

# GEOCHEMISTRY OF ARCHAEOAN METABASALTIC LAVAS, DIEMALS, WESTERN AUSTRALIA

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## ABSTRACT

The Archaeoan sequence of Diemals (Southern Cross Province of the Yilgarn Block) contains a variety of metabasalts ranging in composition from tholeiites to high-magnesian basalts. Thirty new analyses, covering both major and trace elements (as well as rare-earth-element (REE) analyses for two of the samples), are presented. Four distinctive rock groups can be recognized: (1) a low-TiO<sub>2</sub> tholeiitic group (8-10% MgO); (2) a low-MgO (6-8%) group characterized by ocelli textures; (3) a spinifex-textured high-TiO<sub>2</sub>, high-MgO (10-18% MgO) group, in which sprays of amphibole pseudomorph clinopyroxene; and (4) a low-TiO<sub>2</sub>, high-MgO (8-11%), spinifex-textured group. Apart from the ocelli-textured group, the metabasalts all display consistent chemical characteristics which allow the subdivisions to be made. Group 3 and 4 are texturally similar to rocks commonly referred to as komatiitic basalts, but their geochemistry prohibits derivation from komatiites. In particular, their low-Ti/Zr (<75) and light-REE enrichment are difficult to model by fractionation of olivine and/or clinopyroxene from a komatiitic liquid. Conversely, the low-TiO<sub>2</sub> tholeiites (group 1) could be the fractional crystallization products of komatiites. It is argued that those basalts displaying spinifex-type pyroxene textures (i.e. groups 3 and 4) represent close-to-primary melt compositions; the differences in MgO and TiO<sub>2</sub> contents being controlled by depth and amount of melting. A further characteristic of these two groups is their high SiO<sub>2</sub> contents and it is suggested that this is due to the presence of H<sub>2</sub>O during melting. Since the term 'komatiitic basalt' has a genetic connotation, its use should be restricted to those basalts whose geochemistry demonstrates the linkage to komatiite melts. In the case of the Diemals metabasalts, it is the tholeiites which best fit this criterion.

## INTRODUCTION

Detailed geochemical studies of Archaeoan metabasaltic lava sequences in the last decade (e.g. Hallberg, 1972; Hart and others, 1970; Nesbitt and Sun, 1976) have served to provide a comparative data base for genetic models of Archaeoan crustal evolution. Despite this work, there is still no clear picture of the genetic relationships between komatiites (i.e. sub-alkaline, volcanic rocks with >18% MgO), komatiitic basalts (i.e. sub-alkaline, 10-18% MgO basalts associated with komatiites), high-magnesian basalts (i.e. sub-alkaline, 10-18% MgO basalts) and tholeiites (in the sense of Hallberg, 1972).

The confusion over magmatic genetic links is compounded by the combined effects of the mineralogical, chemical and textural overprinting suffered by Archaeoan sequences. This overprinting varies from place to place both in its intensity and nature, with some areas retaining much of the texture and mineralogy of the original rocks whilst others have been completely recrystallized and chemically altered.

Despite these problems, several models have been generated which seek to explain the genesis and

genetic linkage of the komatiite-basalt spectrum. These models are commonly based on field, petrographic and geochemical data obtained from well-documented, well-preserved areas and in particular the Munro Township area, which has tended to dominate current thinking (e.g. Pike and others, 1973; Arndt and others, 1977). The basic model developed from work at Munro is one in which high-magnesian liquids (about 28-30% MgO) fractionate through olivine loss, to high-magnesian basaltic rocks (komatiitic basalts). In this model, the associated tholeiites are either totally unrelated or represent initial melts removed from the ultimate source of the komatiites (e.g. Naldrett and Turner, 1973). In an alternate model, Sun and Nesbitt (1978a) suggested that komatiitic basalt, (particularly those with pyroxene spinifex texture) are primary melts and are not the products of komatiite fractionation. A possible corollary of this model, which was not stated by Sun and Nesbitt (1978a), is that there is a relationship between komatiites *s.s.* and tholeiites, in that the latter are the fractional crystallization products of the former. This model has also been proposed by Francis and Hynes (1979) for the Proterozoic basaltic sequence of Ungava, and in this paper we present data which supports this genetic linkage.

For the purpose of field description, we will use the term high-magnesian basalt for those rocks having MgO between 8 and 18%. Within this group, we arbitrarily refer to those basalts with pyroxene spinifex texture as komatiitic basalts. Such basaltic types are common in parts of the Australian Archaean, e.g. the upper hanging-wall basalts at Kambalda (Ross and Hopkins, 1975), the Negri Volcanics in the Pilbara (Sun and Nesbitt, 1978a) and parts of the Mount Monger sequence (Williams, 1972). Tholeiitic metabasalts in this area commonly have 6-9% MgO and have typical basaltic textures, characterized particularly by the presence of plagioclase laths. They always lack pyroxene spinifex texture and tend to be higher in  $Al_2O_3$  than the high-magnesian basalts.

## FIELD AND PETROLOGICAL RELATIONSHIPS

In this study, we have investigated a series of basaltic rock-types from a well-established stratigraphic section at Diemals. The area is about 200 km by road, north of Southern Cross and occurs within the Southern Cross Province (Gee and others, 1981) of the Yilgarn Block. Structurally the area is dominated by an open south-plunging antiform, the Diemals antiform (Fig. 1) which folds a volcanic succession of basalts, overlain by banded iron-formation, fine-grained metasediments and silicic volcanics. These lithologies have been metamorphosed to greenschist-low amphibolite facies of regional metamorphism. This metamorphism was of a static style and hence there is good preservation of original textures. At Diemals, the massive komatiitic metabasalts form a volcanic pile up to 1.1 km thick (best seen west of the Diemals air-strip) and are characterized by flows with pyroxene spinifex-textured flow tops which grade down into massive cumulate zones. We shall refer to these as Group 3 basalts. In parts, these basalts develop spherical ocelli (Group 2 basalts), which elsewhere (e.g. Gelinas and others, 1976) have been attributed to liquid immiscibility. Medium-grained metabasalts of tholeiitic type conformably overlie the komatiite basalts and these have a thickness of 2.2 km in the core of the antiform (Group 1). On the west limb of the antiform and apparently overlying the tholeiitic sequence is a sequence of komatiitic basalts which we informally refer to as 'west limb basalts' (Group 4).

Large sills and dykes of medium- to coarse-grained metadolerites and gabbros intrude the various lithologies of the succession. These have not been studied in this investigation.

