types of pegmatites need not have obvious parental granitoids. They may contain a variety of mineralization and are likely, at least in the Archean, to be associated with tectonism along crustal-scale fault systems.

Introduction

THE group of pegmatites at Greenbushes (hereafter termed the Greenbushes pegmatite group) falls into the rare metal class of pegmatites as defined by Cerny (1982a) and, as such, represents an important resource of Sn, Ta, and Li. The Greenbushes mineral field (hereafter referred to as the Greenbushes pegmatite district) is situated 250 km south of Perth, in the southwest of the Yilgarn block, within the Western Gneiss terrane (Fig. 1A). The first commercial tin deposits in Western Australia were found at Greenbushes in 1888, and by 1900 tonnages had increased sufficiently to allow a tin smelter to be built to process the alluvial ore. Production peaked in 1908, then declined until 1964 when Greenbushes Tin NL. began dredging operations. Since that time the weathered pegmatite has been a major source of ore, but recently as a result of underground operations and opencut hard-rock mining, fresh pegmatite has been mined for Sn, Ta, and Li. A total of 21,084 metric tons of 72 percent Sn concentrate and 2,043 metric tons of 40 percent Ta_2O_5 concentrate were produced from the Greenbushes pegmatite district until 1982 (Hatcher and Bolitho, 1982). Recent drilling in the southern portion of the Greenbushes pegmatite group has identified a large reserve of high-grade spodumene. Proven reserves to date are reported by Hatcher and Elliot (1986) as 28.3×10^6 metric tons at 2.8 percent Li_2O, which includes a high-grade zone of 6×10^6 metric tons at 4 percent Li_2O. Conse-

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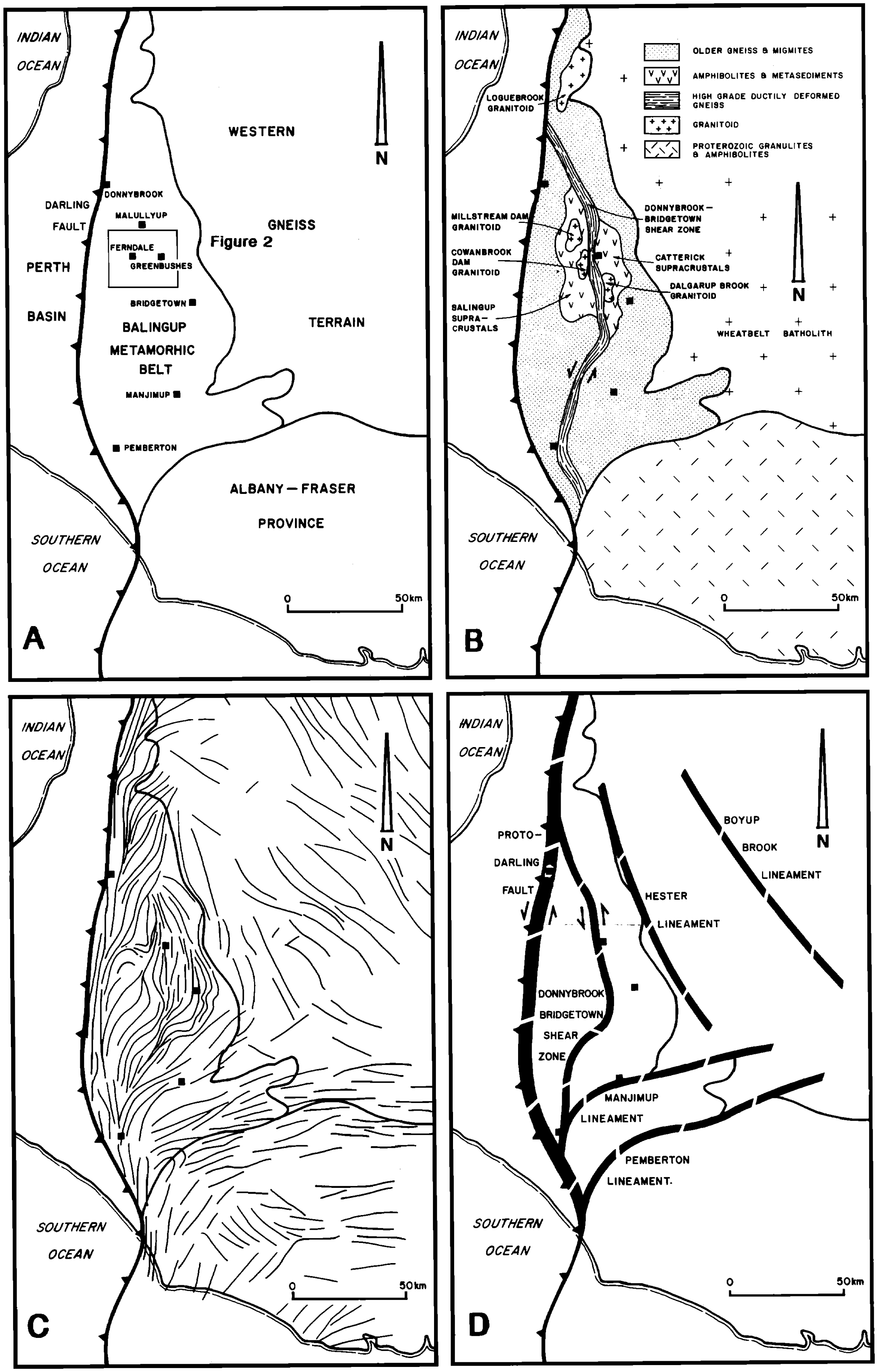


FIG. 1. Balingup metamorphic belt. Location diagram (A), the regional geology of the Balingup metamorphic belt (B), regional foliation trajectory map (C), and regional lineament map (D).

quently, a lithium milling and treatment plant was recently commissioned.

Many attempts have been made to classify and describe rare metal pegmatites using mineralogical and geochemical criteria. Because of the mineralogical and geochemical bias inherent in most classification schemes, many studies have not addressed the timing and controls on intrusion of rare metal pegmatite magmas. Recent studies indicate that the Greenbushes pegmatite group, potentially one of the largest rare metal resources in the world, differs from other rare metal pegmatite deposits in several important aspects (Table 1; Bettenay et al., 1985, 1986; Partington, 1986), particularly in its tectonic setting and syntectonic emplacement. To understand these differences it was necessary to resolve the structural and metamorphic history of the Greenbushes pegmatite group with respect to the structural and metamorphic history of its host rocks. The aim of this paper is to describe the environment and timing of intrusion of the Greenbushes pegmatite group. A preferred model for the intrusion of the pegmatite is also presented, and the implications for exploration for this type of rare metal pegmatite discussed. For the purposes of this paper more emphasis is given to the regional setting and structural evolution of the pegmatite group, with descriptions concentrating on metamorphism and structural geology of the pegmatites and their host rocks. Detailed descriptions of the petrography of the host rocks, internal geology, and geochemistry of the pegmatites are presented in Bettenay et al. (1985, 1986) and Partington (1986, 1988), and isotopic data are given in Partington et al. (1986), Seet (1986) and Partington (1988).

Regional Setting of the Pegmatite Group

The Greenbushes pegmatite district occurs within a 15- to 20-km-wide, north- to northwest-trending regional lineament between Donnybrook and Bridgetown and has a strike length of approximately 150 km (Fig. 1B, C, and D). This structure may be a splay from a regional north-south Archean structure which marks the trace of the Proto-Darling fault (Fig. 1D), as defined by Blight et al. (1981) and White et al. (1986), or it may be a remnant of an Archean structure which is offset by post-Archean movements along the Proto-Darling fault (Fig. 1D). A series of parallel lineaments, which may contain similar structures and be of a similar age, occurs north and south of the Donnybrook-Bridgetown lineament (Fig. 1D). A series of sheared gneisses, orthogneisses, amphibolites, and migmatites crops out along the lineament (Figs. 1B and 2), and the structures in these lithologies suggest that this lineament marks the trace of a ductile deformation zone which had a noncoaxial deformation history (Fig. 3). Furthermore, the rotation of an east-west-striking sequence of gneisses, in the vicinity of

TABLE 1. Comparison of the Greenbushes Pegmatite Group with Other Rare Metal Pegmatites

Formation	Depth (km)	Metamorphism	Elements-minerals	Form	Association	LiO_2 (ppm)	Ta_2O (ppm)	Rb_2O (ppm)
Rock crystal-bearing pegmatites	1.5–4	Greenschist zeolite	Fluorite, beryl, quartz, topaz	Pods in upper parts of epizonal granitoids	Within parental granitoids	200–6,600	10–380	300–2,040
Rare element-bearing pegmatites	4–7	Greenschist, epidote-amphibolite, staurolite-amphibolite	Be, Ta, Nb, and Sn; Be, Li, Cs, Ta, and Rb; Ta, Li, and Be; REE, Nb	Dikes and veins in fractures and along joints	Outside but associated with fractionated granitoids	8.0–1.8 (%)	13–5,000	200–11 (%)
Mica-bearing pegmatites	7–11	Kyanite-almandine, amphibolite	Muscovite; U, REE, and Be	Pods and dikes along foliation planes	Associated with anatectic granitoids	40–450	10–770	200
Ceramic pegmatites	>11	Granulite, sillimanite-almandine, amphibolite	U, REE	Diffuse veins grading into migmatites	Anatectic	2–50	5–50	5–300
Greenbushes pegmatite	>11	Staurolite-almandine-kyanite-amphibolite	Li, Sn, Ta, Nb, Rb, U, and Be	Dikes and pods in a shear zone	No obvious relationship	100–6 (%)	20–1,400	100–1.3 (%)

