MULTI-STAGE MODIFICATION OF THE MANTLE LITHOSPHERE BENEATH THE SLAVE CRATON: EVIDENCE FROM AN UNUSUAL SUITE OF ZIRCON-BEARING ECLOGITE XENOLITHS ENTRAINED IN THE JERICHO KIMBERLITE, CANADA

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INTRODUCTION

Mantle xenoliths provide us with some indication of the antiquity and composition of the mantle lithosphere and processes involved in modifying this lithosphere through geologic time. Recovered mantle xenoliths from kimberlites can be broadly subdivided into peridotitic and eclogitic suites, however within each suite there is enormous petrologic variation. A few kimberlites worldwide are renown for their unusual abundance of eclogite xenoliths including Roberts Victor, Bellsbank/Bobbejaan (South Africa), Koidu (Sierra Leone), Orapa (Botswana), and several pipes from Yakutia, Russia (e.g. Mir, Udachnaya and Zagadochnaya). The Jericho JD-1 kimberlite pipe in northern Canada has also entrained a relatively high proportion of eclogite xenoliths.

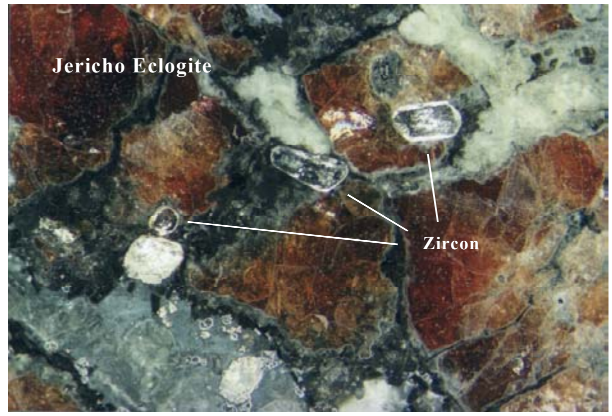
One of the more unusual suite of eclogites identified in the Jericho kimberlite JD-1 include a small proportion (2-3%) that contain both zircon and rutile. In addition, we report for the first time a Jericho eclogite xenolith that contains abundant apatite, rutile and zircon. Such zircon/rutile-bearing eclogites entrained in kimberlites are extremely rare, although zircon-bearing eclogite xenoliths have been reported from a few Group B eclogite localities, where both the timing of protolith formation and high pressure metamorphism are recorded in the U-Pb zircon systematics. To our knowledge there are only two reported examples of entrained mantle xenoliths that contain both zircon and rutile. One is an eclogite (CCS-41) entrained in Calcutteroo micaceous kimberlite located 230 km north of Adelaide, Australia (Chen et al., 1994) and the other is from a veined harzburgite (LB-17) from the Labait volcano, Tanzania (Rudnick et al., 1999).

In this study we document the mineral and whole rock geochemistry for this unusual eclogite suite, constrain the Jericho kimberlite emplacement age using a variety of techniques including Rb-Sr dating of both kimberlite and eclogite phlogopite macrocrysts, U-Pb eclogite rutile and U-Pb dating of kimberlite matrix perovskite. In addition, we attempt to unravel the metamorphic and metasomatic history of these xenoliths by investigating the Sm-Nd mineral-whole rock system, U-Pb zircon growth history and the U-Pb systematics of eclogite garnet, rutile and apatite. Together these data provide evidence that the Jericho eclogite xenoliths record a protracted history involving Paleoproterozoic subduction, metamorphism and multiple periods of mantle metasomatism.