Petrographically, Group 1 basalts (samples 63654-63659) are characterized by their even-grained nature. Typically they consist either of randomly

oriented fine-grained sheaves of tremolite-actinolite interspersed with plagioclase laths (e.g. 63654) or a slightly coarser grained (up to 0.7 mm) rock with well-developed basaltic texture (e.g. 63655, 63656). In this second category plagioclase reaches 40-45%. Both textural types have small amygdales, infilled with epidote and chlorite. Sample 63652 is fine-grained (grain size is about 0.1 mm) and in thin section displays fine-scale layering. We interpret this material to be tuffaceous. Mineralogy of this specimen is difficult to positively identify, but tremolite-actinolite and epidote are certainly present.

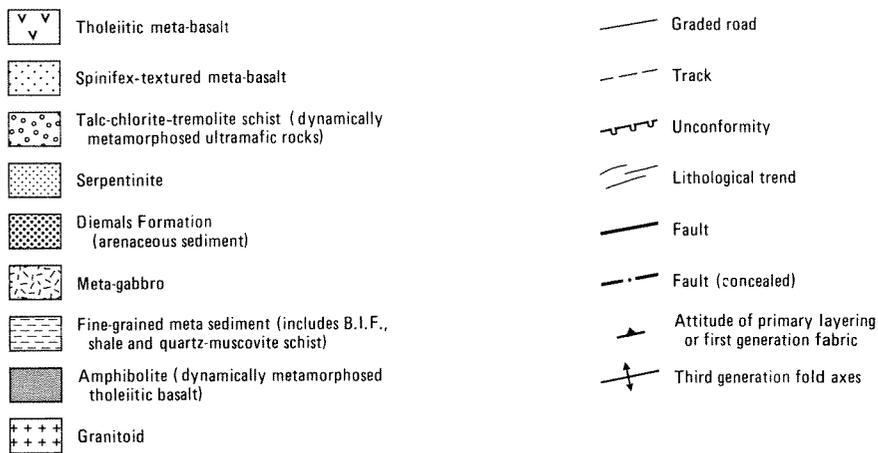
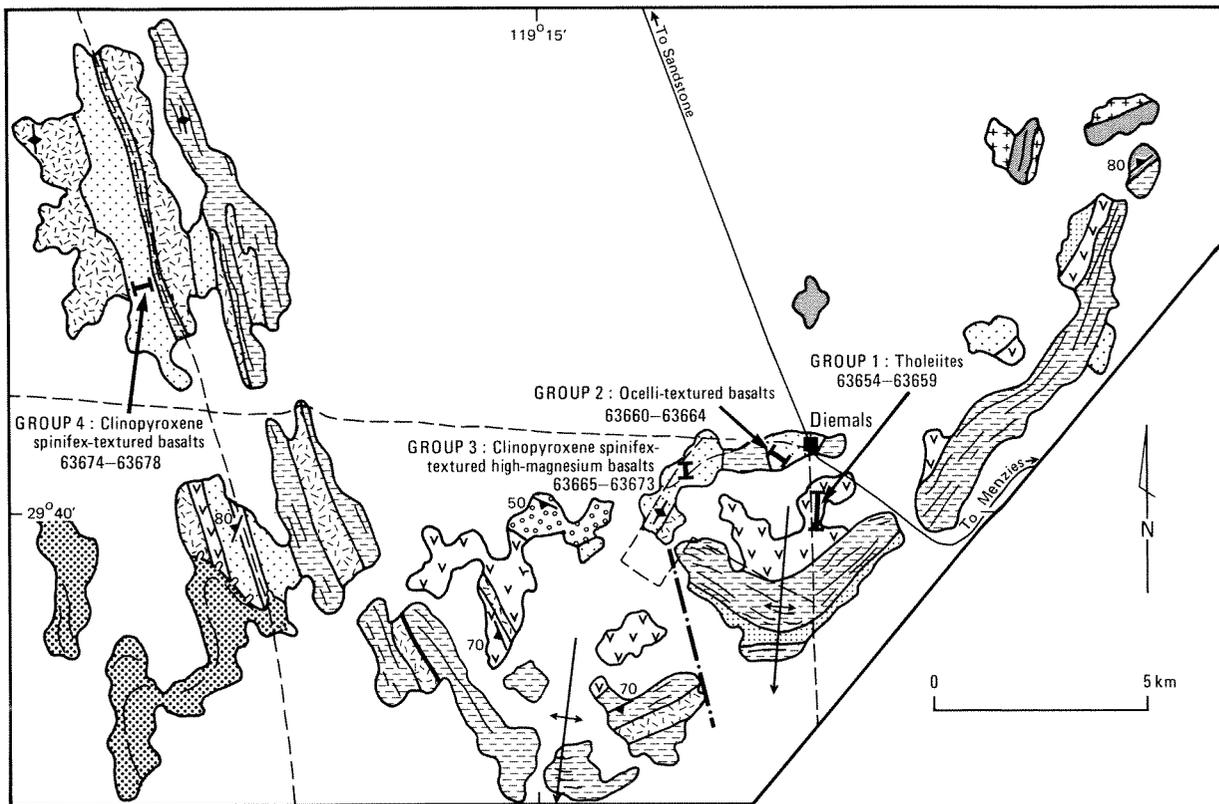
Group 2 basalts (63660-63664) consist of a group of ocelli-textured basalts which present a sampling problem as far as geochemistry is concerned. Sample 63660 has obvious spherical ocelli about 2 mm in diameter, consisting of a micrographic intergrowth of tremolite-actinolite and clear plagioclase. The matrix of the rock is made up of a fine-grained (about 0.3 mm) mass of tremolite-actinolite sheaves with minor plagioclase. The remaining 4 samples have less conspicuous ocelli and are characterized by skeletal plagioclase laths and needles, sometimes occurring in radial form. In these rocks (65661-64) the amphibole (tremolite-actinolite) occurs in stubby form (after clinopyroxene).

The dominant texture in the nine samples of the Group 3 basalts is one of random needles to stubby crystals of tremolite-actinolite set in a matrix of the same material plus clear plagioclase. In some samples, spectacular amphibole (after clinopyroxene) sprays are developed and we refer to these as 'clinopyroxene spinifex texture'. Commonly, the grain size of the sprays shows a progressive decrease of polarity, reminiscent of the spinifex texture (Nesbitt, 1971) found at the tops of komatiite flows. It is this pyroxene texture which is often taken to be diagnostic of komatiitic basalts.

Group 4 (63674-63678) basalts come from the western limb of the Diemals antiform. Some of the samples (particularly 63675 and 63676) have an impressive development of the spinifex or radiating pyroxene (now amphibole) texture, seen in the Group 3 basalts. Plagioclase is always present and is of variable abundance (20-40%). Sample 63678 is coarser grained, with the amphibole being of a stubby nature. We interpret this rock type as being a cumulate.

