

Systematic regional variations in diamond carbon isotopic composition and inclusion chemistry beneath the Orapa kimberlite cluster, in Botswana

Peter Deines¹, Thomas Stachel² and Jeff W. Harris³

¹The Pennsylvania State University, University Park, PA 16802, USA

²The University of Alberta, Edmonton, Canada

³The University of Glasgow, Glasgow, Scotland

Although ¹³C depleted diamonds of various parageneses have been found in a number of kimberlites worldwide, a common link between their carbon isotopic composition and inclusion chemistry has not been identified. However, the diamond suites employed for such studies generally came from spatially significantly separated kimberlites.

Hence, spatial variability in the mantle may be an additional, complicating factor in unraveling any relationship between $\delta^{13}\text{C}$ and inclusion chemistry. Since ¹³C depleted diamonds are relatively common in the Orapa kimberlite and several mined kimberlite pipes are proximal, we have undertaken a comparative study of the diamonds from Orapa, Letlhakane and Damtshaa, the latter two mines being separated from Orapa by 40 and 15 km respectively.

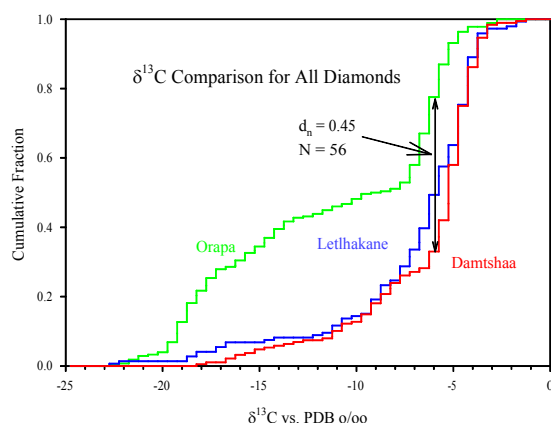


Figure 1: $\delta^{13}\text{C}$ cumulative frequency distributions of diamonds from the Orapa (Deines et al., 1993), Letlhakane (Deines and Harris, 2004), and Damtshaa (this study) kimberlites.

The Carbon Isotope Record

A comparison of diamond $\delta^{13}\text{C}$ from the three mines (Fig. 1) demonstrates that the distribution for Damtshaa is indistinguishable from that of Letlhakane, but that these $\delta^{13}\text{C}$ distributions differ significantly from that of Orapa, where low $\delta^{13}\text{C}$ diamonds occur more frequently.

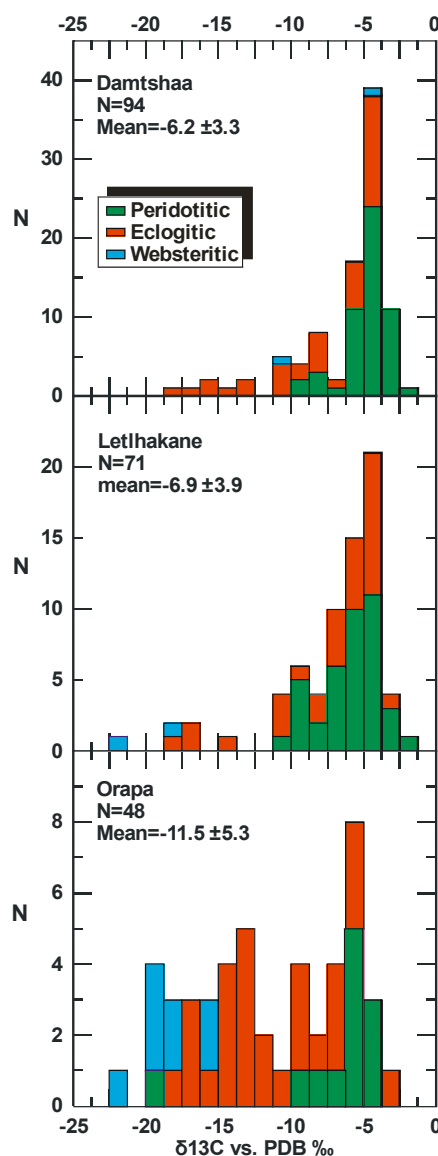


Figure 2: $\delta^{13}\text{C}$ in diamonds from Orapa, Letlhakane and Damtshaa separated according to paragenesis.

Separate $\delta^{13}\text{C}$ comparisons of eclogitic (E-type) and peridotitic (P-type) diamonds (Fig. 2) show that E-type distributions for Damtshaa and Letlhakane are indistinguishable, but, on average, are again

significantly enriched in ^{13}C compared to Orapa. This difference suggests an eastward decline in the abundance of ^{13}C depleted E-type diamonds. In the case of P-type diamonds, the Letlhakane distribution is intermediate between that of Orapa and Damtshaa, with the P-type diamonds from Orapa showing a distinct trend to ^{13}C depleted compositions.