GEOLOGICAL SETTING

The Jericho kimberlites (JD-1, JD-2 and JD-3) are diamondiferous pipes that intrude 2.6 Ga Archean granitoid rocks of the central Slave craton, approximately 150 km north of the main cluster of pipes located near Lac de Gras, Northwest Territories. Other kimberlites have been recently discovered in the area and all apparently belong to a single kimberlite field spatially separated from pipes near Lac de Gras (Cookenboo et al., 1998). The nature of kimberlite magmatism at Jericho has been described in a series of publications reporting the emplacement history (Cookenboo, 1998), petrography and geochemistry (Kopylova et al., 1998a; Price et al., 2000). Most of this research has concentrated on the JD-1 pipe and its northern satellite JD-2. The JD-1 pipe is an elongate body with three discrete lobes that can be traced for approximately 300 meters along strike (Cookenboo, 1998). The JD-2 kimberlite is a small satellite pipe 250 m north of JD-1. These two pipes are connected by a 1-m-wide kimberlite dyke (Cookenboo, 1998). The JD-3 pipe (Figure 2) is a steep-walled, pipe-shaped intrusion of elliptical shape (Cookenboo, 1998). JD-3 kimberlite typically has a fragmental texture, is less dense than JD-1 and there is a conspicuous absence of hypabyssal kimberlite (Cookenboo, 1998).

The Jericho intrusions have been described as non-micaceous Group 1 kimberlite (Kopylova et al., 1998a). Three distinct types of kimberlite have been recognized at JD-1 and can be distinguished by colour, texture, degree of serpentinization, magnetic susceptibility and density (Cookenboo, 1998). From oldest to youngest the Jericho kimberlite phases are; 1) uniform blue-gray to dark gray macrocrystal hypabyssal calcite kimberlite containing macrocrysts of olivine (30 modal percent), orthopyroxene, clinopyroxene and ilmenite, 2) dark green pelletal kimberlite consisting of serpentinized olivine macrocrysts and serpentine inter-clast matrix, 3) greenish-gray pelletal kimberlite with macrocrysts of olivine, phlogopite, ilmenite and chrome diopside hosted in a serpentine matrix (Cookenboo 1998). Kopylova et al. (1998a) concluded that all three phases could be derived from the same parental kimberlite magma based on similarities in trace element contents.



DESCRIPTION OF ECLOGITES

Mantle xenoliths up to 30 cm in diameter are abundant within Jericho kimberlite and include eclogite (ca. 25%), coarse peridotite, porphyroclastic peridotite, megacrystalline pyroxenite and a petrographically distinct suite of ilmenite-garnet wehrlites (Kopylova et al. 1998b). Based on an examination of 206 eclogite xenoliths from Jericho, Cookenboo et al. (1998) report the existence of both massive (c.30%) and foliated varieties. In addition to garnet and omphacite, the Jericho eclogites can contain apatite, ilmenite, rutile and olivine with secondary amphibole, calcite, chlorite, epidote, phlogopite and serpentine (Kopylova et al., 2001; Heaman et al., 2002). Rare eclogite types include a small proportion of zircon- (Figure 1), kyanite- as well as diamond-bearing eclogite. The diamond-bearing eclogites have a massive texture with a remarkably uniform garnet composition characterized by a distinctive high-Mg signature (Cookenboo, 1998). The unique chemical composition of the diamond-bearing eclogites has been interpreted to reflect derivation from a thin mantle layer at considerable depth (Cookenboo, 1998). The mineral chemistry of massive eclogites that lack this signature plus all anisotropic eclogite from Jericho are similar to Group B and C eclogite. These eclogite xenoliths are interpreted to reflect pieces of subducted oceanic crust (Kopylova et al., 1998a). Some Jericho eclogites record paleotemperatures up to 1170^{o}C and, when projected to the Slave geotherm, are interpreted to be derived from depths between 90-195 km (Kopylova et al., 1998b; 2001).

