

# GEOCHEMICAL AND ISOTOPIC EVIDENCE OF A KIMBERLITE-MELNOITE-CARBONATITE GENETIC LINK

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## INTRODUCTION

Identification of the mantle sources that produce alkaline ultramafic and carbonatitic provinces and the potential genetic relationships between these rocks has been of interest to researchers and experimentalists for over 100 years (e.g., Lewis, 1897). Numerous studies have shown that metasomatised lherzolite that undergoes very low degrees of partial melting is the most likely mantle candidate able to produce the highly enriched incompatible element concentrations observed in these rocks (e.g., Dalton and Presnall, 1998). Incompatible element isotopic studies (Nd, Sr, Hf and Pb) all show that this source enrichment likely preceded melting by 100 s to 1000 s Ma (Smith, 1983; Schmidberger et al., 2002).

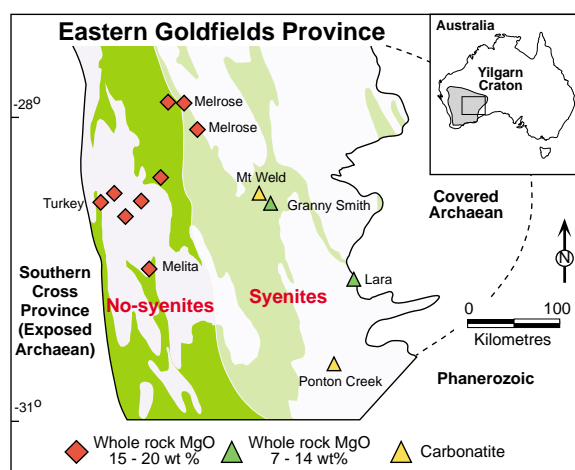
However, these studies have been performed on relatively young rocks that traversed continental lithospheric mantle (CLM) with a multi-stage evolution (Walker et al., 1989). The CLM is also observed to contain incompatible element-enriched and volatile-enriched metasomatic lithologies (Haggerty, 1987; O'Reilly, 1987). These are likely: a) distributed throughout the CLM, b) to have low melting temperatures, and c) formed at various times. Furthermore, some of the minerals within them are so enriched in incompatible elements that Haggerty (1987) proposed that kimberlites acquired their incompatible element signatures from these materials. This implies that isotopic studies of young alkaline ultramafic provinces may not yield any useful information on potential genetic relationships or on the composition and age of the source.

In order to circumvent sampling of CLM with a multi-staged history we have performed a geochemical and isotopic study with samples from the oldest alkaline ultramafic and carbonatite province known (2020 Ma).

## BACKGROUND

The alkaline ultramafic rocks and carbonatites occur in the central part of the Eastern Goldfields Province

(EGP), of the Yilgarn Craton Western Australia. The background geology is composed of greenstone belts and TTG suites that are not older than 3000 Ma (Griffin et al., 2003). Post-Archaeon igneous events are not common. However, two events worthy of mention occurred near the Archaeon-Proterozoic boundary (2500-2400 Ma). Between 2500 and 2400 Ma numerous alkaline felsic and alkaline mafic syenites were emplaced into the Archaeon crust (Libby, 1978). While volumetrically insignificant, the large range in ages and mantle like initial isotopic ratios suggest a long-lived mantle thermal event beneath the eastern half of the EGP at this time (Fig. 1). The second event was the emplacement of the east-west trending mafic Widgiemooltha dykes, which are known to occur within each of the Yilgarn Provinces.



**Figure 1:** Map showing location of EGP kimberlites and melnoites. Also shown by lighter shading of basement rock in the eastern half of the EGP is the region intruded by syenites. Note that symbols used for geochemical classification are used throughout all diagrams.

