

# INTEGRATED MODELS OF DIAMOND FORMATION AND CRATON EVOLUTION

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## INTRODUCTION

An important goal of studies of Archean continents is to relate the age and composition of peridotite, eclogite, and diamonds to the geological processes of craton creation and assembly. For southern Africa, regional patterns of diamond composition and episodes of diamond growth can now be explained with models of cratonic lithosphere creation, stabilization and modification by using these disparate data sets: 1) decades of research on diamonds from major diamond mines, 2) application of the Re-Os isotopic system to age determinations of peridotites, eclogites, and sulfide inclusions in diamond, 3) high-accuracy thermochronometry of the lower crust, and 4) a new seismic pictures of the lithosphere.

## OBSERVATIONS

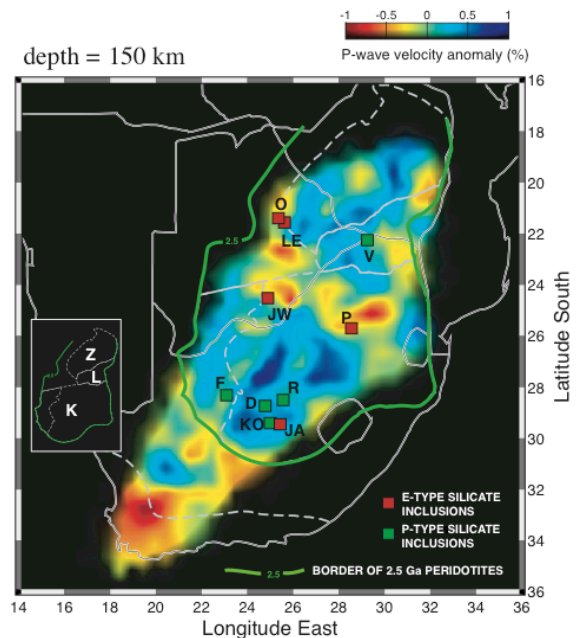
### SEISMIC STRUCTURE

The Kaapvaal-Zimbabwe craton is marked by relatively high P-wave velocity lithospheric mantle that occurs in two prominent but irregularly shaped lobes separated by a broad west-northwest trending band of relatively lower velocity mantle (Fig.1). Kimberlites distributed across southern Africa have diamonds that derive from mantle with differences in seismic velocity (Fig. 2).

### DIAMOND AGE

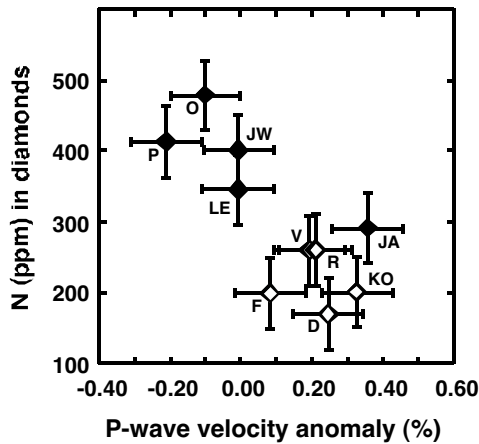
Data on single E-Type sulfides from the De Beers Pool, Jwaneng, Koffiefontein, and Orapa collectively form a  $^{187}\text{Re}/^{188}\text{Os}$  vs  $^{187}\text{Os}/^{188}\text{Os}$  data array that has significant scatter about a circa 2.9 Ga age slope (Pearson et al., 1998; Richardson et al., 2001; Shirey et al., 2001; Shirey et al., 2003). Inclusions from the De Beers Pool show the tightest 2.9 Ga line while the other diamond suites fall around this age but with more scatter. In three localities (De Beers Pool being the exception), there are two generations of sulfide inclusions: an Archean, circa 2.9 Ga age suite and a Proterozoic suite with an age matching the Proterozoic silicate inclusion

age. The circa 2.9 Ga age is not resolvable from the Re-Os model ages obtained on mantle peridotites (Carlson et al., 1999; Carlson et al., 2000; Irvine et al., 2001).



