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1. INTRODUCTION

Evidence for the existence of heterogeneous or 'marble cake' convecting mantle¹ is provided by rare, high MgO (~ 15 wt. %) primitive magmas with anomalously high abundances of FeO* (~13.5 to 16 wt. %^{2,3}) that occur in large igneous provinces (LIP; e.g. Deccan, Ethiopia and Paraná-Etendeka). Some have incompatible trace-element and radiogenic-isotopic ratios (Sr, Nd and Pb) that resemble those of ocean-island basalts (OIBs). This suggests that they are predominantly derived from the convecting mantle². The ferropicrites are mildly- to sub-alkaline and have low contents of Al_2O_3 (< 10 wt.%) and heavy rare-earth elements (e.g. Lu = < 0.18 ppm); this is consistent with the increased stability of garnet, due to the high FeO* content in the ferropicrite mantle source. It has been proposed that the source of the high FeO* may be garnet-pyroxenite streaks derived from subducted mafic oceanic crust².



We have undertaken a series of melting experiments on a ferropicrite from the Paraná-Etendeka continental flood basalt (CFB) province in NW Namibia (Fig. 1). 75 experiments have been performed over a wide range of temperatures (1000 to 1750°C) and pressures (1 atmosphere to 7 GPa) in order to constrain the anhydrous phase relations at conditions appropriate to those in upwelling mantle plumes. The main aim of the experiments was to establish the conditions of petrogenesis of the Paraná-Etendeka ferropicrites and to gain further insight into the composition of the Early Cretaceous Tristan plume starting-head.

2. EXPERIMENTS

2.1 Starting Material

Sample 97SB68 was collected from a ferropicrite flow at the base of the Paraná-Etendeka CFB succession in NW Namibia². It was used as the starting material because it has:

- A low loss-on-ignition value (0.43 wt. %)
- and is petrographically fresh (Fig. 2). • Petrology dominated by olivine phenocrysts (up to 30 modal %) with clinopyroxene. Plagioclase only occurs in the groundmass (Fig. 2).
- Olivine phenocrysts with relatively high NiO contents (Fig. 3), which, combined with relatively low Fo contents (Fig. 4), cannot be due to olivine fractionation.



- High bulk MgO (14.94 wt. %), FeO* (14.90 wt. %) and NiO (0.07 wt. %; Table 1).
- Further characteristics of the bulk-rock composition of 97SB68, such as a high [La/Nb]n ratio (1.4) and eNd value (2.2), suggest that the dominant contributing ferropicrite melt source region resided in the convecting mantle^{2}.
- $eO^* = Total Fe expressed as FeO$ $Mg# = Mg / (Mg + Fe^{2+})$ b MORB-like pyroxenite prepared from natural garnet and cpx + natural kyanite and quartz + synthetic TiO₂ (Pertermann & Hirschmann, 2003)
 c Silica-deficient garnet pyroxenite prepared from natural mineral and rock powders (Kogiso et al., 2003)
 d Coesite eclogite crysallised from average oceanic crust (Yaxley & Green, 1998)
 e MORB pyrolite (Yaxley and Green, 1998)
 f Mixture of 50% GA1 and 50% MPY90 (Yaxley & Green, 1998) [xture of 75% GA1 and 25% MPY90 (Yaxley 2000) Fertile Spinel Iherzolite, Kilborne Hole crater, New Mexico (Takahashi, 1986; Takahashi et al., 1993; Hirose & Kushiro, 1993)
 Fertile garnet Ihezolite, West Kettle River, British Columbia (Walter, 1998)
 pinel Iherzolite, Salt Lake Crater, Hawaii (Takahashi & Kushiro, 1983)
 arnet Iherzolite, Thaba Putsoa kimberlite (Kushiro, 1996)
- Olivine phenocrysts that are more Fe-rich than those from worldwide picrites (Fo85)². On Figure 4, MgO and FeO* contents of 97SB68 (star symbol) and other are Paraná-Etendeka ferropicrites (closed symbols) are compared to those of melts of fertile peridotites KLB-1⁵, and PHN-1611¹⁶, olivine websterite HK66^{6,8}, quartz eclogite G2⁹ and silica-undersaturated garnet pyroxenite MIX1G¹¹. Also shown are other Paraná-Etendeka ferropicrites (closed circles), as well as the melt composition of a mixture of a 50:50 basalt / peridotite starting material $(GA1_{50}MPY90_{50}^{12,13}; open circle).$
- Using a K_d of 0.32^4 , the olivine is in equilibrium with the bulkrock Mg# of 65 (where Mg# = Mg/(Mg + Fe^{$^{2+}$}); Table 1), and suggests that the bulk-rock composition of the ferropicrite has not undergone significant modification by olivine fractionation or accumulation since melt generation.



