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A.Y. Glikson*, R. Davy**, A.H. Hickman**, C. Pride***
and B. Jahn****

* Division of Petrology and Geochemistry,
Australian Bureau of Mineral Resources,
Geology and Geophysics, Canberra, ACT

** Geological Survey of Western Australia
Perth, WA

*** University of Ottawa, Ottawa, Ontario

**** Institute of Geology, University of Rennes,
Rennes, France

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ABSTRACT

Studies of rare earth elements (REE) alkali and alkaline earth elements (Rb, Ba, Sr) and some high field strength elements (Ti, Zr, Nb) in felsic volcanic and plutonic rocks of the Pilbara Block, Western Australia, suggest the occurrence of three associations.

Association (1) (Ca 3.7-3.4 b.y.) consists of Na-rich calc-alkali, occasionally high-Al, andesite-dacite-rhyolite pyroclastics and rare flows intercalated with basic-ultrabasic volcanic sequences of the Warrawoona Group and possible plutonic analogues.

Association (2) (Ca 3.3-2.9 b.y.) includes K-rich rhyolite lavas located at the top of the Warrawoona Group (Wyman Formation) and post-tectonic granites.

Association (3) (Ca 2.9 b.y) comprises rhyolitic pyroclastics (Mons Cupri Volcanics) and related plugs (Mount Brown Rhyolite) of the Whim Creek Group.

The compositions of these suites overlap but Na-rich rocks are confined to Association (1). Association (1) is dominated by rocks of low Rb-Sr (<0.4) moderate to high light/heavy REE fractionation, (Ce/Yb)N < 15, small or no Eu/Eu* anomalies and near-flat heavy REE profiles, (Dy/Lu)N = 0.9-1.2. Association (2) includes rocks of very high Rb/Sr (11-15), moderate (Ce/Yb)N (5-6), marked Eu/Eu* anomalies (<0.4) and flat heavy REE profiles (0.9-1.1). Association (3) includes rocks of moderate Rb/Sr ratios (0.6-1.0), moderate (Ce/Yb)N (5.7-7.0), low Eu anomalies and weakly fractionated heavy REE (Tb/Yb)N<1.0. All units feature very low Nb anomalies. Petrogenetic observations arising from major element data fail to yield a positive discrimination between igneous (I-type) and Sedimentary (S-type) anatectic sources for the felsic magmas. The lack of Eu and Sr depletion in the andesite-dacite magmas indicates a relatively minor role

of plagioclase separation, and therefore an unlikely involvement of a felsic source. A derivation by partial melting or fractional crystallization of a basic source is likely for association (1), and can be modelled by separation from residual clinopyroxene, plagioclase and minor garnet. the origin of the high K rhyolites of Associations (2) and (3) can be modelled in terms of anataxis of a tonalite/trondhjemite crust, possibly including a basic component, and high degrees of partial melting leaving a residue of plagioclase and clinopyroxene. These models are consistent with an evolution from largely mafic sources to largely felsic sources with time in the Pilbara Block.

I. INTRODUCTION

A study has been conducted of rare earth element (REE) and large ion lithophile element (LIL) distribution patterns of Archaean felsic volcanic and some plutonic rocks in the Pilbara Block, Western Australia, and their petrogenetic implications. The composition of silicic magmas reflects the nature of their source materials and assists in deducing the origin and evolution of the early continental crust (Arth and Hanson, 1972, 1975; Arth et al., 1978; Condie and Hunter 1976; Glikson, 1976, 1979; Collerson and Fryer, 1978). The distribution patterns of the REE shed light on the petrogenesis of felsic rocks and their derivation by either partial melting of a range of crustal materials or by fractional crystallization of more basic magmas, using mineral/melt partitioning coefficients (Kd) for specific phases (Arth, 1976; Hanson, 1980; Haskin, 1984; Cullers and Graff, 1984).

The Pilbara Block (Fig. 1) contains a wide range of felsic igneous units of @ 3.7-2.7 b.y. age (Table 1), including (1) thin dacitic to andesitic, mostly tuffaceous, volcanics intercalated with tholeiitic to high-Mg basaltic units in the upper part of the North Star Basalt (NSB) and (2) the Panorama Formation (PF); (3) lenses of andesite-dacite-rhyolite agglomerate and tuff, including minor lava of the Duffer Formation (DF); (4) pyroclastics of the Mons Cupri Volcanics (MCV); (5) flows of rhyolite of the Wyman Formation (WF) and (6) Mount Brown Rhyolite (MBR); (7) early tonalite-trondhjemite-adamellite gneisses (TTG), and (8) post-tectonic granites (PTG) (Table 1). REE characteristics of Pilbara felsic igneous units have been studied earlier by Jahn et al. (1981), Bickle et al. (1983) and Barley et al. (1984). This report discusses the REE and LIL, mainly Rb, Sr, Nb data in terms of (1) nature of the source rocks and/or the magmas from which the felsic igneous rocks were derived; (2) magmatic fractionation processes; (3) alteration effects and metamorphic processes; (4) relations between volcanic and plutonic units and (5) tectonic implications. The discussion is based on the data of Jahn et al. (1981) and new instrumental neutron activation (INAA) data measured by C. Pride, and refers to the data of Bickle et al. (1983) and Barley et al. (1984).

Recent publications on the geology of the Archaean Pilbara Block include Hickman (1983), Groves and Batt (1984) and Glikson (1984). The volcanic and plutonic units from which the samples considered in this paper were derived are described by Hickman (1983). The samples have been collected by AYG, AHH and RD as part of a collaborative BMR-GSWA regional geochemical study of the Pilbara Block. Earlier reports of this study are by Glikson and Hickman (1981a, 1981b) and Glikson et al. (1986). Petrological and stratigraphic classifications of the analyses are given in Table 1 and sample localities in Fig. 1. Analytical data for individual samples and petrographic descriptions are presented in Appendices I and in an annex. Petrochemical indices are given in Appendix II .

Analytical determinations of samples from fragmental rocks of the MCV and rhyolites of the MBR were made by instrumental neutron activation analysis by C. Pride. Accuracy for Ce, Sm, Nd, Eu and Yb is +/-5% and for Tb, Lu and Th +/-10% of the amount present. For a further discussion of qualifications of accuracy and precision of this method refer to Jacobs et al. (1977). Analyses for the REE of samples from the upper part of the NSB, DF, PF, TTG, and PTG were carried out by isotope dilution mass spectrometry (IDMS) by B. Jahn. A discussion of accuracy and precision is given in Jahn et al. (1981) and in Hanson (1976). Analyses for Si, Al, Ti, Fe, Mn, Mg, Ca, Na, K, P, U, Rb, Sr, Y, Zr and Ba and Pb were conducted by

X-ray fluorescence spectrometry at BMR's laboratories (analyst: J. Pyke). Analyses for Cr and Ni were conducted by atomic absorption spectrometry at BMR's laboratories, using a Varian-Techtron spectrophotometer (analyst: T. Slezak). An evaluation of the accuracy and precision of BMR's data is given in Sheraton and Labonne (1978). Computer programs used in conjunction with this paper have been reported in Glikson and Owen (1982).

Major element characteristics of the data are discussed as a background for consideration of the REE and LIL data (Chapter III). No modal classification such as that of Streckeisen (1967) is attempted in view of the abundance of secondary metamorphic minerals and the recrystallization of feldspar. Petrochemical classifications of the analyses are presented in terms of O'Connor's (1965) Ab-An-Or ternary (Fig. 2), the Qz-Ab-Or ternary (Fig. 3), the K_2O-SiO_2 classification scheme (Ewart, 1979) (Fig. 4), CIPW norms and the sedimentary-igneous index molecular $Al_2O_3/(CaO+Na_2O+K_2O)$ (A/CNK) of Chappel and White (1974). Since some potassium is located in biotite, the Ab-An-Or scheme tends to overemphasise the role of Or. Although the petrochemical terms used are those for igneous rocks, the samples studied have undergone chemical alteration associated with late magmatic, hydrothermal and metamorphic processes, rendering the petrochemical classifications provisional.

II. ALTERATION

The abundance of secondary phases in the felsic volcanic rocks, notably sericite, chlorite, leucoxene and recrystallized feldspar, demands caution with regard to interpretations of the geochemical data. Tests of the degree of open chemical redistribution have included: (1) Log molecular proportion plots (LMPR) (Beswick and Soucie, 1978; Glikson and

Hickman, 1981a), allowing an estimate of the departure of the metamorphosed rock composition from the field of least altered volcanics on log (El/K_2O) versus log $(E2/K_2O$ [E - major element]); (2) degrees of compositional scatter of relatively mobile elements (K, Rb, Ca, Sr, Ba, U) relative to the more stable components (Ti, Zr, Y, REE, Nb) (Pearce and Cann, 1971, 1973; Smith and Smith, 1976; Condie et al., 1977), using spidergram plots (Sun et al., 1979); (3) comparisons between the observed composition and those of average granites and felsic volcanic rocks; (4) comparisons between ratios of differentially mobile elements, such as K/Ca and Rb/Sr, with the hydration and carbonatization levels of the samples (H_2O-, CO_2) and oxidation of iron (Fe^{+3}/Fe^{+2}). The nature of the metamorphic phases has essential control over the type of chemical modification; for example, albitization may result in increase in Na and loss of Ca and K and advanced sericitization of plagioclase feldspar may result in an increase in Al and commonly K and Rb and in depletion of Ca and possibly Sr. Thus, the relationships between normative Corundum (C), K/Ca and Rb/Sr may be tested as potential alteration indices. However, in view of primary (igneous) variations it is difficult to apply these criteria to individual samples with confidence. Where a group of samples from any particular rock unit display similar geochemical characteristics it has been assumed that these similarities may be of primary nature. This is supported by the general observation that open chemical redistribution results in an increase in geochemical dispersion (Smith, 1968; Smith and Smith, 1976; Beswick and Soucie, 1979).

An example of extreme alteration is furnished by felsic pillow lava of the Panorama Formation, intercalated within the Salgash Subgroup, upper part of the Warrawoona Group (Table 1). For three samples (3818, 3819, 3820) the major element composition is consistent with that of C-normative sodic rhyolites and dacites (K_2O/Na_2O = 0.17-0.45), with low to average A/CNK values (1.02 - 1.11). However, the rocks have flat to light REE-depleted REE profiles and very low total REE abundances (Sm<1.5 ppm) (Fig. 7e). These features, which are distinct from those of any Archaean felsic igneous rocks but reminiscent of oceanic plagiogranites (Coleman and Donato, 1979), are similar to those of some mafic volcanics of the Salgash Subgroup with which they are intercalated (Glikson et al., 1986). A derivation of these felsic rocks by silicification of mafic rocks is suggested by the high Ni (65-80 ppm), Cr (230 - 310 ppm), V (280 - 460 ppm) and Cu (80 - 120 ppm) contents of the felsic rocks (Hickman, 1983). The reset Rb-Sr isotopic age (2356 +/- 66 m.y.) and high initial $^{87}Sr/^{86}Sr$ ratios obtained by Jahn et al. (1981) for the Panorama Formation samples suggest an early Proterozoic age for this alteration.

With the exception of three samples of the DF (S3810, S3813, S3816) and of K-rich rhyolites and Panorama Formation rocks, samples plot within the limits of the field of least-altered volcanic compositions as defined by Beswick and Soucie (1978). The three DF samples are somewhat depleted in CaO relative to other major elements, and two of these rocks as well as sample S3817 have high Al_2O_3, possibly related to development of sericite. Chondrite-normalized trace element plots (Fig. 7) suggest dispersion ranges of Rb and Ba are similar or higher by factors of up to 3 as compared with the light REE, which suggests enrichment relative to the latter. Plots of K/Ca and Rb/Sr versus normative C and versus the A/CNK index suggest a broad positive correlation for DF samples, possibly reflecting sericitization effects, but no clear trends are seen within or between other felsic igneous units. Further, plots of K/Ca and Rb/Sr against H_20-, H_20 (total) and CO_2 show no clear trends. The close coherence of the REE-LIL normalized patterns between some samples (Fig. 7) suggests near-primary compositions for these elements. For example, the dacites of the DF, the rhyolites of the WF, and the rhyolitic fragmentals in the MCV and MBR display closely grouped chondrite=normalized REE patterns (Fig. 7). whilst the present composition of individual samples cannot be considered representative of an original igneous composition, sample groupings are discussed below in terms of the broad indication they may give for the nature of their igneous precursors.

III. MAJOR ELEMENTS

Barley et al. (1984) emphasised the calc-alkali composition of the felsic igneous rocks of the Pilbara Block as defined on FAM plots, and showed that the andesite- dacite- rhyolite piles are associated with calc-alkali basalts distinct from tholeiites of the main mafic volcanic sequences.

The rocks included in the present study span a wide compositional range, as reflected by differentiation index values (DI) (Hutchinson, 1974) of 45 - 100 and crystallization index values (CI) (Hutchinson, 1974) of 0 - 35 (Fig. 5). High-Al, low-K calc-alkali andesites and low-K dacites of the UNSB are characterized by igneous source-type A/CNK indices (Chappel and White, 1974) (less than 1.1), by low K_2O/Na_2O (0.15 - 0.34) ratios and by Di-normative and Qz-Low normative compositions (Qz = 16-18%).

The DF is dominated by tuff and agglomerates of calc-alkali andesite and dacite and some high-K rhyolite. A/CNK indices are mainly above 1.1 and thus of S-type source, in agreement with the C-normative compositions of these rocks. High-Al and K dacites are present in the DF but have higher Qz, Or and K_2O/Na_2O, lower Ab and no normative Di as compared to the

UNSB samples. As reported earlier (Glikson and Hickman, 1981a), some successions of the DF show an overall increase in differentiation at higher stratigraphic levels, with andesites and dacites dominating at lower levels and K-rhyolites at high levels.

The WF, the highest felsic igneous unit of the Warrawoona Group, comprises K-rich ultrapotassic rhyolites (K_2O = 6-11%). These rocks are highly silicic (Qz = 30-54%), C-normative and Di-free, containing little or no normative Plg and extremely low abundances of ferromagnesian elements. These features are reflected by very high DI indices (91-98) and low CI values (1.0-4.6)(Fig. 5). The rocks have S-type A/CNK values (above 1.1), in accord with their C-normative compositions. The ultrapotassic rhyolites represent either Elvan-type porphyries (Henley, 1972) or advanced alteration. Felsic igneous components of the Whim Creek Group (Table 1) also contain high-K rocks but with K levels substantially lower than the WF rhyolites. The fragmental rocks of the MCV comprise tuffs classified as calc-alkali dacite and moderately high-K rhyolite. Barley et al. (1984) showed that the MCV rocks have lower MgO and Al_2O_3 and higher F/M ratios, Ti, Zr and Y than the DF. The MBR consists of calc-alkali rhyolite (Figs 2 - 4). These rocks are characterized by high Qz and Ab in their norms, are C-normative and Di-free, and have low I-type A/CNK indices (< 1.1). Normative An is mostly low and K_2O/Na_2O ratios are variable. These rocks are more siliceous than DF rhyolites. MCV and MBR rhyolites are similar, except that the latter are somewhat more siliceous, as reflected by higher DI and lower CI values (Fig. 5).

Comparisons between volcanic and plutonic rock samples show important distinctions between (1) tonalite/trondhjemite gneisses (TTG) and dacites of the DF and (2) post tectonic granites (PTG) and rhyolites of the MCV.

Also, distinctions are observed between the plutonic and volcanic rocks. The plutonic rocks plot in higher DI and CI field positions than the volcanic rocks (Fig. 5). Also, contrast to the dacites of the DF the plutonic TTG have I-type A/CNK values (below 1.1), and are either DI-normative or C-normative. On the basis of An-Ab-Or ternary (Fig. 2) and CI - DI relations (Fig. 5), two types of TTG are distinguished on the An-Ab-Or ternary (Fig. 2) - tonalites and trondhjemites, a grouping supported only partly by REE data (see below). Comparisons between the PTG and the MCV are of questionable value due to the geographic distance of these units (Fig. 1). The plutonic rocks have higher K_20, DI values and A/(F+M) ratios (Fig. 6), and slightly higher Qz and An values than the volcanic rocks. Both groups are mostly C-normative rather than Di-normative (Appendix III). Further distinctions will be discussed below.

IV. TRACE ELEMENTS

Comparisons between abundances of large-ion-lithophile (LIL) elements in the Pilbara samples and those of average high-Ca and low-Ca granites of Turekian and Wedepohl (1961) serve as a yardstick for evaluating possible anomalies in the data (Table 2):

(1) Samples of the UNSB and DF volcanic units are depleted in alkali K, Rb, Nb, P and REE, and are enriched in Pb.

(2) Samples of the MCV and MBR have high levels of U, Th, Zr and Pb. As showed by Barley et al. (1984), Ti and Y may also be higher than in the DF. (3) Most felsic volcanic and plutonic rocks show overall enrichment in Pb and depletion in Nb, P and REE in relation to average granites.

Table 3 presents comparisons between LIL and REE elemental ratios of the Pilbara compositions and those of average high-Ca and low-Ca granites. REE patterns and features of the data are portrayed in Figures 7 - 10. Rare dacites and andesites of the UNSB and DF have low Rb/Sr and Ba/Sr ratios and are relatively fractionated with respect to the REE, i.e. $(Ce/Yb)_N \sim 6-14$, in some instances higher than the $(Ce/Yb)_N$ range of 3.5-11.0 reported by Barley et al. (1984) for McPhee dome and Kelly belt volcanics. Trondhjemites of the Mount Edgar batholith are even more REE fractionated, i.e. $(Ce/Yb)_N > 15$ (Fig. 8a). Some of these volcanics have very high total REE levels (Appendix I). The dacites of the UNSB and DF mostly plot in a distinct field on the $(Ce/Sm)_N$-$(Sm/Yb)_N$ diagram (Fig. 9). Most have high Sr (>200 ppm) but Low Eu (<1.3 ppm) abundances. Both dacites and andesites display moderate light/ intermediate REE fractionation ($(Ce/Dy)_N = 5-9$) and little intermediate/ heavy REE fractionation ($(Dy/Lu)_N = 1.1-1.2$). These rocks have only weak or no Eu/Eu* anomalies, which show little relation to the K_2O abundances of the rocks (Fig. 10), except for the DF where fractionation of plagioclase may account for a concomitant increase in K_2O and Eu*/Eu values. Low Nb anomalies (relative to light REE, Ba and Rb) are well pronounced in all compositions. The more fractionated K-dacites and rhyolites of the DF have high Ba/Sr ratios (10-20)(Fig. 13) and low $(Ba/Ce)_N$ ratios. The two K-rich DF rhyolites also show low Eu/Eu* anomalies.

