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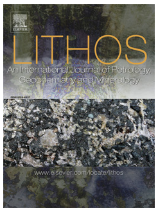

# Crystallographic orientations of olivine inclusions in diamonds

S. Milani [a,*], F. Nestola [a], R.J. Angel [a], P. Nimis [a], J.W. Harris [b]

[a] *Dipartimento di Geoscienze, Università degli Studi di Padova, Via G. Gradenigo 6, I-35131 Padova, Italy*
[b] *School of Geographical and Earth Sciences, University of Glasgow, Glasgow G12 8QQ, UK*

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ABSTRACT

In this work we report for the first time the crystallographic orientations of olivine inclusions trapped in diamonds from the Kaapvaal craton (South Africa) determined by single-crystal X-ray diffraction, and analyze them together with all available data in the literature. The overall data set indicates no preferred orientation of the olivine inclusions with respect to their diamond hosts. However, diamonds containing multiple olivine inclusions sometimes show clusters of olivines with the same orientation in the same diamond host. We conclude that such clusters can only be interpreted as the remnants of single olivine crystals pre-dating the growth of the host diamonds.

## 1. Introduction

A complete picture of the mechanisms of diamond growth and the environment in which it occurs in the Earth's mantle can only be obtained by determining the genetic relationships between diamonds and their mineral inclusions. A common assumption that has developed in the past is that most of the mineral inclusions are syngenetic with their diamond hosts (e.g. Harris, 1968), i.e. the inclusions and diamonds grew simultaneously, in contact and from the same chemical reaction. The assumption of syngenesis appears to have been derived from two observations. The first was that almost all inclusions show a diamond-imposed morphology (Prinz et al., 1975; Sobolev et al., 1972). The second was that some inclusions exhibited a preferred crystallographic orientation with respect to their diamond hosts. It is evident that this then developed into a general belief in the epitaxial relationship between olivines in diamond (e.g. Orlov, 1977), which in turn was used to infer syngenesis.

While the first, morphological, criterion is definitely confirmed by a simple optical observation, the relative orientations of inclusions can only be measured by diffraction methods. As a matter of fact, until recently only a handful of olivine orientations in diamond were fully reported in the literature, and there were too few data to draw general conclusions about the orientations of olivines in diamonds. Nestola et al. (2014) partially addressed this issue by determining the complete orientations (by single-crystal X-ray diffraction) of 43 olivine inclusions in 20 diamonds from the Udachnaya kimberlite in the Siberian craton (Russia). From these measurements it was concluded that olivines did not show any preferred orientations even if they had diamond-imposed morphologies. However, the most intriguing result from Nestola et al. (2014) was that some multiple inclusions of olivine with imposed morphologies in individual diamonds showed similar orientations, which places significant constraints on the mode of growth of the diamonds. In order to investigate whether the results from Udachnaya olivines are characteristic of the world-wide population of olivine inclusions in diamond, we have measured the orientations of a suite of olivines from several mines on the Kaapvaal craton, and combined these results with recently-measured data on olivine inclusions from the Yubileinaya kimberlite in the Siberian craton (Neuser et al., 2015).

## 2. Materials and methods

### 2.1. Geological settings

The newly-measured samples come from the Premier (Cullinan), Koffiefontein and Bultfontein kimberlites, diamondiferous mines located in the Kaapvaal craton. The Kaapvaal craton is one of the two Archean nuclei of the biggest Kalahari Craton (Griffin et al., 2003; Fig. 1). It is surrounded to the north by the Limpopo Belt, to the east by the Lebombo–Sabi monoclines, to the south by the Namaqua–Natal belt and to the west by the Rehobothian subprovince. The Kaapvaal craton itself is an amalgamation of low- to medium-grade Archean terranes that are distinguishable by their structural trends, age and abundance of greenstone belts and the timing of granitoid emplacement (Griffin et al., 2003).

The Premier mine is located in the central terrane (Fig. 1) while the Koffiefontein and Bultfontein mines, are located in the eastern boundary of the western terrane (Fig. 1). All the kimberlites are of the Group I variety (Becker and Le Roex, 2006; Smith, 1983). The Premier kimberlite has a preferred emplacement age of 1180 Ma ± 30 Ma (Richardson et al., 1993) and these authors also suggested that diamond formation was linked to the metasomatism and heating event related to the intrusion

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* Corresponding author.
*E-mail address:* sula.milani@unipd.it (S. Milani).