We therefore believe that the composition of 97SB68 is representative of a primary mantle plume derived melt and an appropriate starting material for our experimental study.

2.2 Experimental and Analytical Procedures

- All experiments were performed in the Experimental Petrology Laboratory (Magma Factory), at Tokyo Institute of Technology⁵. Melting phase relations as well as compositions and modal proportions of all coexisting phases were successfully determined in 60 of the run products.
- 1 atmosphere experiments used a quenching furnace, with oxygen fugacity controlled at the QFM buffer. • Experiments ranging between 1.1 and 3 GPa were conducted using (i) a non-end-loaded ET-type and (ii) an end-loaded Boyd-England-type piston-cylinder apparatus. All experiments used the ¹/₂-inch, talc Pyrex assembly⁶.
 5 - 7 GPa experiments were undertaken in an SPI 1000 multi-anvil apparatus. A MgO/Al₂O₃ (99:1 wt.%) octahedron with 18 mm edge length

The Role of Garnet Pyroxenite in High-Fe Mantle Melt Generation: High Pressure Melting Experiments

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3. RESULTS

Phase relations of ferropicrite 97SB68 are shown on Figure 5. Data points are from experiments using: (i) 1 atmosphere furnace (diamond symbols), (ii) K2-Type piston cylinder apparatus (circles), (iii) Boyd-England Type piston cylinder apparatus (triangles), (iv) SPI-1000 multi-anvil apparatus (squares). The liquidus phase is olivine up to ~ 2.2 GPa, which is replaced by pyroxene and then garnet at 5 GPa. At 3 GPa, the subsolidus assemblage is pyroxene, garnet and olivine. A marked inflection is seen in the solidus, just below 3 GPa. Although pyroxene is succeeded by garnet as the liquidus phase around 5 GPa, the positions of both liquidii are extremely close and a cotectic-like behaviour is observed.



The phase relations of 97SB68 indicate that ferropicrite primary melt separation occurred at either: (i) ~ 2.2 GPa at the olivine-pyroxene liquidus co-saturation point, with an olivine and pyroxene residue but with garnet absent; or (ii) ~ 5 GPa at the garnet-pyroxene liquidus co-saturation point, with a garnet and pyroxene residue, but with olivine totally consumed in the melt.



4. PERIDOTITE VS. PYROXENITE AS THE PRIMARY FERROPICRITE SOURCE

On Figure 7 the bulk-rock composition of 97SB68 is compared to those of experimental melts of peridotite (a; KLB-1, PHN1611 and KR4003) and pyroxenites (b; Hk66, MIX1G, G2 and GA1/MPY90). We use a projection from diopside onto the pseudo-ternary system Mg₂SiO₄ (Fo) $CaAl_2Si_2O_6$ (CaTs) SiO₂ (Qz)^{7,11}. The En - CaTs join represents a thermal divide between silica-saturated and silica-undersaturated compositions. Samples plotting to the left of the Fo-An join are Ne normative, those to the right of the En-An join are Qz normative and those in between are Hy normative. It can be seen that: • The Paraná-Etendeka ferropicrites are distributed across the Enstatite-Ca-Tshermak thermal divide⁷, although most ferropicrites (including

- 97SB68) plot in the silica-poor region.



