QUANTITATIVE NITROGEN AGGREGATION STUDY OF SOME YAKUTIAN DIAMONDS: CONSTRAINTS ON THE GROWTH, THERMAL, AND DEFORMATION HISTORY OF PERIDOTITIC AND ECLOGITIC DIAMONDS.

W.R. Taylor[1,2], G. Bulanova[3] and H.J. Milledge[2]

(1) Research School of Earth Sciences, Australian National University, Canberra, A.C.T. 0200, Australia
(2) Dept of Geological Sciences, University College London, Gower St., London WC1E 6BT, U.K.
(3) Yakutian Institute of Geological Sciences, 39 Lenin St., Yakutsk 677007, Sakha, Russia.

Introduction: Many diamonds exhibit complex multistage growth and deformation histories that provide a record of processes that occurred in the lithosphere over the residence time of the diamond. Residence periods for diamond may be >3 Ga but younger outer growth zones can have significantly shorter residence times so potentially one diamond can contain information over nearly the entire lithosphere history . It is possible to extract this information from diamonds because, unlike oxide and silicate minerals, they are not recrystallized during ordinary geological events. Yakutian diamonds are particularly valuable for these studies because they are generally not strongly resorbed and consequently the latest growth zones tend to be well preserved. In this preliminary study, four inclusion-bearing peridotitic and eclogitic diamonds, one of each type from from the Udachnaya and Mir kimberlite pipes, were selected for detailed investigation of their internal structure by cathodoluminescence (CL) and infrared (IR) methods. These specimens were chosen to be representative of the different diamond internal structures encountered among Yakutian stones and because they contain inclusions that have provided age or geothermometry data.

Methods: For this investigation (110) polished central sections were prepared through the four specimens at the Yakutian Institute of Geological Sciences. In some cases the central plates were repolished or peripheral plates were prepared in order to expose inclusions for geothermometry. Several detailed IR traverses, taken in transmission, were made across the plates using an IR microscope with a 120μm aperture. Particular care was taken to match the CL zonation patterns, detrmined on top and bottom surfaces of the plates, with the IR traverses. Ideally the CL patterns of opposite sides of the plates should be mirror maps of one another if growth proceeded in a regular way from a central nucleus, and in this case (e.g. 1525 in this study) IR measurements can be matched closely with particular growth stages. This situation is not generally the case when nuclei are not central and where growth is irregular, but it is usually possible to select areas from which useful data can be obtained. The IR data was quantitatively processed to yield nitrogen contents and aggregation states. Where age data does not exist, a mantle residence time (tMR) of 2.6 Ga was used to determine nitrogen aggregation temperatures (T[NA]) for the purposes of comparison. This assumes a diamond formation age near 2.9 Ga using a Devonian kimberlite age. Because the kinetics of nitrogen aggregation are not particularly sensitive to residence time, this approach will yield geologically useful temperatures within ~500 Ma of the actual formation age, and for zoned specimens, will give valid temperatures provided core to rim growth took place in less than a few 100 Ma. Such data can be used in conjunction with geothermometry results to deduce the thermal history of the diamonds and hence that of the host lithosphere.

Mir peridotitic plate 1525: This diamond has a complex internal structure built up of successive octahedral growth layers that may be divided into four zones (Fig. 1). The inner core has high nitrogen and hydrogen contents and is composed of fully aggregated type IaB diamond. It yields a T[NA] value of >1324°C for tMR = 2.6Ga. The outer portion of the inner rim has been selectively resorbed and the resorption features have been infilled by very low-nitrogen diamond (type II diamond) having no CL response. This type II region is decorated by non-touching olivine and garnet inclusions which yield a Fe-Mg temperature of 1262°C. The type II region is overgrown by zones of low nitrogen type IaAB diamond (10-60 atomic ppm) giving T[NA] values between 1242 and 1186°C. This outer rim zone shows abundant slip lines under CL which arise from plastic deformation. They are particularly noticable in regions of low nitrogen content.

The slip lines terminate at the inner rim which contains ~300 atomic ppm of nitrogen together with some fine type II bands. The boundary with the outer rim, which contains ~600 ppm nitrogen, is abrupt. T[NA] values for the inner rim are ~1154°C and for the outer rim are ~1099°C. Platelet indices (see Taylor and Milledge, 1995) decrease from low values in the inner core, through values of ~15 in the outer core to ~28 and ~40 in the inner and outer rims, respectively. This indicates the successive zones grew under conditions of decreasing temperature consistent with the calculated T[NA] values. A composite (touching) inclusion, comprising two pyroxenes plus magnesite, is located in a type II patch within the outer core. It yields a temperature of 930°C, indicating the diamond cooled to a cratonic geotherm after formation.

