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INSIDE

Continental Growth, Preservation, and Modification in Southern Africa

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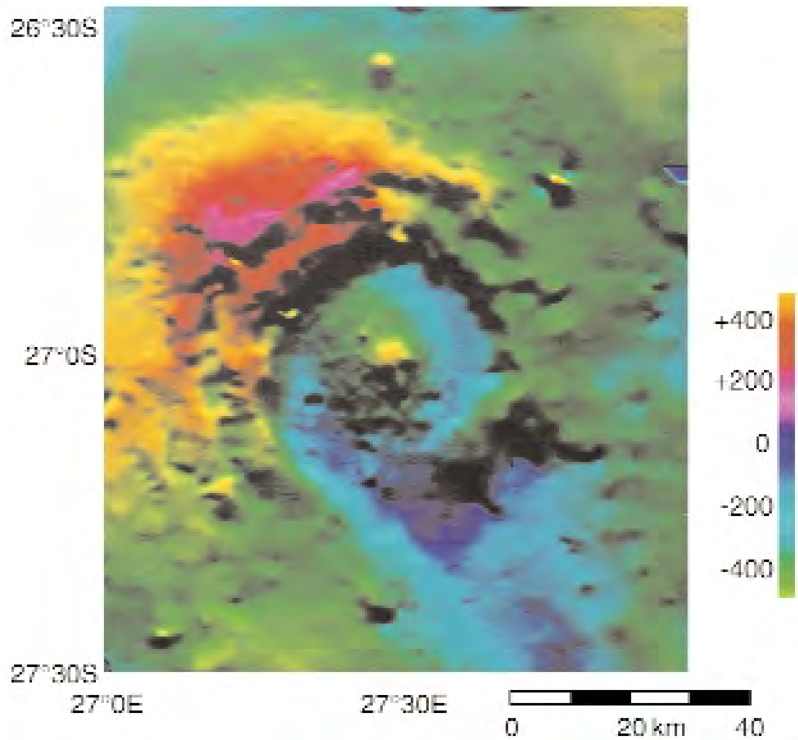

Figure 2. Bouguer gravity image (courtesy of South African Council for Geosciences) across Vredefort impact structure, South Africa. Color scale is in relative units representing total gravity variation of 90 mgal across area of figure. Yellow circular pattern close to geometric center reflects local gravity high that suggests that the core of the structure is underlain by dense mafic or ultramafic rock. Borehole located close to peak of gravity anomaly indicates that rocks beneath surface consist mainly of peridotite.

ABSTRACT

To understand the origin, modification, and preservation of continents on Earth, a multidisciplinary study is examining the crust and upper mantle of southern Africa. Xenoliths of the mantle brought to the surface by kimberlites show that the mantle beneath the Archean Kaapvaal craton is mostly melt-depleted peridotite with melt extraction accompanying crust formation in the Archean. Eclogitic xenoliths from the craton record subduction of altered oceanic crust beneath the craton at ca. 3 Ga. Proterozoic age peridotite found beneath the surrounding Proterozoic accretionary belts provides evidence for crust-mantle coupling and long-term stability of the upper 150 km of the lithosphere. Petrologic examination of Archean ultramafic magmas (komatiites) from South Africa indicates that some komatiitic magmas contain substantial quantities of water (>4 wt%). This finding strengthens the possibility that the cratonic lithosphere formed initially in a subduction zone setting, the demise of which led to accretion of the arc crust and thickening of the lithospheric mantle to create a stable, thick, continental lithosphere. Geochronologic studies of lower crustal xenoliths from the craton show a prolonged thermal evolution of the lower crust extending to 1 Ga. This thermal evolution is also reflected in ca. 1 Ga ages of some eclogitic diamond inclusions from the lithospheric mantle.