## GEOCHEMISTRY

Twenty-eight rocks have been analyzed for this investigation. All, with the exception of 59546 came from the Diemals area; and in Table 1, they are listed as belonging to one of four groups. Sample 59546 is a komatiite with characteristic altered olivine plates from Mount Manning, some 45 km to



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Figure 1. Geological map of Diemals area showing sample locations.

the southeast of Diemals and was analyzed for comparative purposes (Table 1). Because of textural changes across this specimen, three separate slabs were cut off and analyzed (a, b, c). As Table 1 indicates, the textural change (largely changes in morphology of olivine) is not strongly reflected in the geochemistry.

#### MAGNESIUM-TITANIUM

The trends for these two elements are well established for komatiitic and tholeiitic rocks

(Nesbitt and Sun, 1976). MgO concentration reflects the dominance of olivine (clinopyroxene) and can be envisaged as a fractionation and/or partial-melt indicator. TiO<sub>2</sub> reflects the general behaviour of those elements commonly referred to as 'incompatible'. Figures 2A and B illustrate the behaviour of these elements for those basalts analyzed by Hallberg (1972) and for those from Diemals (A and B respectively). Figure 2A illustrates the spread in the Hallberg data, with specific localities clustering in different parts of the diagram. There is little doubt that these basalts

TABLE 1. GEOCHEMICAL DATA FOR DIEMALS BASALT AND MOUNT MANNING SPINIFEX-TEXTURED KOMATIITE

	Mt Manning Komatiite			Group 1 Tholeiites						Group 2 Ocelli-textured basalts				
	59546A	59546B	59546C	63654	63655	63656	63657	63658	63659	63660	63661	63662	63663	63664
SiO <sub>2</sub>	50.93	50.93	50.72	52.09	52.75	53.66	52.66	53.00	53.22	56.94	54.45	53.05	54.26	53.60
Al <sub>2</sub> O <sub>3</sub>	9.88	9.60	10.26	13.75	13.52	13.35	11.36	14.46	13.35	9.22	13.41	12.61	12.87	11.93
Fe <sub>2</sub> O <sub>3</sub>	11.20	11.61	10.89	10.87	10.85	10.35	12.78	10.79	13.06	12.18	12.03	12.66	11.57	12.73
MnO	0.17	0.19	0.16	0.17	0.17	0.18	0.22	0.19	0.17	0.22	0.20	0.18	0.19	0.22
MgO	17.53	18.07	16.98	9.22	8.96	8.74	10.03	8.02	6.50	6.45	6.28	8.12	6.58	6.02
CaO	7.49	6.90	7.86	9.85	9.85	9.96	9.90	10.51	8.89	12.76	8.48	8.35	9.77	10.85
Ma <sub>2</sub> O	2.09	2.01	2.16	3.36	3.20	3.37	0.68	2.20	3.34	1.05	4.03	3.78	3.71	3.74
K <sub>2</sub> O	0.16	0.15	0.14	0.12	0.08	0.08	0.90	0.39	0.09	0.11	0.13	0.12	0.14	0.15
TiO <sub>2</sub>	0.40	0.37	0.41	0.62	0.64	0.60	1.31	0.64	1.19	1.09	1.04	1.20	1.08	0.97
P <sub>2</sub> O <sub>5</sub>	0.06	0.07	0.05	0.10	0.09	0.08	0.13	0.09	0.12	0.12	0.13	0.13	0.13	0.11
Total	99.91	99.90	99.63	100.15	100.11	100.37	99.97	100.29	99.93	100.14	100.18	100.20	100.30	100.32
Loss	1.68	1.99	1.72	1.86	2.05	1.75	2.76	1.62	1.95	0.95	1.59	1.85	1.25	0.58
Zr	24	n.d.	n.d.	40	43	40	83	43	78	84	80	89	81	77
Nb	1	n.d.	n.d.	1	2	3	4	1	4	4	4	6	4	5
Rb	4	4	4	2	1	2	17	9	2	2	2	2	2	2
Sr	145	130	133	85	35	34	66	175	42	106	51	55	58	59
Y	11	11	12	18	18	17	22	19	24	38	38	28	30	24
Ba	70	96	35	48	33	36	543	149	15	29	45	65	61	60
Sc	36	35	39	48	44	42	38	46	41	42	37	46	39	39
Ni	419	485	436	108	134	135	159	114	92	85	95	142	98	61
Cr	1852	1826	1787	494	598	549	479	340	169	120	95	206	114	285
V	199	192	206	266	244	234	304	257	303	276	279	313	276	271

	Group 3 Clinopyroxene spinifex-textured high-magnesian basalts											Group 4 Clinopyroxene spinifex-textured basalts				
	63665	63666A	63666B	63666C	63667	63668	63669	63670	63671	63672	63673	63674	63675	63676	63677	63678
SiO <sub>2</sub>	52.94	50.53	52.66	51.95	53.10	53.18	53.28	52.58	51.67	51.29	49.40	49.22	54.24	52.83	52.09	53.95
Al <sub>2</sub> O <sub>3</sub>	8.84	9.14	8.81	8.48	8.44	9.00	9.06	8.80	8.93	7.91	7.60	12.93	11.95	13.32	13.07	11.97
Fe <sub>2</sub> O <sub>3</sub>	12.80	14.09	12.85	13.33	12.76	12.51	12.64	12.95	13.24	12.07	13.12	13.48	11.16	10.70	11.01	11.89
MnO	0.20	0.22	0.20	0.19	0.21	0.20	0.20	0.20	0.21	0.21	0.21	0.23	0.20	0.16	0.21	0.16
MgO	10.55	11.39	10.93	11.44	10.56	10.82	10.36	10.60	10.88	16.99	18.45	11.31	8.54	8.55	8.68	11.52
CaO	9.36	9.84	9.55	9.84	9.73	9.06	9.18	9.47	9.70	8.29	8.27	9.96	11.14	11.41	12.22	8.42
Na <sub>2</sub> O	3.96	3.66	3.83	3.68	3.89	4.07	4.13	3.95	3.90	2.25	1.55	1.53	1.64	1.89	1.44	1.05
K <sub>2</sub> O	0.12	0.19	0.14	0.14	0.10	0.19	0.11	0.13	0.18	0.06	0.05	0.18	0.22	0.15	0.13	0.10
TiO <sub>2</sub>	1.04	1.13	1.01	1.02	1.01	1.05	1.06	1.05	1.04	0.79	0.78	0.73	0.68	0.75	0.83	0.71
P <sub>2</sub> O <sub>5</sub>	0.11	0.12	1.10	0.10	0.11	0.10	0.11	0.11	0.10	0.12	0.11	0.10	0.11	0.10	0.10	0.09
Total	99.92	100.31	100.08	100.17	99.91	100.18	100.13	99.84	99.85	99.98	99.54	99.67	99.88	99.86	99.78	99.86
Loss	0.83	0.93	0.94	0.88	1.33	0.93	0.81	0.87	0.85	2.49	3.3	1.97	0.58	0.74	0.52	2.51
Zr	79	85	75	77	77	76	82	81	80	59	58	60	57	62	69	57
Nb	4	5	5	4	5	5	5	5	5	3	3	3	3	3	3	3
Rb	1	5	3	4	1	7	1	3	3	2	2	4	3	4	2	3
Sr	105	95	101	93	103	124	106	92	111	54	46	61	114	79	47	31
Y	21	23	21	21	20	19	22	21	20	14	17	20	19	20	21	19
Ba	136	46	282	147	346	32	200	109	525	13	41	40	86	48	19	19
Sc	41	42	39	40	38	39	42	40	41	32	31	42	41	43	46	40
Ni	190	264	224	203	183	202	184	201	204	794	780	177	133	110	107	188
Cr	1402	1721	1513	1391	1394	1451	1386	1312	1700	2929	2834	726	664	530	534	1019
V	267	297	263	274	260	281	275	271	270	215	217	282	267	285	306	276