All data from Cerny (1982a), except for Greenbushes pegmatite

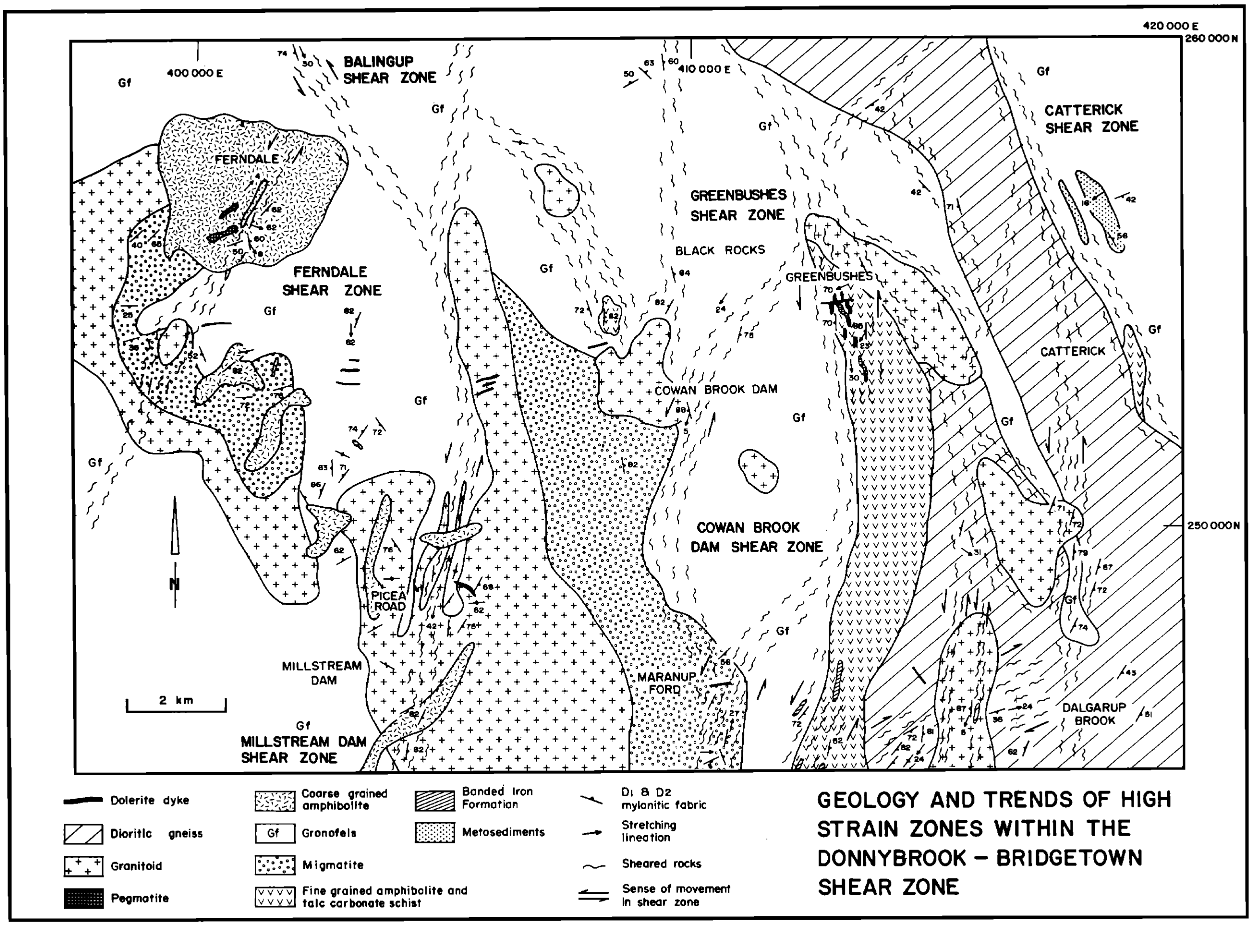


FIG. 2. Interpretive geologic map of the Donnybrook-Bridgetown shear zone in the Greenbushes mineral field showing the trends of high-strain zones.

Bridgetown, into this lineament (Fig. 1C), suggests that deformation occurred as a result of sinistral transcurrent movement along a major crustal shear zone (hereafter referred to as the Donnybrook-Bridgetown shear zone; Partington, 1986, 1988). The Donnybrook-Bridgetown shear zone is truncated to the south by the Proterozoic Albany mobile belt (Fig. 1B), suggesting that deformation occurred during the Archean and that this zone was largely inactive during the Proterozoic.

A sequence of gneisses (3,100 Ma; Fletcher et al., 1983) occurs in the southern part of the Greenbushes pegmatite district in the vicinity of Bridgetown (Figs. 1B and 2). The eastern and western margins of the gneisses are tectonic contacts against two supracrustal sequences to the east and west. Later shearing and granitoid intrusion are concentrated in these contact zones, and the deformation of these younger granitoids produced orthogneiss very similar in character to the older gneisses. Structural and intrusive relationships combined with geochronological evidence indicate that these are probably the oldest in the Greenbushes pegmatite district and as such are probably basement to the supracrustal sequences (Fletcher et al., 1983; Partington et al., 1986; Partington, 1988).

Two regional shear-bounded supracrustal belts (Fig. 1B) containing amphibolites, metasedimentary schists, and granofels occur in the Greenbushes pegmatite district (Wilde and Walker, 1979, 1981). The supracrustal sequence to the northeast of the Donnybrook-Bridgetown shear zone occurs as a northerly trending, 3-km-wide, sequence of schists, granofels, and quartzites. The sequence is bounded to the west by the Donnybrook-Bridgetown shear zone and to the east by older gneisses (Fig. 1B). The supracrustal sequence to the southeast of the Donnybrook-Bridgetown shear zone, in contrast, contains ultramafic-mafic amphibolites, felsic schists, and banded iron-formations (BIF). This supracrustal sequence reaches a maximum width of 30 km and is bounded by older gneisses to the west, by the Donnybrook-Bridgetown

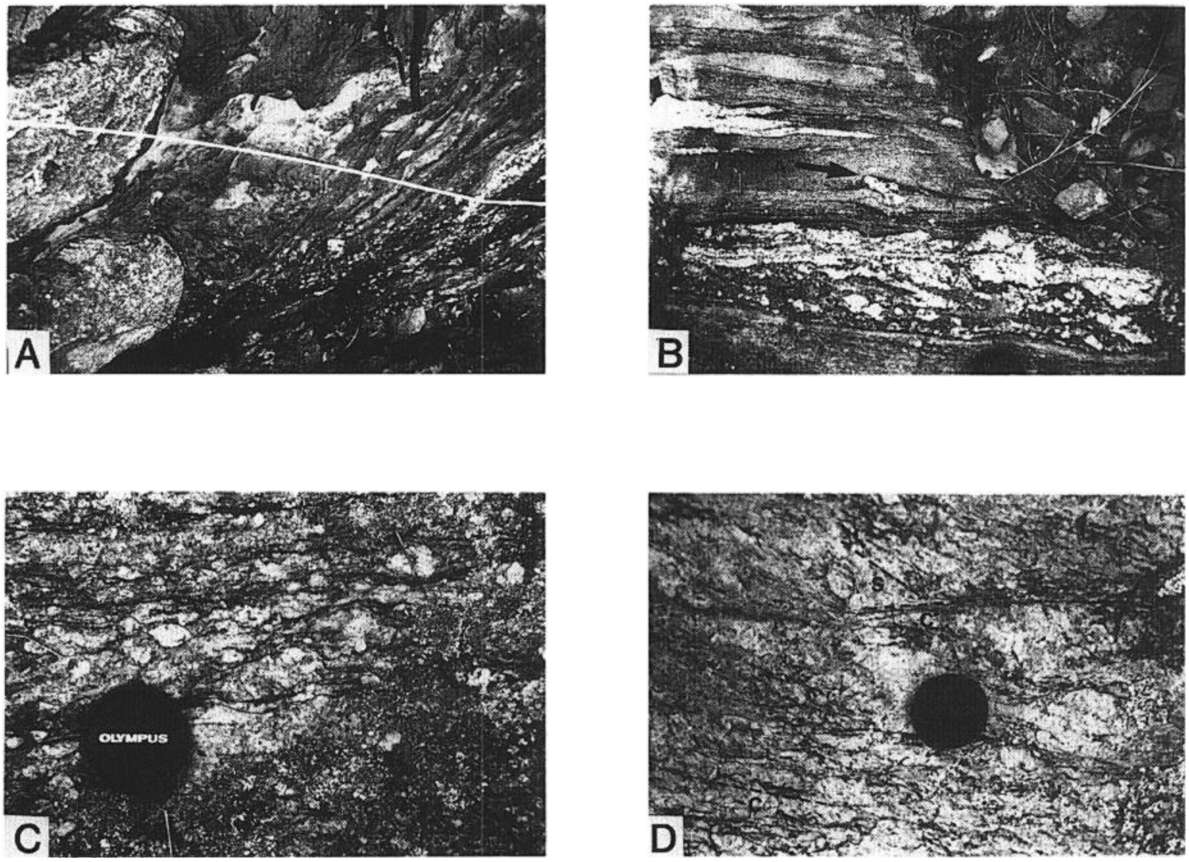


FIG. 3. A. Relationship of granitoid pods to D_2 shear zones from the contact of the Cowan Brook Dam Granitoid. Note the complex conjugate folds in the lee of the granitoid pods (cf. Fig. 4). B. Migmatite from the axial zone of the Donnybrook-Bridgetown shear zone. Note the asymmetric pods of leucosome which suggest sinistral shearing (camera cap is 5 cm in diam). C. Asymmetric pressure shadows in the lee of K feldspar augen from a D_2 shear zone, which cuts the Dalgarup Brook Granitoid, suggesting sinistral movement (camera cap is 5 cm in diam). D. C-S structures dragged into C′ structures from a D_2 shear zone deforming granitoid, which suggests sinistral movement (camera cap is 5 cm in diam).

shear zone to the east and older gneisses to the south (Fig. 1B). The amphibolites and metasediments in the transition zone between the supracrustal belts are sheared, resulting in heterogeneous high-strain zones containing migmatites with transposition structures (Fig. 3B).