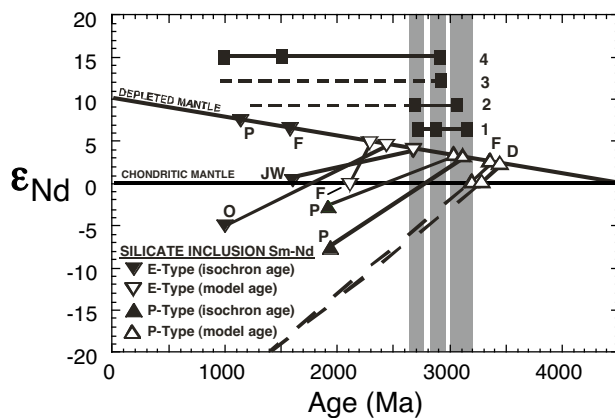
**Figure 1.** Tomographic image of the lithospheric mantle derived from seismic P-wave data at a depth of 150 km (James et al., 2001; James and Fouch, in press). The color scheme depicts % deviation from an average cratonic lithosphere velocity model. Areal coverage spans the lithospheric mantle of the Kaapvaal (K) and Zimbabwe (Z) cratons and the Limpopo mobile belt (L; see inset, left). Bold green line indicates the outermost boundary of the Archean cratons. Diamond mines are shown by colored squares; red for those localities whose silicate inclusion suites are predominately eclogitic (Jagersfontein=JA, Jwaneng=JW, Letlhakane=LE, Orapa=O, Premier =P) and green for those whose silicate inclusion suites are predominately peridotitic (Kimberley area mines of Wesselton, Bultfontein, and Dutoitspan termed De Beers Pool=D, Finsch=F, Koffiefontein=KO, Roberts Victor =R, and Venetia=V). Reprinted with permission from Shirey et al, 2002, *Science*, 297: 1683-1686. Copyright 2002 American Association for the Advancement of Science.

P-Type (harzburgitic) garnets from Finsch and De Beers Pool (Richardson et al., 1984) have the oldest



**Figure 2.** Average N abundance in diamonds versus P-wave velocity anomaly. Error bars have been set at  $\pm 50$  ppm for average N abundance, and  $\pm 0.1$  % for P-wave velocity anomaly. Same lettering scheme as in Fig. 1. Peridotitic = open symbols; eclogitic = closed symbols. After Shirey et al. (2002).

model ages yet recorded for inclusions in diamond from southern Africa (Fig. 3). Premier P-Type (lherzolitic) garnets have a much younger isochron age (1.9 Ga, Richardson et al., 1993) but an Archean (3.0 Ga) depleted mantle model age. All other southern African silicate inclusion suites dated with the Sm-Nd system (Richardson, 1986; Richardson et al., 1990; Smith et al., 1991; Richardson et al., 1999) are E-Types and yield Proterozoic isochron or model ages (Fig. 3).



**Figure 3.** Sm-Nd isochron and model ages of silicate inclusions in diamond compared to the ages of major crust forming events in the Kaapvaal craton (1; Schmitz, 2002), peridotite xenolith Re-Os model ages (2; sources, cited in text), diamondiferous eclogite xenoliths (3; Shirey et al., 2001; Menzies et al., 2002), and sulfide inclusions in diamonds (4; sources cited in text). After Shirey et al. (2003).

## DIAMOND COMPOSITION

Diamonds selected for C isotopic and N studies often provide a more representative diamond sample than those selected for age studies because they include both the P-Type and E-Type parageneses that are typically present at each locality. These undated diamonds reveal a large range in their C isotopic composition and N abundance. It has long been known (Sobolev et al., 1979) that diamonds of both P-Type and E-Type paragenesis show a prevalent mantle-like carbon isotopic composition ( $\delta^{13}\text{C} = -3$  to  $-7\text{‰}$ ) with an isotopically light sub-population ( $\delta^{13}\text{C} = -10$  to  $-34\text{‰}$ ), dominated by diamonds of E-Type paragenesis. Compiled data for the Kaapvaal-Zimbabwe cratons (Kirkley et al., 1991; Shirey et al., 2002; Shirey et al., 2003) adheres to this pattern.

Deines and coworkers (1989; 1993; 1997) previously noted the significantly higher N content of E-Type diamonds from Finsch, Jwaneng, Orapa, and Premier compared to their P-Type counterparts from the same kimberlite. This paragenesis versus diamond N content relationship extends to all ten kimberlites with well-studied diamond populations (Fig. 2). The N content difference apparently does not lead to a significant difference in the aggregation state of N in Type Ia stones (Shirey et al., 2002; Shirey et al., 2003).