Potassic (K_2O = 6-7%) to ultrapotassic (K_2O = 11%) rhyolites of the WF located at the top of the Warrawoona Group, are characterized by moderate REE abundances (Sm = 3.5-5.4 ppm), very low Sr and Eu levels and thus markedly low Eu/Eu* anomalies (Fig. 10), fractionated light/intermediate REE ($(Ce/Dy)_N = 5.5-8.2$) and flat to below-unity intermediate/heavy REE patterns. The overall $(Ce/Yb)_N$ ratio is less than those of any of the underlying volcanic units. The REE patterns are thus similar to those of

Barley et al.'s (1984) high-level porphyries of the Kelly belt, which may correlate with the WF. The ultrapotassic rhyolites have high Rb/Sr ratios (av = 11) and Ba/Sr ratios (av = 22). However, absolute Rb levels are low for high-K rocks, as reflected by high K/Rb ratios for samples S3822 (723) and S3823 (426).

(Ce/Yb)N fractionation of rhyolites of the Whim Creek Group is modest (below 8), and fractionation of heavy REE, expressed by (Sm/Yb)N, is low (1.5 -3.0) but higher than in the WF rhyolites. Other differences with the WF rhyolites are consistently moderate Eu/Eu* anomalies and the lower Rb/Ba ratios of the felsic rocks of the Whim Creek Group (Fig. 7g, h). The negative Nb anomalies of the MCV rhyolites are somewhat more pronounced than those of the WF rhyolites. The trace element characteristics of the MBR and MCV, including low levels of the REE and Eu are very similar, suggesting cogenetic relationships. These observations agree with Barley et al.'s (1984), whose MCV samples have a (Ce/Yb)N range of 5-12, moderate (Sm/Yb)N ratios and high Zr and Y.

Thus, three broad groupings of the felsic volcanic samples emerge: (1) high-Sr UNSB and DF andesite-dacite-rhyolite series, including high-Al types; (2) low-Sr, high-potassium rhyolite (WF); and (3) intermediate-potassium fragmentals and rhyolites (MCV and MBR). Type (1) felsic volcanics are typical of the lower and middle parts of the Warrawoona Groupand have relatively fractionated light/heavy REE; type (2) felsic volcanics occur at the top of the Warrawoona Group and have fractionated light/intermediate REE, flat intermediate/heavy REE and negative Eu anomalics and type (3) occur in the Whim Creek Group and have high intermediate/heavy REE relative to group (2), and high Zr and Y.

Comparisons with the plutonic rock samples suggest that, on the whole, type (1) volcanics are nearer in composition to the tonalite-trondhjemite gneisses (TTG) and type (3) volcanics are nearer in composition to the post-tectonic granites (PTG). However, post-tectonic tonalites have been reported from the Mt Edgar batholith (Da and Lewis, 1986). Most tonalites of the TTG have low (Ce/Yb)N ratios (below 7) and most trondhjemites have high ratios (above 15) compared to the DF samples. These difference arises from the low Yb levels and high (Sm/Yb)N ratios of the trondhjemites. Similarly marked REE fractionation was reported from the North Shaw plutonic suite, where (Ce/Yb)N values up to 46 and low Yb (x2 chondrites) were reported (Bickle et al., 1983). The post-tectonic granites (PTG) differ from high-K rhyolites, having higher Yb levels and lower (Sm/Yb)N ratios. They have lower Eu/Eu* anomalies (below 0.25) as compared to most volcanic rocks (Fig. 10), and have very low Sr abundances (25-70 ppm) and high Nb levels (20-42 ppm). Thus, although the UNSB and DF dacites and rhyolites have some features in common with the TTG, no significant geochemical correlations between volcanic and plutonic suites can be demonstrated.

V. PETROGENESIS OF Na-RICH 3.7-3.3 B.Y. OLD FELSIC IGNEOUS ROCKS

A. Dacites and andesites of the upper North Star Basalt (UNSB)

The andesites and dacites of the UNSB have compositions consistent with primary igneous rocks. Though there is minor sericitization, the low K_2O and moderate to high CaO values suggest little modification by this process. These rocks are similar in composition to the high-Al low-K dacite-andesite association of island arcs (i.e. the Caribbeans) as classified by Ewart (1979). The low Rb abundances (<50 ppm) and Rb/Sr ratios (<0.1) of the UNSB andesites and dacites, if unmodified by alteration, are probably too low for derivation from pelitic source materials following the criteria of Miller (1985). The low A/CNK indices of these rocks are more consistent with derivation from basic igneous source (Gill, 1981). However, Archaean sediments have, on the whole, lower levels of K and Rb and higher levels of Ni and Cr than post-Archaean sediments (McLennan and Taylor, 1984), and thus the above criteria may not apply.

For the above reasons, petrogenetic models invoking anatexis of an I-type source or fractional crystallization of basic magma appear to be more applicable to the UNSB dacites and andesites. The low LIL element abundances, low initial $^{87}Sr/^{86}Sr$ ratios (0.70054 - Jahn et al., 1981) and positive E_{Nd} initial parameter (E_{Nd} = +0.33 - Jahn et al., 1981; + 3.4 to + 4.2, Gruau et al., in prep.) favour a derivation of the andesitic to dacitic magmas from basic materials drived from a source depleted in light REE. The relatively high Ni (38 ppm, 82 ppm) and Cr (42 ppm, 113 ppm) of UNSB dacites (Glikson and Hickman, 1981a) favour patrial melting of basic rocks rather than fractional crystallization of basic magma, since the mineral/melt partitioning coefficients (K_d) for these elements decrease with higher temperature (Irving, 1978). For this reason, the fractional crystallization of ferromagnesian phases (Arth, 1976) would more efficiently deplete the magma in these components.

Calculated fractionation trends for various phases and for assumed residual mineral assemblages are plotted in Figs 8 and 9. In order to test a model involving partial melting of basic source, the starting source composition used in these calculations is the average of 13 analyses of tholeiitic basalts and high-Mg basalts from the Talga-Talga Subgroup (Table

4). K_d values for felsic and intermediate magmas are from Arth (1976), Hanson (1980) and Pearce and Norry (1979). Jahn et al. (1981) remarked on the difficulty in deriving the light REE-enriched dacites and andesites by fractional crystallization of flat REE-patterned MORB-type source materials. The depletion of heavy REE relative to intermediate REE shown by the samples cannot be accounted for except by separation of garnet and/or amphibole. However, fractionation of amphibole should result in concave heavy REE profiles, i.e. (Lu/Yb)N ratios above unity, not shown by the UNSB samples. Plots of (Ce/Yb)N versus (Yb)N (Fig. 8a) suggest that advanced fractional crystallization (F = 0.1) of the model basic magma, precipitating Cpx and Plg in the approximate ratio of 88:17, is capable of producing the Ce-Yb features of UNSB dacite samples S3806 and S3808 (trend C in Fig. 8a). Ce-Yb relations in an andesite sample (S3807) can be produced by high-degree partial melting (F = 0.7) of the model composition, leaving a residue of Cpx:Hbl:Plg:Gnt in the approximate proportion 30:30:30:10 (trend B in Fig. 8a). The REE features of sample S3809 suggest either Plg fractionation or an Yb-rich source. However, the above models do not account for the Sm levels of the samples, which are high in the andesites and dacites as compared to the models. The high (Sm/Yb)N ratios of the dacites (>3.5) can be produced by small degree partial melting (F<0.1) of the model source composition, leaving a small amount of residual garnet (Gnt:Plg:Cpx = 3:27:70) (trend A in Fig 8c). A yet smaller amount of garnet in the residue (@1.0%; F = 0.3) may produce the REE patterns of the andesites (trend E in Fig 9). Modelling of the overall REE patterns of UNSB and DF dacites suggests they can result by partial melting (F = 0.1 - 0.5) of X3-4 REE-enriched model source composition, leaving a residue of Gnt:Plg:Cpx = 10:30:60 (Fig. 7a,b). The main departure of the model from the data isthe upward-curved Yb-Lu section (Lu/Yb)N>1.0 in the model, reflecting the fact that $Kd^{Gnt,Cpx}_{Lu}$ is less than $Kd^{Gnt,Cpx}_{Yb}$. Whilst the above model is inconclusive it suggests the derivation of the andesites and dacites from basic sources, possibly by separation of garnet. Since garnet is only stable in basic rocks under pressures above @ 10kb for anyhydrous compositions and above @ 15 kb for Ptotal = PH_2O conditions (Lambert and Wyllie, 1972), partial melting of deep-seated basic rocks is a more likely mechanism than fractional crystallization and is consistent with the relatively high Ni and Cr abundances in some of the intermediate and felsic rocks.

This general model can be tested with reference to the high-field strength (HFS) elements (Ti, Zr, Nb, Y). The dacites are depleted in Ti and enriched in Zr relative to the model source composition. Given a Kd_{Zr}^{Hbl} value of 1.4 (Pearce and Norry, 1979), amphibole is not capable of accounting for depleting Ti and at the same time enriching Zr to levels of above 200 ppm. Magnetite may have played a role in removing Ti (Fig. 11). The abundances of Nb in the dacites and one andesite sample plot near or below a partial melting trend involving separation of residual Gnt:Plg:Cpx = 3:27:70, in broad agreement with the REE-derived model (trend A in Fig. 12). The high abundances of Sr in UNSB felsic rocks (> 300 ppm) and the high levels of Ba (>700 ppm) in two samples can be accounted for by combined fractionation of Cpx, Hbl and Gnt (Fig. 13).

B. Felsic volcanics of the Duffer Formation

According to the criteria of Chappell and White (1974) the C-normative high A/CNK index (>1.1) dacites, quartz latites and rhyolites of the Duffer Formation (DF) could be derived from peraluminous source materials, namely sediments and reworked equivalents. However, peraluminous magmas can be derived from a wide range of crustal materials, including sediments, felsic to intermediate igneous rocks and metaluminous mafic rocks, and their composition can be further modified by crystal fractionation (Miller, 1985). On the basis of geochemical parameters discussed by the above authors and by O'Neil and Chappel (1977) and Didier et al. (1982), the felsic rocks of the DF may be derived from I-type igneous magmas for the following reasons:

(1) The wide compositional range from andesite to potassicrhyolite may be interpreted in terms of derivation of the more basic members from basic sources and of the felsic members by further fractionation and/or lower degrees of partial melting.

(2) Abundances of Na_20 in the dacites are commonly high (>3.0&) and K_20 levels are commonly low (Fig. 2) relative to Archaean pelitic compositions, which typically contain 1-5% K_2O (McLennan et al., 1983). Some of the andesites and dacites of the DF have K_20 values about or less than 1.0% (Appendix I).

(3) The trace element features of some andesites and dacites argue against their derivation from peraluminous sources. Thus, Rb/Sr ratios are below 0.2 and Rb/Ba ratios are below 0.25, namely less than those of pelitic sediments, assuming that the alkali elements ratios are not too far removed from primary ratios. The low initial $^{87}Sr/^{86}Sr$ ratios of DF samples (0.7007+/-14; Jahn et al., 1981) suggest derivation from Rb-poor sources.

(4) With the exception of a rhyolite sample (S3813), the DF rocks do not show marked Eu/Eu* anomalies. They are therefore probably not derived from strongly fractionated materials and suggest the role of Plg in the residueis limited.

Possible reactions by which peraluminous felsic magmas can be derived from basic source materials include:

Hbl → Cpx + Ol + peraluminous liquid (Helz, 1976) ...(1)

Gnt → Cpx + peraluminous liquid (Stern and Wyllie, 1978) ...(2)

Partial melting of amphibolite or eclogite has been invoked in connection with the generation of peraluminous trondhjemites with low-LIL elements and mantle-type isotopic signatures (Size, 1979; Wood and Miller, 1984). If a basic source of average Talga-Talga Subgroup composition is assumed (Table 4), seven samples of the DF plot along both (1) a partial melting trend produced by segregation of liquid from residual Cpx (70%), Plg (27-29%) and Gnt (1-3%)(trend A in Figs 8a, 9), and (2) a fractional crystallization trend produced by Cpx precipitation. The relatively high Ni and Cr levels in some DF dacites (Glikson and Hickman, 1981a) (Appendix I) support partial melting, for reasons given above. A partial melting model is only broadly consistent with model trends on (Ce/Sm)N versus (Sm)N plots (Fig 8b, trend A), although considerable scatter occurs around this trend. However, the degree of melting varies between different types of plots. Since the DF dacites show REE patterns that are broadly similar to those of the UNSB dacites, they can be likewise modelled in terms of partial melting of a basic Talga Talga Subgroup type source, leaving a residue of Cpx, Plg and minor (<10%) Gnt (Fig. 7b). Separation of magnetite may again account in part for Ti depletion and that of Cpx for Zr enrichment (Fig. 11). Fractional crystallization of Cpx is capable of producing the high Sr and Ba of some samples (S3810, S3811). The low-Sr and high-Ba samples (S3813, S3815, S3816) may be produced by fractionation of Plg from the Sr-rich magma (Fig. 13), although the little development of Eu anomalies restricts this process (Fig. 10). The uncertainties in the nature of petrogenetic processes indicated by the above discussion reflect problems related to the model assumptions, i.e., possible heterogeneous sources and varying physical conditions of magma genesis.

C. Tonalite/trondhjemite gneisses

It has been suggested earlier that the Duffer Formation and tonalite/trondhjemite gneisses (TTG) of the Pilbara batholiths may represent contemporaneous volcanic and plutonic magmatic activity (Glikson, 1979; Jahn et al., 1981), a possibility supported by isotopic ages and initial ratios (Pidgeon, 1978; Collerson and McCulloch, 1983; Williams et al., 1983). With the exception of one sample of peraluminous trondhjemite (S3830), the low A/CNK indices (<1.1) of the plutonic rocks suggest I-type sources. This is supported by commonly low LIL element abundances and ratios (Rb/Sr<0.5; Ba/Sr<2.0). However, the data suggest important differences between the plutonic and volcanic rocks. Four samples, including three trondhjemites (S3825, S3827, S3830) and one tonalite (S3829), have high (Ce/Yb)N ratios (>15) as compared to DF volcanics (Fig. 8a). If a basic source similar to that for the DF rocks is assumed, for low degrees of partial melting (F = 0.1) and a residue of Cpx:Plg:Gnt = 70:25:5, a light/heavy REE fractionation of the plutonic TTG magma could be modelled to approximate trend D (Fig. 8a). Samples with lower (Ce/Yb)N ratios (S3824, S3826, S3828) imply lower degree fractionation (F = 0.3-0.4) and a residue of Cpx:Plg = 83:17 (Fig. 8a, trend C). (Ce/Sm)N and Sm values for these rocks are similar to those of DF volcanics (Fig. 8b), and could indicate similar model patterns (Fig. 7d), but for the lower Yb level and higher (Sm/Yb)N ratios of some of the trondhjemites (Fig. 8c). The only phase with a Kd value high enough to result in this fractionation is garnet (Kd_{Yb}^{Gnt} = 39.9; Arth, 1976), which must have played a role in producing the Na-rich felsic magmas (Jahn et al., 1981). Since garnet is stable in dry basic compositions only above 10 kb (Lambert and Wyllie, 1972), the magmas that gave rise to these rocks may have been derived from deep crustal levels. Derivation of the tonalitic magma by partial melting of a basic source is supported by the high Ni and Cr abundances of one tonalite (S3824: Ni = 50 ppm; Cr = 104 ppm). This contrasts with the very low abundances in the trondhjemites (S3825: Ni = 5ppm; Cr = 8 ppm), and could suggest derivation of the trondhjemitic magma from the tonalitic magma by fractional crystallization of ferromagnesian minerals from the latter. The low Eu/Eu* and Sr values of two trondhjemites (S3826: Eu/Eu* = 0.60; S3820: Eu/Eu* = 0.52) indicates some separation of plagioclase, but no systematic difference is observed between tonalites and trondhjemites in this regard. Because of the increase in Kd_{RE}^{Plg} with ionic radii of the REE (Hanson, 1980), fractionation of plagioclase would tend to lower the (Ce/Sm)N and (Sm/Yb)N ratios, but no such relation is observed between the tonalites and the trondhjemites. In summary, whereas the REE data can be interpreted in terms of heterogeneous basic sources and of either partial melting or fractional crystallization, the former process is favoured for the tonalites and the latter for the trondhjemites.

VI. PETROGENESIS OF K-RICH 3.3-3.0 B.Y. OLD FELSIC IGNEOUS ROCKS

In view of the broadly similar REE patterns of rhyolites of the Wyman Formation (WF), Mt Brown Rhyolite (MBR), Mons Cupri Volcanics (MCV) and the post tectonic granites (PTG) (Fig. 7), similar petrogenetic models may apply to these units. The very high Qz and C proportions in the norms of two samples of the WF (S3821, S3822), as well as their high A/CNK indices and extreme fractionation (DI>90), may support their derivation from peraluminous source materials (Chappell and White, 1974; Miller, 1985). The markedly low Eu/Eu* anomalies of WF samples (0.11, 0.42, 0.78) and their very low Sr abundances (<26 ppm) suggest strong fractionation of plagioclase. Alternatively, diagenesis of the volcanics may have resulted in K-enrichment. The ultrapotassic rhyolites (S3823: K_20 = 11.05%) have been interpreted in terms of late stage pneumatolatic alteration in upper parts of granitic cupolas by Si and K-rich fluids, followed by fracture and escape of hydrous magmas to the surface (Henley, 1972; Glikson and Hickman, 1981a). The rhyolites have embayed (resorbed) quartz phenocrysts, which could arise by a decrease in pressure in the ascending magma (Green, 1968). On the other hand, WF rhyolites with lower K_20 abundances (6.1%, 6.6%) could be derived by partial melting of felsic source materials or fractional crystallization of basic magma, leaving plagioclase and clinopyroxene in the residue, however, Secondary addition of K and Si to these rocks is more likely.