Granitoids in the Greenbushes pegmatite district are subdivided on the basis of geochronology and tectonic association. A series of younger granitoids occurs as stocks and lens-shaped bodies which intrude the gneisses, amphibolites, and metasedimentary lithologies of the supracrustal sequences (Figs. 1B and 2). The granitoids are associated with felsic sheets and dikes and elongate migmatite zones (Fig. 2). The migmatites not only occur as elongate north-trending zones around the granitoid plutons but also as linear belts in shear zones outside the immediate contact zones of the granitoids (Fig. 2). Migmatite formation occurred synchronously with deformation as suggested by the (1) gradation from undeformed stromatic migmatites to ptygmatic migmatites from the margins to the centers of the regional shear zones, (2) the veins of leucosome crosscutting the regional mylonitic foliation, which were also deformed by later movements along the foliation planes, (3) the asymmetric form of the boudinaged pods of leucosome, and (4) the similarity between the asymmetry of mineral porphyroclasts from the regional shear zones and the asymmetry of the porphyroblastic pods of leucosome from the migmatite zones (cf. Fig. 3B and C). Although some granitoids crosscut the regional mylonitic foliation, many contain gradations in strain from undeformed zones with igneous textures to highly deformed orthogneiss with mylonitic fabrics (Fig. 3C and D). Many granitoids are oval shaped and are cut, but are also wrapped on a macroscopic and

mesoscopic scale by a regional mylonitic foliation (Figs. 3A and 4). This suggests that, like the migmatites, the granitoids were intruded synchronously with the regional deformation in the Greenbushes pegmatite district (cf. Hanmer et al., 1982; Castro, 1986). Most of the granitoids in the district have mineralogies and/or major oxide chemistry compatible with tin granites. However, none have comparable contents of Li, Rb, or Sn nor the typically low K/Rb ratios of traditionally accepted source granites (Blockley, 1980). Geochronological studies indicate emplacement of these granitoids between 2,610 and 2,580

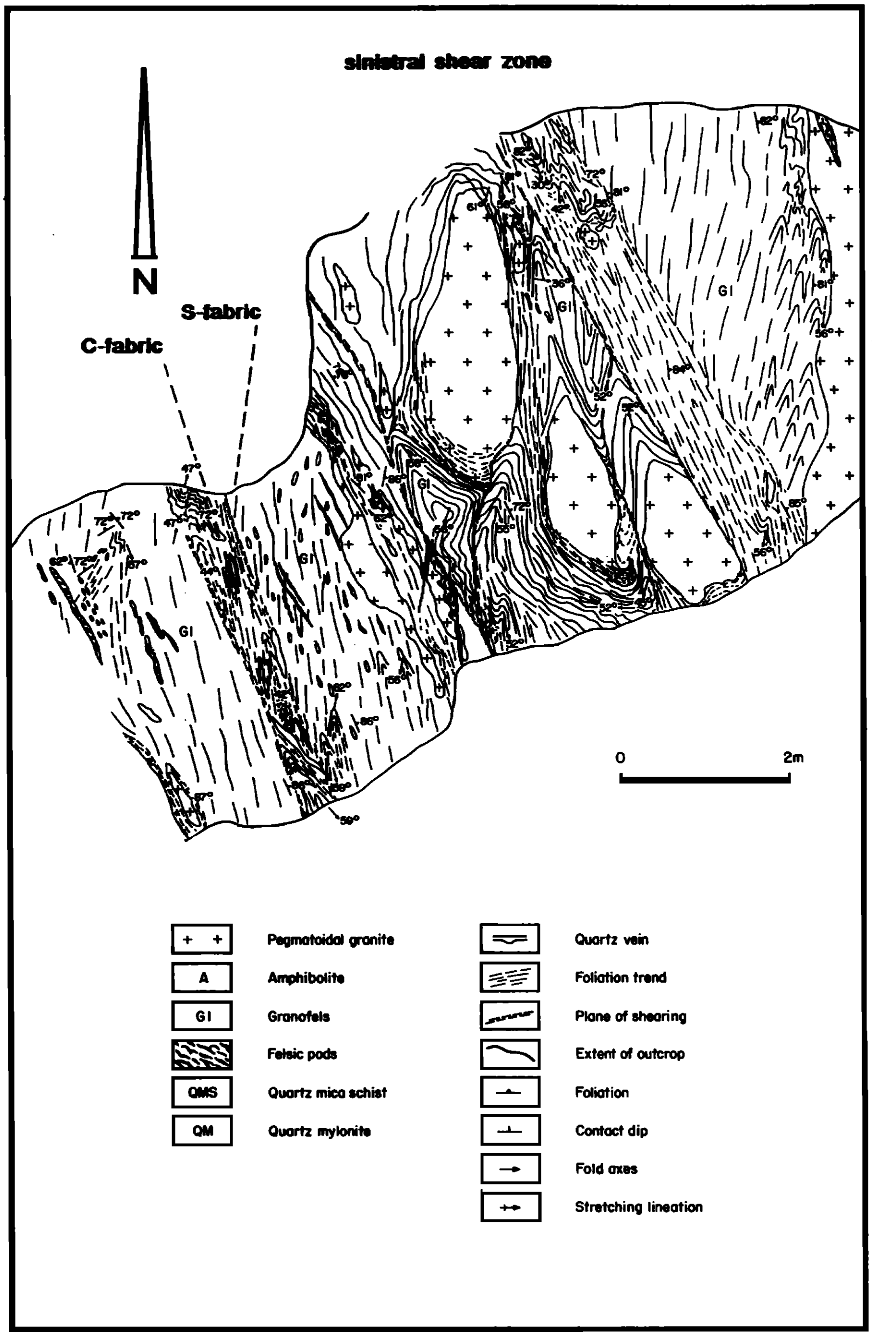


FIG. 4. A map of the contact zone of the Cowan Brook Dam Granitoid, which is deformed by D_2 shearing, showing the relationship between the C and S shear fabrics, granitoid intrusion, and the formation of conjugate folds (cf. Fig. 3A).

Ma, some 50 Ma before the intrusion of the Greenbushes pegmatite group (Blight et al., 1981; Partington et al., 1986; Partington, 1988). Two separate episodes of pegmatite intrusion followed granitoid intrusion in the Greenbushes pegmatite district. The older pegmatites (ca. 2,530 Ma; Seet, 1986; Partington, 1988) include the mineralized Greenbushes pegmatite group and the unmineralized Maranup Ford pegmatite group. The younger pegmatites (ca. 700 Ma) include the Ferndale pegmatite group and the Mullalyup pegmatite group (Kepert, 1985; Seet, 1986).

Mine Geology

Pegmatites of the Greenbushes pegmatite group occur as a series of linear dikes, varying in length from 2 to 3 km and 10 to 300 m in thickness, to individual pods of a few meters across. The pegmatite dikes, and en echelon pods emanate from an intrusive center (Fig. 5A). The pegmatite and its subsidiary dikes and pods are concentrated within shear zones which mark the boundaries between major sequences of granofels, ultramafic schists, and amphibolites (Figs. 2 and 5A). Primary magmatic textures and structures in the Greenbushes pegmatite group have been modified to varying degrees by later deformation and metamorphism (Fig. 6; Bettenay et al., 1985; Partington, 1988). As the deformation is heterogeneous, some areas retain primary features whereas other areas are completely recrystallized and mylonitized (cf. Fig. 6A and F).

Four major and four subsidiary compositional zones are recognized in the Greenbushes pegmatite group. As noted by Bettenay et al. (1985), the macroscopic zonation in the Greenbushes pegmatite group is unusual, and perhaps unique, in that those zones (e.g., lithium zones) normally expected to crystallize last, and hence, occur in the center of the pegmatite (Jahns, 1982; Norton, 1983), occur as footwall and hangingwall zones in the Greenbushes pegmatite group (Fig. 5B). Many smaller subzone variations occur within the broad zonal sequence, e.g., muscovite-apatite-beryl in the K feldspar zone, tourmaline-rich layers in the albite zone, and quartz layers in the lithium zone (Fig. 5B; Paterson, 1983; Bettenay et al., 1985, 1986; Partington, 1986, 1988).

The highest grade tin-tantalum ore shoots occur exclusively in the albite zones in the pegmatite and generally within tourmaline-rich subzones. Tin and tantalum oxides are associated with uraninite and appear to have crystallized synchronously with tourmaline. Cassiterite is the main tin-bearing phase occurring as euhedral swallow-tailed crystals which when deformed have pulled-apart and cataclastic textures. Early formed tantalum minerals occur as inclusions (mainly wodginite and ixiolite) within cassiterite crystals and tourmaline crystals. In contrast, the later coexisting tantalum phases (microlite, tantalite, and

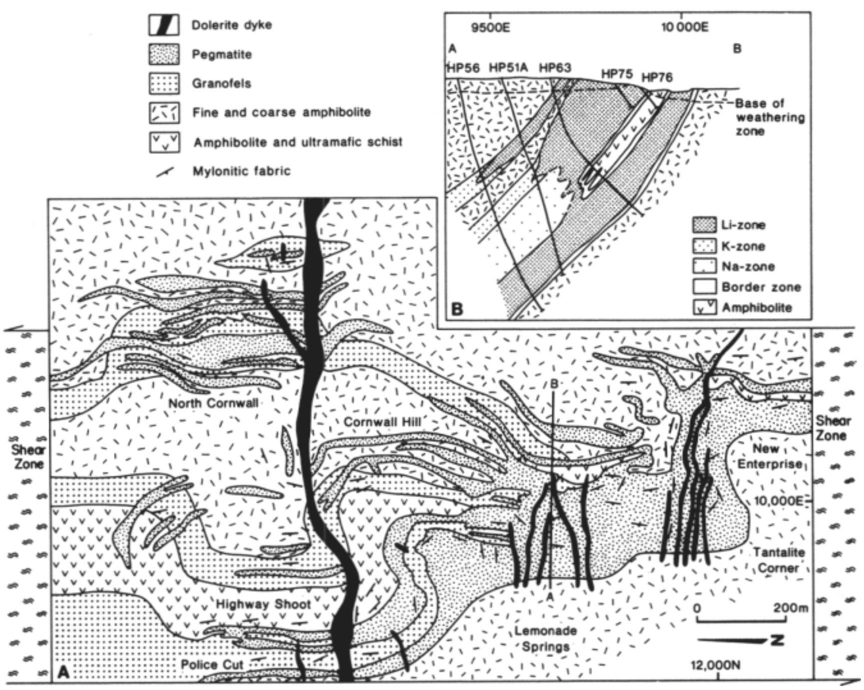


FIG. 5. Geologic map of the Greenbushes pegmatite group (A) showing the zonation in the pegmatite (B).