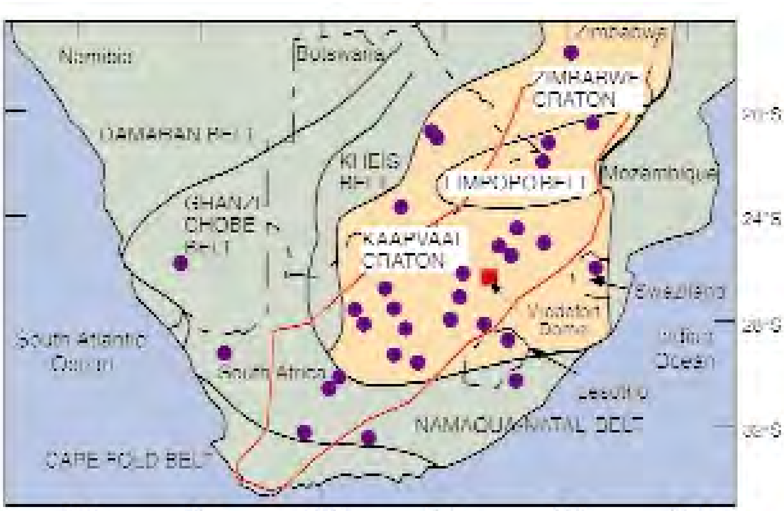

Figure 1. Geologic sketch map of southern Africa. Brown indicates areas underlain by Archean basement; green indicates Proterozoic metamorphic belts; blue dots indicate major kimberlites (Gurney et al., 1991); red square marks Vredefort impact structure. Portable, broad-band seismometer deployment covers area outlined in red.

INTRODUCTION

To explore the causes of continent formation and preservation, a multidisciplinary study involving geology, geochemistry, geochronology, petrology, and

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IN THIS ISSUE

CORRECTION: Cordilleran Section Field Trips 8 and 9

Field trip 8 for the Cordilleran Section meeting has NOT been canceled, contrary to what appears on page 31 of January 2000 *GSA Today.* Trip 8, Tertiary Geology of the Eastern Flank of the Central Cascade Range, Washington, is still on the schedule and should not be crossed out on the preregistration form.

Field trip 9, Quesnel Terrane—Always There?, IS canceled, and should be crossed out on the preregistration form.

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seismology was initiated 3 years ago with support from the National Science Foundation Continental Dynamics Program. The study focuses on the current structure and geologic history of southern Africa. A general description of the project and list of participants can be found at www.ciw.edu/mantle/kaapvaal/. The centerpiece of the study is an array of 55 portable broadband seismometers placed in 82 sites along a rectangular array from Cape Town to Zimbabwe (Fig. 1; Carlson et al., 1996; James et al., 1999). This report summarizes early results from the geochemical, geochronologic, and petrologic components of the Kaapvaal Craton Project.

Southern Africa provides an excellent field laboratory to study the history of ancient continents. The region (Fig. 1) comprises the Archean Kaapvaal and Zimbabwe cratons, separated by a late Archean metamorphic terrane, the Limpopo Belt (Tankard et al., 1982). Overall, the Kaapvaal craton is made up of a number of granite-greenstone terranes with distinctive igneous rocks, deformation histories, and tectonic styles that were welded together to form the core of the continent (de Wit et al., 1992). Surrounding the cratons are accretionary belts added in the middle to late Proterozoic. Of particular interest, the southern African lithosphere has been penetrated by hundreds of kimberlite diatremes (Fig. 1) that have brought xenoliths of lower crust and upper mantle to the surface (Gurney et al., 1991).

CRUSTAL GROWTH AND MODIFICATION

Whereas the geology of the shallow crust of the Kaapvaal craton is relatively well known, the deeper crust is not well exposed. One exception is the large circular Vredefort structure in the middle of the Kaapvaal craton (Fig. 2). It is widely regarded as a deeply eroded remnant of a 2.02 Ga impact crater (Kamo et al., 1996; Moser, 1997). Hart et al. (1990) suggested that the impact turned the crust on its side so that traversing from rim to center leads one from near-surface sediments through mid-crustal granite to granulite grade supracrustal rocks. At the center of the impact structure is a large positive gravity anomaly (Fig. 2) that has been drilled and found to consist predominantly of peridotite. Re-Os systematics of this peridotite are similar to those of the kimberlite-borne xenoliths from the Kaapvaal lithospheric mantle that have very low Re/Os and $^{187}Os/^{188}Os$ ratios, and Re-depletion model ages of 3.3 to 3.5 Ga (Tredoux et al.,

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Dialogue

Sara Foland, CEO

© Paul Abdoo

At Dinosaur Ridge near Morrison, Colorado.