(a) Peridotites: KLB-1 partial melts^{5,14} are plotted as trends with pressure values indicated in bold. KR4003 melts¹⁵ (unfilled fields) and PHN-1611 melts¹⁶ (hatched fields) are separated into pressure intervals. Peridotite partial melts at low pressure are silica-saturated; those at ~ 3 GPa are close to 97SB68 in the silica-undersaturated region of the projection. As stated above, we propose that the primary ferropicrite melts separated from their mantle source region at 5 GPa rather than 2.2 GPa. The cotectic-like behaviour of garnet and pyroxene may indicate that the co-saturation point at ~ 5 GPa is a minimum depth of melt separation. This requires: (i) total consumption of residual olivine during mantle melting and implies that the original source was less olivine normative than the liquidus co-saturation melt composition at 5 GPa¹⁷; and (ii) the source composition to be less olivine-normative than the first melt composition produced. Both of these factors are inconsistent with a peridotite mantle source. Although peridotite melts do plot close to 97SB68, the pressures at which they were produced are not consistent with the phase relations of 97SB68. Peridotite melts that are closest in composition to 97SB68 were formed at 3 to 3.5 GPa but the 97SB68 phase relations within this pressure interval indicate a melt in equilibrium with pyroxene only.

(b) **Pyroxenites:**

increase in MgO with pressure and melts at 5 GPa plot close to the ferropicrite. The starting compositions of Eclogite / Peridotite (GA1 / MPY90^{12,13}) mixtures and sandwich experiments at 3.5 GPa are illustrated as a trend line with the percentage of GA1 shown in bold. It must be noted that this is not a mixing line, since the En-CaTs join represents a thermal divide. It is likely that at > 3.5 GPa the picritic partial melt of $GA1_{50}^{\circ}MPY90_{50}$ will become more olivine normative and, therefore, move further away from the composition of 97SB68. At 3.5 GPa, a partial melt of GA1₇₅MPY90₂₅ would lie very close to the CaTs-En divide, just in the silica-undersaturated field. At 5 GPa, however, the partial melt composition would be more olivine normative and may be closer in composition to 97SB68.

Figure 6 shows a comparison of 97SB68 and other Paraná-Etendeka ferropicrites^{2,19} with picrites from Disko Island and Nuussuaq²⁰, East Greenland²¹, Hawaii²², the Skye Main Lava Series²³ and Siberia²⁴. Also shown are aluminium depleted and aluminium undepleted komatiites. It is apparent the low Al_2O_3 (9 wt.%; Table 1) and fractionated HREEs (e.g. $[Gd/Yb]n = 3.1^2$) indicate that garnet was a residual phase at the time of melt separation. We therefore propose that the primary melts separated from their mantle source region at 5 GPa rather than 2.2 GPa.

• 97SB68 is among the most Fo normative of the Paraná-Etendeka ferropicrites and plots close to the field of 3 GPa peridotite melts.

Òlivine Websterite (HK66^{6,8}) partial melts at ~ 3 to 3.5 GPa (stippled fields with pressure in GPa indicated) are silica-undersaturated and most are slightly more Fo-normative than 97SB68. HK66 melts become silica-saturated at pressures < 1.5 GPa.

Both Quartz Eclogite (G2⁹) partial melts (unfilled field) and the starting material are silicasaturated at 2 to 3 GPa and are separated from 97SB68 by the CaTs-En thermal divide. G2 partial melts at higher pressures may become more MgO-rich but the nature of the starting G2 material is likely to still produce melts that are less olivine-normative than 97SB68. Partial melts of Silica-Undersaturated Garnet Pyroxenite (MIX1G^{10,11}; hatched field)

5. COMPARISON WITH PYROXENITES

Peridotite melts ~ 5 GPa are different in composition to 97SB68 and it is unlikely that peridotite was the sole source of the ferropicrites. Melting of a garnet-pyroxenite source may have been significant. A comparison of peridotite and pyroxenite melts with 97SB68 is shown on Figure 8.