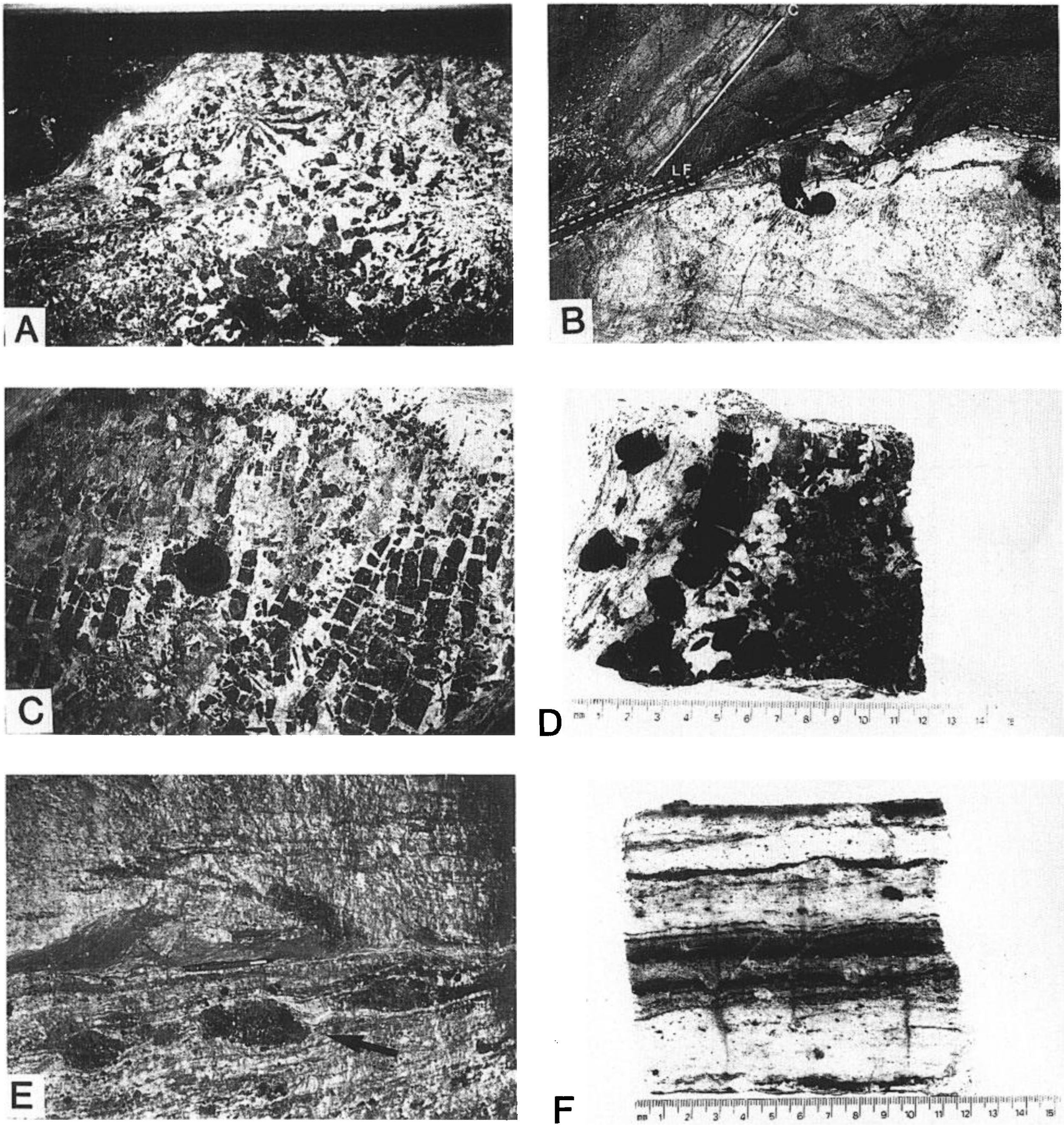


FIG. 6. A. Undeformed pegmatite with radial tourmalines from the 1160 level of the Greenbushes mine. B. Contact of the pegmatite with mafic country rocks. Note the D_2 fabric cut by the pegmatite (c), the foliation parallel to the contact (LF) and the xenolith of country rock (x) at the pegmatite margin (camera cap is 5 cm in diam). C. Pulled-apart tourmalines in the pegmatite (camera cap is 5 cm in diam). D. Gradation of brittle to ductile deformation in the pegmatite. Note the more rounded crystal fragments produced by the ductile deformation. E. Asymmetric boudinaged pods of a quartz-rich layer in the pegmatite, which indicates sinistral movement (pencil is 15 cm long). F. Highly deformed pegmatite, compare with Figure 5A.

tapiolite) in silicates are Sn free (Bettenay et al., 1985). Characteristic ore zone accessories include zircon, monazite, and uraninite. Preserved low-strain textures in the mineralized zones are typically magmatic and suggest that tin and tantalum minerals crystallized at an early stage (Bettenay et al., 1985) in

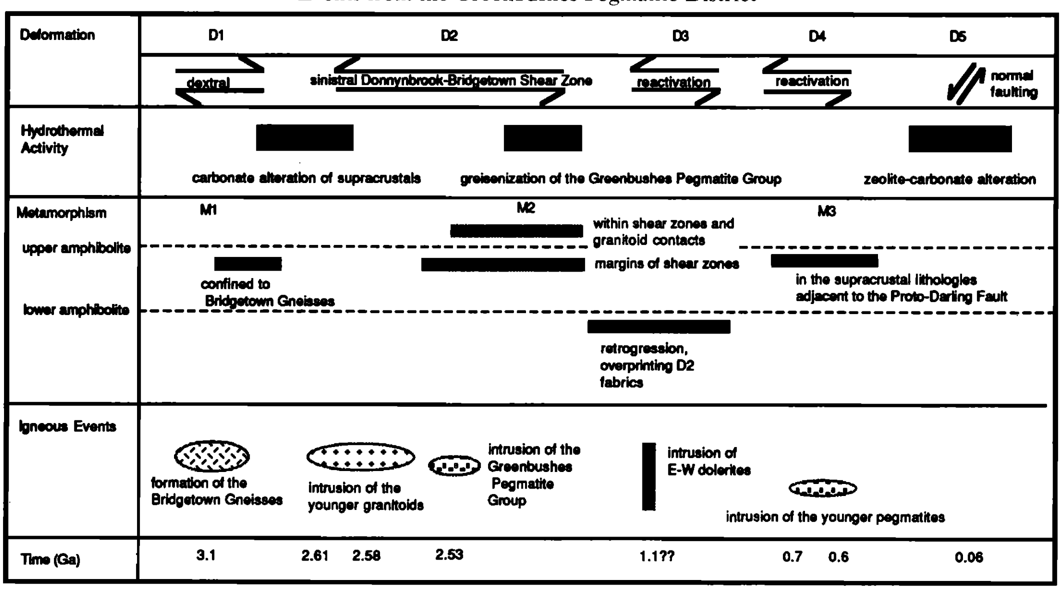
association with tourmaline and other accessories (notably garnet, zircon, and uraninite). The lithium ore zones comprise mainly primary spodumene, Mn apatite, and quartz. Very high grade lithium zones occur in the Greenbushes pegmatite group with some assays returning above 5 percent LiO_2.

Structure

Several phases of continuous ductile deformation, each with a noncoaxial deformation history, occurred in the Greenbushes pegmatite district and these are defined in Table 2. The intrusion of the Greenbushes pegmatite group occurred post-D_1 deformation, synchronous with D_2 deformation and pre-D_3 deformation as defined by overprinting relationships and temporal constraints (Table 2; Partington, 1988). Therefore, only the D_2 deformational event and its controls on the intrusion of the pegmatite group are discussed further in this paper. Information regarding the earlier or later deformation events are given in Bettenay et al. (1985) and Partington (1986, 1988).

Mylonitic fabrics formed during D_2 deformation occur in both the Greenbushes pegmatite group and its host rocks (Fig. 6E and F). Three types of foliation are recognized which, following the terminology of Berthé et al. (1979), Simpson and Schmidt (1983), and Lister and Snoke (1984), are defined as S, C, and C′ fabrics, respectively. S fabrics occur in medium- to low-strain zones in the D_2 shear zones which generally strike north to northwest with a vertical dip. These fabrics form clockwise to the D_2 shear zone boundaries (Fig. 4) indicating sinistral movement (cf. Berthé et al., 1979; Simpson and Schmidt, 1983; Hanmer, 1986). C fabrics are restricted to the high-strain mylonitic zones in the D_2 shear zones and strike north to northwest with a subvertical dip (Fig. 7). However, local variations in dip and strike (up to 60°) occur in the areas where the D_2 mylonitic fabric wraps lozenge-shaped pods of undeformed rock (Figs. 3A and 4). Both C and S fabrics form a distinctive asymmetric cleavage and mica "fish" (e.g., as defined by Lister and Snoke, 1984), where mica wraps around garnet and hornblende porphyroclasts or lobate clusters of recrystallized quartz in the granofels and schists. These microstructures are typical of micaceous mylonitic rocks (Bell and Hammond, 1984). In the moderate- to high-strain D_2 shear zones, C and S fabrics contain a lineation which may occur as elongate quartz rods or elongate aggregates of hornblende and feldspar in the mafic units, anthophyllite and holmquistite needles in the ultramafic units, and quartz, mica, and feldspar aggregates and rods in the granofels units. These lineations all have a subhorizontal plunge and north to northwest trend, though local variations in plunge and trend occur (Fig. 7). These variations are mainly concentrated in the vicinity of C′ structures, where the lineations parallel mesoscopic fold axes, and along the margins of curvilinear or anastomosing shear planes. They also occur in granitoid and pegmatite contact zones, where the lineations are dominantly oblique-slip and movement criteria are variable. The variations in plunge and trend of the D_2 lineations are very localized and seem mainly to be the result of either structural instabilities developed during granitoid intrusion or refolding of C planes during reactivations along D_2 shear zones.

TABLE 2. Deformation, Metamorphism, and Alteration in Relation to Geochronology and Igneous Events from the Greenbushes Pegmatite District