Quantifying the Science of Geology

> Geology is ... the study of Earth and other planets and planetary objects using any and all available techniques; it includes geochemistry and geophysics.
>
> *—GSA Council, 1989*

The January 2000 Dialogue discussed geology as an art form, in the context of our ability (or lack thereof) to define all the parameters from observation in this grand experiment we call Earth. The November 1999 column talked about how GSA is fostering integrative solutions to the complex geoscience problems that challenge us today. This month, we define our Society's role as facilitator for members and their colleagues to discuss and debate the science of geology.

GSA's Strategic Planning Group took the key elements from the 1989 definition of geology and incorporated them into the following vision:

The Geological Society of America is a broad, unifying scientific society:

- Fostering the human quest for understanding Earth, planets, and life;
- Catalyzing new scientific ways of thinking about natural systems;
- Applying geoscience knowledge and insight to human needs and stewardship of the Earth.

This vision sets forth our charge as members of GSA and of society as a whole. From these statements, we also derive our values—science, stewardship, and service. In support of our vision and values, GSA, with its Divisions and Associated Societies, provides members with various venues to carry on open scientific debate. These venues are publications, meetings at the national and regional level, and various philanthropic programs for students and society.

Publications

We publish a variety of journals and books on a wide range of geoscience topics. In 1999, we published twelve Special Papers on subjects from faults in the northern Appalachians to the geomorphology of the Himalayas. *Geology* and the *Geological Society of America Bulletin* contained 451 articles (329 in *Geology;* 122 in *Bulletin*) in 3,072 pages. Our journals continue to be among the most frequently cited geoscience references, ranking as two of the top five geoscience journals in the Science Citation Index. Additionally, *Geology* and the *Bulletin* are well regarded as two of the most rigorously peer-reviewed publications. One map was produced in 1999, and work is being completed on the final Decade of North American Geology (DNAG) map (the Geological Map of North America). In response to many requests, we began a new field guide series that gathers in one volume all the supporting information for field trips held at the GSA Annual Meeting. *Geology* and the *Bulletin* are now available in PDF format on-line (www.geosociety.org). As we enhance the presentation with links and searchable archives, we will offer subscriptions to institutions and individuals. A feasibility study is underway to evaluate archiving past issues of our current journals and the lead science article from *GSA Today.*

Meetings

Each year GSA holds one national meeting and six regional Section meetings. The 1999 Annual Meeting in Denver had the largest number of submitted abstracts—2,942—ever. More than 108 technical and Pardee sessions covered topics as diverse as the subject of geology itself. Of the 6,389 registrants, 1,701 were students. The global nature of our science and our Society is indicated in the 465 attendees from foreign countries. Richard Kerr (*Science,* November 12, 1999, v. 286, p. 1279–1281) highlighted our meeting and noted that topics ranged from asteroids of today to the various geochronological techniques used to date critical moments in geological time. His review article exemplifies the topical diversity that our members and associates present from their research. The 2000 Section meetings, which begin in March, will provide students an opportunity to present their work in smaller, less intimidating venues.

Philanthropic Programs

The GSA Foundation and our members support 69 science, education, and outreach programs. Of these, student research grants, a program begun in 1933, provide the most direct and immediate support of geoscience. In 1999, GSA, in partnership with the National Science Foundation, supported 212 research projects (averaging $1,865 per grant; to date, GSA has given 6,555 research grants totaling $6,820,341 to students). Whether for an additional geochemical analysis, a few more days in the field, or travel to a meeting to share results, grants to students continue to be supported by GSA and its members. Toward our goal to promote integrative approaches to understanding natural systems, we are working with partners to establish a grants program for teams of graduate student researchers, representing earth, life, planetary, and/or social scientists and economists.

GSA, its Divisions, and our Associated Societies continue to provide members with forums for active debate. Although the formats for these forums may change over the next several years, the need for the most timely and highest quality opportunities for scientific debates will continue to grow.

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1999). These data suggest that the deep crust–mantle transition is exposed in the Vredefort section.