NOTE: The three samples of Mount Manning komatiite (59546A-C) come from the same sample but cover different tectural types. Samples 63666A-C come from the same specimen and cover an increasing grain size of pyroxene needles. Samples analysed by XRF and conventional wet chemistry at the University of Adelaide; methods are described in Nesbitt and Stanley (1980).

represent evolved liquids (because of their low Mg/Mg + Fe ratios), and therefore, to some extent, the scatter can be ascribed to the removal of varying proportions of olivine, plagioclase, and pyroxene. It can, however, also be argued that the scatter also reflects the variation in the composition of their parental liquids. The two olivine-control lines shown on Figure 2A are taken from the data of Nesbitt and Sun (1976) and Nesbitt and others (1979), and bracket the range in compositions of komatiitic liquids. The two lines are constructed so as to cut the abscissa at 50% MgO. Also shown on Figure 2A is the field of mid-ocean ridge basalt glasses (Melson and others, 1977). This wide-spread field is largely produced by the removal of plagioclase and clinopyroxene from melts having about 10% MgO and 0.6% TiO<sub>2</sub>. It is worth noting at this point that many of the Archaean basalts of Hallberg (1972), including his grand average, lie on the MgO poor side of the MORB spectrum.

Turning now to the Diemals data (Fig. 2B), the data like those of Hallberg group into specific

localities. Group 3 (the pyroxene spinifex basalts) are notable in that they have a combination of high TiO<sub>2</sub> and MgO and fall outside the olivine control lines delineated by komatiitic liquids. It follows that they cannot be fractional crystallization products of the commonly occurring komatiites. This point is emphasized by the position of the Mount Manning pyroxene spinifex-textured komatiite (Fig. 2B).

The Group 1 basalts (=tholeiites) plot close to the "west limb basalts" (Group 4), and, on this diagram, are similar to the most primitive MORB glasses. Both groups of liquids could have evolved from komatiitic liquids since they lie within the projected olivine fractionation trends. Group 2 (the ocelli-textured basalts) appear to form an unusual trend which is not seen in any group of basalts. We prefer not to speculate on these ocelli-textured basalts at this stage. Clearly, an understanding of their geochemistry must entail a study of the ocelli which immediately poses a sampling problem.

Figure 2B highlights the position of two apparently anomalous specimens. The first (63657)