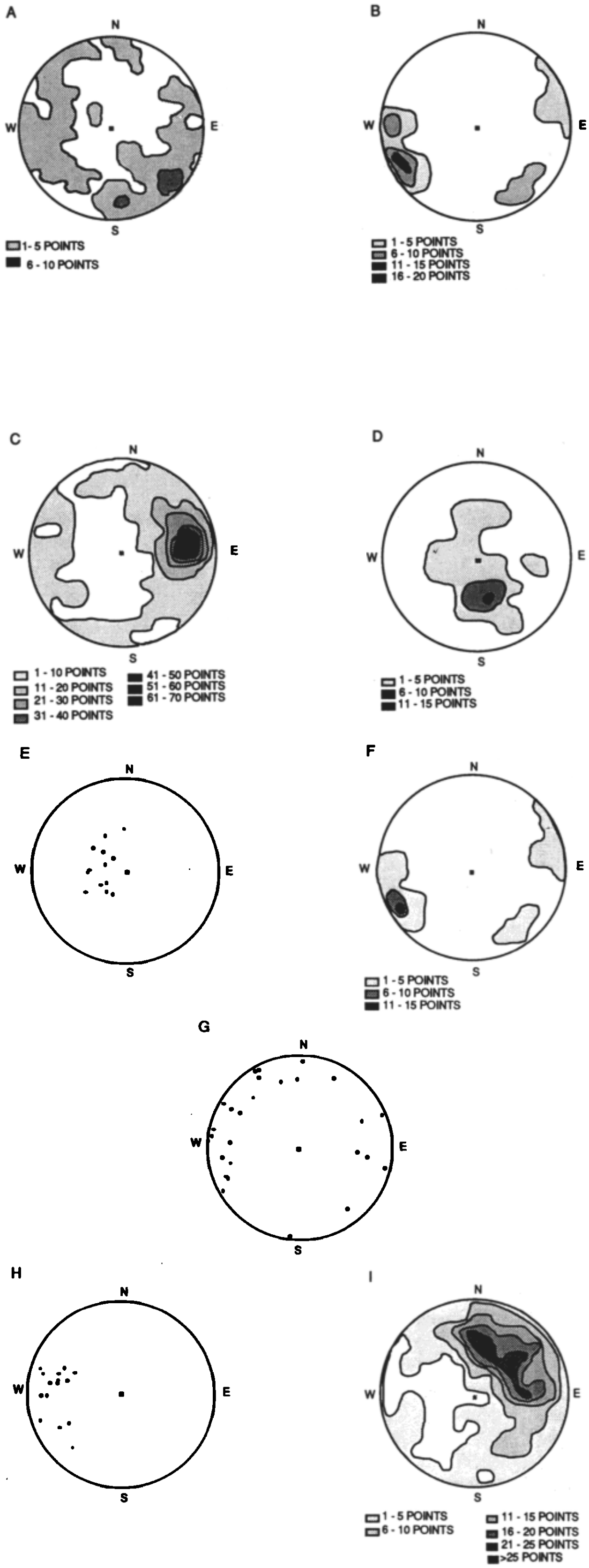


FIG. 7. Various stereograms showing the orientation of the D_2 shear fabrics. A. Lineations from the 1160 level. B. Poles to the mylonitic foliation from the Cowan Brook Dam area. C. Poles to the mylonitic foliation and pegmatite layering from the Highway Shoot open cut. D. Orientation of fold axes from the Cowan Brook Dam area. E. Orientation of fold axes from the Highway shoot open cut. F. Poles to the mylonitic foliation and pegmatite layering from Lemonade Springs open cut. G. Poles to the mylonitic foliation from the Millstream Dam area. H. Lineations from the Tantalite Corner open cut. I. Poles to the mylonitic foliation and pegmatite layering from the Tantalite Corner open cut.

C′ structures occur in the D_2 shear zones associated with C and S structures. These have an anticlockwise rotational sense, generally making an angle of 30° to the mylonitic fabric (Fig. 3D). Most have the same sinistral shear sense as suggested by other criteria in the D_2 Donnybrook-Bridgetown shear zone (Fig. 3D). These structures cause refolding of the C and S fabrics on a mesoscopic scale, forming asymmetric kinks in the amphibolites and granofels units, and conjugate and disharmonic intrafolial folds in the quartz-rich units (Fig. 4). The anastomosing character of the foliation in the D_2 shear zones occurs at all scales of observation, particularly in areas of competency contrast (e.g., between pods of granitoid and mafic host or between plagioclase porphyroblasts and a more ductile, quartz-rich matrix; Figs. 3A and 4), as shown by most mylonite zones (Bell and Hammond, 1984; Hanmer, 1986).

Four groups of mesoscopic fold styles are associated with D_2 shearing in the Greenbushes pegmatite district (Fig. 4). However, because of the nature of the deformation, these groups are not considered to have formed during separate deformational events. Instead, it appears that they were formed during a continuous progressive deformational event (cf. Platt, 1983; Ghosh and Sengupta, 1984). The folds are entirely restricted to the shear zones, tend to die out along their axial surfaces in both directions, and in profile define lens-shaped folded domains. The plunge and trend of the fold axes in these zones are highly variable as a result of rotation with each increment of deformation. The correlation of the orientations of the folds in different parts of the Greenbushes mine is very poor (Fig. 7), emphasizing the heterogeneous nature of the deformation. However, a strong relationship seems to exist between fold axes and an associated stretching mineral lineation within each structural domain (Fig. 7). The axial plane foliation of the folds within the megascopic shear zones is microstructurally similar to the folded foliation, and as the folding becomes tighter, the axial plane foliation becomes crenualated, especially in the hinge areas of the folds. The folds vary continuously in style from open and nearly concentric to virtually isoclinal similar folds (Figs. 4 and 8). The open folds have axial planes at high angles to the plane of the shear zone with near

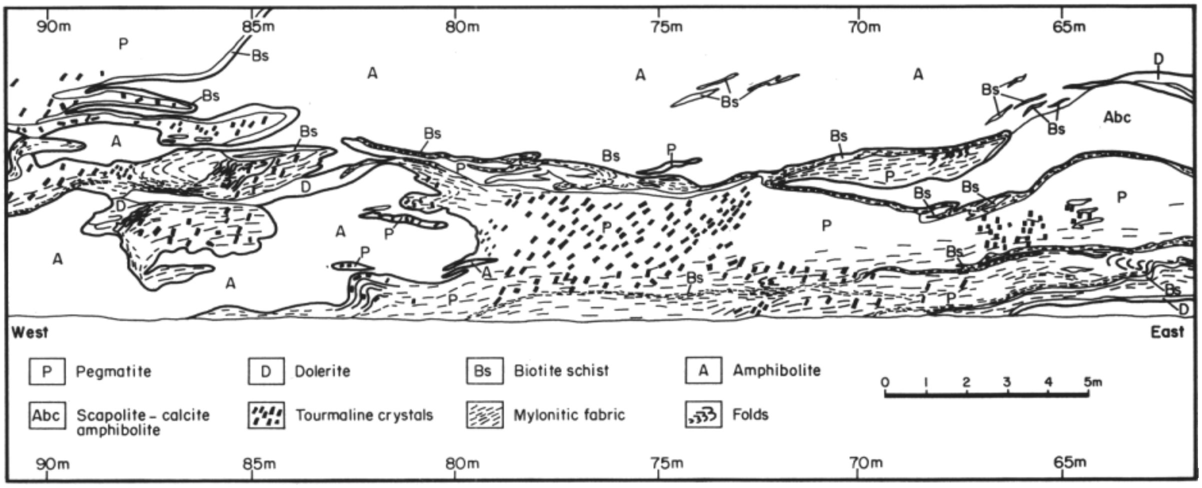


FIG. 8. A wall map from the 1160 level of the Greenbushes mine showing the pegmatite contact where pods of pegmatite are wrapped by D_2 shear fabrics (cf. the contact zone of the Cowan Brook Dam granitoid; Figs. 3A and 4).

vertically plunging hinge lines. The tighter and flattened folds are inclined at lower angles with gently plunging hinge lines which are parallel to an associated stretching lineation. This suggests that the folds formed episodically during deformation (e.g., Platt, 1983) and were progressively tightened, flattened, and rotated toward the direction of movement within the shear plane (e.g., Figs. 4 and 8). As the folding becomes tighter, transposition structures become more common, especially in the more heterogeneous rock types such as the granofels units in the hanging wall of the Greenbushes pegmatite group.

Structures synchronous with and postdating pegmatite intrusion

Further D_2 deformation occurred after the crystallization of the Greenbushes pegmatite group, resulting in structural overprinting of the magmatic textures in the pegmatite (Fig. 6). This deformation produced similar structures, mylonitic fabrics, folds, and shear zones to those produced by deformation predating pegmatite intrusion (Figs. 6 and 9). Therefore, the deformational event which postdates pegmatite intrusion is considered to be a continuation of D_2 deformation (i.e., sinistral movements along the Donnybrook-Bridgetown shear zone).

Although the intrusion of the pegmatite occurred during D_2 deformation, it caused localized reorientation and overprinting of D_2 structures. Similar modifications also occur in the contact zones of other granitoids in the Greenbushes pegmatite district (e.g., Figs. 3A, 4, 6B, and 8). An envelope of oblique-plunging lineations, suggesting a component of vertical movement, surrounds the Greenbushes pegmatite group and some granitoids (Fig. 7). The stretching lineations plunge 50° to the southwest in the Greenbushes mine. On a more localized scale, original strike-slip lineations are overprinted by later dip-slip movements and a reorientation of shear criteria. It appears that some of the C planes which were active during the strike-slip movements were inactive during later events and retained the earlier lineation. The intrusion of the pegmatite melts into the country rocks resulted in a wrapping of the earlier D_2 mylonitic foliation around the pods of pegmatite and localized refolding of the earlier mylonitic fabric during further reactivation along the C planes (Figs. 6B and 8). These folds have subhorizontal hinge lines and a vertical axial plane foliation parallel to the borders of the D_2 shear zones. Very complex fold geometries and apparent refolding relationships occur in these areas as a result of the combined progressive movements in both a vertical and horizontal sense. These folds are very similar in form to those developed in the contact zones of the younger granitoids.

A mylonitic fabric occurs in the contact zones of many of the individual pegmatite bodies in the mine sequence, especially in those contacts with biotite-schist alteration halos (Fig. 8). The fabric extends up to several meters from the contact and may completely surround the body, following all irregularities of the pegmatite contact (Figs. 6B and 8). The mylonitic fabric is usually defined by muscovite and biotite and wraps porphyroclasts of mica, forming mica fish. Quartz is commonly present as highly recrystallized polygonal grain aggregates which define elongate ribbons or quartz augen. A stretching lineation, which plunges 50° to the southwest, is commonly associated with the elongated quartz aggregates. Since