## DIAMOND AGE, COMPOSITION AND STRUCTURE OF THE MANTLE KEEL

Kramers (1979) and Richardson (1984) first showed that diamonds are late- to mid- Archean, confirming that parts of the craton were underlain by mantle keel that could be as old as the oldest crust. Subsequent work of Richardson and coworkers (1986; 1990; 1993; 1999) on diverse eclogitic and lherzolitic silicate inclusions in diamonds produced Proterozoic ages suggesting a progression to more fertile silicate inclusion compositions with time. Recent Re-Os data show that all four of the eclogitic sulfide inclusion suites studied have late Archean ages that agree with late Archean Re-Os mantle model ages on cratonic peridotite (Carlson et al., 1999; Irvine et al., 2001; Shirey et al., 2001). The P-Type silicate inclusion model ages of 3.2-3.4 Ga, overlap some of the oldest crustal U-Pb ages obtained in the western Kaapvaal craton (Moser et al., 2000; Schmitz, 2002) and predate many other materials in the lithosphere (Fig. 3).

The old, P-Type, harzburgitic silicate inclusions in diamonds from the De Beers Pool and Finsch were

derived from seismically faster lithospheric mantle. The other P-Type silicate inclusion suite dated (Premier) which is lherzolitic and Proterozoic (Richardson et al., 1993), was derived from seismically slower mantle. All the other silicate inclusion suites dated so far are eclogitic, Proterozoic (Richardson, 1986; Richardson et al., 1990; Richardson et al., 1993; Richardson et al., 1999) and derived from seismically slower mantle. Sulfide inclusions from the four localities studied so far which are eclogitic, mostly Archean in age (Pearson et al., 1998; Richardson et al., 2001; Shirey et al., 2001), and derived from both fast and slow mantle. Of these four localities, De Beers Pool, with diamonds from seismically faster mantle, has the lowest percentage of Proterozoic inclusions.

Diamond paragenesis determines the pattern of C isotopic composition of diamond relative to lithospheric mantle seismic velocity. The frequency distribution of C isotope composition for E-Type diamonds appears nearly identical to that for diamonds from the seismically slow lithospheric mantle (Shirey et al., 2002). Additional complexities from Premier, Jagersfontein and Roberts Victor that are masked by the large number of specimens from Jwaneng and Orapa E-Type diamonds with C isotopic compositions less than  $-9\%$  (Shirey et al., 2003).

Nitrogen abundance also shows some correspondence with lithospheric seismic structure linked to paragenesis (Shirey et al., 2002; Shirey et al., 2003). Diamonds from Jwaneng, Letlhakane, Orapa, and Premier, the majority of which are eclogitic, have a higher percentage of Ia types and an average N content above 290 ppm, and were derived from seismically slower mantle. Diamonds from Koffiefontein, Finsch, Roberts Victor, Venetia and the De Beers Pool, the majority of which are peridotitic, have a lower percentage of Ia types and an average N content below 290 ppm, and were derived from seismically faster lithospheric mantle. The aggregation state of N in the Ia diamonds displays no clear systematic variation with lithospheric seismic velocity although De Beers Pool, Finsch and Roberts Victor diamonds from seismically fast mantle display the lowest percentages of aggregation to B-centers (Shirey et al., 2002; Shirey et al., 2003).

## **DIAMOND FORMATION AND CRATON EVOLUTION**

The current lithospheric seismic structure of the craton is interpreted to be a mid-Proterozoic overprint to a predominantly 2.9-3.4 Ga keel as evidenced by the

occurrence of inclusions and xenoliths of both Archean and Proterozoic age in the same or closely-spaced kimberlites from seismically slow lithosphere (e.g. Orapa-Letlhakane, Jwaneng, Premier). Correlation of the seismically slow regions of the northern Kaapvaal Craton that trend ESE-WNW south of the Limpopo belt (Fig. 1) with surface outcrop of the 2.05 Ga Bushveld Complex in South Africa and Molopo Farms Complex in Botswana suggests that the modification may be closely related to Bushveld-Molopo magmatism. For the seismically slow mantle that trends N-S on the west side of the Zimbabwe craton (Fig. 1), regional metamorphism that created the Mogondi-Okwa terranes was likely to have been the surface manifestation of the tectonism that modified the craton on this margin.