Fifteen zircon-bearing eclogite xenoliths from eleven different drill holes were examined in this study. The majority of xenoliths investigated are of the granular variety and some show evidence of pervasive alteration. The alteration can occur as 0.5 to 2.0 mm irregular milky white patches (carbonate?) and/or as thin (0.2-2.0 mm) anatomizing grayish-green veins dominated by serpentine and chlorite. Garnet in all samples has a relatively uniform habit and chemistry, occurring as large (up to several mm) transparent reddish-orange crystals devoid of alteration or kelyphite. In general, the garnet chemistry in these eclogite xenoliths is relatively homogeneous with no evidence for chemical zoning. Garnet in the Jericho zircon/rutile-bearing eclogites typically contain low-MgO (4.0-9.9 wt.%), low-chromium (<0.05 wt.%), moderate CaO (6.9-11.3 wt.%) and FeO (21.6-27.5 wt.%). In this respect, garnet from these Jericho eclogites are quite similar to many of the low-MgO eclogites from Koidu. Garnet compositions from the Jericho zircon/rutile-bearing eclogites are quite distinct from the Jericho diamond-bearing eclogites (Cookenboo et al., 1998), which have high concentrations of MgO (19.4 to 21.3 wt.%) and low and relatively constant CaO contents (4.0-4.3 wt.%). Alteration veinlets transect garnet crystals and embayment features are common where garnet is in contact with alteration.

Clinopyroxene is somewhat more variable. In some xenoliths the clinopyroxene occurs as large (up to 5 mm), transparent, unaltered, forest green crystals. In others, clinopyroxene has a much lighter aquamarine hue. Clinopyroxene can be extensively altered to serpentine where only small islands of original clinopyroxene are preserved. The chemical composition of clinopyroxene in Jericho zircon/rutile-bearing eclogites is quite uniform with Group C traits: SiO_2 (56.1-56.5 wt.%), TiO_2 (0.12-0.16 wt.%), Al_2O_3 (12.9-14.3 wt.%), FeO (6.5-7.0 wt.%), MgO (4.9-5.8 wt.%), CaO (8.6-9.9 wt.%) and Na_2O (8.5-9.4 wt.%). The clinopyroxene sodium content in these Jericho eclogites is relatively high compared to the Jericho diamond-bearing eclogites (Cookenboo et al., 1998) and eclogites from many other xenolith localities.

JERICHO KIMBERLITE EMPLACEMENT

The timing of Jericho kimberlite emplacement has been determined by four different approaches and all indicate a Jurassic emplacement age. The first approach involved investigating the Rb-Sr systematics of phlogopite megacrysts from two of the Jericho pipes (JD-1 and JD-3) and from entrained eclogite and peridotite xenoliths. The majority of Jericho phlogopite megacrysts analysed in this study plot along a single isochron indicating a date of 173.3±1.3 Ma and a relatively precise initial strontium ratio of 0.7053±0.0003. These data indicate that there is no detectable difference in emplacement age between the Jericho JD-1 and JD-3 pipes. Furthermore, the reasonably good fit of most phlogopite data to the calculated regression line (MSWD=0.53) indicates that the majority of phlogopite likely formed from the same strontium reservoir. If this is the case then the Jericho kimberlite magma(s) have a similar strontium isotope signature and the xenolith phlogopite could have formed from interaction with fluids derived from this magma.

A similar emplacement age of 176.6±3.2 Ma was obtained using the U-Pb technique on matrix perovskite separated from the JD-3 kimberlite, corroborating the Rb-Sr phlogopite results discussed above. In addition, rutile isolated from one eclogite xenolith entrained in JD-1 yields a relatively precise weighted average $^{206}Pb/^{238}U$ date of 172.8±0.7 Ma, in excellent agreement with the Rb-Sr phlogopite and U-Pb matrix perovskite dates. Although the eclogite garnet analysis has a much lower $^{238}U/^{204}Pb$ composition (236) than the companion rutile (>4000), these two minerals plus the JD-3 matrix perovskite define a precise isochron date of 172.1±2.1 Ma, which is interpreted as a good independent estimate of the Jericho kimberlite emplacement age.

The fourth approach to estimating the time of kimberlite emplacement is reflected in the lower intercept dates for discordant zircon grains isolated from JD-1 eclogite xenoliths. The best-constrained zircon lower intercept date of 178±5 Ma is from xenolith JDLGS-021-MX10.