Pyrope garnet and Cr-diopside xenocryst compositions from Melrose and Melita show that the host melts were derived from depths greater than 150 km. Compared to other Archaeon cratons the garnets recovered are unusually Ca-saturated with none plotting within the field of diamond inclusions on a Cr<sub>2</sub>O<sub>3</sub> vs CaO diagram. Furthermore, garnets from Melita are less Ca-saturated than those from Melrose, which is closer to the syenite-line (Fig. 1). Mantle silicates were not recovered from, or identified in, any of the other bodies

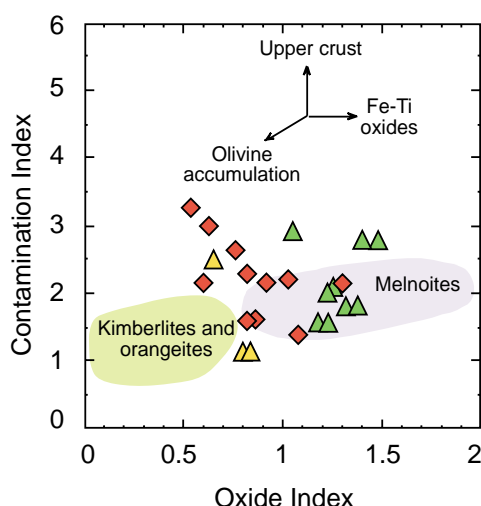
studied. Chromites from Melrose, Melita and Turkey also suggest a melt source deeper than 100 km (e.g., Grütter and Apter, 1998). Chromites with chemistries indicating a depth of > 100 km were not observed in any of the other samples.

Radiometric dating studies yield a large range in estimated emplacement ages for the EGP alkaline ultramafic rocks (2010 Ma to 2188 Ma). The large variation is however a reflection of using model ages and minerals of uncertain paragenesis. The most reliable radiometric data indicate igneous activity between 2020 and 2060 Ma.

## RESULTS AND DISCUSSION

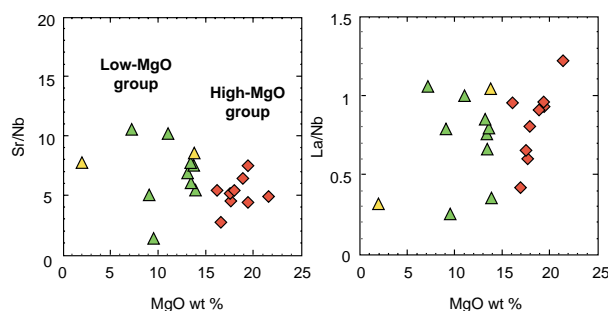
### MAJOR AND TRACE ELEMENT COMPOSITION

Selected major element data for the EGP rocks are shown graphically in Figure 2. On this diagram most samples show strong major element affinity with the melnoite field. However, for samples with high MgO the CLM composition and overall low abundance of xenocrysts may influence this geochemical trend.



**Figure 2:** Contamination Index vs Oxide Index for the EGP alkaline ultramafic rocks

The samples form separate groups, corresponding to MgO content and samples with high MgO, Ni and Cr contents (Melrose and Melita), consistent with the higher CLM xenocryst content of in these rocks. The melnoites, kimberlites and carbonatites are also characterised by extreme incompatible element enrichment. However, the samples irrespective of MgO content exhibit only limited variation in  $La_N/Yb_N$ ,  $La/Nb$ ,  $Sr/Nb$  and  $Sm/Nd$  ratios (Fig. 3).



**Figure 3:** Incompatible element ratios versus MgO for the EGP rocks.

Two samples, not plotted on Figure 3, have incompatible element ratios that do not plot within the range of the other samples; Turkey and the carbonate segregation removed from Lara. The Turkey kimberlite is extensively altered (laterised) and has a distinctive negative Ce anomaly, a feature present in granites from the area. It is therefore likely that this sample concentrated the LREE from the weathering granites it intruded. The carbonate segregation from the Lara melnoite is enriched in Sr and LREE and depleted in Nb and has overall lower REE contents than the whole rock sample. It is proposed that variations represent incompatible element fractionation between carbonate melt and silicate melt during emplacement.