Three models for formation of K-rich magmas are considered:

(1) REE model patterns similar to those of the WF rhyolites can be obtained assuming partial melting (F = 0.3-0.5) of a tonalite/ trondhjemite source, leaving residual Plg with or without Cpx (@20%)(Fig. 7f)

(2) This model assumes a source consisting of 75% tonalite/ trondhjemite of the Mount Edgar Batholith type and 25% greenstones of the Talga-Talga Subgroup type (Table 4), or an equivalent sedimentary composition, which has been subject to high degrees of partial melting (F = 0.5), leaving residual Plg (@ 50%) and Cpx (@ 50%)

(3) Plagioclase-dominated crystal fractionation (F = 0.1-0.2) of basic magma of average Talga-Talga Subgroup composition (Table 4), precipitating Cpx and Plg in the approximate proportion of 50:50 (Fig. 7f).

In all these models the effect of Plg fractionation is the decrease of Ce/Yb, Eu and Sr, and the increase of Yb in the magma. These models are capable of accounting for the low Nb anomalies by residual Ti-rich phases and for the high (Rb/Ce)N and (Ba/Ce)N spikes in terms of alkali enrichment (Fig. 7f,g,h), but are not capable of explaining the high-K compositions of some of the WF rhyolites.

It is important to attempt discriminations between models which involve anatexis of a felsic crust (with or without a greenstone component) (models 1 and 2 above), and those involving fractional crystallization of basic magma (model 3). However, since both types of models ultimately invoke basic precursors, either by one-stage or two-stage fractionation, REE modelling is unable to distinguish between these processes. Indirect considerations, including the lack of contemporaneous basic rocks in the WF, suggest that partial melting of felsic igneous rocks is a more likely mechanism. The problem is amenable to Sr and Pb isotopic studies, to assess whether the initial ratios are of older crustal origin or of mantle type. The Rb-Sr data published by Jahn et al. (1981) for the WF samples are inconclusive in this respect as they merely represent the period of alteration.

The above considerations are also applicable to the MCV and MBR rhyolites. Because no REE in the range between Tb and Yb have been analysed by the INNA method, no detailed model-data matchings for the heavy rare earth element are feasible. The more fractionated intermediate/heavy REE of those rocks, as compared to the WF rhyolites, may hint at either different sources or fractionation of amphibole or garnet from the MCV magma. Marked depletion in heavy REE was reported for an adamellite intruding the MCV (Barely et al., 1984). The post-tectonic granite samples show high total REE abundances and lower Eu/Eu* ratios than the other felsic rocks, both features being suggestive of marked fractionation of plagioclase. The data can be modelled in terms of @ 50% melting of an average tonalite/ trondhjemite source or an equivalent sedimentary composition (Table 4), leaving mainly Plg or Plg + @10% Cpx in the residue (Fig. 7i). The main departure from this model is the absence of Nb anomalies in the two samples of Moolyella post-tectonic granite. A relevant observation is the Nb enrichment in pegmatites associated with the Moolyella granite (Davy and Lewis, 1986).

VII. DISCUSSION AND CONCLUSION

The preceding discussion indicates the occurrence of three geochemically and temporally distinct intermediate to felsic igneous associations in the Pilbara Block, including (1) Na-rich calc-alkali andesite-dacite-rhyolite pyroclastics, intercalated with basic-ultrabasic volcanic sequences of the Warrawoona Group, and intruded by essentially contemporaneous tonalite/trondhjemite intrusions; (2) K-rich rhyolites located at the top of the Warrawoona Group and possibly contemporaneous with post-tectonic intrusions; (3) high-K felsic volcanics of the Whim Creek Group. The age range of the first association is approximately 3.7-3.4 b.y. and that of associations (2) and (3) approximately 3.3-2.9 b.y. (Blake and NcNaughton, 1984). Felsic igneous components of the overlying Fortescue Group include the Spinaway Porphyry which yielded a U-Pb zircon age of 2768 +/- 16 (R. Pidgeon, cited in Blake and McNaughton, 1984) and the Bamboo Creek Porphyry yielding Rb-Sr isochron ages of 2124 +/- 195 m.y. (Ri = 0.7126) and 2820 +/- 516 (Ri = 0.7010). (Trendall, 1975). The high Rb abundances of the porphyry samples (160 - 190 ppm) and their high Rb/Sr ratios (average of 19 samples - 1.32) are similar to those of associations (2) and (3) above. No Na-rich felsic rocks of the type which dominate the lower association have as yet been observed above the Warrawoona Group. The REE models suggest derivation of the volcanic rocks of association (1) mainly from basic materials, since derivation from felsic source materials is inconsistent with the common lack of negative Eu anomalies. The K-rich rocks of associations (2) and (3), on the other hand, may be derived either from felsic source materials or by advanced fractionation of basic magmas. A discrimination between these possibilities may be achieved from the initial $^{87}Sr/^{86}Sr$ ratios (Ri) of the felsic rocks. As shown above, the Ri values of andesites and dacites from the upper part of the North Star Basalt and from the Duffer Formation are mostly below 0.701. Likewise, Ri values determined for the tonalite/ trondhjemite gneisses (TTG) are low, for example @ 3.2 b.y. old granodiorites of the Corunna Downs batholith yield an Ri values in the range 0.7006 - 0.7032 (Cooper et al.,§ (1982). By contrast the post-tectonic granites (PTG) may yield high Ri values; for example the 2.67 b.y. old Moolyella adamellite (0.7397) and the 2.606 b.y. old Cooglegong adamellite (0.7303) (DeLaeter and Blockley, 1972; deLaeter et al., 1975). 2.8 b.y. old gneisses from the Tambourah area have yielded Ri value of 0.7289 (Cooper et al., 1982). However, the felsic volcanics of the Whim Creek Group have low Ri values of about 0.700 (Barley et al., 1984). These parameters, in addition to the REE characteristics, may support a more evolved, possibly intrasialic origin for some members of associations (2) and (3).

Both chemical similarities and differences are seen between the Duffer Formation and the broadly contemporaneous tonalite/trondhjemite/ granodiorite gneisses. Broadly coeval relations between the plutonic rocks and felsic volcanism in the Warrawoona Group are suggested by model Sm-Nd ages of gneisses of the Shaw batholith (3460-3260 m.y.) and the Mount Edgar Batholith (3310-3280 m.y.) (Collerson and McCulloch, 1983), U-Pb zircon analyses (3560 +/- 70 m.y. by conventional analyses, 3485 +/- 30 m.y. by ion probe technique) (Williams et al., 1983) and Rb-Sr isochron age of ca 3.6 b.y. of tonalites in the southern part of the Mount Edgar Batholith (W. Collins, pers comm., 1986) Coeval relations are supported by field relations where in most, though by no means all, instances the gneisses intrude the lower Warrawoona Group but not the upper Warrawoona Group (Hickman, 1983). Model Sm-Nd ages of DF dacites (about 3.4 b.y.) (Collerson and McCulloch, 1983) and Sm/Nd ages by M.T. McCulloch (pers. comm., 1979) (3.52±0.03 b.y., 3.55±0.03 b.y.) are close to the 3.45 b.y. U-Pb zircon age of Pidgeon (1978), suggesting little secondary redistribution of the REE. A Rb/Sr whole rock isochron for least-altered DF volcanics from McPhee dome yields an age of 3471±125 m.y. with a low Ri of 0.6998 (Barley and DeLaeter, 1984), whereas otherwise Rb/Sr systematics are secondarily disturbed. The older felsic volcanic and plutonic rocks yield near-chondritic initial ENd values (0.5 +/- 0.4) (Collerson and McCulloch, 1983), in contrast to the Talga-Talga Subgroup greenstones which have values of 1.8 +/- 0.3 (Hamilton et al., 1981) or of 1.64±0.46 (Gruau et al., in prep). Dacites and andesites of the Talga-Talga Subgroup have a higher initial Nd value than those of the greenstones. These observations may support the concept of mantle heterogeneities reflected by basic magmas (Glikson et al., 1986) and their acid derivatives.

The tectonic setting in which the calc-alkaline volcanic and plutonic activity took place has been discussed by Jahn et al., (1981), Hickman (1983), Bickle et al., (1983) and Barley et al., (1984). Although the volcanic piles are geochemically similar to Andean-type continental margin volcanics, with the exception of Lower Al and higher Ni and Cr in the

Archaean rocks, notable differences occur in their geological setting. As indicated by Hallberg et al. (1976) in connection with the Marda Volcanic complex, central Yilgarn,the calc-alkaline volcanic activitiy took place at a late stage of cratonization of the granite-greenstone terrain. Other late Archaean intermediate to felsic volcanic centers in the eastern Yilgarn have been related to ensialic faulting and rifting (Hallberg and Giles, 1986). The stratigraphic continuity of greenstone belts throughout the eastern to central parts of the Pilbara Block militates against the occurrence of major tectonic sutures and thus lateral crustal accretion. This factor, as well as the predominantly vertical tectonic processes signified by the granitic domes and upright folds in the Pilbara, suggest that the calc-alkaline igneous activity took place in an environment distinct from that of Phanerozoic accretional terrains.

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REFERENCES

Arth, J.G., 1976 - Behaviour of trace elements during magmatic processes: a summary of theoretical models and their application. U.S. Geol. Surv. J. Res. 4: 41-47.

Arth, J.G. and Hanson, G.N., 1972 - Quartz diorites derived by partial melting of eclogite or amphibolite at mantle depths. Contr. Mineral. Petrol., 317: 161-174.

Arth, J.G. and Hanson, G.N., 1975 - Geochemistry and origin of the early Precambrian crust of northeastern Minnesota. Geochim. et Cosmochim. Acta, 39: 325-362.

Arth, J.G., Barker, F., Peterman, Z.E. and Friedman, I., 1978 - Geochemistry of the gabbro-diorite-tonalite-trondhjemite suite of southwest Finland and its implications for the origin of tonalitic and trondhjemitic magmas. J. Petrol. 19: 289-316.

Barley, M.E., Sylvester, G.C., Groves, D.I., Borley, G.D. and Rogers, N., 1984 - Archaean calc-alkaline volcanism in the Pilbara Block, Western Australia. Precambrian Res., 24: 285-319.

Barley, M.E. and deLaeter, J.R., 1984 - Disturbed Rb-Sr systems of the Archaean Duffer Formation, Eastern Pilbara Block, Western Australia. J. Roy. Soc. W. Aust., 66: 129-134.

Beswick, A.E. and Soucie, G., 1978 - A correction procedure of metasomatism in an Archaean greenstone belt. Precambrian Res., 6: 235-248.

Bickle, M.J., Betnay, L.F., Barley, M.E., Chapman, H.J., Groves, D.I., Campbell, I.H. and deLaeter, J.R., 1983 - A 3500 Ma plutonic and volcanic calc-alkaline province in the Archaean east Pilbara Block. Contr. Mineral. Petrol., 84: 25-35.

Blake, T.S. and McNaughton, N.J., 1984 - A geochronological framework for the Pilbara region. In: Geology Dept. and University Extention, Univ. W. Austr., Publ. No. 9, pp 1-22.

Chappell, B.W. and White, A.J.R., 1974 - Two contrasting granite types. Pacif. Geol., 8: 173-174.

Coleman, R.G. and Donato, M.M., 1979 - Oceanic plagiogranites revisited. In: Trondhjemites, Dacites and Related Rocks (ed. F. Barker). Elsevier, Amsterdam, pp. 149-165.

Collerson, K.D. and McCulloch, M.T., 1983 - Field and Sm-Nd isotopic constraints on Archaean crust and mantle evolution in the east Pilbara Block, Western Australia (Abstract). In: Lithosphere Dynamics and Evolution of Continental Crust. Geol. Soc. Aust. Abstracts Vol. No. 9: 167-168.

Collerson, K.D. and Fryer, B.J., 1978 - The role of fluids in the formation and subsequent development of early continental crust. Contr. Mineral. Petrol., 67: 151-169.

Condie, K.C. and Hunter, D.R., 1976 - Trace element geochemistry of Archaean granitic rocks from the Barberton region, South Africa. Earth Planet. Sci. Lett., 29: 389-400.

Condie, K.C., Viljoen, M.J. and Kable, E.J.D., 1977 - Effects of alteration on element distributions in Archaean tholeiites from the Barberton greenstone belt, South Africa. Contr. Mineral. Petrol., 64: 75-89.

Cooper, J.A., James, P.R. and Rutland, R.W.R., 1982 - Isotopic dating and structural relationships of granitoids and greenstones in the east Pilbara, Western Australia. Precambrian Geol., 18: 199-236.

Cullers, R.L. and Graf, J.L., 1984 - Rare earth elements in igneous rocks of the continental crust: intermediate and silicic rocks - ore petrogenesis. In: Rare Earth Element Geochemistry (Ed. P. Henderson). Elsevier, Amsterdam, pp. 275-308.

Davy, R. and Lewis, J.D., 1986 - The Mount Edgar Batholith, Pilbara area, Western Australia: Geochemistry and petrology. Geol. Surv. W. Aust. Report, 17.

deLaeter, J.R. and Blockley, J.G., 1972 - Granite ages within the Archaean Pilbara block, Western Australia. J. Geol. Soc. Aust., 19: 363-370.

deLaeter, J.R., Lewis, J.D., Blockley, J.G., 1975 - Granite ages within the Shaw Batholith, Pilbara region, Western Australia Geol. Surv. W. Aust. Ann. Report, 1974, pp. 73-79.

Didier, J., Duthon, J.L. and Lameyre, J., 1982 - Mantle and crustal granites : specific classification of orogenic granites and the nature of their enclaves. J. Volcan. Geotherm. Res., 14: 125-132.

Ewart, A., 1979 - A review of the mineralogy and chemistry of Tertiary-Recent dacitic, latitic, rhyolitic and related salic volcanic rocks. In: Elsevier, Amsterdam, pp. 13-112.

Gill, J.B., 1981 - Orogenic Andesites and Plate Tectonics. Springer-Verlag, Berlin.

Glikson, A.Y. 1976 - Trace element geochemistry and origin of early Precambrian acid igneous series, Barberton Mountain Land, Transvaal. Geochim. et Cosmochim. Acta, 40, 1261-1280.

Glikson, A.Y., 1979 - Early Precambrian tonalite-trondhjemite sialic nuclei. Earth Sci. Rev., 15: 1-73.

Glikson, A.Y., 1984 - Significance of early Archaean mafic-ultramafic xenolith patterns. In: Archaean Geochemistry (ed. A. Kroner, G.N. Hanson, A.M. Goodwin). Springer-verlag, Berlin, pp. 262-282.

Glikson, A.Y. and Hickman, A.H., 1981a - Geochemistry of Archaean volcanic successions, eastern Pilbara Block, Western Australia. Aust. Bur. Miner. Resour. Rec. 1981/36.

Glikson, A.Y. and Hickman, A.H., 1981b - Geochemical stratigraphy of Archaean mafic-ultramafic volcanic successions, eastern Pilbara Block, Western Australia. Geol. Soc. Aust. Sp. Publ., 7: 287-300.

Glikson, A.Y. and Owen, M., 1982 - HP9825A software system for electron probe data, major/trace and RE element geochemistry magmatic fractionation models and Rb-Sr isotopic prameters. Aust. Bur. Miner. Resour. Rec. 1982/39.

Glikson, A.Y., Pride, C., Jahn, B., Davy, R. and Hickman, A.H., 1986 - RE and HFS elements evolution of Archaean mafic-ultramafic volcanic suites, Pilbara Block, Western Australia Aust. Bur. Miner. Resour. Rec. 1986/6.

Groves, D.I. and Batt, 1984 - Spatial and temporal variations of Archaean metallogenic associations in terms of evolution of granitoid-greenstone terrains, with particular emphasis on the Western Australia shield. In: Archaean Geochemistry (ed. A. Kroner, G.N. Hanson, A.M. Goodwin). Springer Verlag, Berlin, pp. 73-98.

Gruau, G., Jahn, B., Glikson, A.Y., Davy, R. and Hickman, A.H., in prep., Age of the Talga-Talga Subgroup, Pilbara Block, Western Australia, and early evolution of the mantle: New Sm-Nd isotopic evidence.

Hanson, G.N., 1979 - Rare earth element analysis by isotope dilution. Nat. Bur. Standards Sp. Publ., 422: 937-949.

Hanson, G.N., 1980 - Rare earth elements in petrogenetic studies of igneous systems. Ann. Rev. Earth Planet. Sci., 8: 371-406.

Hallberg, J.A. and Glikson, A.Y., 1981 - Archaean granite-greenstone terrains of Western Australia. In: Precambrian of the southern continents (ed. D.R. Hunter). Elsevier, Amsterdam, pp. 33-103.

Hallberg, J.A., Johnson, C. and Bye, S.M., 1976 - The Archaean Marda igneous complex, Western Australia. Precambrian Res., 3: 111-136.

Hallberg, J.A. and Giles, C.W., 1986 - Archaean felsic volcanism in the northeastern Yilgarn Block, Western Australia. Aust. J. Earth Sci., 33: 413-328.

Hamilton, P.J., Evensen, N.M., O'Nions, R.K., Glikson, A.Y. and Hickman, A.H., 1981 - Sm-Nd dating of the Talga-Talga Subgroup, Warrawoona Group, Pilbara Block, Western Australia Geol. Soc. Aust. Sp. Publ. 7, pp. 187-192.

Haskin, L.A., 1984 - Petrogenetic modelling of rare earth elements. In: Rare Earth Element Geochemistry (ed. P. Henderson). Elsevier, Amsterdam, pp. 115-148.

Helz, R.T., 1976 - Phase relations of basalts in their melting ranges at PH_20 = 5kb. Part II: melt compositions. J. Petrol, 17: 139-193.

Henley, S., 1972 - Petrogenesis of quartz porphyry dykes in southwest England. Nature, 235: 95-96.

Hickman, A.H., 1983 - Geology of the Pilbara Block and Environs. Geol. Surv. W. Aust. Bull. 127.

Hutchinson, C.S., 1974 - Laboratory Handbook of Petrographic Techniques. Wiley and Sons, London.

Jacobs, J.W., Korotev, R.L., Blanchard, D.P. and Haskin, L.A., 1977 - A well tested procedure for instrumental neutron activation analysis of silicate rocks and mineral. J. Radioanal Chem., 40: 93-114.

Jahn, B., Glikson, A.Y., Peucat, J.J. and Hickman, A.H., 1981 - REE geochemistry and geochronology of Archaean silicic volcanics and granitoids from the Pilbara Block, Western Australia. Geochim. et Cosmochim. Acta, 45: 1633-1652.