All four approaches yield similar age results and represent the first time that such a variety of techniques have been applied to a single kimberlite or kimberlite cluster. It is recommended that the more precise Rb-Sr phlogopite age of 173.1±1.3 Ma be used as the best estimate for the timing of kimberlite magmatism at Jericho. These results also document for the first time the presence of mid-Jurassic kimberlite magmatism in the Slave Province, Canada.

TIMING OF METASOMATISM/ METAMORPHISM

The Jericho eclogite whole rock Nd isotopic data display considerable scatter, indicating that these xenoliths preserve some Nd isotopic structure. If the xenoliths were equilibrated up to the time of entrainment in the kimberlite magma then the whole rock and minerals from a single xenolith should conform to an isochron that coincides with the time of kimberlite emplacement. To a first approximation, the Jericho eclogite xenolith JDLGS-046-MX8 approaches this situation. A reference line constructed through these two analyses yields a date of 166.5±7.5 Ma, within error of the 173 Ma Jericho kimberlite emplacement age. In other words the garnet has equilibrated with its host eclogite up to the time of entrainment. If this is the correct interpretation then a series of 173 Ma reference lines constructed to pass through the eclogite whole rock data indicates that the Jericho eclogites had variable initial Nd isotopic compositions prior to entrainment in the kimberlite and that isotopic homogenization occurred at the mineral scale but perhaps not over distances of several centimeters. If the diffusion distances for rare earth elements like Sm and Nd has been restricted to less than a few centimeters while the eclogites remained in the mantle then whole rock model Nd ages may record important information pertaining to the pre-eruption history of the mantle lithosphere.

The consistency of the model Nd T_{DM} ages of between 0.98-1.27 Ga is interpreted to indicate that the Jericho eclogites were either derived from protoliths of about this age or more likely that there was a significant REE-enrichment or equilibration event (e.g. metamorphism, metasomatism, or thermally driven equilibration) that took place at about this time. The Sm/Nd ratios of these Jericho eclogites are slightly lower (as low as 0.18) compared to values reported for relatively pristine oceanic basalts (0.26-0.36). The Mesoproterozoic model Nd dates could therefore reflect the time of REE-enrichment, which is most extreme in the apatite/rutile/zircon-bearing eclogite xenolith. We interpret these model Nd dates to record the time of at least one metasomatic event and note that the older model dates are quite close in time to 1.27 Ga Mackenzie Igneous Events. Interestingly, Jericho peridotite xenoliths record model Re depletion dates that vary between 3.1 and 0.5 Ga (Irvine et al., 2001) with a peak of model dates in the 1.2-1.5 Ga range, similar to many of the model Nd dates reported here. These authors interpret this young peak in model dates to reflect Re-Os modification by large-scale thermal/magmatic events such as the 1.27 Ga Mackenzie Igneous Events.

The Jericho eclogite xenoliths studied here are unique among kimberlite-borne eclogites in that they contain zircon. Zircon has a very high closure temperature to Pb diffusion (e.g. >900°C) so the U-Pb zircon systematics could provide a more robust record of the pre-kimberlite history of the Jericho eclogite xenoliths. The preservation of a multi-component age history in these eclogites is supported by both the complex internal structure preserved in the zircon crystals, with visible overgrowths that are especially revealed with CL imaging, and the discordance pattern of the U-Pb data. The U-Pb zircon results for five Jericho eclogite xenoliths display a similar pattern with a large range of model ^{207}Pb/^{206}Pb dates between 403-1593 Ma with all analyses documenting moderate to high degrees of discordance (39-69%). If continuous Pb diffusion is excluded as the principle mechanism causing the scatter displayed by most of the Jericho eclogite U-Pb data, then the zircon discordance pattern reflects subsequent thermal and/or metasomatic events that caused episodic Pb-loss or new zircon growth. Visible core/overgrowth relationships are preserved in some Jericho zircon and the complex growth structure revealed CL imaging is most likely a result of multiple periods of zircon growth. The very fact that such internal geochemical structure and ages older than the time of eclogite entrainment are preserved in zircon is testament to the very high closure temperature (>900^{o}C) to element diffusion in this mineral.