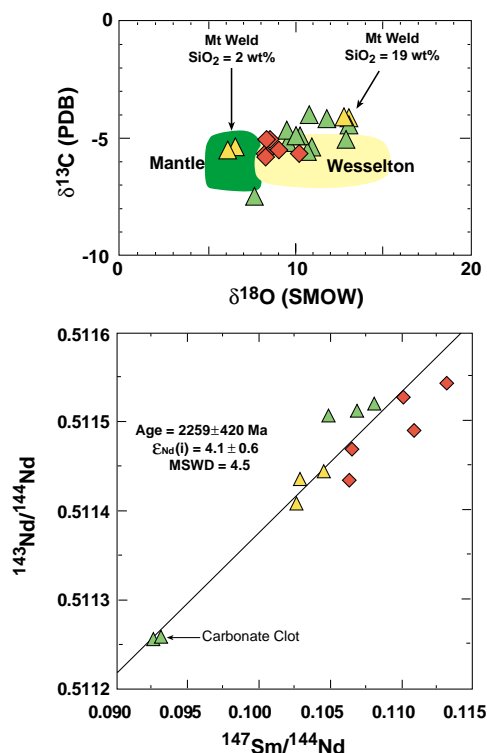
It is commonly assumed that the carbonated lherzolite sources of alkaline ultramafic rocks undergo low (< 2%) degrees of partial melting. It is also assumed that small variations in the degree of melting result in different rock types being generated, with carbonatites being generated at the lowest degrees of melting (e.g., Dalton and Presnall, 1998). Very small variations in the degree of partial melting should theoretically produce large variations in  $La/Nb$  and  $La/Sr$  ratios because the bulk partition coefficient La is 70% lower than for Nb or Sr during partial melting of carbonated lherzolite (Adam and Green, 2001). This is not observed. Also the incompatible element ratios are not correlated with MgO, suggesting that CLM contamination has not influenced these ratios. The incompatible element ratios are therefore controlled by the melt, and the lack of variation in the ratios, irrespective of enrichment level, points to the source undergoing large degrees of partial melting of the fusible components.

### ISOTOPE DATA

Carbonate stable isotope data are shown in Figure 4. The carbonate  $\delta^{18}O$  and  $\delta^{13}C$  values vary between 6.3 and 13 ‰ and -2.6 and -8.4 ‰, respectively,

features typical of carbonatite and kimberlite carbonate (e.g., Kirkley et al., 1989). Oxygen isotopes show much greater variation than C isotope. As shown on Figure 3 it is possible that the slightly positive stable isotope trend observed occurred during emplacement, with the most evolved melts yielding the highest  $\delta^{18}\text{O}$  and  $\delta^{13}\text{C}$  values.

Sm-Nd isotopic data obtained for 13 whole rock samples have low  $^{147}\text{Sm}/^{144}\text{Nd}$  ratios and 2020 Ma  $\epsilon\text{Nd}$  values range from +0.1 to +1.6 (mean = +0.9 – 1.0 (2SD) showing that the rocks come from an enriched mantle source that was laterally homogeneous over a wide area. Compared to the other samples the Turkey kimberlite yields a low initial  $\epsilon\text{Nd}$  value of -5.3. Coupled with the trace element data from this sample we interpret this to be a result of alteration and REE enrichment during laterisation.

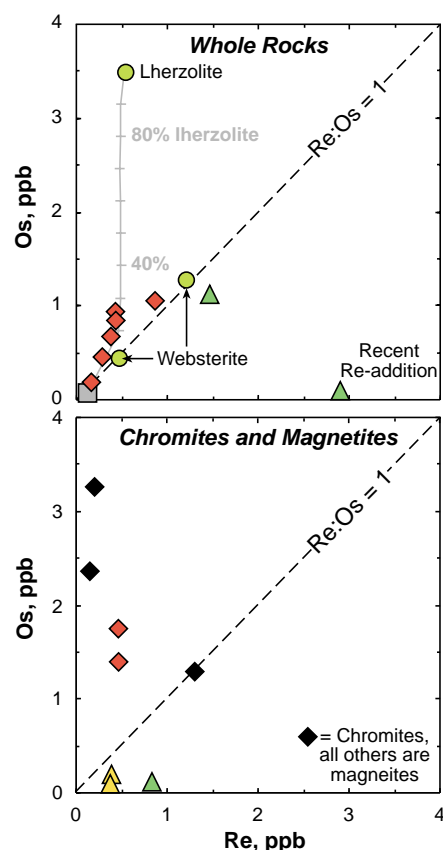


**Figure 3:** Top stable isotope data for carbonates within the samples. Bottom Sm-Nd isotope diagram for whole rock samples. Note the very low Sm/Nd of the carbonate clot removed from the Lara melnoite.