Lambert, I.B. and Wyllie, P.J., 1974 - Melting of tonalite and crystallization of andesite liquid with excess water to 30 kilobars. J. Geol., 82: 88-97.

McLennan, S.M. and Taylor, S.R., 1984 - Archaean sedimentary rocks and their relation to the composition of the Archaean continental crust. In: Archaean Geochemistry (ed. A. Kroner, A.M. Goodwin, G.N. Hanson), Springer-Verlag, Berlin, pp. 47-72.

Miller, C.F., 1985 - Are strongly peraluminous magmas derived from pelitic sedimentary sources. J. Geol., 93: 673-689.

O'Connor, J.T., 1965 - A classification of quartz-rich igneous rocks based on feldspar ratios. U.S. Geol. Surv. Prof. Paper, 525B.

O'Neil, J.R. and Chappell, B.W., 1977 - Oxygen and hydrogen isotope relations in the Berridale batholith. J. Geol. Soc. London, 133: 559-571.

Pearce, J.A. and Cann, J.R., 1971 - Ophiolite origin investigated by discriminant analysis using Ti, Zr and Y. Earth Planet. Sci. Lett., 12: 339-349.

Pearce, J.A. and Cann, J.R., 1973 - Tectonic setting of basic volcanic rocks determined using trace element analyses. Earth Planet. Sci. Lett., 19: 290-300.

Pearce, J.A. and Norry, M.J., 1979 - Petrogenetic implications of Ti, Zr, Y, and Nb variations in volcanic rocks. Contr. Miner. Petrol., 69: 33-47.

Pidgeon, R.T., 1978 - 3450 m.y. old volcanics in the Archaean layered greentstone succession of the Pilbara Block, Western Australia. Earth Planet. Sci. Lett., 37: 421-428.

Sheraton, J.W. and Labbone, B., - Petrology and geochemistry of acid igneous rocks from northeastern Queensland. Aust. Bur. Miner. Resour. Bull, 169.

Smith, R.E., 1968 - Redistribution of major elements in the alteration of some basic lavas during burial metamorphism. J. Petrol., 9: 191-219.

Smith, R.E. and Smith, S.E., 1976 - Comments on the use of Ti, Zr, Y, Sr, K, P and Nb in classification of basaltic magmas Earth Planet. Sci. Lett., 32: 114-120.

Stern, C.R. and Wyllie, P.J., 1978 - Phase compositions through crystallization intervals in andesite-basalt-$H_2 0$ at 30 kb with implications for subduction zone magmas. Am. Mineral., 63: 641-663.

Streckeisen, A.L., 1967 - Classification and nomenclature of igneous rocks. Neues Jahrb. Miner. Abhandb, 107: 144-240.

Sun, S., Nesbitt, R.W. and Sharaskin, A.Y., 1979 - Chemical characteristics of mid-ocean ridge basalts. Earth Planet.

Sci Lett., 44: 119-138.

Trendall, A.F., 1975 - Preliminary geochronological results from two Pilbara prophyry bodies. Geol. Surv. W. Aust., Ann. Rep. for 1974, pp. 103-106.

Turekian, K.K. and Wedepohl, K.H., 1961 - Distribution of the elements in some units of the Earth's crust. Geol. Soc. Am. Bull., 72.

Williams, I.S., Page, R.W., Froude, D., Foster, J.J. and Compston, W., 1983 - Early crustal components in the Western Australian Archaean: zircon U-Pb ages by ion microprobe analysis from the Shaw batholith and Narryer metamorphic belt (abstract). In: Lithosphere Dynamics and Evolution of Continental Crust. Geol. Soc. Aust. Abstracts Vol. No. 9, 169-170.

Wood, L.F. and Miller, C.F., 1984 - Chemistry and genesis of peraluminous trondhjemite dykes, Blue Ridge, North Carolina-Georgia. Southeast. Geol., 25: 13-24.

CAPTIONS

1. Geological sketch map of the northern part of the Pilbara Block, Western Australia, showing localities of REE-analysed samples.

2. An-Ab-Or ternary diagrams for volcanic and plutonic felsic, igneous rocks of the Pilbara Block, Western Australia. Classification after O'Connor (1965).

3. Qz-Ab-Or ternary diagram showing the eutectic crystallization compositions for magmas with various An contents for 1 kb H_2O pressure (from Ewart, 1979). Symbols as in Fig. 2.

4. Classification of Pilbara data in terms of the K_2O-SiO_2 diagram and the compositional fields outlined by Ewart (1979). Symbols as in Fig. 2.

5. Crystallization index (An + Di' + Fo' + Sp') versus differentiation index (Qz + Or + Ab) plots of Pilbara data (Hutchinson, 1974). Symbols as in Fig.2.

6. F-A-M ternary plots of Pilbara data, showing the boundary of the tholeiitic and calc-alkaline fields. symbols as in Fig. 2.

7. Rare earth elements, Rb, Ba and Nb chondrite-normalized plots (normalizing values from Sun, 1982) of Pilbara felsic igneous rocks, showing model fields for melts produced from assumed source compositions, degree of fractionation (F) and residual phases as specified in the diagrams and explained in the text.

8 a (Ce/Yb)N versus (Yb)N plots of Pilbara felsic igneous rocks. Symbols as in Fig. 2. Model fractionation trends from a parental basic composition (Table 4) are shown for individual residual minerals (discontinuous lines; P-partial melting; F-fractional crystallization) for specific residual assemblages (continuous lines) as follows:

A-Partial melting. Residue-- 3Gnt : 70Cpx : 27Plg
B-Partial melting. Residue--10Gnt : 30Hbl : 30Cpx : 30Plg
C-Fractional crystallization. Precipitates : 83Cpx : 27Plg
D-Partial melting. Residue-- 5Gnt : 70Cpx : 25Plg

Numbers along fractionation trends (0.1-1.0) represent the fraction of liquid (F).

8 b (Ce/Sm)N versus (Sm)N plots of Pilbara felsic igneous rocks. Symbols as in Fig. 2. Fractionation trends as in Fig. 8a.

8 c (Sm/Yb)N versus (Yb)N plots of Pilbara felsic igneous rocks. Symbols as in Fig. 2. Fractionation trends as in Fig. 8a.

9. (Ce/Sm)N versus (Sm/Yb)N plots of Pilbara felsic igneous rocks. Symbols as in Fig. 2. Fractionation trends as in Fig. 8a.
E-Partial melting. Residue - 1Gnt : 70Cpx : 29Plg

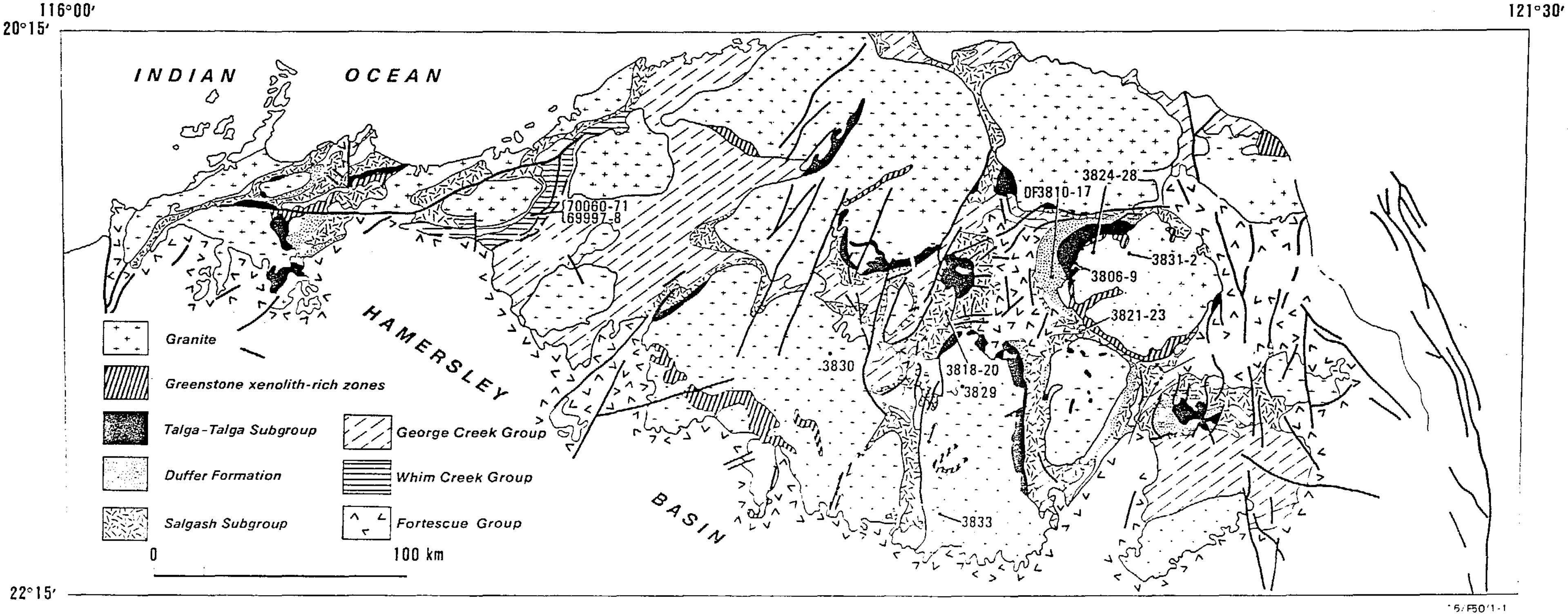
10. Eu/Eu* versus K_2O plots of Pilbara felsic igneous rocks. Symbols as in Fig. 2 (Eu*-value of Europium assuming a smooth chondrite normalized curve between Sm and Gd).

11. Zr-Ti plots of Pilbara felsic igneous rocks. Symbols as in Fig. 2.

12. Nb-Zr plots of Pilbara felsic igneous rocks. Symbols as in Fig. 2. Fractionation trends as in the legend for Fig. 8a.

13. Ba-Sr plots of Pilbara felsic igneous rocks. Symbols as in Fig. 2. Fractionation trends as in the legend for Fig. 8a.

FIG 1



116°00′
121°30′
20°15′
22°15′
INDIAN OCEAN
HAMERSLEY BASIN
70060-71
69997-8
3824-28
DF3810-17
3831-2
3806-9
3821-23
3830
3818-20
3829
3833
Granite
Greenstone xenolith-rich zones
Talga-Talga Subgroup
Duffer Formation
Salgash Subgroup
George Creek Group
Whim Creek Group
Fortescue Group
0
100 km
6/F50/1-1

FIG 2

PILBARA FELSIC IGNEOUS ROCKS

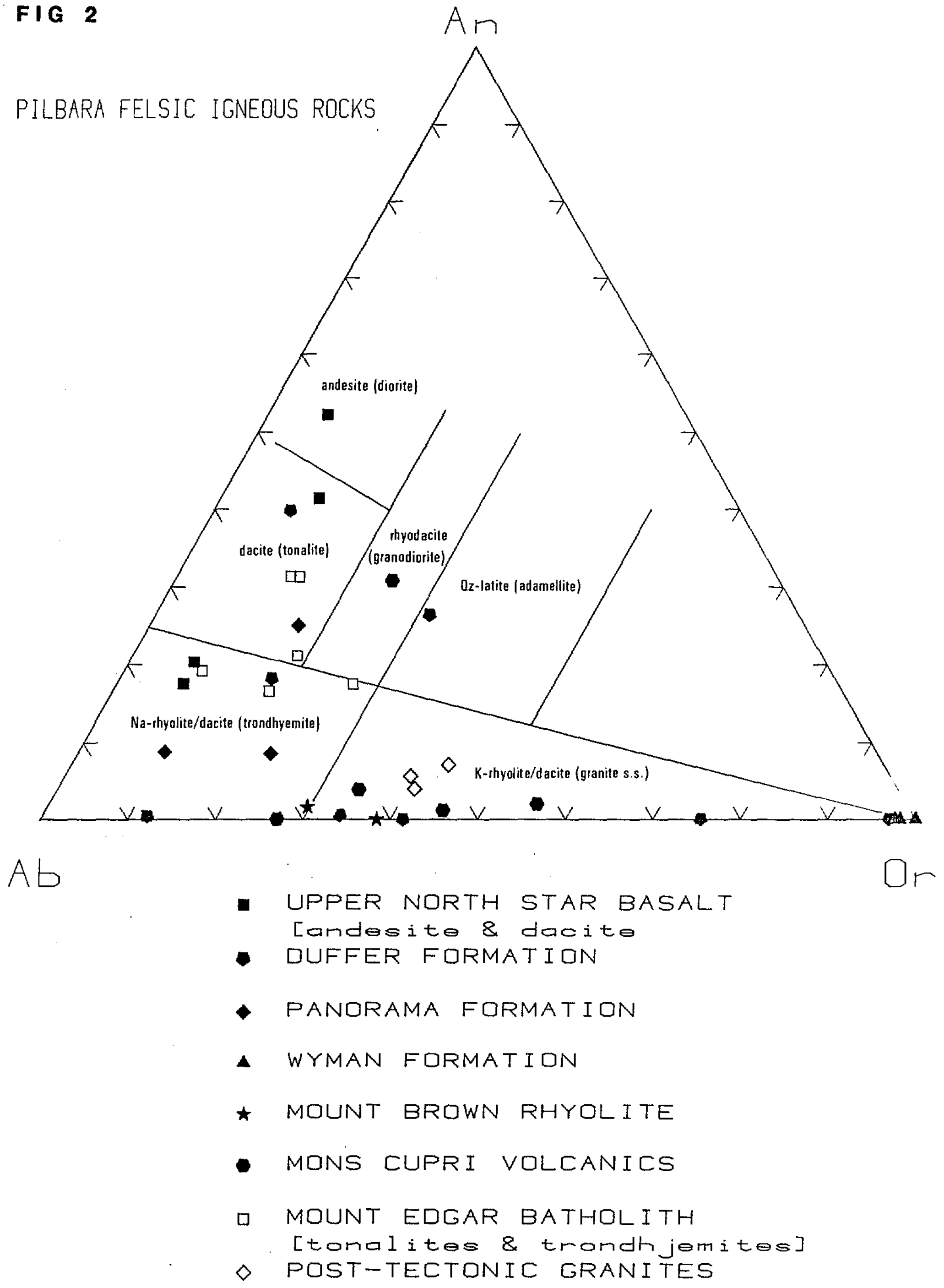
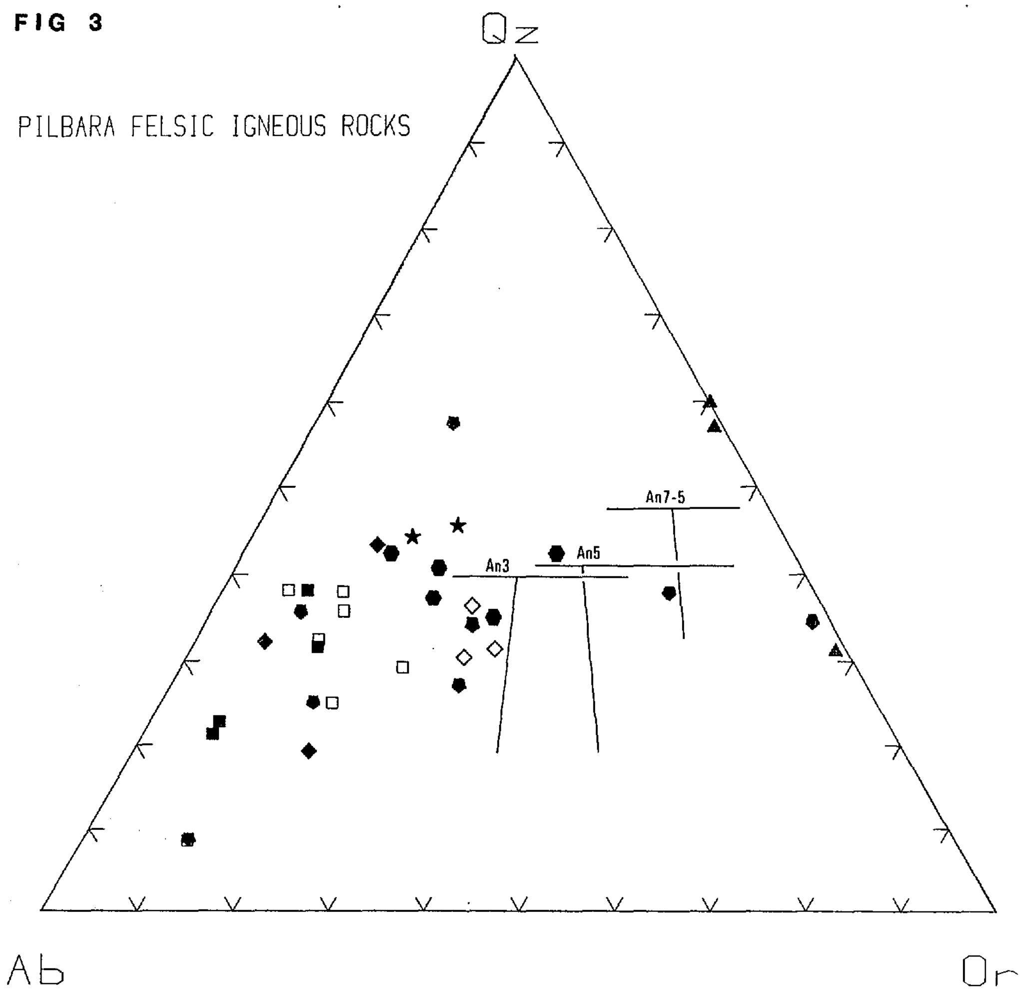