At least three dates can be gleaned from the U-Pb zircon data, Paleoproterozoic (>1.79 Ga) and Mesoproterozoic (0.96-1.06 Ga) upper intercept projections that are anchored by the time of kimberlite emplacement and the lower intercept date of 178±5 Ma. The difficulty is deciphering which date possibly corresponds to the time of eclogite metamorphism.

The Paleoproterozoic upper intercept dates can be explained in at least three ways: 1) the age of a primary mafic magmatic zircon component (minimum estimate of 1786 Ma), 2) the age of an inherited Pb component from zircon xenocrysts or 3) the age of high grade metamorphism (±metasomatism). Considering the possibility that the Paleoproterozoic zircon component is primary magmatic, it is important to note that very few mafic or ultramafic rocks contain primary zircon. In mafic/ultramafic samples that do contain primary magmatic zircon they tend to be small, often lacking well-developed crystal faces (forming shards), have moderate to high uranium contents (>200 ppm) and are characterized by quite high Th/U, unlike the zircon recovered from Jericho eclogites (e.g. low U: <70 ppm; low Th/U: 0.05-0.37). A xenocrystic origin for the Paleoproterozoic component is also possible and consistent with the correlation between high Th/U ratios and older ^{207}Pb/^{206}Pb dates recorded in some Jericho eclogite zircon. However, zircon is a rare mineral in mantle rocks so it is difficult to envisage a process whereby zircon inheritance occurred in a mantle-derived magmas intruding the subcontinental lithosphere or from subducted oceanic crust.

Petrographically, zircon occurs most commonly as subhedral inclusions randomly distributed in garnet and clinopyroxene. There is no evidence that the Jericho zircon is preferentially associated with alteration or veining. This together with the low uranium contents and low Th/U is taken as evidence for a dominantly metamorphic origin. The oldest Paleoproterozoic zircon growth (>1786 Ma) likely occurred during initial eclogite metamorphism and the data scatter reflects subsequent thermal and/or metasomatic events that caused episodic Pb-loss or new zircon growth. One of these events occurred at around 1.0 Ga. The upper intercept dates for the youngest zircon grains are relatively consistent and vary between 957-1061 Ma, overlapping the younger model Nd eclogite whole rock dates and one of the peaks of Re depletion ages recorded in Jericho peridotite xenoliths (Irvine et al., 2001). It is unclear at this point whether the range between 0.96-1.27 Ga in young zircon upper intercept and model Nd dates reflects the influence of more than one Proterozoic thermal and/or metasomatic event in the Slave subcontinental mantle or not. Known magmatic events in this time interval that may have influenced the Slave mantle lithosphere include the 1.27 Ga Mackenzie, 0.78 Ga Gunbarrel and 0.72 Ga Franklin Igneous Events.

SUMMARY

The Jericho kimberlite JD-1 is an important new source of mantle xenoliths that hold clues to the nature of the Slave craton subcontinental mantle. A high proportion of the mantle xenolith population consist of various eclogite types including a small number of kyanite-, diamond-, apatite- and zircon-bearing eclogite. Kimberlite-borne zircon-bearing eclogite is extremely rare but comprises 2-3% of the Jericho eclogites. A variety of dating techniques were applied to constrain the age of two Jericho kimberlites, JD-1 (170.2±4.3 Ma Rb-Sr phlogopite megacrysts, 172.8±0.7 Ma U-Pb eclogite rutile, 178±5 Ma U-Pb eclogite zircon lower intercept) and JD-3 (173±2 Ma Rb-Sr phlogopite megacryst; 176.6±3.2 Ma U-Pb matrix perovskite) and all yielded identical results within analytical uncertainty. There is no discernable difference in age dates obtained for these two pipes therefore the composite Rb-Sr phlogopite megacryst date of 173.1±1.3 Ma is interpreted as the best estimate for the emplacement age of both Jericho pipes. The initial Sr isotopic composition of 0.7053±0.0003 derived from phlogopite megacrysts confirms the Jericho kimberlite is a Type 1 kimberlite.