Besides abundant mantle xenoliths, many southern African kimberlites contain excellent suites of lower crustal xenoliths. High-resolution U-Pb accessory-mineral geochronology of these lower crustal xenoliths furthers our understanding of the interrelationships between the surficial geologic record and nascent mantle geochronology. Sapphirine granulite xenoliths in the Lace, Voorspoed, and Star kimberlites, a southwest-trending alignment of kimberlites between the Vredefort structure and the city of Bloemfontein in the central craton, preserve evidence for a dramatic transient thermal pulse in the deep crust of the Kaapvaal craton. Thermobarometry of these garnet-quartz-sapphirine assemblages indicate extreme peak temperatures of >1100 °C at pressures from 1.0 to 1.5 GPa (Dawson et al., 1997). Zircon and monazite from these xenoliths give identical U-Pb dates of 2723 Ma, which are interpreted as dating early cooling and metamorphic zircon growth from the ultrahigh temperature metamorphism (Schmitz et al., 1998). This 2723 Ma episode of ultrahigh temperature metamorphism in the intracratonic lower crust appears to be synchronous with the initiation of Ventersdorp flood basalt volcanism (Armstrong et al., 1991).

In contrast to the Late Archean ages of central craton granulite xenoliths, the abundant garnet-bearing granulite and upper amphibolite facies xenoliths from the Markt kimberlite, at the southwestern edge of the craton, yield Mesoproterozoic metamorphic zircon U-Pb dates ranging from 1114 to 1092 Ma (Schmitz and Bowring, 1999). Similarly, metamorphic zircon and monazite in felsic to mafic granulite xenoliths from the northern

Continental Growth *continued on p. 4*

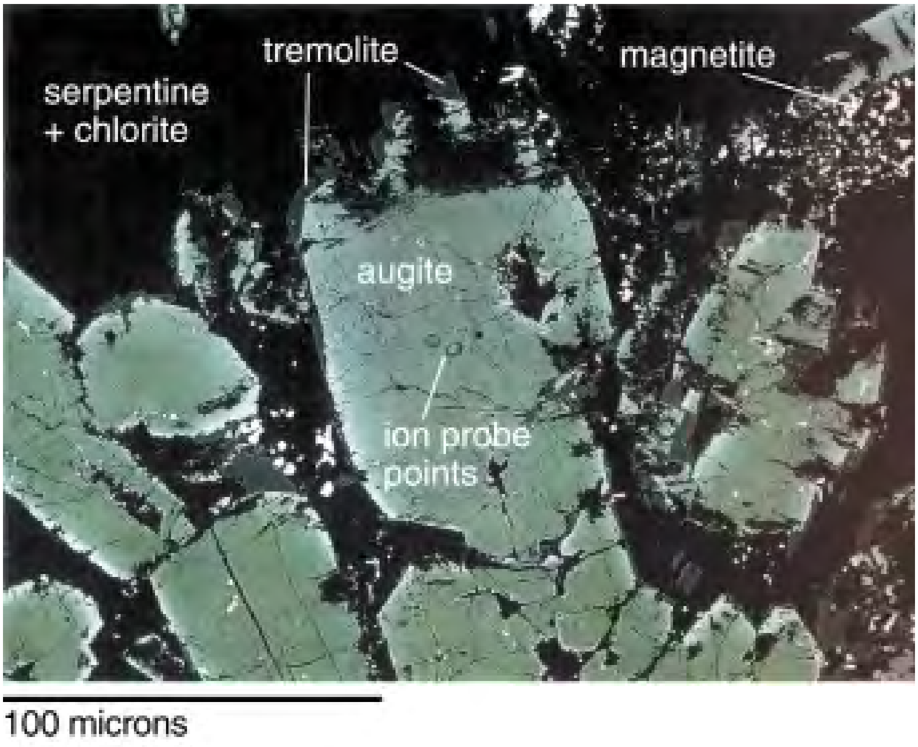

Figure 3. Backscattered electron image of minerals in a metamorphosed Barberton komatiite. Light gray, tabular minerals are preserved high-Ca igneous augitic pyroxenes. Pyroxene grains display change in contrast from dark in center to light at edges. Contrast shows igneous zoning from magnesian core to iron-enriched rim. Metamorphic amphibole (tremolite) surrounds pyroxene. Dark areas represent metamorphosed groundmass consisting of serpentine, chlorite, and magnetite. Sample is B95-7 from Parman et al. (1997). Ion microprobe pits are from measurements of rare earth elements (Parman et al., 1996).