FIG 3



PILBARA FELSIC IGNEOUS ROCKS

FIG 4

PILBARA FELSIC IGNEOUS ROCKS

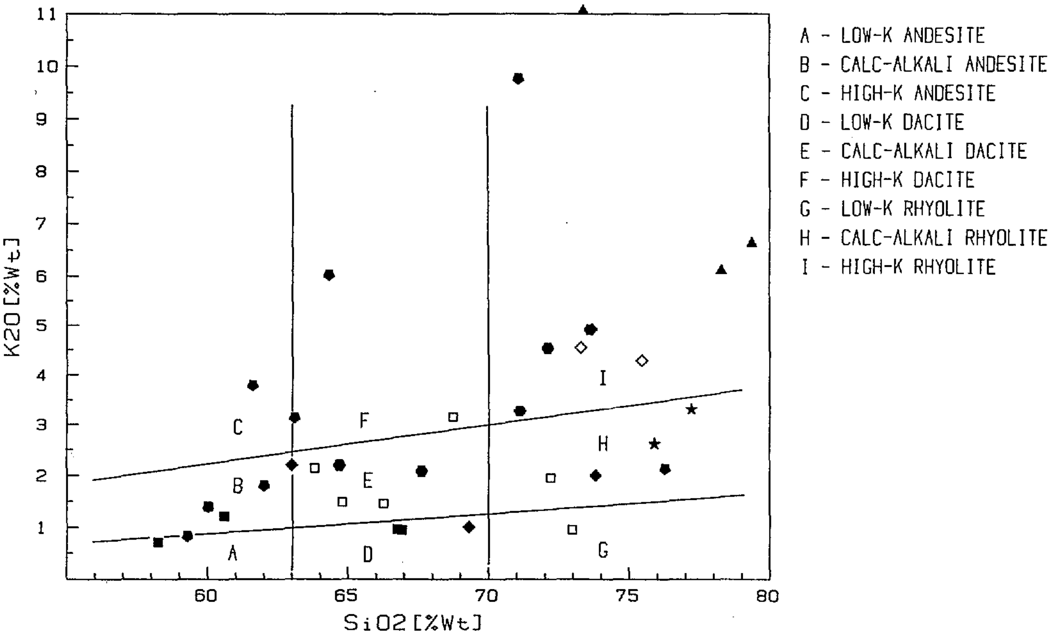


FIG 5

PILBARA FELSIC IGNEOUS ROCKS

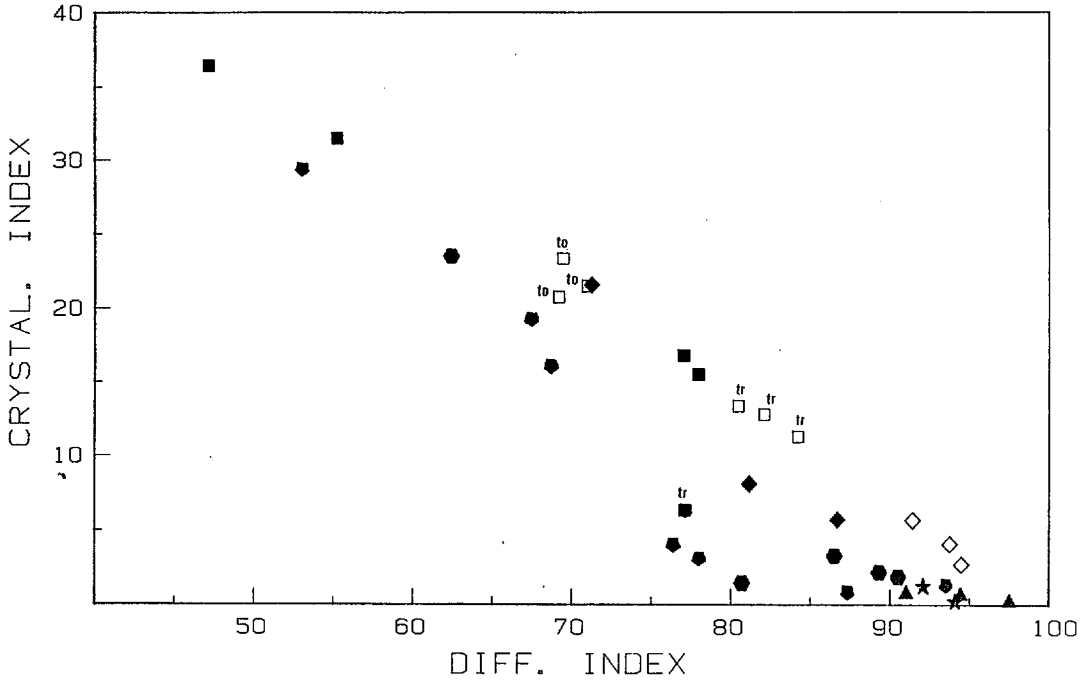


FIG 6

PILBARA FELSIC IGNEOUS ROCKS

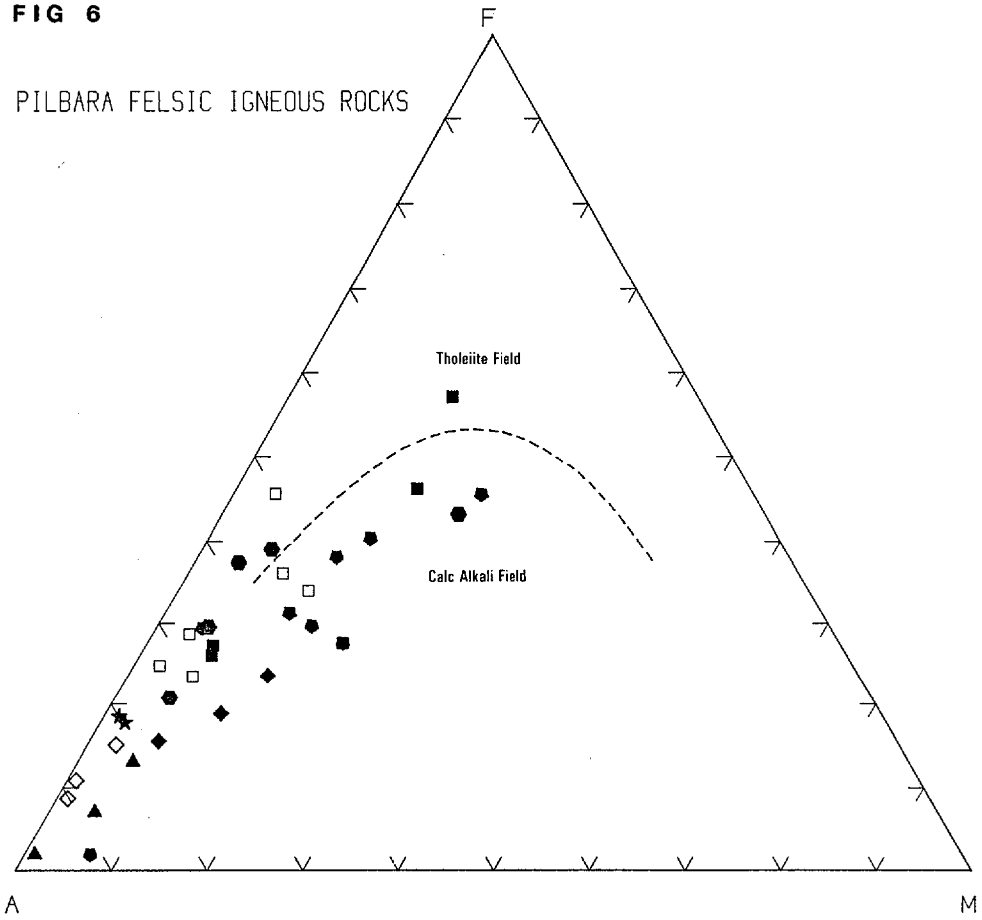
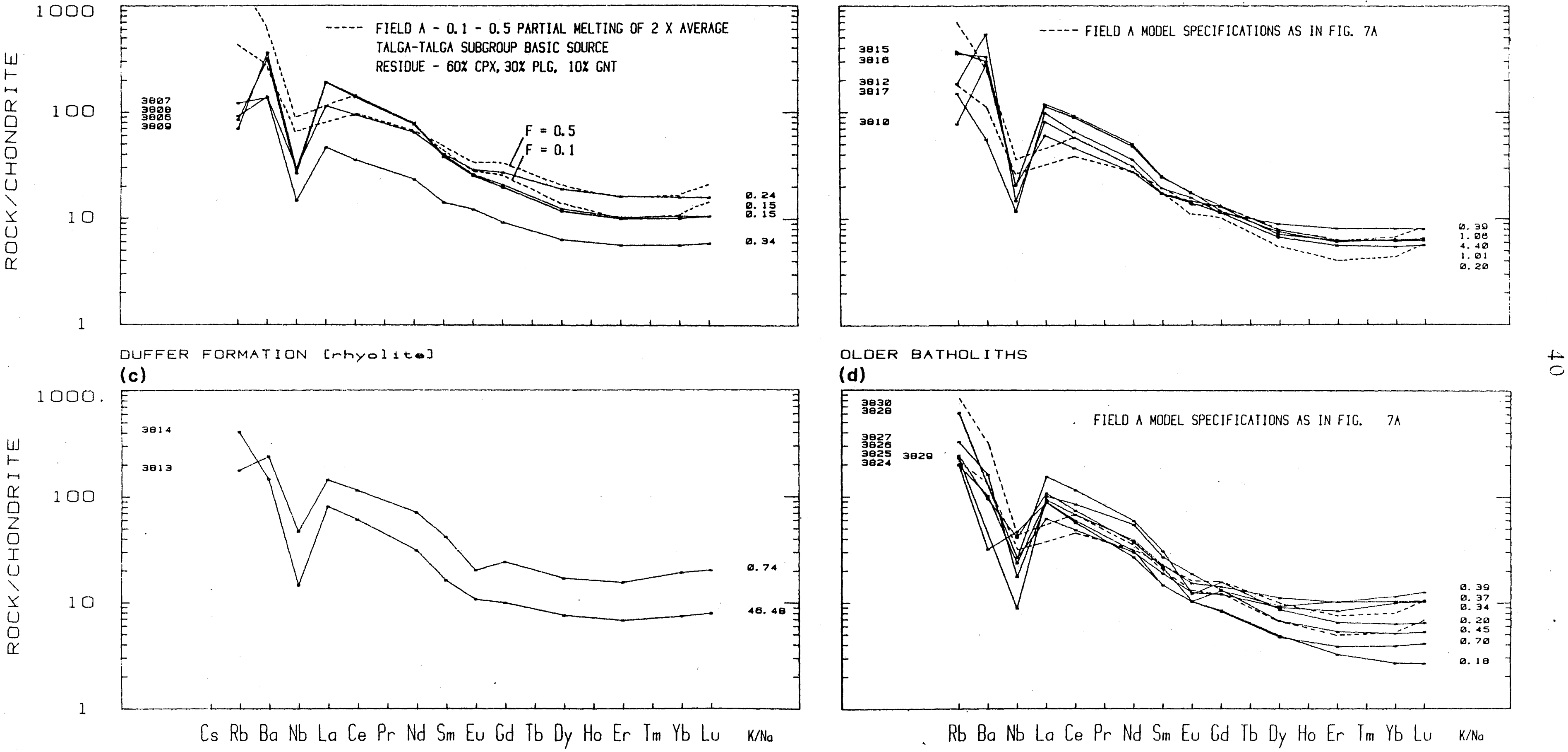


FIG 7



UPPER NORTH STAR BASALT [DACITES & ANDESITES]

(a)

DUFFER FORMATION [dacites]

(b)

DUFFER FORMATION [rhyolite]

(c)

OLDER BATHOLITHS

(d)

FIG 7(e)

PANORAMA FORMATION

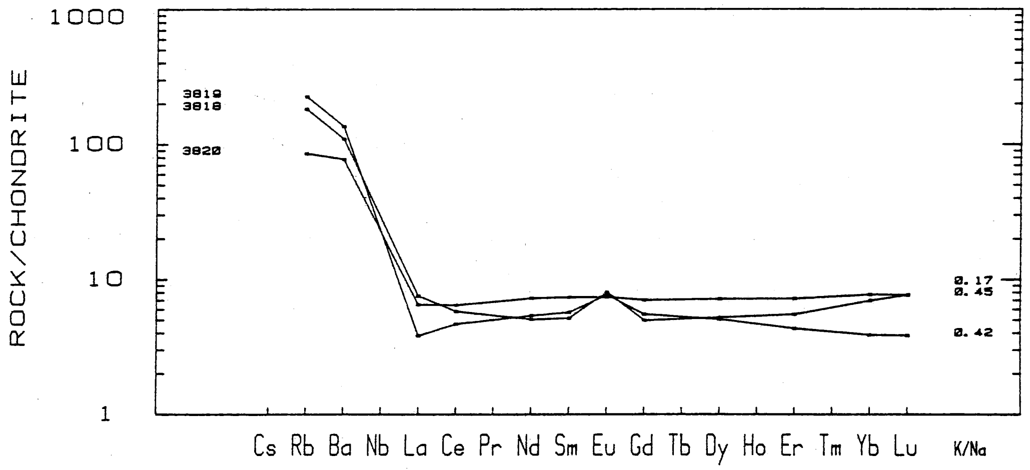
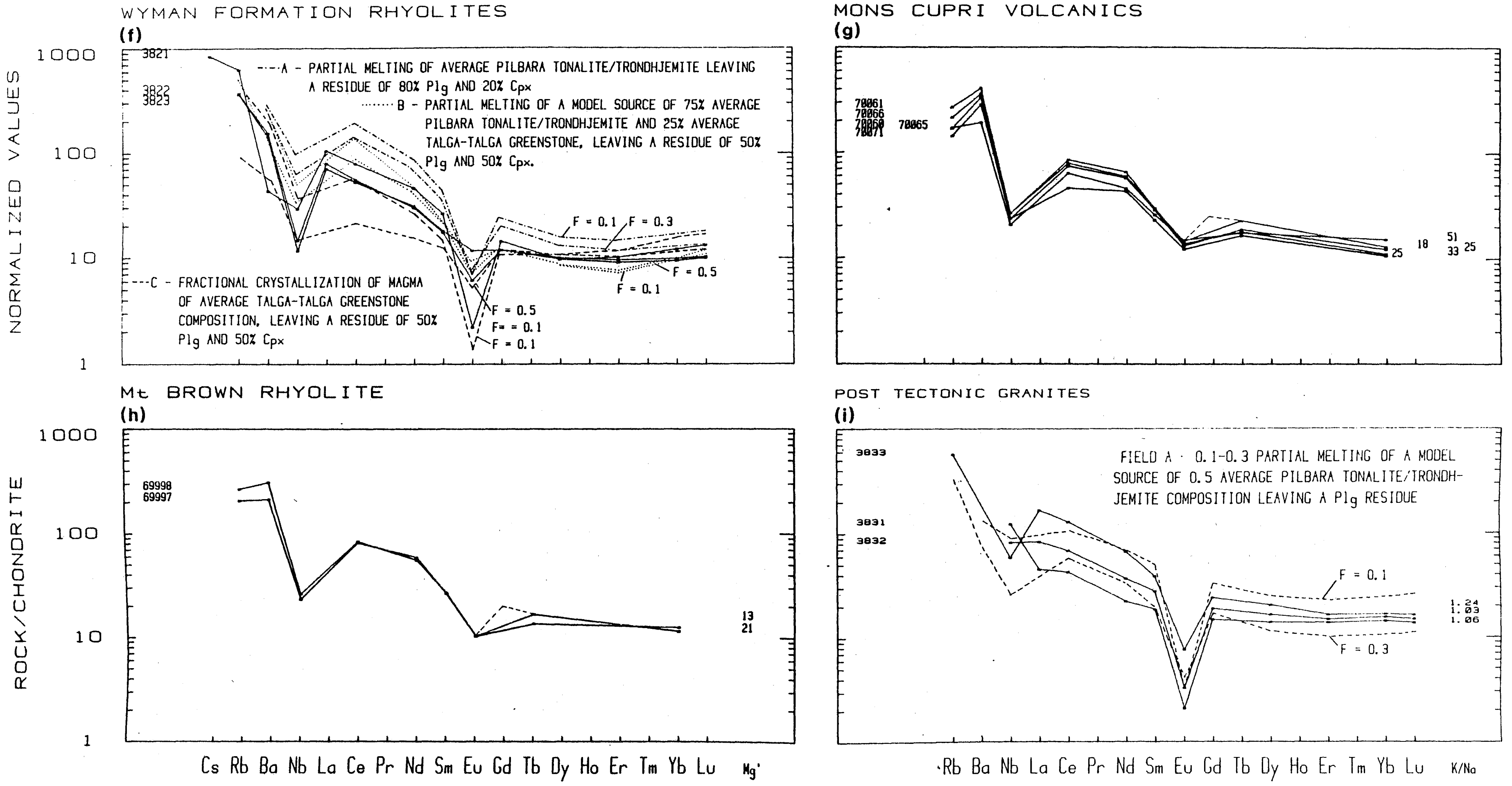


FIG 7



WYMAN FORMATION RHYOLITES (f)

MONS CUPRI VOLCANICS (g)

Mt BROWN RHYOLITE (h)

POST TECTONIC GRANITES (i)