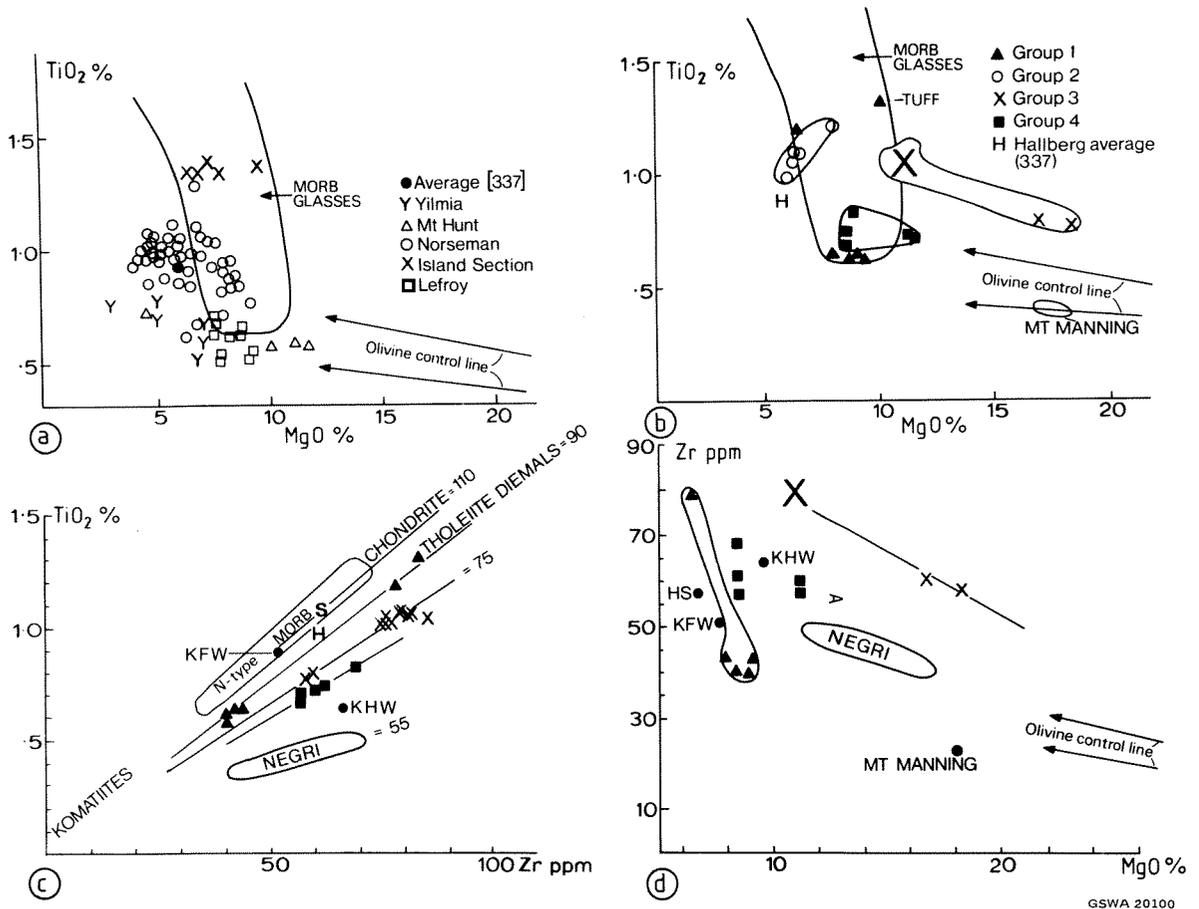


Figure 2. (a) TiO<sub>2</sub>—MgO plot of Hallberg's (1972) basalt data from the Kalgoorlie-Norseman belt. The field of mid-ocean ridge basalts is outlined. The olivine control lines bracket the known compositional range of komatiites (Nesbitt and others, 1979). (b) TiO<sub>2</sub>—MgO plot of Diemals' data. The large X symbol for group 3 basalts covers 9 sample points. (c) TiO<sub>2</sub>—Zr data; KFW=Kambalda footwall basalt, KHW=Kambalda Hanging Wall basalt, S=Scotia footwall basalt, H=average of Hallberg data (see Fig. 2a). The indicated values are for Ti/Zr ratios. (d) MgO—Zr data.

is the tuff of the Group 1 tholeiites and the second (63659) is an apparently fractionated tholeiite at the top of the tholeiite section (Group 1).

#### MAGNESIUM-ZIRCONIUM

In their original study of the behaviour of trace elements in Archaean high-magnesium liquids, Nesbitt and Sun (1976) pointed to the coherent chemistry of Ti and Zr. Despite extensive mineralogical alteration, it is a remarkable fact that the Ti/Zr ratio of the majority of komatiites *s.s.* is close to that of carbonaceous chondrites (110). Hence, we can predict that the general conclusions reached from the MgO-TiO<sub>2</sub> diagram would also hold for MgO-Zr. These data are presented in Figure 2D. Again the pyroxene spinifex-textured basalts (STB) of Group 3 outline a fractionation trend outside that of the common komatiite liquids. This supports the view (and our final conclusion) that these must be close to primary liquids in their own right. Group 1 basalts (tholeiites) form a fractionation group (with sample 63659) which is entirely predictable on the basis of plagioclase and clinopyroxene removal. The data do not exclude the possibility that these liquids originate from high-magnesium liquids of komatiite type (e.g. the Mount Manning liquids). Group 4 ('west limb basalts') have higher Zr contents than the tholeiites, and in this respect, their relative position in this diagram differs from that in the MgO-TiO<sub>2</sub> diagram. Such a position is compatible with fractionation from a komatiite liquid, provided clinopyroxene removal began at about 12-14% MgO. Alternatively, since the Ti/Zr ratio is low, this may indicate a liquid of Group 3 type (or Negri type), i.e. with an inherently low Ti/Zr ratio. The ocelli basalts of Group 2 (not plotted on Figs. 2C, D) fall close to sample 63659.

On Figure 2C, the positions of the Kambalda and Scotia footwall basalts, are plotted (Nesbitt, unpublished data). The data plot close to the tholeiite fractionation trend of Group 1 tholeiites. The position of the Kambalda hanging-wall basalt is also plotted on Figure 2C and indicates that it is of significantly different composition to the Kambalda footwall sequence (see also Sun and Nesbitt, 1978).

#### TITANIUM-ZIRCONIUM

Figure 2C is a plot of TiO<sub>2</sub>-Zr (ppm), but the ratios shown on the diagram are for Ti/Zr. This diagram illustrates the subtlety of Ti and Zr as discriminant elements. Group 1 basalts (tholeiites) all have ratios close to 90 whilst Group 4 basalts ('west limb') have the lowest ratio (72). It is interesting to note that the tholeiitic tuff (63657) fits the Ti-Zr pattern of the surrounding tholeiites, which

suggests that its aberrant position on Figure 28 is due to Mg metasomatism. The Ti/Zr ratio of 90 for the Group 1 basalts is consistent with a model of fractionation from a high-MgO liquid of komatiite type. If this is the case, then it is necessary to envisage some Ti loss due to clinopyroxene, since komatiites commonly have Ti/Zr ratios of 110.

The positions of Kambalda footwall- and hanging-wall basalts, as well as that of Scotia and the Hallberg average, are shown on Figure 2C. These data are consistent with what has been deduced from the MgO-Zr plot *viz* that the footwall basalts are of tholeiitic type, whilst the hanging-wall basalt has a low Ti/Zr ratio, which is characteristic of basalts of this type. Finally, Figure 2C shows the position of the Negri Volcanics, which have very well developed clinopyroxene spinifex texture. These basalts have very low Ti/Zr ratios (55), and their unusual chemistry is a characteristic of basalts of this type (e.g. Group 3).

The important aspect of Figure 2C is the way each set of basalt types conforms to a series of unique but different radiating lines. This suggests that we are dealing with a series of individual liquids whose parental liquids had differing compositions.

#### ZIRCONIUM-VANADIUM AND ZIRCONIUM-SCANDIUM

Figures 3A and 3B further illustrate the point previously made from the Ti-Zr diagram. Both Zr-V and Zr-Sc plots consist of a set of positive trends, converging on the origin. The V/Zr ratio varies from 6 (Group 1, tholeiites, Kambalda footwall basalt) through to 3.4 (Group 3, Kambalda hanging-wall basalt and Negri Volcanics). The behaviour of V is controlled primarily by pyroxene, and primary melts leaving the mantle reflect the partition of V into the liquid and residual pyroxene. Thus high V/Zr ratios signify in general, high degrees of mantle melting (komatiites are about 8). The same conclusions can be drawn from Sc/Zr ratios, since Sc is also held by the pyroxene structure and we can predict that high values for the ratio indicate little or no pyroxene left in the residue. It also follows (as for V) that pyroxene extraction during fractionation will lower the ratio. We interpret the positions of the two tholeiite samples (63657 and 63659), with ratios much lower than the other tholeiites, as a result of this factor. The Sc/Zr ratios for the Group 1 (tholeiites) basalts are the highest found in the Diemals area whilst Group 3 (clinopyroxene spinifex-basalts) have the lowest (0.5). The 'west limb' basalts (Group 4) have intermediate values and are similar to those found in the Negri volcanics. The Kambalda hanging-wall basalt is close to Group 3 basalts as would be predicted from its texture.