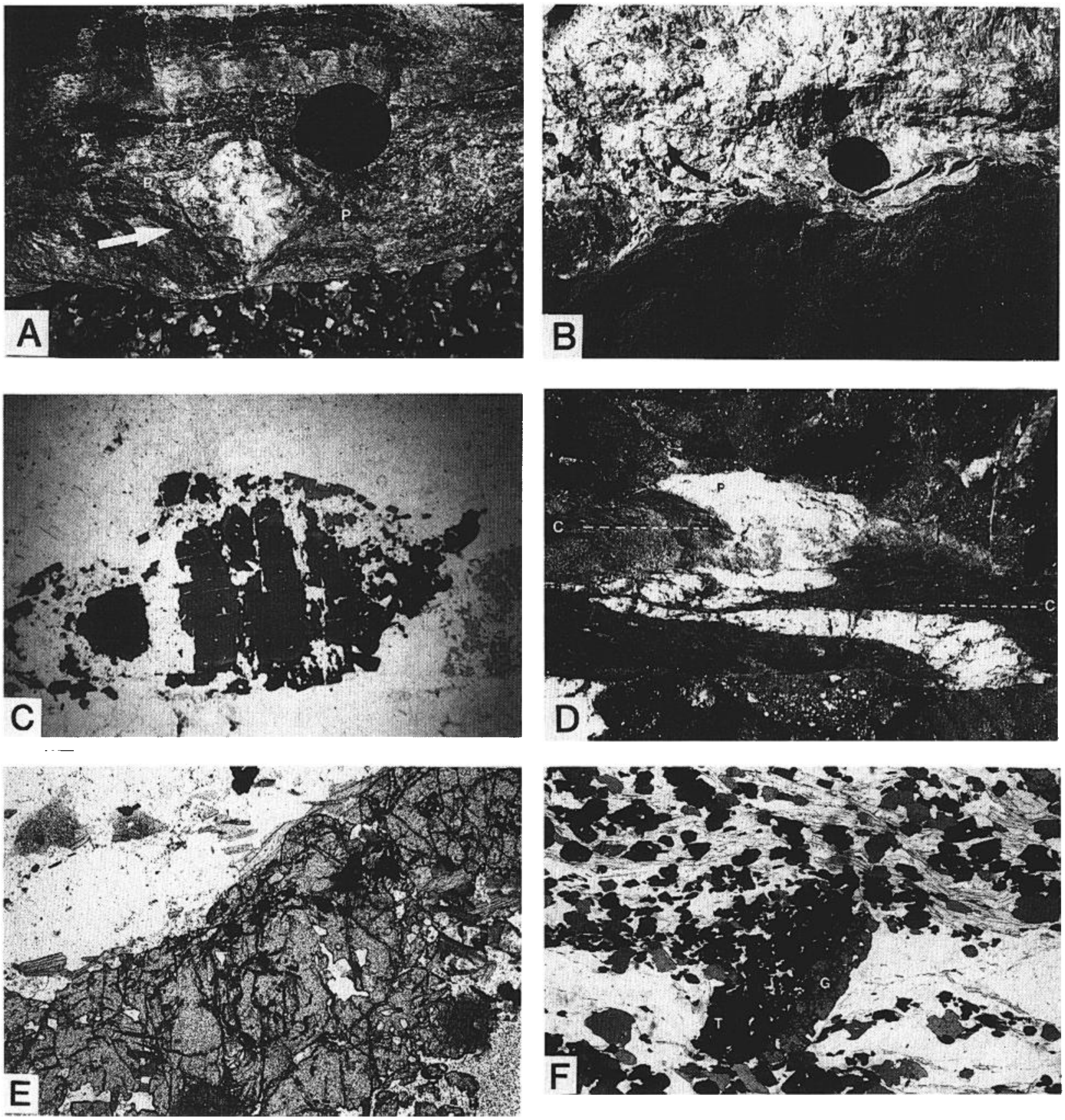


FIG. 9. A. Asymmetric pressure shadows (P) in the lee of a K feldspar megacryst (K) indicating sinistral movement (camera cap is 5 cm in diam). B. Tourmalines (T) initially perpendicular to the pegmatite contact now dragged parallel to the contact as a result of sinistral shearing (camera cap is 5 cm in diam). C. Photomicrograph of a pulled-apart tourmaline wrapped by fragments of tourmaline. Note the continuous zoning round the pulled-apart fragments suggesting growth during deformation (filed of view 14 mm). D. Pegmatite vein (P) deformed by shearing suggesting sinistral movement. Note the vein cuts but is also deformed by the C structures (C) in the shear zone (field of view is 2 m). E. Snowball garnet from the contact of the pegmatite. Note the internal inclusions are tantalite, whereas the outer inclusions are microlite suggesting that growth and deformation were synchronous (field of view 14 mm). F. Fragmented and recrystallized tourmaline (T) asymmetrically wrapped by the mylonitic foliation. Note the occurrence of garnet (G) in the pressure shadow of the porphyroclast (field of view 14 mm).

the overall strike of the pegmatite is parallel to the D_2 mylonitic fabric, the fabric caused by pegmatite intrusion can only be readily identified in areas where the pegmatite contact is grossly discordant to the D_2 fabric (e.g., Fig. 6B). Exocontact fabrics of this type are well documented from other pegmatites in North America (e.g., Page et al., 1953; Kretz, 1968).

Evidence for syntectonic crystallization

The regional structural relationships, and mesoscopic and microscopic structures in the Greenbushes mine sequence, suggest that D_2 deformation continued throughout the intrusive and subsolidus evolution of the granitoids and the Greenbushes pegmatite group. The evidence for syntectonic intrusion and crystallization is present at all scales in the Greenbushes mine. Numerous pegmatite veins crosscut the early D_2 mylonitic foliation and these were subsequently deformed by further continuous movements along the D_2 shear zones (Fig. 9D). Many of the pegmatite veins were emplaced subparallel to the dominant C structures in the host rocks and these were also subsequently deformed, causing transposition of the pegmatite veins parallel to the shear direction (Fig. 9D). Similar structures occur in the D_2 shear zones associated with granitoids in the Greenbushes pegmatite district (Fig. 4). The granitoids often cut the regional D_2 mylonitic foliation and yet are also sheared and folded by later movements associated with the same deformational event. Asymmetric boudinaged pods of pegmatite which occur at the margins of the Greenbushes pegmatite group (Fig. 8) are similar in character to the pods of granitoid emplaced into and wrapped by the D_2 shear zones in the contact zones of the regional plutons (compare Figs. 3A and 4 with Fig. 8). The pods of pegmatite contain tourmaline crystals that have grown perpendicular to the walls of the pods, which are also wrapped by sheared pegmatite and biotite schist, suggesting that these pods formed as a result of melts migrating into subsidiary structures in the shear zone in response to movements at various stages during the crystallization history of the pegmatite.

During crystallization of the pegmatite, D_2 deformation caused widespread recrystallization and the fragmentation of many of the brittle minerals (e.g., Figs. 6C and D and 9C). These were then pulled apart, wrapped by C and S structures, and the minerals cementing the fragments were then also deformed during further movements. As deformation continued, the pull-apart structures were wrapped by smaller fragments of tourmaline and recrystallized quartz, mica, and spodumene, forming distinctive asymmetric tails (Fig. 9C). Some of the pulled-apart fragments of tourmaline are zoned, suggesting that crystallization of the pegmatite melt continued after the minerals were fractured (Fig. 9C). Many of the late-crystallizing phases, such as spodumene, garnet, and microlite, commonly occur in the low-strain areas around the fragments of brittle minerals (Fig. 9F). Although D_2 deformation is ductile, many of the minerals in the pegmatite are deformed in a brittle manner. This deformation caused en echelon and conjugate fractures to occur in many of the larger crystals of tourmaline and albite. These fractures caused reduction in grain size of the larger brittle minerals, by progressively fracturing and plucking fragments from the crystal being deformed. The distribution of the late-crystallizing minerals, such as spodumene, garnet, albite, biotite, microlite and tantalite, is also controlled by these fractures. The restriction of some tantalum-bearing phases to microfractures in brittle minerals such as albite and tourmaline may explain some of the high-grade ore distributions that occur at a macroscopic scale (Partington, 1988).

Syntectonic intrusion and crystallization of the Greenbushes pegmatite group is also suggested by the presence of garnets and tourmalines with spiral inclusion trails of quartz, muscovite, and tantalum-bearing minerals. The tantalum-bearing phases in the garnets change in composition from tantalite-columbite at the center of the inclusion trail to microlite at the outer margins of the inclusion trail (Fig. 9E). These snowball garnets generally occur at or near the contacts with the mafic country rocks or mafic xenoliths within the pegmatite. Many of the early tourmalines in the contact zone of the pegmatite and country rocks enclose an early mylonitic fabric defined by cummingtonite. These crystals are in turn wrapped by a similar fabric to the one which forms the internal spiral inclusion trail. The spiral inclusion trails within the garnets and tourmalines suggest that deformation occurred synchronously with the growth of these crystals during crystallization of the pegmatite magma.

Metamorphism

Metamorphic studies were undertaken to test the findings of structural studies, i.e., that the depth of intrusion of the Greenbushes pegmatite group, as indicated by its ductile structural setting, was deeper in the crust than would normally be expected for a mineralized group of pegmatites (Cerny, 1982a). Three metamorphic events can be identified using structural fabric analysis, isotopic data, and the timing of igneous events. The relationship of these metamorphic events to the structural and igneous events is summarized in Table 2. M_2 metamorphism is related to D_2 deformation and hence provides evidence for the environment of intrusion of the Greenbushes pegmatite group. The M_1 and M_3 metamorphic events post- and predate pegmatite intrusion and are there-

fore not considered further. A more detailed description of these events is presented in Partington (1986, 1988).

Mineral assemblages

Typical mineral assemblages found in the host rocks to the Greenbushes pegmatite include muscovite-staurolite-kyanite, biotite-muscovite- K feldspar, biotite-hornblende-garnet-plagioclase, Ca scapolite-calcite-Ca plagioclase, grossularite-calcite-diopside, Ca plagioclase-scapolite-hornblende (or holmquistite), and grossularite-diopside-scapolite. The high-strain zones in the Donnybrook-Bridgetown shear zone contain migmatites which consist of varying proportions of biotite, quartz, and feldspar in the leucosomes compared with biotite, hornblende, garnet, and plagioclase in the melanosomes. All the metamorphic minerals used to constrain M_2 metamorphism are contained within and/or wrapped by D_2 mylonitic fabrics, suggesting that these assemblages were formed synchronously with D_2 tectonism (e.g., Spry, 1976). M_2 garnets have straight and sharp crystal faces when in contact with biotite, and the other minerals have subhedral to euhedral crystal forms, suggesting that textural equilibrium between the M_2 metamorphic mineral assemblages was attained (e.g., Spry, 1976).

Temperature estimates of M_2 garnet-biotite pairs using the Thompson (1976) computation were made, and these range from 495° to 525°C for garnet rim and 530° to 570°C for garnet core analyses. The Ferry and Spear (1978) computation gave a wider temperature range of 490° to 530°C for rim and 540° to 590°C for core analyses. Calculated temperatures of M_2 garnet-hornblende pairs using the Graham and Powell (1984) computation, on each average garnet composition and its associated surrounding hornblende, give a temperature range of 550° to 570°C, which is within the interval suggested by the garnet-biotite geothermometry. The data for these computations are given in Kepert (1985) and Partington (1988).

Pressures and temperatures associated with M_2 metamorphism

The temperatures attained during M_2 metamorphism in the low- and medium-strain zones can be estimated from the presence of staurolite and biotite-garnet pairs in metasediments and from plagioclase (An_{30-50}) and hornblende, and from one hornblende-garnet pair in amphibolites from the supracrustal sequences. According to Winkler (1979) the boundary between greenschist facies metamorphism and amphibolite facies metamorphism in pelites is defined by the breakdown of chloritoid and chlorite and the formation of staurolite. This occurs at 520° at 2 kbars and 565°C at 7 kbars. This boundary is also marked by a change in plagioclase composition ($<An_{17}$ to $>An_{30}$) and the formation of hornblende in mafic rocks (Winkler, 1979). Thompson (1976), who discusses the effects of continuous Fe-Mn reactions on the stabilities of minerals, notes that this boundary is effected by the Mg/Fe composition of the host rocks and that the Fe/Mg compositions of the assemblages in the host rocks to the Greenbushes pegmatite puts the staurolite boundary at 550° at 3 kbars and 580°C at 6 kbars. These temperatures are in agreement with the temperatures derived from the biotite-garnet pairs and the temperature derived from the single garnet-hornblende pair. Thus, the temperatures attained during M_2 metamorphism in the low- and medium-strain domains in the Donnybrook-Bridgetown shear zone were in the vicinity of 550° to 570°C (Fig. 10). The mineral assemblages and the form of the migmatites in the Donnybrook-Bridgetown shear zone suggest that higher temperatures and/or higher fluid activities may have occurred in the high-strain zones during M_2 metamorphism compared with those attained in the low- and medium-strain zones (Fig. 10).