FIG 8a

PILBARA FELSIC IGNEOUS ROCKS

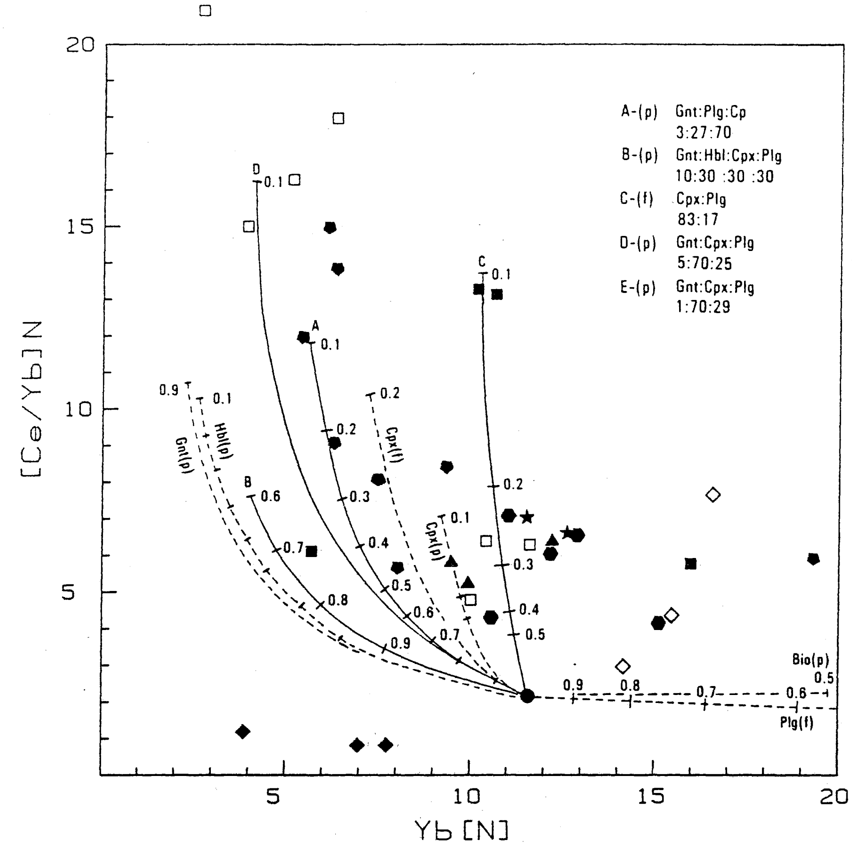


FIG 8b

PILBARA FELSIC IGNEOUS ROCKS

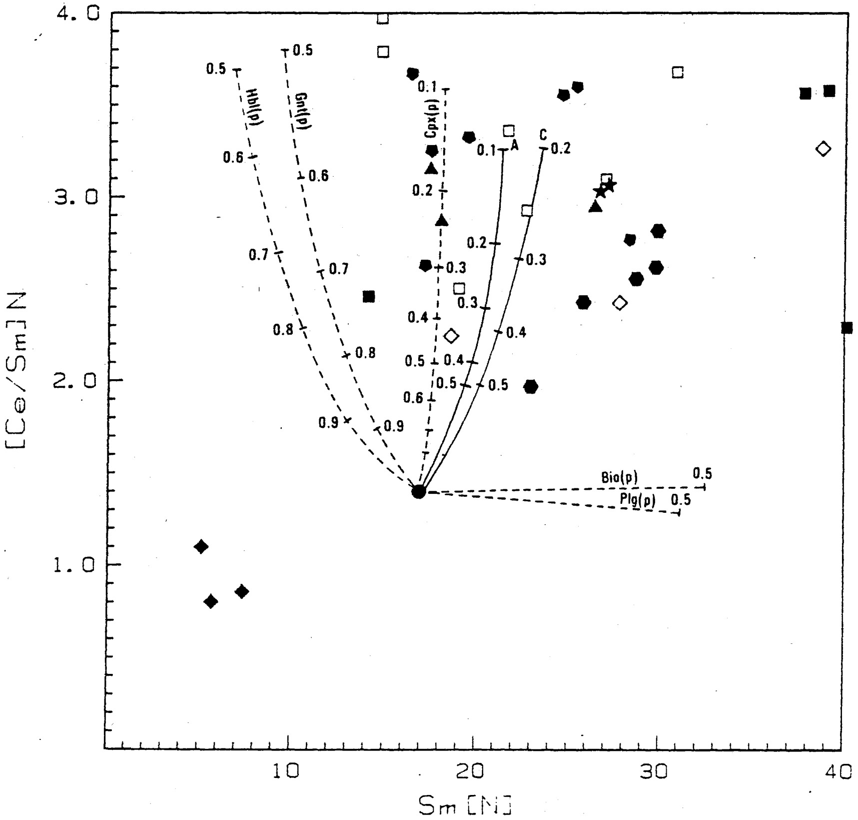


FIG 8c

PILBARA FELSIC IGNEOUS ROCKS

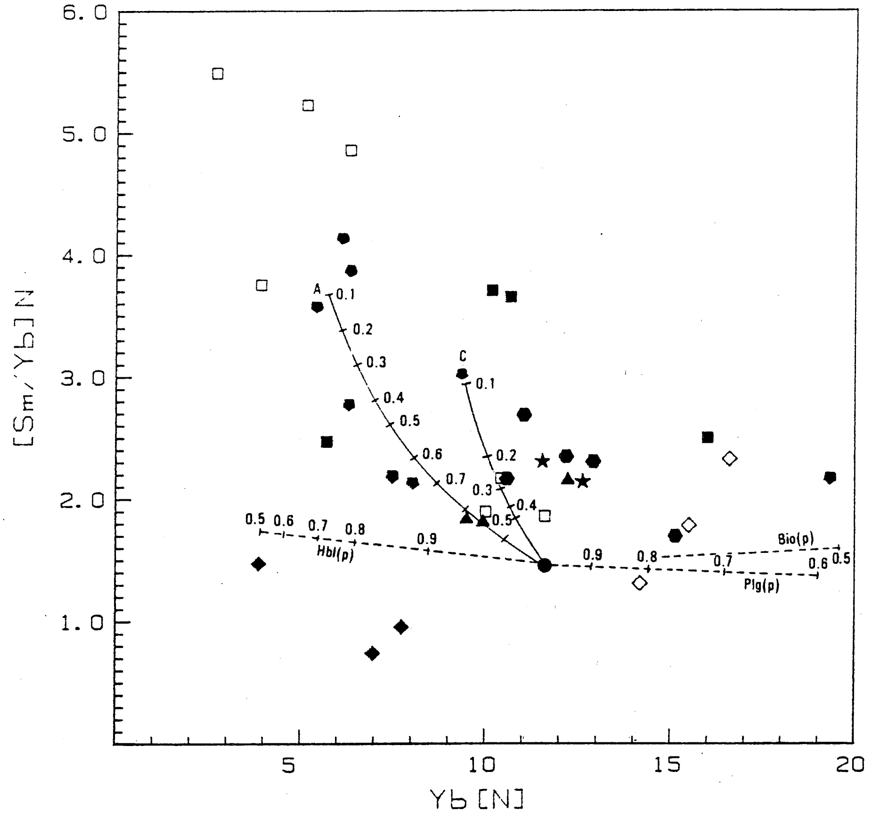


FIG 9

PILBARA FELSIC IGNEOUS ROCKS

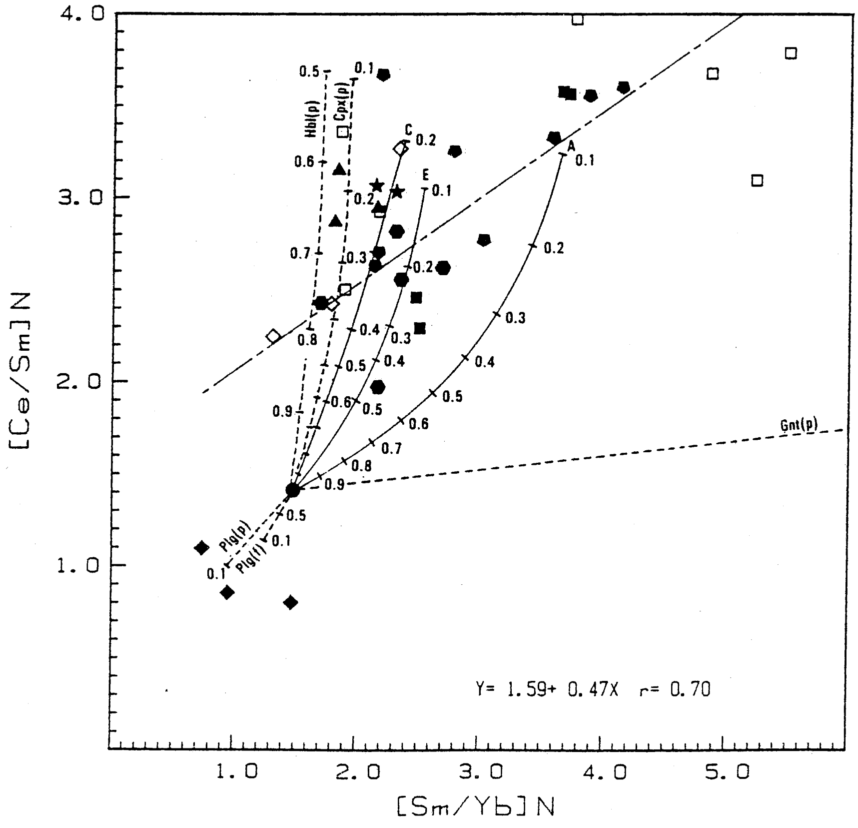


FIG 10

PILBARA FELSIC IGNEOUS ROCKS

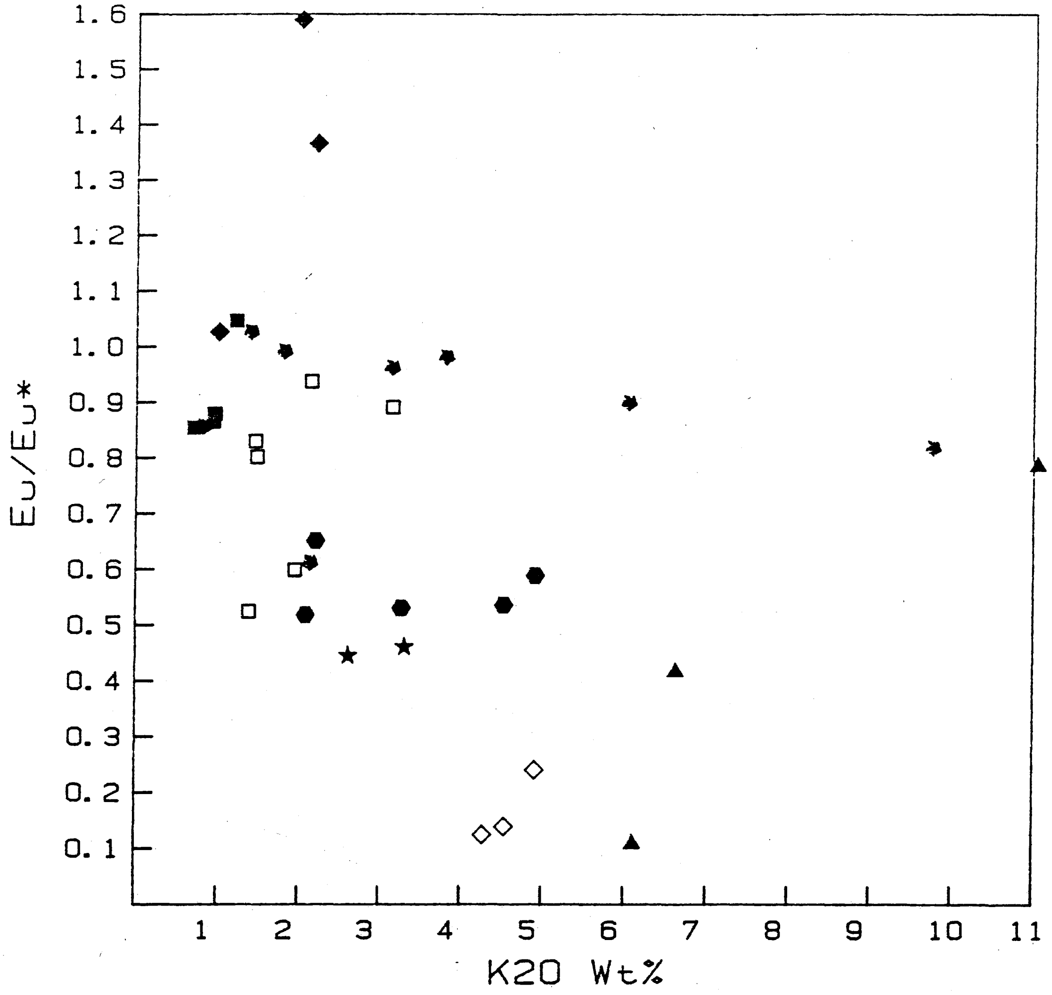


FIG 11

PILBARA FELSIC IGNEOUS ROCKS

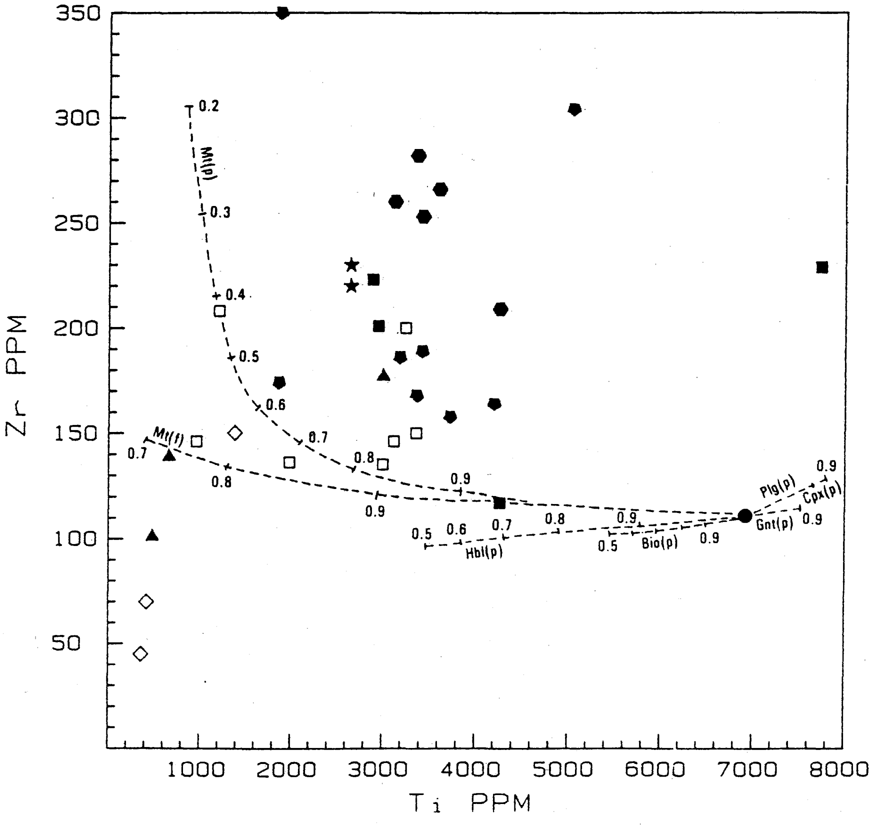


FIG 12

PILBARA FELSIC IGNEOUS ROCKS

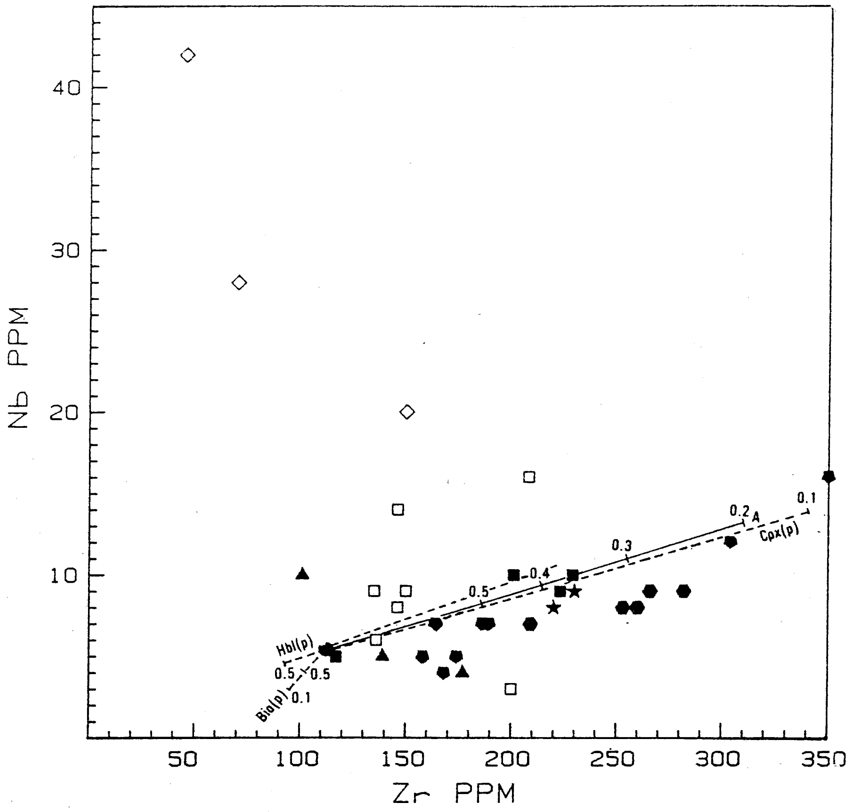


FIG 13

PILBARA FELSIC IGNEOUS ROCKS

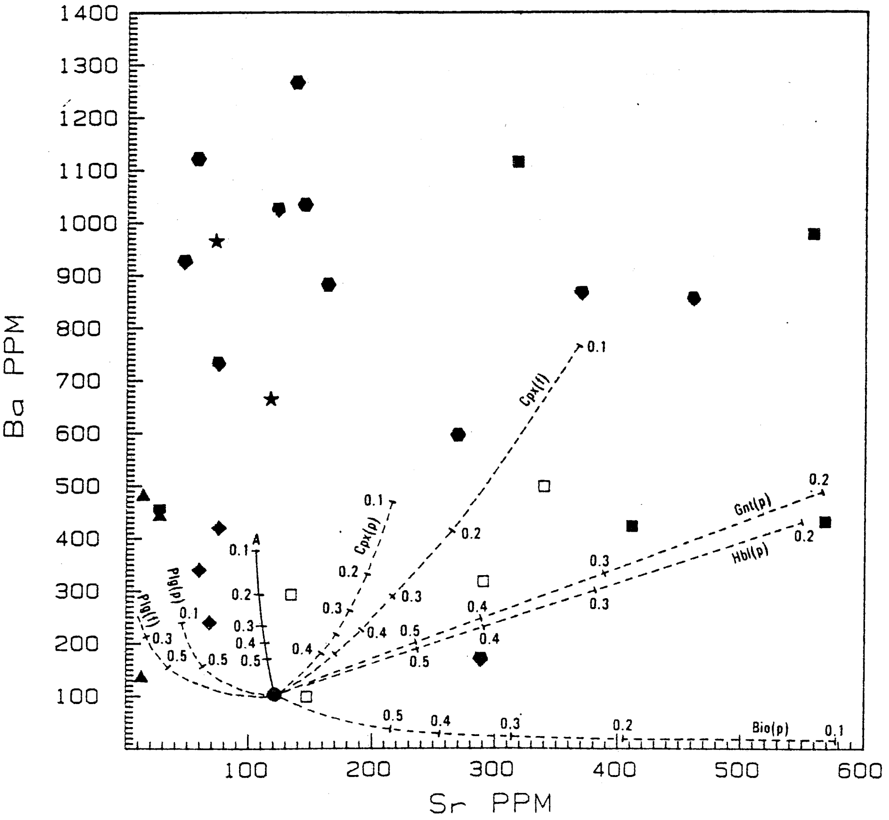


Table 1 - Classification of RE-analysed Pilbara Block felsic igneous rocks in terms of unit and petrochemistry

		andesite	dacite	Na-dacite	K-dacite	rhyodacite	rhyolite	K-rhyolite	silicified basalts	tonalite	trondhjemite	granite (S.S.)	Total
Warrawoona Group	Upper North Star Basalt	2	2										4
	Duffer Formation (3.45 b.y.)	1	4		1		1	1					8
	Panorama Formation (Ca 3.3 b.y.)								3				3
	Wyman Formation							3					3
Whim Creek Group	Mons Cupri Volcanics (Ca 3.0-2.8 b.y.)			1		1		3					5
	Mt Brown rhyolite							3					3
	Gneiss, Mt Edgar batholith									3	4		7
	Post-tectonic granites											3	3
	Total	3	6	1	1	1	1	10	3	3	4	3	36

Table 2 - Enrichment/depletion relations in Pilbara felsic igneous rocks in comparison with the average granites of Turekian and Wedepohl, 1961

	K	Rb	Ba	Sr	Pb	Th	U	Zr	Nb	P	RE
UNSB dacites	-	-	v	v	+	v	v	v	-	-	-
DF dacites	-	-	v	v	+	v	v	v	-	-	-
DF rhyolite	+	v	v	-	+	v	v	v	-	-	-
Panorama Fm Silicified basalt	-	-	-	-						-	-
WF rhyolites	+	v	v	-	+	v	v	v	-	-	-
Mons Cupri Volcanics	v	-	+	v	+	+	+	+	-	v	-
Mt Brown Rhyolite	v	v	v	v		+	+	+	-	-	-
Tonalite-trondhjemite gneisses, Mt Edgar Batholith	-	-	-	v	+	v	v	v	-	-	-
Post-tectonic granite (S.S.)	v	+		-					v	-	v

+	HIGH
-	LOW
V	NORMAL RANGE

Blanks represent inconsistent abundance relations or lack of data.