Sun and others (1979) have suggested that the relative behaviour of Zr and Y (in effect the Zr/Y ratio) give some indication of the slope of the heavy-rare-earth pattern (HREE). Figure 3C illustrates this point. The chondrite value of Zr/Y is about 2.5 (Nesbitt and Sun, 1976), and this is very close to the value obtained for the Group 1 tholeiites, which conforms to the value found in komatiites. As for Sc and V, Y is a good indicator of pyroxene involvement and this produces higher Zr/Y ratios in the two fractionated tholeiite samples from the Group 1 basalts. The high Zr/Y ratios (about 3.6) of the Group 3 basalts is not a function of fractionation, since they plot on a good array with a near constant ratio. Thus the basalts of this group with the highest MgO content (18%) have the same high ratio as those with 10% MgO. The logical interpretation of these data is that the source for the pyroxene spinifex-textured Group 3 basalts also had this ratio. We can therefore predict that they will show heavy REE depletion relative to the middle REE.

The consistent relationships between the Group 1 (tholeiite) basalts and the basalts from the footwall sequence of Kambalda and Scotia are again seen here. Similarly, the hanging-wall basalts at Kambalda plot with Group 3 basalts.

The  $\text{Al}_2\text{O}_3/\text{TiO}_2$  ratios (Fig. 3D) for the most common type of komatiite (not the Barberton-type) ranges from 20-24 (Nesbitt and others, 1979) and this value is close to the range found in carbonaceous chondrites. Similarly, the most primitive MORB have this ratio, as do the Group 1 tholeiites from Diemals. Sun and Nesbitt (1977) conclude that a close-to-chondrite value indicated that most of the  $\text{Al}_2\text{O}_3$  in the source of the melt had been released into the melt. They suggested that this was mainly controlled by the melting of pyroxene. We can conclude from this, that the Group 1 tholeiites, like komatiites, represent extensive melting of a mantle source (or alternatively, a re-melting of an already depleted source). Similar arguments can be advanced for the 'west limb' basalts (Group 4), as well as the Scotia and Kambalda basalts (both hanging and footwall). This is an interesting and perhaps important point, bearing in mind the suggestion that Group 4 basalts and the Kambalda hanging-wall basalts have HREE depletion. The data suggest that in these melts, Ti is decoupled from the middle REE and is in fact depleted. Thus, the low Ti/Zr ratios found in the Kambalda hanging-wall basalts and Group 4 basalts are due to Zr (= middle and light REE) enrichment.

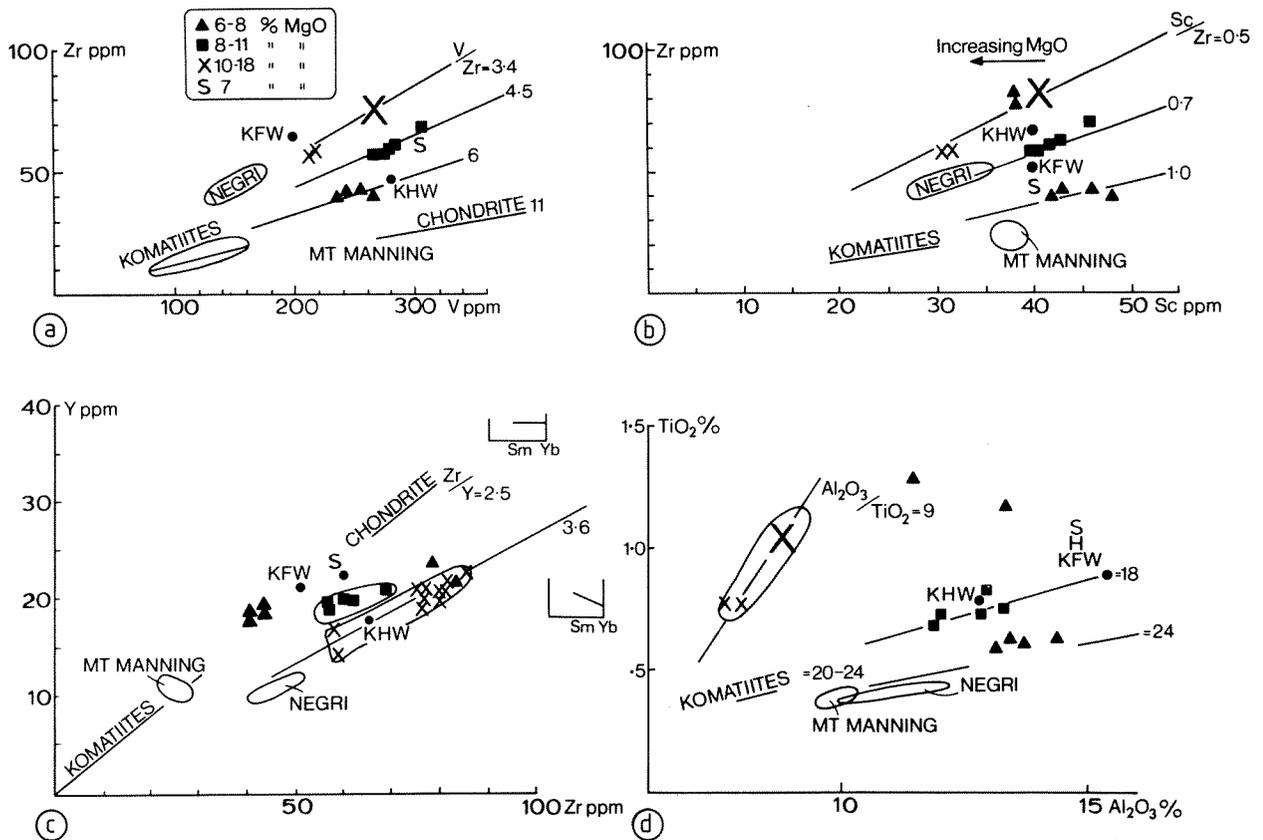


Figure 3. (a) Zr—V, (b) Zr—Sc, (c) Zr—Y, (d)  $\text{TiO}_2$ — $\text{Al}_2\text{O}_3$  plots for Diemals data. The pseudo-rare earth element plots in Figure 3c indicate the correlation between increasing Zr/Y ratio and HREE depletion. Symbols as for Figure 2. Chondrite values from Nesbitt & Sun (1980).

Uniquely, the Group 3 Diemals' basalts have low  $Al_2O_3/TiO_2$  ratios (about 9) even in the high MgO members. This suggests that the ratio is that of the parental melt and we suggest it is probably produced by the retention of  $Al_2O_3$  in the source. Such data constrain possible models of melt genesis and the most plausible is that the Group 3 basalts represent small amounts of melting of a mantle source (to limit the  $Al_2O_3$  entering the melt). However, in order to generate 18%-MgO-melts at small degrees of melting it would be necessary to produce the melt at higher pressure than say the tholeiites of Group 1.