Mir eclogitic plate 1168: This plate comprises a complexly zoned octahedral core with plastic deformation slip lines and regions containing giant platelets (>10 microns size). The core is off-centre perpendicular to the plate making IR measurements difficult to interpret in this region. Nevertheless the core is highly aggregated with T[NA] >1200°C for tMR = 2.6Ga. Non-touching garnet and clinopyroxene inclusions in the core yield an Fe-Mg temperature of 1244°C. The core is surrounded by a cuboid growth zone having a high H content and pink CL colour. Such a zone seems to be a common feature of many Yakutian eclogitic diamonds. This zone is overgrown by more regular octahedral growth zones with T[NA] values ~1100-1150°C. A pair of non touching inclusions in the rim yield an Fe-Mg temperature of 1189°C. Platelet indices of this specimen increase from core to rim indicating growth and residence under different thermal regimes.

Udachnaya peridotitic plate 3648: This plate, of a slightly resorbed octahedron, was the subject of a SHRIMP study by Rudnick et al. (1993). Sulphide inclusions within the diamond core give an age of ~2.0 Ga while other inclusions in the rim give either poorly constrained ages or very young ages near that of kimberlite eruption. Under CL the internal structure of the diamond was found to be more complex than indicated by original UV photoluminescence studies. To a first order, the diamond is composed of a core region containing ~300-400 atomic ppm nitrogen with T[NA] ~1166°C for tMR = 2.0Ga. It is surrounded by a low nitrogen rim (<100 atomic ppm) with T[NA] ~1150°C for the same tMR. If the diamond remained at the same mantle temperature throughout its history then the rim would have formed at a later time, in fact at around 950 Ma, but there is no IR evidence that outer zones of the diamond formed at a very young time. Detailed CL study of the diamond reveals that its final form does not reflect only octahedral layer growth. It is, in fact, composed of a mosaic of fragments with angular or conchoidal boundaries together with type II infill regions. Type II regions are common in the outer part of the rim and zones in which displacement and rotation of the fragments occurred can be identified. At some stage in its history the diamond was broken into small fragments and the fractures were later rehealed. Because old fracture boundaries are decorated by platelets, the fracturing must have been an ancient event that occurred prior to significant nitrogen aggregation. There is no hint in ordinary light that the diamond is composed of fragments and the specimen appears to be a normal single crystal. Sulphide inclusions located on healed fracture boundaries may have been exposed to exchange with mantle fluids causing their isotopic composition to be reset. This may be the reason for the disturbed ages of the rim sulphide inclusions. This diamond is one example of a number of similar specimens from Udachnaya which show brittle deformation textures. Such diamonds were presumably deformed under cool mantle conditions at high strain rates.

Udachnaya eclogitic plate 3105: This diamond shows complex zonation and has a geometrically off-centre core containing ~450 atomic ppm nitrogen and high hydrogen levels with T[NA] of ~1140°C. The core is enclosed by a zone containing type II diamond. Part of the core appears to have been fractured and rehealed and other irregularly shaped regions, surrounded by type II diamond, are present. The core region is surrounded by regular octahedral growth layers with ~200- 250 ppm nitrogen which give T[NA] values of ~1125°C. Non-touching garnet and clinopyroxene inclusions in this growth zone gives an Fe-Mg temperature of 1160°C. The diamond has been overgrown at a late stage by fibrous diamond. It is of mixed type IaA-Ib character with ~1100 atomic ppm nitrogen and ~20% Ib component giving it a deep yellow colour. If it grew and resided in the mantle at ≥950°C, then this outer zone would have formed <5Ma before kimberlite eruption (see Taylor et al., 1995).

Discussion: Yakutian diamonds show multistage growth histories which in some cases involve a late phase of growth that appears to have immediately preceded kimberlite eruption. The cores of many diamonds grew and resided under high temperature conditions (>1200°C) and those cores show evidence of plastic deformation. Other diamonds have been brittly deformed presumably under cool, subsolidus conditions (<1000°C) at high strain rates within the lithosphere. In such circumstances, inclusions located on fracture surfaces are open to exchange of components with their surroundings until the fractures are rehealed. If careful CL studies of the host diamond have not been done then geochemical study of such inclusions may give misleading results. Core temperatures are consistent with growth of the diamonds from either volatile-bearing melts or fluids, whereas late overgrowths such as that on plate 3105 most probably grew from the fluid phase. In either case, regular octahedral growth requires that substantial volumes of melt or fluid are present to ensure growth is not inhibited by grain to grain contact. Inclusion temperatures are generally several 10's of °C higher than T[NA] values for the same zones and platelet indices increase from core to rim. This is good evidence that Yakutian diamonds grew during a period of thermal perturbation of the lithosphere, and following this event, the diamonds and their host rock cooled to the ambient geotherm.

References:

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FIG. 1
MIR 1525
Peridotitic Plate
CL Zonation