Table 3 - Chondrite-normalized LIL and REE elements ratios of average Pilbara felsic igneous units compared to average high-Ca and low-Ca granites (Turekian and Wedepohl, 1961).

Unit (No. of samples)		Rb/Sr	Ba/Sr	$(Ba/Ce)_N$	$(Ce/Yb)_N$	$(Ce/Dy)_N$	$(Dy/Lu)_N$	$(Sm/Nd)_N$	Eu*	Nb*
UNSB andesites	(2)	0.09	2.3	3.8	6.0	5.3	1.13	0.6	0.94	0.15
UNSB dacites	(2)	0.06	1.2	1.6	13.4	11.6	1.13	0.5	0.87	0.16
DF andesite	(1)	0.05	1.86	3.5	8.5	6.8	1.23	0.57	0.85	0.20
DF dacites	(4)	0.35	2.85	5.0	10.3	8.7	1.15	0.55	0.99	0.11
DF rhyolites	(2)	3.2	14	2.2	7.1	7.4	0.89	0.55	0.71	0.20
Panorama Fm Silicified basalts	(3)	0.86	4.96	20	0.96	0.98	0.98	1.03	1.32	
Wyman Fm rhyolites	(3)	11.3	22.3	2	5.9	6.4	0.9	0.58	0.43	0.24
Mons Cupri Volcanics	(5)	0.59	8.8	4.7	5.7			0.50		0.13
Mt Brown Rhyolite	(2)	0.96	9.6	3.1	6.9			0.47		0.14
Early tonalites	(3)	0.3	1.1	1.5	9.3	8.0	1.06	0.58	0.85	0.28
Early trondhjemites	(4)	0.85	1.4	1.5	15.3	11.3	1.3	0.53	0.72	0.57
Post tectonic granites	(3)	14.6			5.0	4.5	1.1	0.7	0.16	
High-Ca granites		0.25	0.95	1.4	5.9	5.1	0.56	0.82	0.48	0.51
low-Ca granites		1.7	8.4	2.5	5.8	5.0	0.59	0.83	0.49	0.33

TABLE 4 - Average composition used as model sources in partial melting and fractional crystallization calculations

	A	B	C
SiO_2	49.50	66.98	62.5
TiO_2	1.15	0.40	0.58
Al_2O_3	13.20	15.78	15.1
FeOt	11.83	3.63	5.7
MRO	0.23	0.07	0.11
M_2O	7.14	1.15	2.64
CaO	9.08	3.17	4.64
Na_2O	1.46	5.00	4.11
K_2O	0.30	1.79	1.42
P_2O_5	0.10	0.11	0.107
Rb	14	120	94
Ba	102	302	252
Sr	120	334	280
Nb	5.1	9.3	8.2
Zr	111		
La	5.2	32.8	26
Ce	20.8	62.7	52
Nd	10.8	25	21.4
Sm	3.5	4.4	4.1
Eu	1.0	0.99	1.0
Gd	2.9	3.4	3.2
Tb	0.7		
Dy	3.6	2.7	2.9
Ho	16.6		
Er	1.7	1.54	1.6
Tm	3.4		
Yb	2.6	1.57	1.8
Lu	0.54	0.25	0.32
Y	23	15.5	17.3

A - Average of 13 high-Mg basalts (4 samples) and tholeiitic basalts (9 samples) from the North Star Basalt and Mount Ada Basalt (Glikson et al., 1986)

B - Average of 7 tonalites and trondhjemites of the Mount Edgar batholith

C - 25 percent of composition A plus 75 percent of composition B

Annex to Appendix I - sample definitions

UPPER NORTH STAR BASALT

3806 - chlorite-bearing Na-dacite
3807 - amphibole-chlorite-plagioclase andesite
3808 - Na-dacite
3809 - amphibole-bearing andesite

DUFFER FORMATION

3810 - epidote-albite Na-dacite
3811 - epidote-chlorite-albite andesite
3812 - saussurite-epidote dacite
3813 - sericite-bearing rhyolite
3814 - K-rich rhyolite
3815 - K-rich dacite tuff
3816 - dacite tuff
3817 - Na-rich dacite

PANORAMA FORMATION

3818 - silicified lava, pillow margin
3819 - silicified lava, pillow margin
3820 - silicified lava, pillow core

WYMAN FORMATION

3821 - high-K rhyolite
3822 - high-K rhyolite
3823 - K-rich rhyolite

MONS CUPRI VOLCANICS

70060 - crystal-lithic rhyodacite tuff
70061 - porphyritic K-rhyolite tuff
70065 - porphyritic K-rhyolite tuff
70066 - porphyritic K-rhyolite tuff
70071 - crystal-vitric Na-dacite tuff

MOUNT BROWN RHYOLITE

69997 - spherulitic porphyritic K-rhyolite
69998 - spherulitic porphyritic K-rhyolite

TONALITE/TRONDHJEMITE GNEISSES

3824 - tonalite, Mt Edgar batholith
3825 - trondhjemite, Mt Edgar batholith
3826 - trondhjemite, "
3827 - trondhjemite, "
3828 - tonalite gneiss, Mt Edgar batholith
3829 - hornblende tonalite gneiss, Shaw batholith
3830 - biotite trondhjemite, Yule batholith

POST-TECTONIC GRANITE

3831 - granite s.s., Moolyella granite
3832 "
3833 - granite s.s., Coondina granite

APPENDIX I - A: UPPER NORTH STAR BASALT

Sample number	3806	3807	3808	3809
ROCK TYPE	dacite	andesite	dacite	andesite
GEOLOGICAL UNIT	UNSB	UNSB	UNSB	UNSB
REFERENCE	Jahn et al 1981	Jahn et al 1981	Jahn et al 1981	Jahn et al 1981
SiO_2	66.75	60.60	66.92	58.23
TiO_2	0.48	0.71	0.49	1.29
Al_2O_3	16.60	16.76	17.05	17.13
Fe_2O_3	3.27	6.98	3.37	8.92
FeO				
MnO	0.09	0.11	0.09	0.17
MgO	0.85	2.58	0.78	2.42
CaO	3.57	5.83	3.45	7.01
Na_2O	6.56	3.55	6.37	2.92
K_2O	0.96	1.21	0.94	0.70
P_2O_5	0.13	0.12	0.14	0.35
H_2O+	0.69	0.97	0.68	1.01
H_2O-				
CO_2	0.13	0.18	0.05	0.04
TOTAL	100.08	99.60	100.33	100.19
Cs				
Rb	29.60	42.40	32.10	24.30
Ba	978.00	423.00	431.00	1115.00
Nb	9.00	5.00	10.00	10.00
La	62.36	15.26	62.70	37.45
Ce	118.50	30.59	123.00	81.07
Pr				
Nd	47.90	14.70	49.20	40.10
Sm	7.65	2.86	7.91	8.13
Eu	1.94	0.94	1.99	2.21
Gd	5.42	2.55	5.74	7.49
Tb				
Dy	4.01	2.18	4.23	6.47
Ho				
Er	2.25	1.27	2.33	3.65
Tm				
Yb	2.23	1.25	2.34	3.51
Lu	0.36	0.20	0.36	0.54
Y	24.00	12.00	36.00	24.00
Sr	556.80	410.60	567.40	315.90
Mg´ NUMBER	37.7	46.3	35.0	38.7
Na2O/K2O	6.83	2.93	6.78	4.17
TOTAL REE	252.62	71.80	259.80	190.62
Eu/Eu*	0.88	1.04	0.86	0.85
(Ce/Yb)N	13.52	6.22	13.37	5.87
(Ce/Sm)N	3.64	2.51	3.65	2.34
(Sm/Yb)N	3.72	2.48	3.66	2.51

APPENDIX I - B: DUFFER FORMATION

Sample number	3810	3811	3812	3813	3814	3815	3816	3817
ROCK TYPE	dacite	andesite	dacite	rhyolite	K-rhyolite	K-dacite	dacite	dacite
GEOLOGICAL UNIT	DUFFER FM	DUFFER FM	DUFFER FM	DUFFER FM	DUFFER FM	DUFFER FM	DUFFER FM	DUFFER FM
REFERENCE	Jahn et al 1981	Jahn et al 1981	Jahn et al 1981	Jahn et al 1981	Jahn et al 1981	Jahn et al 1981	Jahn et al 1981	Jahn et al 1981
SiO_2	62.00	59.27	63.08	76.27	71.07	64.32	61.60	60.02
TiO_2	0.70	0.84	0.62	0.31	0.31	0.53	0.57	0.56
Al_2O_3	16.09	15.16	16.63	11.56	11.62	15.35	17.32	18.51
Fe_2O_3	6.76	7.41	5.42	2.48	0.23	0.88	0.91	1.16
FeO						3.35	3.30	3.45
MnO	0.12	0.12	0.08	0.06	0.06	0.06	0.06	0.05
MgO	2.56	3.82	1.86	0.37	0.75	1.73	2.24	3.34
CaO	2.44	5.92	3.55	1.87	1.61	1.73	1.61	0.68
Na_2O	4.65	3.37	2.94	2.87	0.21	1.37	3.74	7.10
K_2O	1.80	0.82	3.13	2.13	9.76	6.03	3.79	1.39
P_2O_5	0.12	0.22	0.13	0.04	0.09	0.17	0.15	0.13
H_2O+	2.08	1.97	1.62	1.01	0.80	2.21	2.47	2.71
H_2O-					0.04	0.15	0.15	0.13
CO_2	0.03	0.93	0.19	1.39	1.45	1.75	1.75	0.35
TOTAL	99.35	99.85	99.25	100.36	98.00	99.63	99.66	99.58
Cs								
Rb	27.20	24.70	64.60	62.10	142.10	130.40	124.20	52.60
Ba	868.00	858.00	1667.00	742.00	454.00	928.00	1030.00	172.00
Nb	7.00	12.00	5.00	16.00	5.00	7.00	7.00	4.00
La	19.86	32.80	26.70	47.60	26.76	39.14	37.10	32.34
Ce	39.75	68.90	50.00	99.80	52.90	80.20	76.90	56.90
Pr								
Nd	17.41	31.40	19.60	45.10	19.80	31.80	30.17	22.70
Sm	3.48	5.73	3.54	8.50	3.32	5.13	4.98	3.94
Eu	1.09	1.50	1.13	1.56	0.83	1.34	1.38	1.22
Gd	3.15	4.76	3.61	6.72	2.76	3.70	3.31	3.16
Tb								
Dy	3.06	3.99	2.43	5.84	2.60	2.69	2.58	2.29
Ho								
Er	1.81	2.20	1.39	3.50	1.53	1.42	1.35	1.25
Tm								
Yb	1.76	2.05	1.38	4.24	1.64	1.34	1.39	1.19
Lu	0.27	0.32	0.22	0.69	0.27	0.21	0.21	0.19
Y	18.00	41.00	15.00	53.00	13.00	14.00	15.00	13.00
Sr	368.70	459.90	432.10	73.20	25.40	45.80	121.60	286.60
Mg´ NUMBER	46.9	54.6	44.4	25.8	88.4	46.7	53.3	60.9
Na2O/K2O	2.58	4.11	0.94	1.35	0.02	0.23	0.99	5.11
TOTAL REE	91.64	153.65	110.00	223.55	112.41	166.97	159.37	125.18
Eu/Eu*	0.99	0.85	0.96	0.61	0.82	0.90	0.98	1.02
(Ce/Yb)N	5.74	8.55	9.22	5.99	8.20	15.22	14.07	12.16
(Ce/Sm)N	2.68	2.82	3.31	2.76	3.74	3.67	3.62	3.39
(Sm/Yb)N	2.14	3.03	2.78	2.17	2.19	4.15	3.88	3.59

APPENDIX I - C: PANORAMA FORMATION

Sample number	3818	3819	3820
ROCK TYPE	Silic.lava	silic.lava	silic.lava
GEOLOGICAL UNIT	Panorama Formation	Panorama Formation	Panorama Formation
REFERENCE	Jahn et al 1981	Jahn et al 1981	Jahn et al 1981
SiO_2	73.80	63.00	69.30
TiO_2	0.58	1.04	0.64
Al_2O_3	14.20	19.40	15.60
Fe_2O_3	0.20	0.30	0.40
FeO	1.10	1.74	2.21
MnO	0.04	0.10	0.08
MgO	0.60	1.30	1.60
CaO	1.89	4.40	2.11
Na_2O	4.40	5.21	5.77
K_2O	2.00	2.20	1.00
P_2O_5	0.02	0.04	0.04
H_2O+	1.15	1.96	1.45
H_2O-	0.09	0.13	0.14
CO_2	0.73	0.39	0.78
TOTAL	100.80	101.21	101.12
Cs			
Rb	63.90	79.00	29.90
Ba	340.00	420.00	240.00
Nb			
La	2.48	1.26	2.14
Ce	5.02	4.05	5.59
Pr			
Nd	3.19	3.41	4.59
Sm	1.05	1.16	1.50
Eu	0.62	0.59	0.57
Gd	1.37	1.52	1.94
Tb			
Dy	1.79	1.73	2.46
Ho			
Er	1.24	0.97	1.62
Tm			
Yb	1.53	0.85	1.70
Lu	0.26	0.13	0.26
Y	10.00	10.00	20.00
Sr	59.10	75.10	67.80
Mg´ NUMBER	49.6	57.6	56.6
Na2O/K2O	2.20	2.37	5.77
TOTAL REE	18.55	15.67	22.37
Eu/Eu*	1.58	1.36	1.02
(Ce/Yb)N	0.83	1.21	0.84
(Ce/Sm)N	1.12	0.82	0.87
(Sm/Yb)N	0.74	1.48	0.96

APPENDIX I - D: WYMAN FORMATION

Sample number	3821	3822	3823
ROCK TYPE	K-rhyolite	K-rhyolite	K-rhyolite
GEOLOGICAL UNIT	Wyman Formation	Wyman Formation	Wyman Formation
REFERENCE	Jahn et al 1981	Jahn et al 1981	Jahn et al 1981
SiO_2	78.27	79.34	73.36
TiO_2	0.08	0.11	0.50
Al_2O_3	12.36	11.19	13.11
Fe_2O_3	1.09	0.43	0.08
FeO		0.15	0.15
MnO	0.02	0.01	0.02
MgO	0.43	0.36	0.12
CaO	0.22	0.03	0.21
Na_2O		0.11	0.14
K_2O	6.11	6.62	11.05
P_2O_5		0.02	0.07
H_2O+	0.81	1.21	0.35
H_2O-		0.15	0.03
CO_2	0.26		0.25
TOTAL	99.65	99.73	99.44
Cs			
Rb	219.10	129.20	127.40
Ba	135.00	480.00	442.00
Nb	10.00	5.00	4.00
La	34.58	26.08	23.25
Ce	68.30	48.30	45.50
Pr			
Nd	29.20	18.90	19.70
Sm	5.34	3.53	3.65
Eu	0.17	0.47	0.90
Gd	3.97	3.29	3.26
Tb			
Dy	3.31	3.32	3.43
Ho			
Er	2.29	2.04	2.15
Tm			
Yb	2.68	2.08	2.18
Lu	0.45	0.34	0.35
Y	29.00	22.00	18.00
Sr	11.70	12.50	26.00
Mg´ NUMBER	47.9	58.4	53.1
Na2O/K2O		0.02	0.01
TOTAL REE	150.29	108.35	104.37
Eu/Eu*	0.11	0.42	0.78
(Ce/Yb)N	6.48	5.91	5.31
(Ce/Sm)N	3.00	3.21	2.93
(Sm/Yb)N	2.16	1.84	1.81