The pressures attained during M_2 metamorphism can be constrained by the presence of almandine garnet and staurolite-kyanite assemblages in the supracrustal sequences. The presence of almandine in the amphibolites and granofels suggests, assuming temperatures of approximately 550°C, that pressures of

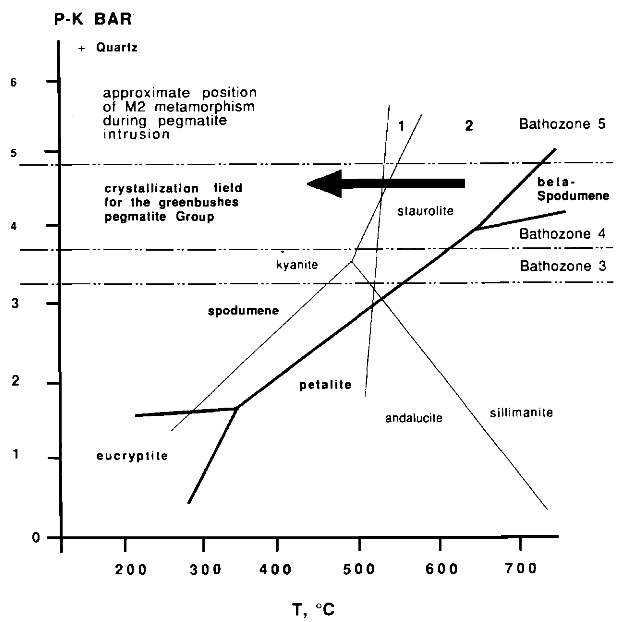


FIG. 10. Pressure-temperature data for the various mineral assemblages in the host rocks to the Greenbushes pegmatite group; metamorphic mineral stability fields are taken from Thompson (1976), Carmichael (1978), and Winkler (1979). Also shown are stability fields for the lithium phases in Li pegmatites in relation to the metamorphic assemblages in the host rocks to the Greenbushes pegmatite group; adapted from London and Burt (1982).

greater than 4 kbars must have existed during M_2 metamorphism (e.g., Carmichael, 1978; Winkler, 1979). The presence of staurolite-kyanite assemblages suggests that the pressures attained during M_2 metamorphism were in the region of bathozone 5, as defined by Carmichael (1978), or between 4 and 5 kbars (Fig. 10). The pressures suggested for M_2 metamorphism by the staurolite-kyanite assemblages are confirmed by the presence of primary spodumene, rather than petalite, in the Greenbushes pegmatite group (e.g., London and Burt, 1982; Fig. 10).

Discussion

Tectonic environment

Structural and metamorphic studies suggest that the Greenbushes pegmatite group was intruded deeper in the crust than would normally be expected for rare metal pegmatites (e.g., Cerny, 1982a). A comparison is therefore made, in the following section, between other documented shear systems and the Donnybrook-Bridgetown shear zone to establish more accurately the possible environment and depth of intrusion of the Greenbushes pegmatite group. Ductile noncoaxial deformation in strike-slip shear zones produces an intense linear fabric with horizontal orientations associated with two vertical foliations at 30° to each other (Nicolas et al., 1977). As strain increases, these fabrics become parallel, forming a distinctive braided S-shaped texture (Berthé et al., 1979). This type of ductile deformation is believed to be comparable with deformation in the deeper parts of currently active fault systems such as the San Andreas and Alpine fault systems in California and New Zealand, respectively (e.g., Davis and Burchfiel, 1973; Scholz, 1977; Harding, 1976). The Ikertoq shear zone in Greenland is believed to be an example of a deep-crustal Archean transcurrent structure, and as in the Donnybrook-Bridgetown shear zone, deformation is distinctively heterogeneous and strains are concentrated into narrow mylonite zones over the 40-km-wide shear zone (Grocott, 1977). At higher levels transcurrent shear zones become increasingly discrete and deformation becomes even more heterogeneous. The form of these upper-crustal transcurrent fault systems suggests that the Donnybrook-Bridgetown shear zone represents the root zone of an Archean sinistral transcurrent fault system analogous to the Phanerozoic San Andraeas fault system in California and the Alpine fault system in New Zealand (e.g., Wilcox et al., 1973; Hubert et al., 1985).

The coincidence of high-grade metamorphism, including anatexis, and intrusion of granitoid magmas in shear zones is documented by Nicolas et al. (1977), Ramsay and Allison (1979), Brun and Choukroune (1981), Halden (1982), Hanmer et al. (1982), and Castro (1986). The dominant structures in the Anger-Lanvaux shear zone in France are a horizontal stretching lineation, which parallels fold axes, and a foliation or slaty cleavage, which wraps the axis of the shear zone. The folds in this shear zone, as in the Greenbushes pegmatite district, have axes parallel to the general trend of the shear zone. In the Anger-Lanvaux shear zone and the Savanrantena shear zone in eastern Finland, high-grade metamorphism is centered in the axial region of the shear zone and lower grade assemblages occur symmetrically away from the axial region (Nicolas et al., 1977; Halden, 1982). A similar metamorphic bilateral symmetry seems to be present in the macroscopic shear zones in the Greenbushes pegmatite district. The high-strain zones in the Greenbushes pegmatite district contain evidence for migmatization and anatexis, whereas the low-strain zones contain medium-grade assemblages and show no evidence for migmatization. High-strain lithologies containing evidence for partial melting are also described from the axial regions of the Anger-Lanvaux shear zone, the Savanrantena shear zone, and the Mayadan shear zone, in Afghanistan. There is also a general association of pegmatite and granitoid intrusion with increasing strain in the Mayadan shear zone, which is also present in the Donnybrook-Bridgetown shear zone.

Factors controlling the intrusion of pegmatites

Pegmatites are, in general, characterized by a variety of sizes, shapes, orientations, and structural relationships to host rocks. The variety of pegmatite shapes is discussed in reviews by Brisbin and Trueman (1982) and Cerny (1982a, b). They may occur as single tabular bodies, as multiple tabular bodies with a preferred orientation, or as lenslike or podiform bodies. In some cases the bodies are connected, in others, unconnected. They may have smooth curviplanar or extremely irregular but sharp contacts when not in contact with their parental granitoid. However, pegmatites may have gradational contacts when in contact with their parental granitoid.

In general, the contact relationships between host rock and pegmatite and internal structure provide strong evidence that most pegmatites were in a melt or fluid state during intrusion and crystallization (Cerny, 1982a, b; London, 1986a, b). Such melts lie on the boundary between fluids and silicate melts (London, 1986a, b) and have greatly reduced viscosities, and therefore may be channeled in a manner similar to hydrothermal or metamorphic fluids (e.g., Etheridge et al., 1983, 1984; Guha et al., 1983; Kerrich, 1986). The intrusion of pegmatites is characteristically associated with increased fluid pressure, so that intrusion will occur when the fluid pressure of the melt exceeds the minimum principal stress within that rock. During intrusion the melt pressure will adjust downward to the lower ambient level of pressure

in the host rocks, and the intrusion will expand within the intrusive site until external and internal pressures are equalized.

It is assumed in the literature that many pegmatites are intruded into dilational sites associated with extension. The stress relationships within the crust are more complex (Brisbin, 1986), since in most cases the state of stress within the crust is dominantly compressive. Consequently, most pegmatites can only intrude when their magmatic pressure is greater than the confining pressure of their host rocks. Furthermore, the form that a pegmatite body takes is dependent on the rheological state of the host rocks at the site of intrusion. The most important control on the shape of intruding pegmatites and the manner of intrusion is that of the effect of structural weaknesses. In massive, solid, structurally isotropic rocks in the brittle domain, pressurized pegmatite magmas must overcome the tensional strength of the rock as well as the compressive normal stress acting as a result of lithostatic pressure or directed stress. In this environment hydraulic fracturing is common, i.e., pore pressure is such that it builds until it exceeds lithostatic pressure and consequently failure occurs (e.g., Etheridge et al., 1984). If the rock is not anisotropic with respect to tensile strength the only factor controlling the failure orientation will be that of the minimum stress at that site due to lithostatic pressure and deviatoric stress. However, many rocks that host pegmatites are characterized by structural weaknesses such as preexisting fractures, foliations, schistosities, and layering. These planar features have tensile strengths across them that are usually considerably lower than other directions in the rock. In essence, a host rock can be structurally prepared for the intrusion of pegmatite magmas by earlier or synchronous deformational processes. In the ductile domain the stress conditions are such that dilation of the intrusive site by pressurized pegmatite magma forms balloon-like or turnip-shaped intrusive bodies. However, as strain increases, the ductile domain may approach similar conditions to those observed in the brittle domain.

Structural control on the intrusion of the Greenbushes pegmatite

As noted by Brisbin (1986), there are few descriptions of the types of structures which control the intrusion of pegmatite bodies. Many of the examples described in the reviews by Chadwick (1958) and Cerny (1982a and b) occur in the brittle field and are associated with structures similar to those seen in other vein deposits. Intrusion of the Greenbushes pegmatite group occurred in the ductile field of the crust as suggested by structural and metamorphic studies. The host rocks to the Greenbushes pegmatite group were structurally prepared for the intrusion of the pegmatitic melts by D_2 sinistral shearing which resulted in regional north to northwest and south to southeast structural zones of weakness in the form of C structures (Fig. 11) and secondary structural zones of weakness in an east to west direction as a result of C′ structures (Fig. 11). The most important control on the intrusion of the pegmatite was that, not only had the host rocks been structurally prepared but movement along the shear system continued during intrusion and for some time after crystallization.