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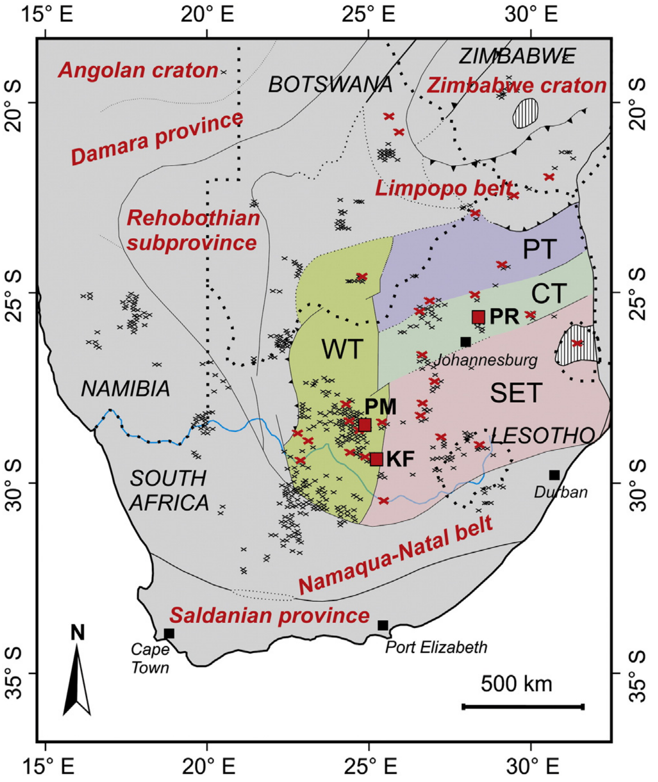

**Fig. 1.** Map of southern Africa showing the boundaries of the Kaapvaal craton and its terrane subdivisions and the location of the Premier (PR), Bultfontein (PM), and Koffiefontein (KF) mines (red filled squares), which are the sources of the samples studied in this work. WT — west terrane, SET — south eastern terrane, CT — central terrane, PT — Pietersburg terrane. Dotted lines are political boundaries. Red crosses — diamondiferous kimberlites; black crosses — non-diamondiferous kimberlites. Modified after Pearson et al. (1998), Friese et al. (2003), Griffin et al. (2003, 2004), Shirey et al. (2004), Aulbach et al. (2009). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

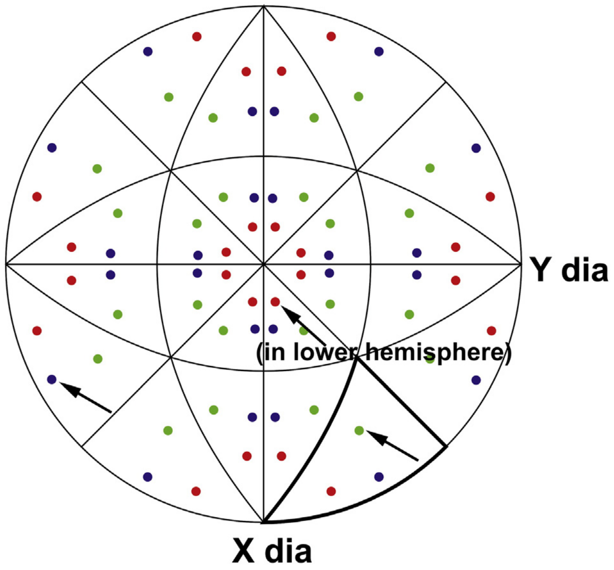

**Fig. 2.** Stereographic projection of the 96 possible, symmetrically-equivalent descriptions of the orientation of olivine PR1_2 in diamond PR1. All poles are duplicated in the upper and lower hemispheres. If a random selection of these orientations is made, the general population of olivine orientations will appear more random than it really is. We therefore consistently choose for all inclusions one unambiguous orientation (arrowed) based on symmetry criteria, in which the olivine b-axis (green dots) lies in a particular asymmetric unit of the stereogram (outlined by thick line) and the olivine c-axis (blue dots) points upward. The orientation of the a-axis (red dots) is then automatically constrained for a right-handed system. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

of the Bushveld complex. Inclusions in the diamonds have both peridotitic and eclogitic affinities (Richardson et al., 1993; Viljoen et al., 2010) and geothermobarometry of chromian diopside inclusions (Nimis, 2002) suggests diamond formation in a thermally perturbed lithosphere with temperatures of 1100 to 1400 °C and a wide range of pressures, 4.5 to 6.5 GPa. The Koffiefontein kimberlite was emplaced <90 Ma (Rickard et al., 1989) into Karoo sediments that directly overlie an Archean granite gneiss basement (Pearson et al., 1998). Peridotitic inclusions in the diamonds are far more abundant than the eclogitic ones (Rickard et al., 1989) and both suites are regarded as being of lithospheric origin. However, the presence of ferro-periclase inclusions testifies to an inclusion suite from the deep mantle (Deines et al., 1991). The Bultfontein mine