#### CHROMIUM-TITANIUM

The use of Cr and Ti as discriminants (Fig. 4A) has been advocated by several authors, principally Pearce (1975), and Pearce and Flower (1977). If a plot of Cr/Ti vs Ti is used, liquid lines of descent are shown as negative, steeply sloping lines. The negative slope is developed because more primitive liquids have high Cr and low Ti and as fractionation proceeds Cr is rapidly stripped from the liquid, by spinel, clinopyroxene and olivine. Conversely Ti tends to increase in value in the liquid, because the crystal-liquid distribution coefficients for this element are less than one of the common silicate minerals.

In Figure 4A, the data are plotted as Cr/Ti vs Ti. It can be seen that each of the 3 groups of basalts from Diemals forms discrete domains, approximately parallel to one another. Also plotted on the diagram

are fractionation lines for plagioclase, olivine and clinopyroxene, with the latter mineral being most effective in removing Cr. The most important conclusion we can draw from this diagram is the fact that Group 1 basalts cannot be derived from Group 3 by any fractionation mechanism involving commonly occurring basaltic minerals. It would appear that Group 1 basalts evolved from a parental liquid having a much higher Cr/Ti ratio (like the Group 3 basalts) but lower Ti (unlike Group 3).

The absolute position of Group 3 basalts relative to Groups 1 and 2 is important. If we consider the three groups at a fixed value of Ti, it can be seen that the Cr/Ti ratio rises from Group 1 through to Group 3. This change also equates with an increase in MgO. One obvious model to account for the data is to produce the Group 3 liquids at higher pressure and by smaller degrees of melting.

#### RARE-EARTH-ELEMENTS

Figure 4B shows two rare-earth-elements (REE) patterns for the Diemals basalts. The two samples are 63655 (Group 1) and 63668 (Group 3). As we predicted from the trace element geochemistry, the two REE patterns are significantly different. The Group 1 basalt, has a flat, heavy-REE pattern, a slight positive Eu anomaly and a flat, light-REE pattern up to Nd. The increase in La and Ce relative to other REE may be due to an intrinsic magmatic process (probably a source characteristic) or may be

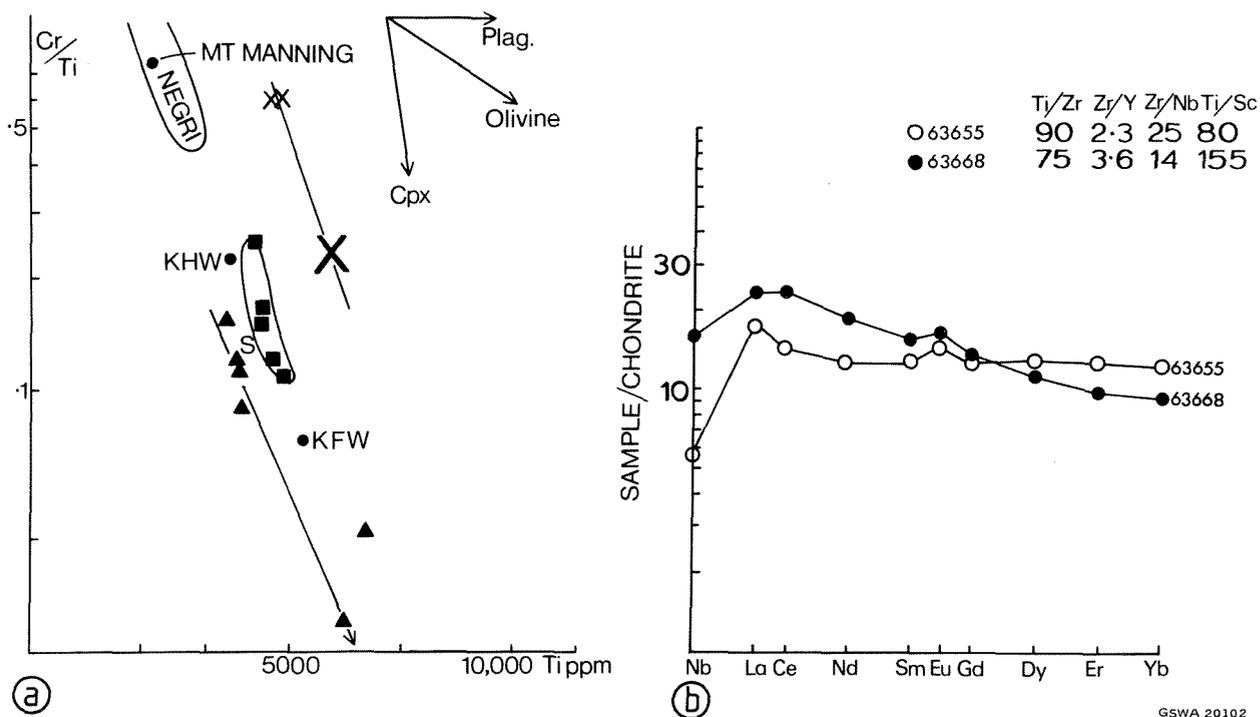


Figure 4. (a) Log Cr/Ti—log Ti plot; fractionation vectors are taken from Pearce & Flower (1977). Symbols as for Figure 2, large X = 9 data points for Group 3. (b) Rare earth element data for sample 63655 (Group 1) and 63668 (Group C) REE by isotope dilution, Nb by XRF.

a product of alteration. We would need to measure several other samples to make a decision on this problem. The pyroxene spinifex-textured Group 3 basalt (63668) shows significant heavy-REE depletion with (Yb/Gd) N = 0.68. This heavy-REE depletion is matched by a light-REE enrichment pattern, typical of such basalts (e.g. the Negri Basalts described by Sun and Nesbitt, 1978).

The difference in the two REE patterns is fundamental and cannot be related by a crystal fractionation process (see Sun and Nesbitt, 1978; and Arth and others, 1977 for further discussion). We conclude that the two patterns reflect different source characteristics.