For initial intrusion of a pegmatite magma to occur in the ductile field, the fluid pressures contained within the pegmatite melt must be greater than the host-rock confining pressure. Experimental work and computer modeling indicate that during movements in ductile shear zones high strains result in eventual strain hardening (White et al., 1980; Ramsay and Huber, 1987). This continues until failure occurs and movement continues within the shear zone. In the upper crust at the time of failure major fracture zones occur (Fig. 11) which, combined with the major pressure reduction that accompanies failure, may channel pegmatite melts (e.g., Brisbin and Trueman, 1982) and other metamorphic or ore-bearing fluids (e.g., Kazansky, 1972; Guha et al., 1983). At greater depths in the ductile field, structural weaknesses can also occur. For example as predicted by computer modeling (Mcintyre, 1985), sites of major structural weakness can occur in the lee of ridged bodies, or as is the case in the Greenbushes pegmatite group, along curved shear planes (e.g., Harris and Cobbold, 1985; Fig. 11). Any melts or fluids in the system at this time would be channeled by such zones, in this case initiating intrusion of the pegmatite melt. The fluid

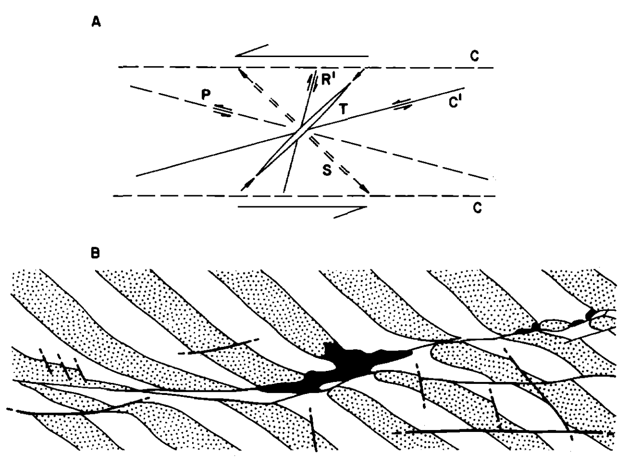


FIG. 11. Experimental analogue of the possible structural control on the Greenbushes pegmatite group. A. Theoretical structures developed in a regional transcurrent shear zone. C = C planes, C′ = C′ structures, S = S planes, T = tension fractures, R′ = antithetic shears, and P = P shears. B. Experimental model after Harris and Cobbold (1985) and Harris (1987).

pressure in the pegmatite magma may then have increased, causing further failure, zones of structural weakness, and further intrusion of pegmatite. This process, combined with internal stresses generated by the crystallizing pegmatite magma, caused emplacement to occur generally parallel to the mylonitic fabric in the shear zone.

The geologic and tectonic environment of intrusion of the Greenbushes pegmatite group is not unique to the Archean of Western Australia, and the structural controls on the intrusion of the Greenbushes pegmatite recorded here have also been recognized to control the localization of other Archean ore deposits and metamorphic fluids (e.g., Kazansky, 1972; Guha et al., 1983; Etheridge et al., 1984; Groves et al., 1984). Preliminary data suggest that strike-slip movement occurred both prior to and during peak metamorphism between ca. 2,800 and 2,500 Ma across the Yilgarn craton. This tectonism would have allowed fluids or melts to become mineralized because of access to large volumes of rock through craton-wide fault systems, increased solubility of metals at higher P-T conditions, and the concentration of rare elements by granitoid emplacement and/or anatexis deep in the crust. The presence of rare element pegmatites in similar structures hosting other Archean mineralization suggests that these magmatic fluids utilized similar structural channelways to other mineralizing fluids, emphasizing the importance of crustal-scale shear zones in localizing fluid flow in the Archean.

Implications for exploration

Rare metal pegmatites are part of the ore association related to granitoid magmatism and are related to other deposits such as disseminations in granitoids or pegmatites, pyrometasomatic deposits (metamorphic aureoles, skarns), hydrothermal pneumatolytic deposits (veins, stockworks, breccia pipes, greisens, replacement lodes, dikes) and hydrothermal-epithermal and xenothermal deposits (veins, stockworks, breccia pipes). Ginsberg et al. (1979) defined four fields of pegmatite formation within the deep-seated granitoid and pegmatite association (Table 3). These fields are based on geobarametric calculations which characterize the metamorphic grade of the enclosing host rocks. The individual pegmatite formations are also defined by typical ranges in absolute age, structural styles of their geologic environment, relationship to parental granitoids, reaction with host rocks, morphology of internal structure and mineralogy, and trace element geochemistry. It is generally believed that those pegmatites that host most of the important mineralization are found in a specific geologic environment (i.e., within rocks subjected to low-pressure and medium-temperature Abukuma facies metamorphism; Cerny, 1982a, b; Trueman and Cerny, 1982).

TABLE 3. Comparison of the Greenbushes Pegmatite Group with Pegmatite Formations Defined by Cerny (1982a)

Pegmatite group	Country rocks	Depth (km)	Metamorphism	Ore minerals	Pegmatite form and association	Zonation scheme
Greenbushes pegmatite, Western Australia	Amphibolite, ultramafic schist, metasediment	>11	Mid-amphibolite	Spodumene, cassiterite, tantalite, uraninite, microlite	Dikes or pods within foliation; intruded syndeformation; 5 km × 1 km × 400 m	Hanging; spodumene-K feldspar-albite-Li; footwall
Karibib, Southwest Africa (1)	Amphibolite, migmatite, paragneiss	7–11	Upper amphibolite	Petalite, tantalite, lepidolite	Small undeformed dikes or pods; related to late leucogranites	K feldspar-cleavlandite-Li quartz core
Tanco, Canada (2)	Metavolcanic, metasediment, metagabbro	7–11	Greenschist to low amphibolite	Petalite, cassiterite, tantalite, lepidolite, spodumene	Subhorizontal sheets; related to hidden late granitoid; 1,440 × 820 × 100 m	Albite-quartz-K feldspar-Li quartz core
Bikita, Southern Africa (3)	Amphibolite	7–11	Amphibolite	Petalite, lepidolite, beryl, tantalite, cassiterite	Irregular tabular intrusion with a gentle dip; post-tectonic; 1,500 × 55 × 30 m	Albite-muscovite-K feldspar-Li quartz core
Vartutrask, Sweden (3)	Amphibolite	7–11	Amphibolite	Petalite, spodumene, lepidolite, beryl	Flat trough-shaped sheet; late; 300 × 30 × 30 m	Quartz-muscovite-tourmaline-K feldspar-Li pollucite-quartz core
Black Hills, South Dakota (4)	Amphibolite, schist, gneiss	5–7	Upper amphibolite	Amblygonite, spodumene, tantalite, cassiterite	Small dikes, pods and sheets; post-tectonic granitoids	Muscovite-quartz-K feldspar-albite-Li quartz core

Data taken from (1) Cerny (1982a, b); (2) Roering (1966); (3) Heinrich (1976); (4) Redden (1963)

These pegmatites are further subdivided into series which emanate from a central granitoid source, with the most economically important pegmatites occurring a certain distance from their source granitoid. If these classifications are correct, then these features should provide criteria for assessing the potential of prospects for rare element mineralization during regional exploration (e.g., Trueman and Cerny, 1982). That is to say, the most prospective areas for rare metal pegmatites should occur in low-pressure, medium-temperature Abukuma facies metamorphic rocks adjacent to source granitoids which show evidence of fractionation. The Greenbushes pegmatite group, however, occurs in a higher temperature and higher pressure metamorphic terrane, is not associated with nearby fractionated granitoids, and was intruded some fifty million years after regional granitoid intrusion. According to most models it should be unmineralized. It is clear from the tectonic environment and mechanisms of intrusion of the Greenbushes pegmatite group discussed above that the present models and exploration techniques need to be refined. Giant rare metal pegmatites can occur in medium- to high-temperature and medium-pressure metamorphic terranes, and this type of pegmatite need not have obvious parental granitoids. Such pegmatites may contain mineralization not usually associated with rare element pegmatites intruded at this depth and are likely in the Archean to be associated with tectonism along crustal-scale fault systems. These data provide additional criteria to be used during regional exploration for rare metal pegmatites in Precambrian terranes and consequently should open new areas to exploration considered nonprospective in the past.

Conclusions

1. The Greenbushes pegmatite group was emplaced into the Donnybrook-Bridgetown shear zone, a major north-northwest-trending, 150-km-long, and 15- to 20-km-wide crustal structure. Displacement and rotation of macroscopic structures indicate that a major sinistral strike-slip component of movement occurred along this shear zone in the vicinity of the Greenbushes pegmatite district.

2. The Greenbushes pegmatite group intrudes a sequence of gneisses and supracrustal rocks consisting of mafic and ultramafic metavolcanic and metasedimentary sequences. The gneisses contain evidence for an earlier deformational event, and are interpreted as basement to the supracrustal sequences. The early structures are overprinted by a regional D_2 dynamothermal event, whose structures confirm a progressive ductile event with a noncoaxial deformation history related to the regional shear zone.

3. The regional distribution of a series of granitoids (2,612-2,577 Ma) along major tectonic contacts, the nature of their marginal zones, and the migmatitic layering within the gneisses and supracrustal lithologies all indicate emplacement synchronously with D_2 shearing. These granitoids are not fractionated and were intruded some 50 Ma before the intrusion of the Greenbushes pegmatite group to which they cannot be genetically related.

4. The metamorphic history of the Greenbushes pegmatite district is complex. The metamorphic grade within the D_2 shear zones is upper amphibolite facies, with temperatures of between 550° to 625°C being recorded. The occurrence of staurolite-kyanite assemblages near Bridgetown suggest relatively high-pressure conditions during regional metamorphism, as does the occurrence of spodumene rather than petalite as a primary phase in the pegmatite.

5. Detailed fabric analyses reveal that the pegmatite was deformed by ductile D_2 sinistral shearing associated with movements along the Donnybrook-Bridgetown shear zone. Also the preservation of rare relic igneous structures in pegmatite dikes, which intrude D_2 structures but which are also deformed by later progressive D_2 deformation, suggests that the pegmatite was emplaced during the shearing event. Microstructures from the less deformed domains also indicate that pegmatite crystallization occurred synchronously with D_2 shearing.

6. Any melts or fluids present during movement along the Donnybrook-Bridgetown shear zone would have been channeled into it, hence localizing intrusion of the pegmatite. The fluid pressure in the pegmatite magma then may have increased causing further failure, zones of structural weakness, and further intrusion of pegmatite generally parallel to the mylonitic fabric in the shear zone.

7. Large rare metal pegmatites may occur in medium- to high-temperature and medium-pressure metamorphic terranes and these types of pegmatites need not have obvious parental granitoids. They may contain a wide range of ore minerals and are likely, in the Archean, to be associated with tectonism along crustal-scale fault systems. These data provide additional criteria to be used during regional exploration for rare metal pegmatites in Precambrian terranes.

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