On an Sm-Nd isochron diagram (Fig. 3) the  $^{147}\text{Sm}/^{144}\text{Nd}$  and  $^{143}\text{Nd}/^{144}\text{Nd}$  ratios are correlated, although the limited spread in Sm/Nd ratio does not calculate a precise isochron. The calculated age is within uncertainty of emplacement age (2020 Ma) and the average of the  $T_{\text{DM}}$  model ages (2385 – 71 Ma, 2SD).

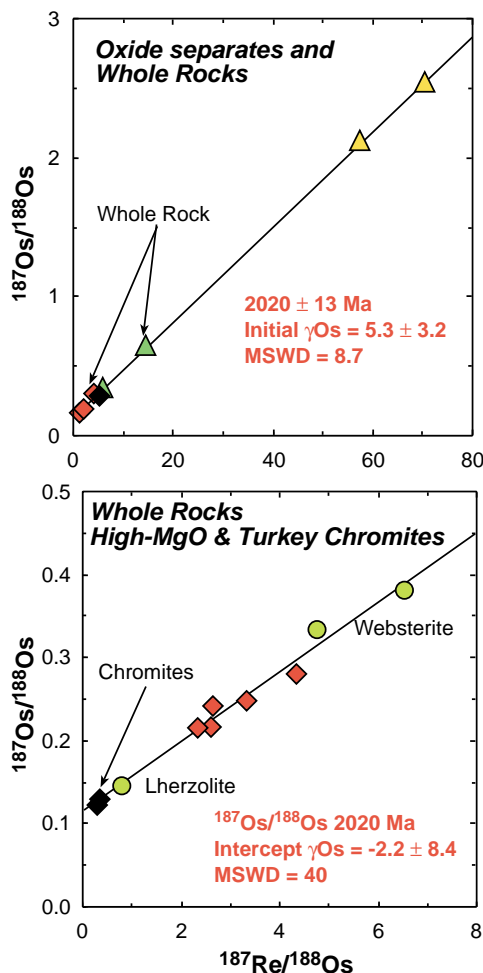
However, this diagram illustrates that although the rocks have widely varying petrographic and compatible trace element systematics the Sm/Nd ratios do not vary significantly.

Rhenium-Os isotopic data were obtained from 8 whole rock, including 2 xenoliths, and 8 mineral separate samples. Rocks from the province have variable Re and Os concentration systematics (Fig. 4). One sample (Lara) shows Os isotopic evidence of recent Re addition. As shown on Figure 4, the high-MgO samples in both whole rock and magnetite separates tend to have  $\text{Re}/\text{Os} < 1$  whereas the low-MgO samples tend to be  $> 1$ . The websterite xenolith yields a consistent  $\text{Re}/\text{Os}$  of 1, whereas the lherzolite has a  $\text{Re}/\text{Os} < 1$  (both samples removed from Melita drill core), Re and Os concentration systematics typical for these types of rocks (Carlson and Irving, 1994; Graham et al., 1999; Schaefer et al., 2000a).



**Figure 4:** Re vs Os concentration diagrams for EGP samples. Mixing curve generated by assuming initial melt with 0.1 ppb Re, 0.05 ppb Os (grey box). Low-MgO sample with high Os and Re also has high Ni and Cr which are inconsistent with this samples low MgO values. It is considered that this sample contains cumulate phases. Chromites and magnetites are macrocryst and groundmass phases, respectively.