Hence, the ^{13}C enrichment in diamonds from Damtshaa observed in the summary distributions (Fig. 1) is attributable to ^{13}C enrichment in diamonds from both suites (E- and P-type) and suggests a more general eastward decline of ^{13}C depleted diamonds. We conclude that while the $\delta^{13}\text{C}$ distributions of Orapa, Letlhakane and Damtshaa diamonds share some overall similarities, there are significant differences among them, a result that supports the concept that diamonds from different kimberlite pipes have distinctive $\delta^{13}\text{C}$ distribution features, even if they are separated by only a few tens of km.

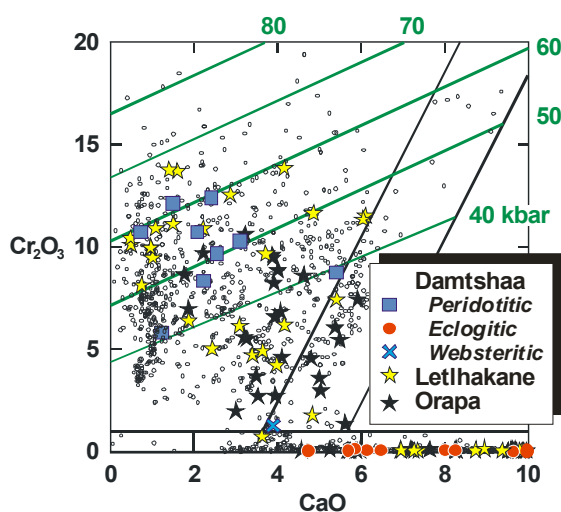


Figure 3: The composition of garnet inclusions in diamonds from Damtshaa, compared to Letlhakane, Orapa and worldwide sources. The field for lherzolitic garnets and the cut-off at 1 wt% Cr_2O_3 for eclogitic garnets is taken from Grütter et al. (2004). P_{38} (Cr-in-garnet barometer of Grütter et al., 2006) indicates pressure of origin for garnet in equilibrium with Mg-chromite along a 38mW/m^2 model geotherm. For garnet without co-existing spinel, a minimum pressure estimate is obtained. Compared to Orapa, peridotitic garnet inclusions from Damtshaa and Letlhakane are derived from in part highly depleted dunitic-harzburgitic reservoirs ($\text{CaO} < 2 \text{ wt\%}$) extending to greater depth (minimum pressure exceeds 60 kbar).

Inclusion Chemistry

The isotopic differences between diamonds from the three kimberlites noted above are not matched by highly distinctive inclusion chemistries. Some differences do, however, exist: E-type garnet chemistries from the three mines, for example, differ in their Al and Si content (with the majority of garnets from Damtshaa being slightly silica deficient) whereas the chrome contents and Mg# for E-, P-, and W-type (websteritic) garnets overlap. The $\text{Al}_2\text{O}_3/\text{Cr}_2\text{O}_3$ ratios

of eclogitic and websteritic garnets show considerable variability.

With P-type inclusions, as expected, there is little variation in the composition of olivine inclusions from the three kimberlites. P-type garnets (Fig. 3), however, differ significantly in Cr_2O_3 content, indicative of either a generally shallower origin or lower Cr/Al ratios in the source of P-type diamonds from Orapa.

Relationship of $\delta^{13}\text{C}$ to the $\text{Al}_2\text{O}_3/\text{Cr}_2\text{O}_3$ Ratio in Websteritic and Eclogitic Garnets

Both field and laboratory studies support the concept that the composition of inclusion garnets and the environment in which they form are related. Hence any conclusions about the nature of the relationship between garnet chemistry and the carbon isotopic composition of the diamond host may provide new insights into the carbon isotope geochemistry of the mantle.

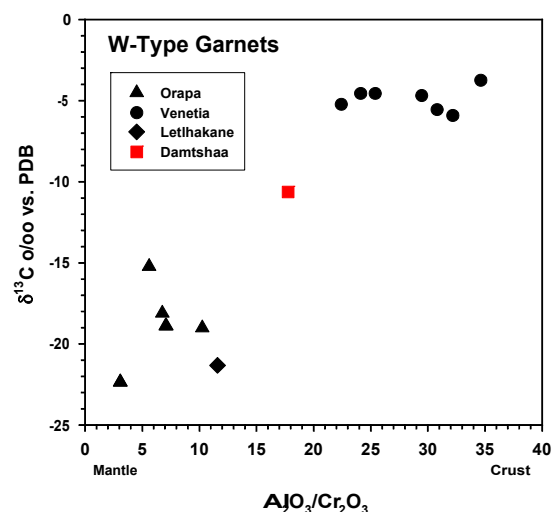


Figure 4: $\text{Al}_2\text{O}_3/\text{Cr}_2\text{O}_3$ ratio of websteritic garnets and the carbon isotopic composition the host diamond.