APPENDIX I - E: MONS CUPRI VOLCANICS

Sample number	70060	70061	70065	70066	70071
ROCK TYPE	rhyod.tuff	K-rhy.tuff	K-rhy.tuff	K-rhy.tuff	N-dac.tuff
GEOLOGICAL UNIT	Mons Cupri Fragmental	Mons Cupri Fragmental	Mons Cupri Fragmental	Mons Cupri Fragmental	Mons Cupri Fragmental
REFERENCE	Pride	Pride	Pride	Pride	Pride
SiO_2	64.70	72.10	71.10	73.60	67.60
TiO_2	0.71	0.60	0.56	0.52	0.57
Al_2O_3	12.80	12.70	12.20	10.90	11.70
Fe_2O_3	1.76	0.72	1.93	1.18	0.91
FeO	5.03	1.67	2.99	2.34	3.55
MnO	0.15	0.03	0.04	0.05	0.11
MgO	3.80	0.64	0.58	0.62	0.81
CaO	3.48	1.26	1.40	1.25	3.71
Na_2O	2.74	3.72	4.08	2.60	3.94
K_2O	2.20	4.52	3.26	4.90	2.08
P_2O_5	0.08	0.15	0.14	0.13	0.15
H_2O+	2.25	0.94	0.94	0.78	1.34
H_2O-	0.12	0.12	0.16	0.13	0.26
CO_2		0.72	0.60	0.68	2.75
TOTAL	99.82	99.89	99.98	99.68	99.48
Cs	20.90	26.60	28.20	26.00	25.30
Rb	60.00	94.00	59.00	75.00	50.00
Ba	596.00	1266.00	1034.00	1122.00	882.00
Nb	7.00	9.00	9.00	8.00	8.00
La					
Ce	55.11	68.52	73.96	39.86	64.44
Pr					
Nd	29.06	37.66	41.55	27.21	36.41
Sm	5.22	6.02	6.04	4.65	5.80
Eu	1.15	1.06	1.12	0.94	1.01
Gd					
Tb	0.87	0.89	1.14	0.82	0.94
Dy					
Ho	15.00	17.00	16.00	11.00	15.00
Er	9.24	14.38	10.78	12.20	3.77
Tm	4.13	5.57	5.97	5.38	4.97
Yb	3.32	2.42	2.83	2.32	2.67
Lu					
Y	28.00	23.00	25.00	20.00	25.00
Sr	268.00	136.00	143.00	56.00	162.00
Mg′ NUMBER	54.6	36.7	20.5	27.6	28.0
Na2O/K2O	1.25	0.82	1.25	0.53	1.89
TOTAL REE	123.10	153.52	159.39	104.38	135.01
Eu/Eu*	0.65	0.54	0.53	0.59	0.52
(Ce/Yb)N	4.22	7.20	6.65	4.37	6.14
(Ce/Sm)N	2.48	2.67	2.87	2.01	2.61
(Sm/Yb)N	1.70	2.70	2.31	2.17	2.35

APPENDIX I - F: Mt BROWN RHYOLITE

Sample number	69997	69998
ROCK TYPE	K-rhyol	K-rhyol
GEOLOGICAL UNIT	Mt Brown Rhyolite	Mt Brown Rhyolite
REFERENCE	Pride	Pride
SiO_2	75.90	77.20
TiO_2	0.44	0.44
Al_2O_3	11.60	11.80
Fe_2O_3	0.59	0.50
FeO	0.98	1.16
MnO	0.02	0.04
MgO	0.22	0.14
CaO	1.67	0.24
Na_2O	4.22	3.70
K_2O	2.61	3.30
P_2O_5	0.11	0.10
H_2O+	0.58	0.65
H_2O-	0.21	0.20
CO_2	1.06	0.46
TOTAL	100.21	99.93
Cs	22.00	23.00
Rb	73.00	94.00
Ba	664.00	965.00
Nb	8.00	9.00
La		
Ce	71.15	73.13
Pr		
Nd	37.27	34.98
Sm	5.40	5.49
Eu	0.80	0.80
Gd		
Tb	0.84	0.68
Dy		
Ho	12.00	12.00
Er	23.64	22.59
Tm	4.91	4.98
Yb	2.53	2.77
Lu		
Y	27.00	23.00
Sr	116.00	71.00
Mg´ NUMBER	23.4	15.4
Na2O/K2O	1.62	1.12
TOTAL REE	158.54	157.42
Eu/Eu*	0.44	0.46
(Ce/Yb)N	7.15	6.71
(Ce/Sm)N	3.09	3.13
(Sm/Yb)N	2.31	2.15

APPENDIX 1 - G: EARLY TONALITE/TRONDHJEMITE GNEISSES

Sample number	3824	3825	3826	3827	3828	3829	3830
ROCK TYPE	tonalite	trondhjem.	trondhjem.	trondhjem.	tonalite	tonalite	trondhjem.
GEOLOGICAL UNIT	Mt Edgar Batholith	Mt Edgar Batholith	Mt Edgar Batholith	Mt Edgar Batholith	Mt Edgar Batholith	Shaw Batholith	Yule Batholith
REFERENCE	Jahn et al 1981	Jahn et al 1981	Jahn et al 1981	Jahn et al 1981	Jahn et al 1981	Jahn et al 1981	Jahn et al 1981
SiO_2	66.28	72.98	72.21	68.74	64.80	63.80	60.02
TiO_2	0.52	0.20	0.16	0.33	0.50	0.54	0.56
Al_2O_3	15.18	14.18	14.16	16.11	17.00	15.30	18.51
Fe_2O_3	5.49	2.96	2.62	2.84	1.78	2.41	1.16
FeO					2.34	2.30	3.45
MnO	0.10	0.05	0.07	0.05	0.10	0.09	0.05
MgO	0.48	0.36	0.26	0.75	1.08	1.79	3.34
CaO	4.72	2.70	2.35	2.61	4.35	4.77	0.68
Na_2O	3.97	5.32	4.96	4.49	4.41	4.74	7.10
K_2O	1.46	0.95	1.95	3.14	1.48	2.14	1.39
P_2O_5	0.13	0.04	0.05	0.08	0.08	0.29	0.13
H_2O+	0.86	0.54	0.63	0.55			2.71
H_2O-					1.49	0.99	0.13
CO_2	0.17	0.04	0.03	0.07			0.35
TOTAL	99.36	100.32	99.45	99.76	99.41	99.16	99.58
Cs							
Rb	69.00	70.00	85.00	114.00	212.00	80.00	215.00
Ba	317.00	99.00	293.00	498.00			
Nb	8.00	16.00	14.00	6.00	9.00	3.00	9.00
La	30.89	29.12	35.60	29.34	20.42	33.32	51.12
Ce	58.50	49.40	64.10	51.60	42.00	73.60	99.90
Pr							
Nd	24.70	16.90	23.50	19.40	18.80	34.40	37.45
Sm	4.60	3.00	4.39	2.99	3.86	5.47	6.25
Eu	1.18	0.79	0.80	0.79	0.96	1.45	0.94
Gd	3.93	2.36	3.61	2.29	3.33	3.65	4.35
Tb							
Dy	3.84	1.68	3.21	1.62	3.11	2.32	2.97
Ho							
Er	2.30	0.73	2.32	0.87	1.89	1.20	1.47
Tm							
Yb	2.29	0.59	2.55	0.86	2.20	1.13	1.39
Lu	0.36	0.09	0.43	0.14	0.35	0.18	0.22
Y	23.00	9.00	19.00	11.00			
Sr	290.00	147.00	134.00	339.00	360.00	955.00	110.00
Mg´ NUMBER	16.9	22.1	18.8	38.1	36.5	45.6	60.9
Na2O/K2O	2.72	5.60	2.54	1.43	2.98	2.21	5.11
TOTAL REE	132.59	104.66	140.51	109.90	96.92	156.72	206.06
Eu/Eu*	0.83	0.88	0.60	0.89	0.80	0.94	0.52
(Ce/Yb)N	6.50	21.30	6.39	15.26	4.86	16.57	18.28
(Ce/Sm)N	2.98	3.86	3.43	4.05	2.55	3.16	3.75
(Sm/Yb)N	2.18	5.51	1.87	3.77	1.90	5.25	4.87

APPENDIX I - H: POST-TECTONIC GRANITES

Sample number	3831	3832	3833
ROCK TYPE	granite,ss	granite,ss	granite,ss
GEOLOGICAL UNIT	Moolyella Granite	Moolyella Granite	Coondina Granite
REFERENCE	Jahn et al 1981	Jahn et al 1981	Jahn et al 1981
SiO_2	75.44	73.28	73.66
TiO_2	0.06	0.07	0.23
Al_2O_3	13.54	14.00	13.60
Fe_2O_3	0.16	0.41	0.65
FeO	0.66	0.73	1.04
MnO	0.05	0.06	0.04
MgO	0.10	0.09	0.32
CaO	0.52	0.78	1.25
Na_2O	4.05	4.41	3.96
K_2O	4.28	4.54	4.91
P_2O_5	0.01		0.06
H_2O+	0.72	0.57	0.95
H_2O-			
CO_2			
TOTAL	99.59	98.94	100.67
Cs			
Rb	700.00	530.00	200.00
Ba			
Nb	42.00	28.00	20.00
La	14.90	27.50	55.10
Ce	36.80	59.20	111.40
Pr			
Nd	14.00	23.20	41.90
Sm	3.77	5.62	7.85
Eu	0.16	0.25	0.58
Gd	4.07	5.20	6.62
Tb			
Dy	4.75	5.63	6.97
Ho			
Er	3.09	3.33	3.69
Tm			
Yb	3.11	3.40	3.64
Lu	0.46	0.50	0.55
Y			
Sr	25.00	40.00	70.00
Mg´ NUMBER	20.7	14.7	29.2
Na2O/K2O	0.95	0.97	0.81
TOTAL REE	85.11	133.83	238.30
Eu/Eu*	0.12	0.14	0.24
(Ce/Yb)N	3.01	4.43	7.78
(Ce/Sm)N	2.29	2.47	3.33
(Sm/Yb)N	1.31	1.79	2.34

Appendix I - I : Ni, Cr, Zr, Pb, Th and U values

		UNSB				DUFFER Fm								WYMAN Fm		
		3806	3807	3808	3809	3810	3811	3812	3813	3814	3815	3816	3817	3821	3822	3823
Ni	ppm		24			32	79	9	6	3	25	21	36	5	2	7
Cr	ppm	5	67	7	11	18	129	15	8	10	35	38	38	3		18
Zr	ppm	223	117	201	229	164	304	158	350	174	186	189	168	101	139	177
Pb	ppm	12	12	8	14	6	5	8	6		11	15	15	5	7	5
Th	ppm	17	17	7	19	8	9	8	15	8	11	13	9	25	11	6
U	ppm	2	2	nd.	2	1	2	1	3		3	3	2	4	2	2

		Mons Cupri Volcanics					Mount Brown Rhyolite		Gneisses Mount Edgar batholith			
		70060	70061	70065	70066	70071	69997	69998	8324	3825	3826	3827
Ni	ppm	105	5	4	5	7	9	27	50	5	3	9
Cr	ppm		5		3				104	8	9	12
Zr	ppm	209	266	282	312	253	220	230	146	208	146	136
Pb	ppm	6	8	16	6	13	26	31	7	8	13	18
Th	ppm	8	15	14	18	14	21	22	8	9	14	8
U	ppm	2	3	3	4	2	5	5		1	2	2

Appendix II - CIPW norms and petrochemical ratios

	Upper North Star Basalt				Duffer Formation								Panorama Formation		
	Na-dacite	andesite	Na-dacite	andesite	dacite	andesite	dacite	rhyolite	K-rhyolite	K-dacite	dacite	dacite	silicified basalt	silicified basalt	silicified basalt
	3806	3807	3808	3809	3810	3811	3812	3813	3814	3815	3816	3817	3818	3819	3820
Qz	16.59	17.48	17.54	17.96	17.24	18.89	23.06	50.16	32.30	29.46	20.72	6.73	37.45	13.71	26.20
Ab	55.68	30.50	53.93	25.01	40.52	29.17	25.48	24.47	1.83	11.91	32.57	61.91	37.37	44.44	49.02
An	13.05	26.63	15.16	31.96	11.46	22.56	15.94	0.23	0	0	0	0.32	4.65	19.26	5.30
Or	5.69	7.26	5.56	4.19	10.95	4.96	18.95	12.68	59.35	36.61	23.05	8.47	11.86	13.11	5.93
Di	2.50	0.65	0.60	0.57	0	0	0	0	0	0	0	0	0	0	0
Hy	2.75	12.37	3.57	13.46	12.67	16.14	9.23	3.15	1.92	9.01	9.99	12.57	2.28	4.35	6.54
C	0	0	0	0	2.49	0.66	2.77	4.48	0.73	6.75	7.27	5.37	3.11	1.46	3.10
Mt	0.95	2.05	0.98	2.62	2.0	2.2	1.61	0.72	0	1.31	1.36	1.73	0.29	0.44	0.58
Il	0.91	1.37	0.93	2.48	1.37	1.63	1.21	0.59	0.30	1.03	1.11	1.10	1.11	1.99	1.22
Ap	0.31	0.29	0.33	0.84	0.29	0.53	0.32	0.10	0.22	0.41	0.37	0.32	0.05	0.1	0.10
Ca	0.30	0.42	0.11	0.09	0.07	2.16	0.44	3.19	3.39	4.09	4.1	0.82	1.67	0.89	1.78
Py	1.04	0.77	1.06	0.59	0.69	0.86	0.81	0.14	0.05	0.09	0.23	0.54	0.11	0.14	0.13
SI.Index[1]	0.91	0.94	0.96	0.94	1.15	0.88	1.13	1.11	0.84	1.29	1.31	1.28	1.11	1.02	1.08
Diff.Index[2]	77.9	55.2	77.0	47.2	68.7	53.0	67.5	87.3	93.5	78.0	76.33	77.1	86.7	71.33	81.1
Solid.Index[3]	7.5	18.9	7.0	17.2	17.0	26.0	14.5	4.8	6.9	13.0	16.1	20.5	7.2	12.1	14.6
Crystal Index[4]	15.5	31.4	16.7	36.4	17.5	29.8	20.9	2.5	2.1	6.9	8.7	10.3	7.9	22.7	10.2
Plg (An)	19	47	22	56	22	44	38	0.9	0	0	0	0.5	11.1	30.2	9.7
K_2O/Na_2O	0.15	0.34	0.15	0.24	0.39	0.24	1.06	0.74	46.5	4.4	1.0	0.2	0.45	0.42	0.17

1 - Al/Ca+Na+K
2 - Qz+Or+Ab+Ne+Le+Ka
3 - 100 MgO/(MgO+FeO+Fe_2O_3+Na_2O+K_2O)
4 - Di'+Fo'+Sp'+An (Hutchinson, 1974, p.396)

	Wyman Formation			Mons Cupri Volcanics					Mt Brown Rhyolite	
	K-rhyolite 3821	K-rhyolite 3822	K-rhyolite 3823	rhyodacite 70060	K-rhyolite 70061	K-rhyolite 70065	K-rhyolite 70066	N-dacite 70071	K-rhyolite 69997	K-rhyolite 69998
Qz	54.42	53.69	30.36	25.40	31.68	32.16	37.72	34.12	40.70	42.82
Ab	0	0.95	1.20	23.72	31.80	34.86	22.26	34.00	35.87	31.57
An	0	0.02	0	16.51	0.73	2.26	1.07	0.04	0.87	0
Or	36.56	39.76	65.90	13.30	27.0	19.45	29.30	12.54	15.49	19.67
Di	0	0	0	0	0	0	0	0	0	0
Hy	2.2	0.91	0.30	15.65	2.83	4.16	3.94	6.65	0.90	1.20
C	5.82	3.90	0.93	0	1.44	1.15	0.94	3.01	1.52	2.16
Mt	0.32	0.12	0	2.61	1.05	2.83	1.73	1.35	0.86	0.73
Il	0.15	0.21	0.26	1.38	1.15	1.07	1.0	1.10	0.84	0.84
Ap	0	0.05	0.17	0.19	0.36	0.33	0.31	0.36	0.26	0.24
Ca	0.60	0	0.57	0	1.65	1.38	1.56	6.38	2.42	1.06
Py	0.02	0.02	0.05	0.50	0.25	0.27	0.1	0.30	0.22	0.13
SI.Index	1.76	1.51	1.04	0.97	0.95	0.95	0.92	0.76	0.91	1.17
Diff.Index	90.9	94.4	97.4	62.4	90.5	86.47	89.3	80.7	92.1	94.06
Solid.Index	5.7	4.7	1.0	24.7	5.7	4.59	5.4	7.2	2.6	1.60
Crystal.Index	4.0	4.6	1.1	23.5	2.8	3.76	2.6	2.6	2.3	1.01
Plg(An)	0	1.9	0	41.0	2.2	6.1	4.6	0.12	2.4	0
K_2O/Na_2O		60.2	78.9	0.8	1.22	0.8	1.88	0.53	0.62	0.89

	Early gneisses							Post-tectonic granites		
	tonalite	trondhjemite	trondhjemite	trondhjemite	tonalite	tonalite	trondhjemite	granite	granite	granite
	3824	3825	3826	3827	3828	3829	3830	3831	3832	3833
Qz	26.28	31.32	30.06	23.54	22.59	17.77	6.57	34.23	28.54	28.74
Ab	34.15	45.15	42.50	38.25	37.97	40.46	62.03	34.65	37.92	33.58
An	19.61	12.04	10.75	12.06	21.43	14.28	0.32	2.54	3.93	4.84
Or	8.77	5.63	11.67	18.68	8.90	12.76	8.48	25.57	27.26	29.07
Di	1.94	0.75	0.46	0		5.98	0	0	0	0.81
Hy	5.20	3.31	2.94	3.94	4.03	1.72	12.96	1.19	1.05	1.25
C	0	0	0	0.94	0.43	0	5.38	1.34	0.42	0
Mt	1.62	0.86	0.77	0.83	2.63	2.45	1.74	0.23	0.60	0.94
Il	1.00	0.38	0.31	0.63	0.97	1.03	1.10	0.12	0.14	0.44
Ap	0.31	0.10	0.12	0.19	0.19	0.69	0.32	0.02	0	0.14
Ca	0.39	0.09	0.07	0.16	0	0	0.82	0	0	0
Py	0.54	0.28	0.25	0.63	0.67	1.79	0.21	0.05	0.07	0.13
SI.Index	0.91	0.97	0.97	1.04	1.01	0.81	1.28	1.11	1.03	0.96
Diff.Index	69.2	82.1	84.2	80.48	69.5	71.0	77.1	94.4	93.7	91.4
Solid.Index	4.4	3.9	2.7	6.9	9.9	12.6	20.5	1.1	0.9	3.0
Crystal.Index	20.7	12.8	11.3	13.9	23.7	21.5	10.2	3.1	4.2	5.7
Plg(An)	36.5	21.1	20.2	24.0	36.1	26.1	0.52	6.8	9.4	12.61
K_2O/Na_2O	0.37	0.18	0.39	0.70	0.34	0.45	0.20	1.06	1.03	1.24