All of the samples, apart from the Mt Weld magnetites, are radiogenic at 2020 Ma, including the lherzolite. The Mt Weld magnetites have the high Re/Os ratios and hence do not yield a precise initial  $\gamma_{Os}$  values. The low-MgO whole rock, the high-MgO sample with the lowest Os concentration and all oxide (chromite-magnetite) mineral separates define a precise Re-Os age of 2023 – 13 Ma (MSWD = 37) and a radiogenic initial  $\gamma_{Os}$  value of 3.3 – 3.2, which is comparable to mantle plumes (e.g. Schaefer et al., 2000b). Removing the Turkey chromites, which may be of CLM origin, greatly improves the regression statistics but does not alter the age (Fig. 5), which is in excellent agreement with those previously determined and confirms that the high-MgO and low-MgO rocks and carbonatites were emplaced during the same event.



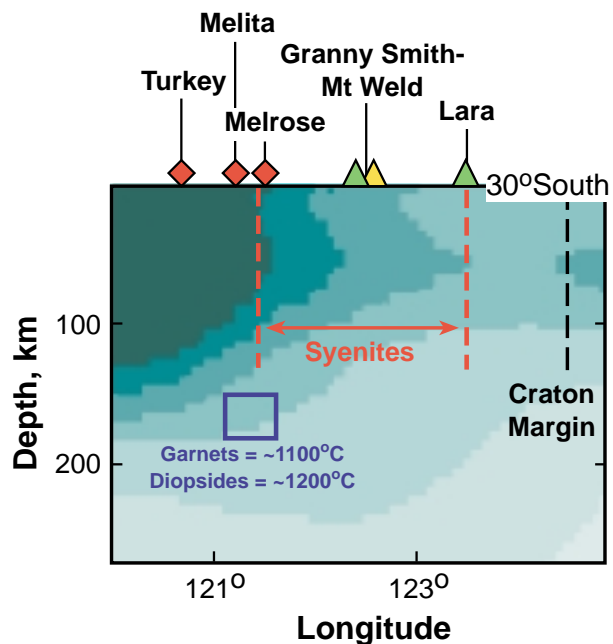
**Figure 5:** Re-Os isochron diagrams for EGP samples. Top diagram yields an emplacement age because these rocks and minerals are dominated by the melt. Bottom diagram correlation results from mixing and hence yields no age information.

The whole rock high-MgO samples, including the two xenoliths are also correlated on a Re-Os isochron diagram. However, by definition this correlation does not yield any age information, although does imply that the isotopic composition, as well as the Re and Os concentrations (Fig. 4), of these rocks can be explained by mixing between two endmembers, one of which was the CLM.

## CONCLUSIONS

Alkaline ultramafic rocks and carbonatites were emplaced into the EGP at 2020 Ma. Geochemically these rocks show strong enrichments of incompatible elements. The compatible elements are only moderately enriched a feature that is likely related to the low abundance of CLM xenocrysts and ultimately the composition of these xenocrysts. The lack of variation of the incompatible element ratios suggests that the components that melt at low temperatures were completely extracted from the source, and that this source was laterally homogeneous beneath the EGP.

The rocks become more Mg-rich toward the western margin of the craton, which also correlates with the distribution of syenites and seismic wave speed (Fig. 6).



**Figure 6:** SKIPPY (teleseismic) cross section of Australia at 30°S (after Kennett pers. comm., 1999). Note the correlation between seismic velocity and distribution of syenites, high- and low-MgO rocks. Dark colours represent fast wave speeds.

We therefore propose that the syenite event (and possibly the Widgiemooltha dyke event) resulted in extensive refertilisation of the EGP CLM, and that because all of the melts are genetically related the transition from kimberlite to carbonatite is ultimately controlled (in this province) by depth and composition of the CLM: Refractory CLM = kimberlites.

The data do not provide any firm constraints on the location of the source (e.g., plume or CLM) as all isotopic data are similar to values expected for these reservoirs. However, it is interesting to speculate that the average of the Nd model ages (2390 Ma) and the Os  $T_{RD}$  age calculated from the xenolith-high-MgO mixing line intercept (2390 Ma) correlate with the syenite event and show that the source of the melts was the CLM.

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