The most profound aspect of the Jericho zircon/rutile-bearing eclogite xenoliths is their peculiar geochemistry. The eclogite whole rock compositions are very unusual displaying enormous enrichment in HFSE such as Nb (133-1134 ppm), Ta (5-28 ppm), Zr (1779-4934 ppm) and Hf (23-64 ppm). This HFSE-enrichment is linked to the prolific growth of large (up to 2 mm) zircon and niobian rutile crystals (up to 3 modal percent) near the time of eclogite metamorphism.

The integration of information from petrographic, whole rock and mineral geochemistry, zircon geochronology and isotope tracer techniques indicate that the Jericho zircon-bearing eclogites have had a complex history involving Paleoproterozoic eclogite metamorphism (>1.79 Ga), partial melting, thermal perturbations and two or more episodes of mantle metasomatism. The oldest metasomatic event occurred near the time of Paleoproterozoic metamorphism and partial melting and is responsible for the extreme HFSE enrichment and growth of zircon and high-niobian rutile. A second thermal perturbation and concomitant carbonatite metasomatism occurred in the period 1.0-1.3 Ga and is recorded in relatively consistent whole rock eclogite model Nd ages and secondary U-Pb zircon upper intercept dates. The eclogite protoliths could represent metasomatized pieces of oceanic crust, possibly linked to east-dipping subduction beneath the Slave craton during 1.88-1.84 Ga Great Bear Magmatic arc time, or could be pieces of mafic/ultramafic sill complexes that intruded the Slave lithospheric mantle at depths of about 150 km. Whether the fluids responsible for metasomatism and HFSE-enrichment are linked to Paleoproterozoic carbonatite magmatism or are partly derived from devolitization of carbonated oceanic crust, is unclear. The existence of HFSE-enriched mafic material in the Slave subcontinental mantle cannot be disputed and such material provides a perfect geochemical complement to subduction zone magmatism.

REFERENCES

Chen, Y.D., O'Reilly, S.Y., Kinny, P.D., and Griffin, W.L., 1994. Dating lower crust and upper mantle events: an ion microprobe study of xenoliths from kimberlitic pipes, South Australia. Lithos v.32, p.77-94.

Cookenboo, H.O. 1998b. Emplacement history of the Jericho kimberlite pipe, northern Canada. Extended Abstracts, 7th International Kimberlite Conference, Cape Town, 161-163.

Heaman, L.M., Creaser, R.A., and Cookenboo, H.O. (2002). Extreme enrichment of high field strength elements in Jericho eclogite xenoliths: A cryptic record of Paleoproterozoic subduction, partial melting, and metasomatism beneath the Slave craton, Canada. Geology v.30, 507-510.

Kopylova, M.G., Russell, J.K. and Cookenboo, H., 1998a. Petrography and chemistry of the Jericho kimberlite (Slave Craton, Northern Canada). Extended Abstracts, 7th International Kimberlite Conference, Cape Town, p.449-451.

Kopylova, M.G., Russell, J.K. and Cookenboo, H., 1998b. Upper-mantle stratigraphy of the Slave craton, Canada: insights into a new kimberlite province. Geology v.26, 315-318.

Kopylova, M.G., Russell, J.K., and Christensen, N.I., 2001. Composition and fabric of the N. Slave eclogite as evidence for mantle metasomatism. Lithoprobe Report 81, Proceedings from Pan-Lithoprobe Workshop III: Mantle Lithosphere and Lithoprobe: Views of Continental Evolution from the Bottom Up, 61-70.

Price, S.E., Russell, J.K., and Kopylova, M.G., 2000. Primitive magma from the Jericho pipe, N.W.T., Canada: Constraints on primary kimberlite melt chemistry. Journal of Petrology 41, 789-808.

Rudnick, R.L., Ireland, T.R., Gehrels, G., Irving, A.J., Chesley, J.T., and Hanchar, J.M., 1999. Dating mantle metasomatism: U-Pb geochronology of zircons in cratonic mantle xenoliths from Montana and Tanzania.7th IKC Capetown 728-735.