## DISCUSSION

Using textural considerations, we can identify three types of basalt, *viz* tholeiitic (Group 1), pyroxene spinifex-textured basalts (Groups 3 and 4) and ocelli-textured pyroxene-rich basalts (Group 2). Geochemically, the Group 3 and 4 basalts become distinct both from each other and the tholeiites. Unfortunately, we can say little about the Group 2 ocelli-textured basalts because there appears to be little system in their geochemical characteristics. However, we can make some generalizations concerning the other three groups. Primarily, the data indicate that the so-called komatiitic basalts (i.e. those with sprays or long needles of clinopyroxene) cannot be related to the commonly occurring komatiitic *s.s.* rocks by any known crystal fractionation process. Indeed, the fractionation trends suggested by the geochemistry are those connecting the komatiites to the tholeiites. We do not know of any material (i.e. > 20% MgO) capable of being parental to the Group 3 (= pyroxene spinifex) basalts and we therefore believe they must be close to primary liquids. Such a conclusion has previously been reached by Sun and Nesbitt (1978), Arth and others (1977) and Arndt and Nesbitt (1982). Furthermore, there appears to be a wide diversity in the geochemistry of the pyroxene spinifex basalts (e.g. Groups 3 and 4).

The bulk of the chemical data indicate that the Group 3 basalts in particular have unusual chemical characteristics compared to the other groups. Notable is the high TiO<sub>2</sub> in rocks with high MgO as well as the rather low Al<sub>2</sub>O<sub>3</sub> contents. These characteristics (including the REE pattern) are best explained by producing a high-magnesian liquid at high pressures (say 300 MPa). In such a model, melting is not extensive and an aluminous phase (pyroxene ± garnet) remains in the residue, thus holding back Al<sub>2</sub>O<sub>3</sub> and the heavy-REE. The low percentage melting would also explain the high TiO<sub>2</sub>, Nb and possibly the light-REE enrichment.

The clinopyroxene texture, which is so characteristic of these rocks, is a major problem since liquids with 12-18% MgO, would be expected to precipitate copious olivine. However, both Group 3 and Group 4 basalts are notable in their relatively high (about 52%) SiO<sub>2</sub> contents, a factor which explains the lack of olivine. One possible explanation for the high SiO<sub>2</sub>/MgO ratio is to provide it by fractionation. If Group 3 and Group 4 basalts had a more magnesian parent (> 20% MgO) the precipitation and removal of olivine would automatically produce a trend of increasing SiO<sub>2</sub>. However, the light-REE enrichment, low Al<sub>2</sub>O<sub>3</sub>/TiO<sub>2</sub> and low Ti/Zr ratios preclude these basalts fractionating from common komatiitic liquids. This is not necessarily an argument against the model for one could postulate that the parental liquid was unable to reach the surface without losing olivine. However, if the parent liquid contained 45% SiO<sub>2</sub> (as for komatiites) then about 60% olivine extraction would be necessary to arrive at a liquid with 52% SiO<sub>2</sub>. This would require a starting liquid of about 30% MgO (close to that of komatiites) but (unlike komatiites) it would be unusually rich in TiO<sub>2</sub> (about 0.6%). Furthermore, it is probable that 60% olivine removal would lower the Ni content of the resultant liquid well below the 200 ppm found in the Group 3 clinopyroxene spinifex-textured basalts.

Taking the *mg* values (100 Mg/(Mg + Fe<sup>2+</sup>)) of these liquids into account, it is clear that some fractionation must be involved since their *mg* values are too low to be in equilibrium with pyrolite. On the other hand, Group 3 samples 63672-3, containing about 18% MgO are of obvious cumulative origin and must therefore represent maximum MgO parental compositions. We conclude that the parental liquid for the Group 3 lavas, contained about 16% MgO. The problem thus resolves into formulating a model which will explain a relatively high SiO<sub>2</sub> content with only limited olivine fractionation from an initial liquid of 16% MgO. One such model involves wet melting of pyrolite. Although there has been considerable debate (e.g. Green, 1973; Kushiro, 1974; Tatsumi and Ishizaka, 1981) over exactly how siliceous a melt can be produced by wet melting of pyrolite, there is equally a general consensus that siliceous melts do result. In the case of the Diemals' lavas with about 52% SiO<sub>2</sub>, these would easily fall below the most pessimistic view of possible silica enrichment by wet melting. We thus arrive at a possible model in which mantle melting in the presence of H<sub>2</sub>O (but not water saturated) produces a 16-18% Mg liquid, unusually rich in elements such as TiO<sub>2</sub>, but is low in alkalis. Fractionation of olivine (± clinopyroxene) drops the MgO content of the liquid to about 10-12% MgO at which time the liquids erupt.

Arndt and Fleet (1979) have suggested that the spectacular needle-shaped clinopyroxene crystals found at the flow tops of some Archaean flows (the so-called "string-beef" texture) indicate strong undercooling. Such an explanation is in accord with that proposed by Nesbitt (1971) for the spinifex-textured olivines found at the tops of komatiite flows. The presence of the 'string-beef' texture however, does seem to have a positive correlation with unusual chemistry, as previously outlined. It would therefore appear that the conditions necessary to produce liquids with low Ti/Zr, light REE enrichment, high SiO<sub>2</sub>/MgO ratios also naturally led to the production of clinopyroxenes with "quench" morphologies. It is this morphology which has led to their correlation with komatiites—a view which is refuted by the data from Diemals.

### CONCLUSIONS

Geological and geochemical data on the basaltic sequences at Diemals, Western Australia, led to the following conclusions:

- (1) The various stratigraphic levels have basaltic types which evolved from parents with differing compositions.
- (2) The succession at Diemals has very well developed high-magnesian basalts with distinctive clinopyroxene spinifex (or 'string-beef') texture. Because of this texture, the basalts are commonly referred to as komatiitic basalts, but geochemistry precludes any connection with common komatiitic liquids.
- (3) The high-magnesian basalts are characterized by their clinopyroxene morphology, by low Ti/Zr ratios (even with 18% MgO) and light-REE enrichment. We suggest that they evolved from a 16-18% MgO primary liquid by olivine, followed by clinopyroxene fractionation.
- (4) The clinopyroxene morphology of these basalts, is only developed near the margins of flows and resembles spinifex texture in that it displays progressive grain size changes with respect to the cooling surface. We are in agreement with Arndt and Fleet (1979) that this represents non-equilibrium cooling under conditions of undercooling.
- (5) The dominance of clinopyroxene in such high-magnesian liquids is caused by slightly enriched SiO<sub>2</sub> values. This may be a function of wet melting in the source region. However, the high TiO<sub>2</sub>, Zr, Nb, light-REE and high MgO, also suggest that low degrees of melting took place at pressures higher than those which generated the accompanying basaltic types.

- (6) Tholeiitic basalts, very similar in composition to those described by Hallberg (1972) are believed to represent the fractional crystallization products of komatiitic (i.e. > 18% MgO) liquids.
- (7) Since all of the various basalt types are temporally and spatially related, we assume that extensive melting occurred over a significant depth interval. Thus although the basalts are not genetically related in the petrologic sense, they are the products of the same tectono-thermal event.

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