Figure 4 summarizes the $\text{Al}_2\text{O}_3/\text{Cr}_2\text{O}_3$ ratio of websteritic garnets and the carbon isotopic composition of their hosts (including data from the Venetia Mine, Deines et al., 2001). Low $\text{Al}_2\text{O}_3/\text{Cr}_2\text{O}_3$ ratios (characteristic for the mantle) are associated with low $\delta^{13}\text{C}$ values, while high $\text{Al}_2\text{O}_3/\text{Cr}_2\text{O}_3$ ratios (characteristic for the crust) are associated with high $\delta^{13}\text{C}$ values. The one analysis of a garnet bearing websteritic diamond for Damtshaa, falling between the Venetia and the Orapa/Letlhakane groups, confirms this trend and the conclusion that there are mantle compositions reflected in the websteritic garnet composition that are low in ^{13}C .

We can test this reasoning by examining the relationship between the carbon isotopic composition of E-type diamonds and the $\text{Al}_2\text{O}_3/\text{Cr}_2\text{O}_3$ of the garnets

included in them (see Fig. 5). Rather than forming a linear array (c.f. Fig. 4), the eclogitic diamond and inclusion data are restricted to a triangular area.

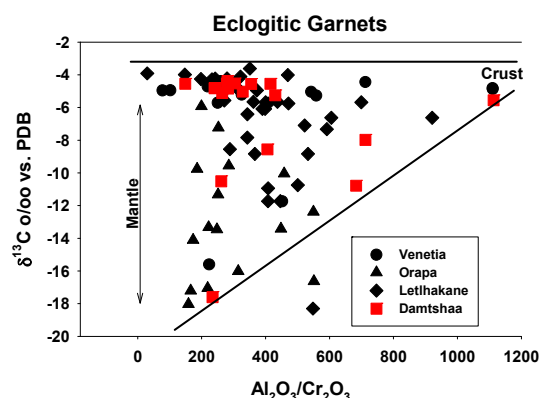


Figure 5: $\text{Al}_2\text{O}_3/\text{Cr}_2\text{O}_3$ ratio of eclogitic garnets and the carbon isotopic composition of the host diamond.

Because there is no systematic association of high $\text{Al}_2\text{O}_3/\text{Cr}_2\text{O}_3$ garnet inclusions and low ^{13}C diamond hosts, the distribution of data points is best explained by the proposition that mantle or otherwise externally derived carbon with a range in isotopic composition extending to -20 ‰, associated with mantle like $\text{Al}_2\text{O}_3/\text{Cr}_2\text{O}_3$ ratios, contributed to the formation of the host.

P-T Equilibration Conditions

Coexisting garnet-clinopyroxene pairs permit the determination of temperature conditions of equilibration. Based on data from Orapa, Deines et al. (1993) suggested the existence of a ^{13}C depleted zone beneath this kimberlite, indicated by the shaded area in Figure 6. The analyses from Damtshaa are consistent with this conclusion and indicate that this zone, albeit with different relative abundance of ^{13}C depleted diamonds, extends at least over an area of some 200 km².

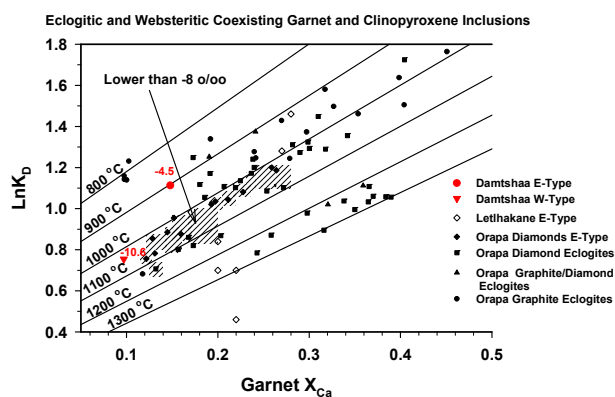


Figure 6: Variation in experimentally determined $\text{Ln}K_D$ ($[\text{Fe}/\text{Mg}]_{\text{garnet}}/[\text{Fe}/\text{Mg}]_{\text{cpx}}$) with X_{Ca} in garnet at 50 kbar pressure for a temperature range of 800 to 1300 °C (Ellis and Green, 1979). The shaded area corresponds to the field of Deines et al. (1993) for diamonds and diamondiferous eclogites from Orapa with $\delta^{13}\text{C} < -8\text{‰}$.

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