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Lesotho kimberlites, along the southern edge of the craton, have been dated at 1050–1000 Ma (Schmitz and Bowring, 2000). The new geochronology confirms that the lower parts of the thickened crust along the southern and eastern edge of the craton were modified in the Mesoproterozoic and indicates that the cratonic crust experienced a dynamic metamorphic history that significantly postdates the ostensible time of cratonization around 3.0 Ga.

TECTONIC SETTING OF CONTINENT FORMATION

Archean greenstone belts contain komatiite, an igneous rock that has an unusually high MgO content (22%–25%) compared to any volcanic rock observed today. Detailed mapping, geochemical, and petrographic study of komatiites in their type locality in the Komati formation in the Barberton Mountains, South Africa, provides several new clues to the origin and possible tectonic setting of formation of this magma type (Grove et al., 1996b). Some of the southern African komatiites retain part of their original igneous mineralogy (Fig. 3). The freshest Barberton komatiites have igneous olivine and/or pyroxene whose compositions are consistent with these komatiites preserving magmatic compositions (Parman et al., 1997). In addition, the mapping effort has led to the suggestion that some of the Komati units represent sills rather than flows (Grove et al., 1996b). In some of these sills, the composition of preserved igneous pyroxenes (Fig. 3) indicates that the magmas contained over 4 wt% water (Parman et al., 1997).

Wet primary komatiite magma is further supported by the appearance of spinifex crystallization textures as dissolved water in magma lowers nucleation rate and increases crystal growth rate, leading to the formation of the elongate, skeletal, olivine, and pyroxene crystals that typify the spinifex texture (Grove et al., 1996a). High water contents in primary komatiitic magmas could either imply substantially higher water content in the Archean mantle, or that the southern African komatiites formed in a convergent margin setting, the water being provided to the mantle source by dewatering of the subducted plate. In the latter case, the more Mg-rich nature of the komatiites compared to modern arc basalts could simply reflect hotter mantle temperatures, leading to higher degrees of melting in the Archean.

Supporting evidence for a convergent margin setting for komatiitic volcanism in the Kaapvaal craton comes from the Nondweni greenstone belt found ~200 km south of Barberton (Wilson and Versfeld, 1994a). The Nondweni sequence consists predominantly of mafic and ultramafic lavas with felsic volcanic rocks in a structurally intermediate unit (Wilson and Versfeld, 1994b). Compared to the Barberton komatiites, the Nondweni komatiites have relatively low MgO contents (<21 wt%) and higher silica contents (>50 wt%) and display pyroxene, rather than olivine, spinifex flows. Initial Nd isotopic compositions of the mafic and ultramafic lavas vary with lava composition in a manner that suggests progressive contamination of the differentiating lavas by felsic crust ~3.5 b.y. old, like that now found just to the north (Wilson and Carlson, 1989). This result indicates that the Nondweni sequence formed in proximity to the preexisting Kaapvaal craton, not in an intraoceanic setting.

Additional evidence for the importance of subduction in continent formation comes from eclogite xenoliths in on-craton kimberlites. Many eclogite xenoliths have oxygen isotopic compositions outside the normal range for mantle derived rocks (MacGregor and Manton, 1986; Shirey et al., 1999a), suggesting that some eclogite xenoliths represent the high-pressure equivalent of subducted ocean floor basalt. The correlation of Re abundance with oxygen isotopic composition in these xenoliths suggests that their Re-Os system was affected by hydrothermal alteration on the Archean seafloor (Shirey et al., 1999a). Curiously, all diamond-bearing eclogites from the Roberts Victor kimberlite analyzed so far have oxygen isotopic compositions overlapping mantle values. Also, diamond-bearing eclogites from the Roberts Victor and Newlands (Menzies et al., 1999) kimberlites show limited scatter about a 3 Ga Re-Os reference isochron, whereas diamond-free samples show considerable scatter on an isochron plot of Re-Os (Shirey et al., 1999a). These results may suggest that seafloor alteration oxidizes the oceanic crust sufficiently to retard diamond growth upon its subduction. Alternatively, the highly disturbed Re-Os systematics of diamond-free eclogites may indicate that diamond is lost from previously diamond-bearing eclogite by metasomatism and/or partial melting in the mantle (Shirey et al., 1999a).