Thermal structure of the Kaapvaal lithospheric mantle from surface heat flow (Jones, 1988) and cratonic geotherms from Premier xenoliths (Danchin, 1979) show that in at least one part of the seismically slow lithosphere a normal cratonic geotherm has existed since 1.2 Ga. This is key evidence that the lithosphere is seismically slower chiefly because it is compositionally different (e.g. higher in basaltic components and metasomatizing veins), not hotter. Diamond suites from seismically slower lithosphere have a greater percentage of eclogitic inclusions which are in direct agreement with regions of the lithosphere that would have a higher proportion of basaltic components.

Cratonic nuclei were first created by mantle melting processes that produced severe depletion of the lithospheric mantle (Richardson et al., 1984) and an early phase of crustal differentiation. The existence of these early cratonic nuclei could have provided a locus against which to accrete cratonic lithosphere created in the second step of the process (Shirey et al., 2002). In this phase, subduction, which may have included depleted oceanic harzburgite and/or the roots of Archean oceanic plateaus, built the rest of the lithospheric mantle. A second phase of lithosphere creation such as this could account for many geochemical features of the lithospheric mantle. This two-step lithosphere creation model also fits the detailed geochronological record for the lower and upper crust of the western Kaapvaal craton in which the earliest crustal components are formed from 3.20-3.26 Ga and the craton is sutured together by subduction convergence at 2.88-2.94 Ga (Schmitz, 2002).

Subduction for the western craton is supported by stable isotopic data from Orapa and Jwaneng. Orapa E-Type diamonds have light C and heavy N isotopic compositions (Cartigny et al., 1999) and sulfide

inclusions with mass-independent sulfur isotopic fractionations (Farquhar et al., 2002). These signatures are consistent with incorporation of C, N, and S from surficial sedimentary endmember reservoirs (Navon, 1999; Farquhar et al., 2002) even though intra-mantle fractionation (e.g. Cartigny et al., 2001) that changed C and N isotopic composition of fluids during diamond growth, are required.

The near one-to-one correspondence of Proterozoic diamond suites having a majority of E-Type silicate inclusions with seismically slow mantle suggests that craton modification and Proterozoic diamond formation were part of the same process that involved basaltic components. These were generated in conjunction with Bushveld-Molopo Farms magmatism under the center of the northern Kaapvaal craton or in conjunction with some form of subduction along the western Kaapvaal-Zimbabwe craton margin (Shirey et al., 2002). Both sublithospheric magmatism and western craton margin subduction were tectonothermal events that altered the composition of the lithosphere and added new diamonds to an already extensive Archean diamond population resident in the lithosphere.

## APPLICATION TO NEW AREAS AND OTHER CRATONS

The correlation of existing diamond age, composition and inclusion paragenesis data with lithospheric seismic structure provides a set of predictions that can be applied to future diamond studies: a) the eastern domain of the Kaapvaal-Zimbabwe craton should have its own clustering of diamond ages that are systematically older than those in the western domain, b) new suites of P-Type inclusions should be 3.2 Ga old or greater and be rare outside of seismically fast lithosphere, c) additional suites of E-Type diamonds should be widely distributed in all domains of the craton, and d) Proterozoic diamonds from the seismically slower part of the lithosphere might be expected to have the greatest range in age and composition.

Inclusion paragenesis versus age shows a remarkable similarity from craton to craton. The oldest inclusions yet dated on the Kaapvaal-Zimbabwe, Siberian and Slave craton are all P-Types (harzburgitic silicate or sulfides) in the 3.2-3.4 Ga age range (Richardson et al., 1984; Pearson et al., 1999a; Westerlund, this volume; Pearson et al., 1999b). Both the Kaapvaal-Zimbabwe craton and the Siberian craton have abundant 2.9 Ga eclogitic components associated with diamonds (Pearson et al., 1995; Shirey et al., 2001; Shirey et al.,

2003). Both cratons have a Proterozoic, lherzolitic silicate inclusion suite that has a negative initial epsilon Nd yielding Archean model ages (Richardson et al., 1993; Richardson and Harris, 1997; Richardson et al. this volume). These similarities in age and paragenesis of diamond suites among cratons that are now so widely separated may indicate that diamond formation on the Archean Earth was controlled by global scale events in mantle/crustal evolution and/or that Kaapvaal/Zimbabwe, Siberian, Slave, and Australian cratons were situated close together in an Archean supercontinent that may have become disassembled by the mid-Proterozoic.

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