**Table 1**
Calculated angles between the axis of each olivine and its host diamond from the Kaapvaal craton.

| Olivine axes | a | | | b | | | c | | |
|---|---|---|---|---|---|---|---|---|---|
| Diamond axes | $a_1$ | $a_2$ | $a_3$ | $a_1$ | $a_2$ | $a_3$ | $a_1$ | $a_2$ | $a_3$ |
| *Samples* | | | | | | | | | |
| *Bultfontein* | | | | | | | | | |
| PM2_1 | 89.00 | 135.14 | 134.85 | 143.35 | 65.74 | 115.66 | 53.37 | 55.01 | 124.16 |
| PM2_2 | 86.11 | 129.18 | 140.55 | 158.93 | 76.48 | 105.85 | 69.32 | 42.35 | 125.01 |
| PM2_3 | 99.80 | 91.51 | 9.92 | 17.45 | 104.76 | 80.91 | 75.71 | 14.84 | 86.07 |
| PM3_1 | 46.54 | 89.58 | 43.46 | 97.26 | 169.57 | 82.56 | 44.37 | 100.42 | 132.49 |
| PM3_2 | 68.16 | 157.03 | 96.77 | 48.09 | 69.29 | 130.90 | 49.87 | 80.51 | 41.71 |
| PM3_3 | 18.54 | 104.11 | 78.21 | 108.37 | 143.77 | 59.99 | 87.54 | 122.58 | 147.30 |
| PM4_1 | 89.84 | 112.36 | 157.64 | 38.36 | 54.92 | 103.53 | 51.64 | 136.43 | 72.55 |
| PM4_2 | 57.83 | 52.49 | 53.98 | 48.28 | 82.63 | 137.33 | 121.54 | 38.48 | 109.69 |
| PM4_4 | 47.87 | 103.18 | 134.89 | 102.24 | 166.12 | 83.57 | 135.29 | 85.72 | 134.39 |
| PM4_5 | 131.95 | 76.70 | 44.99 | 102.29 | 166.01 | 83.43 | 44.55 | 94.25 | 45.76 |
| *Koffiefontein* | | | | | | | | | |
| KF1 | 134.61 | 135.37 | 88.95 | 64.18 | 114.16 | 36.70 | 124.27 | 55.18 | 53.32 |
| KF4 | 44.74 | 45.26 | 89.81 | 65.70 | 114.29 | 144.41 | 124.83 | 54.62 | 125.58 |
| *Premier* | | | | | | | | | |
| PR1_1 | 35.12 | 124.78 | 94.29 | 62.02 | 42.55 | 119.14 | 70.55 | 68.71 | 29.51 |
| PR1_2 | 85.14 | 73.57 | 17.17 | 61.68 | 33.72 | 106.75 | 151.19 | 61.47 | 93.65 |
| PR1_3 | 94.87 | 106.46 | 162.79 | 61.67 | 33.75 | 106.79 | 28.82 | 118.54 | 86.34 |
| PR1_4 | 97.31 | 104.61 | 163.59 | 58.83 | 36.09 | 106.33 | 32.21 | 122.16 | 88.41 |
| PR1_5 | 85.63 | 72.50 | 18.07 | 58.53 | 36.84 | 107.16 | 148.16 | 58.75 | 95.51 |
| PR1_7 | 144.95 | 55.29 | 85.76 | 118.01 | 137.57 | 61.02 | 70.71 | 68.78 | 29.35 |
| PR2_2 | 69.75 | 100.63 | 23.09 | 120.62 | 38.14 | 69.56 | 141.99 | 126.11 | 79.73 |
| PR3 | 134.74 | 89.56 | 135.26 | 114.77 | 144.28 | 66.02 | 125.00 | 54.28 | 54.92 |

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