6. CONCLUSIONS

The results of our 1 atmosphere to 7 GPa experiments on a ferropicrite from the Paraná-Etendeka CFB have allowed us to constrain the following mantle processes operating during the initial sub-lithospheric inpact of the Tristan mantle plume. A model is shown (Fig. 9), expressed as a P-T plot with the solidii $(\pm 50^{\circ}\text{C})$ of fertile peridotite KLB-1^{5,25}, garnet pyroxenite MIX1G¹¹ and the liquidus of 97SB68. Mantle potential temperature (Tp) adiabats of 1300°C, for ambient mantle and 1550°C, thought to be appropriate for impacting mantle plume starting heads^{26,27} are also shown, along with the base of continental lithosphere ~ 125 km^{28} and the base of continental crust ~ 35 km.

1. It is unlikely that the primary Paraná-Etendeka ferropicrite melts were generated from a purely peridotitic convecting mantle source. The results of our experiments suggest that the primary melts separated from either an olivine-pyroxene residue at ~ 2.2 GPa or a garnet pyroxene residue at 5 GPa. Of these, high-pressure melting of a garnet-pyroxene rich mantle is more plausible since the Paraná-Etendeka ferropicrites are characterised by $low Al_2O_3$ contents and fractionated heavy rare-earth element ratios (Fig. 6).

2. At 5 GPa, the ferropicrite liquidus is at 1650°C, which is similar to the solidus of silicaundersaturated garnetpyroxenite¹¹ (Fig. 9). At these pressures and temperatures, the garnet-pyroxenite solidus would be intersected by an upwelling plume with a mantle potential temperature of 1550°C.

3. Subsequent upwelling and melting of the Tristan plume would be restricted by thick overlying continental lithosphere (Fig. 9). Intersection of the peridotite solidus would occur at ~ 4.5 GPa, for a Tp of 1550°C, and only limited melting would occur beneath a ~ 125 km thick lithosphere. More extensive peridotite melting, and hence dilution of garnet-pyroxenite derived melts, would occur beneath thinner oceanic lithosphere and may explain the apparent absence of ferropicrites in intra-plate oceanic settings. In OIB successions, ferropicrite magmas may be difficult to form due to the absence of thick lithosphere. They may be rare because: i) OIBs do not represent the emplacement stage of the plume; ii) the exposure is usually not deep enough in OIB sections to see the initial stage of magmatism.

4. The results of our study are in agreement with previous investigations which have proposed that mantle plumes consist of both garnet pyroxenite and peridotite (Fig. 10). The garnet pyroxenite may relate to the presence of subducted oceanic lithosphere that has been entrained within the upwelling plume.

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 Al_2O_3 concentrations of MIX1G partial melts decrease and SiO₂ contents increase with increasing pressure, due to the presence of residual garnet, such that 5 GPa melts of MIX1G are similar to 97SB68 (Fig. 8). Na₂O concentrations of 5 GPa melts are also similar to 97SB68 but all the garnet pyroxenite melts have lower K₂O and FeO* and higher CaO concentrations than 97SB68, which probably reflect the composition of the starting

Partial melting of equal proportions of basalt and peridotite $(GA1_{50}MPY90_{50})$ at 1500°C and 3.5 GPa produces a picritic melt that is similar in composition to 97SB68 (Fig. 8; the percentage of GA1 is indicated in bold next to each open circle along the trend line). Other analyses of GA1/MPY90 partial melts are not available, but low-degree melts of mixed runs containing > 50% peridotite are expected to be nephelinenormative picrites¹³. We believe that a mixture of 75% basalt and 25% peridotite may yield a melt composition similar to 97SB68 at ~ 5 GPa.