The Archean age for diamond-bearing eclogites contrasts with Proterozoic ages for eclogitic diamond crystallization observed at several other kimberlite localities (Finsch, Orapa, Jwaneng, and Premier). These ages were based on the Sm-Nd isochron relationships between garnet and clinopyroxene inclusions (Richardson et al., 1999). Re-Os study of individual sulfide grains in diamonds from Orapa shows two age groups, one near the ca. 1 Ga age obtained for silicate inclusions and another giving a Re-Os isochron age near 3 Ga (Shirey et al., 1999b). These results clearly indicate more than one generation of eclogitic diamond growth in the Kaapvaal craton and suggest that subduction of oceanic crust, to depths within the diamond stability field, was occurring during formation of both the craton in the Archean and the surrounding accretionary belts in the Proterozoic.

MANTLE ROOT

As is typical of Archean cratons, preliminary seismic results from the Kaapvaal project (James et al., 1999) show that the Kaapvaal and Zimbabwe cratons are underlain by a thick, seismically fast "root" that extends to depths of at least 200–250 km. Samples of the upper 200 km of this root, brought to the surface by kimberlites, are predominantly peridotite that is highly depleted in those major elements (Ca, Al, Fe) that partition into melts (Boyd and Mertzman, 1987). Low Fe and low abundance of garnet resulting from less Al in the restitic peridotite (Boyd and McCallister, 1976) causes this residual peridotite to be less dense than fertile mantle at the same temperature. These characteristics gave rise to the idea of the "tectosphere" (Jordan, 1988) beneath cratons, consisting of a chemical boundary layer of melt-depleted peridotite that adds buoyancy and long-term stability to the overlying crust.

The antiquity of these mantle roots was first indicated by ancient (>2 Ga) ages for silicate and sulfide inclusions in diamonds (Kramers, 1979; Richardson et al., 1984). Re-Os dating of individual diamond sulfide inclusions confirms an Archean age for some diamonds (Pearson et al., 1998b; Shirey et al., 1999b). Other diamonds have sulfide inclusions with Re-Os ages ranging from mid-Proterozoic to Mesozoic (Pearson et al., 1998b; Shirey et al., 1999b). Thus, diamond growth in the lithospheric mantle was not restricted to the Archean, in accord with earlier results for silicate inclusions (Richardson et al., 1993), but appears to have occurred episodically, perhaps in association with subduction and/or magmatic underplating beneath the craton.

Walker et al. (1989) showed that Re-Os isotope systematics of whole rock peridotites track and potentially date the melt-depletion events important to lithosphere formation. In southern Africa, most peridotite xenoliths extracted from on-craton kimberlites give Archean Re-depletion model ages (Fig. 4), and show no clear trend in age versus depth of origin, at least to depths of 180–200 km (Walker et al., 1989; Pearson et al., 1995; Carlson et al., 1999). Thus, most of the upper 180–200 km of the Kaapvaal craton mantle root formed in the Archean and has been attached to the overlying crust since that time. This also is true of the mantle beneath the Limpopo belt, as indicated by Archean ages for xenoliths from the Venetia kimberlite, but not for the area beneath the 2.05 Ga Bushveld igneous complex (Eales and Cawthorn, 1996). Many of the mantle xenoliths from the Premier kimberlite, which penetrated the Bushveld complex, give ca. 2 Ga ages suggesting substantial modification of the mantle during intrusion of the Bushveld (Carlson et al., 1999).

The most obvious age differences in the mantle beneath southern Africa are seen in peridotite xenoliths from on- and off-craton (Fig. 4). Whereas the majority of xenoliths in on-craton kimberlites give Re-depletion model ages in excess of 2.5 Ga, all but one peridotite from off-craton kimberlites give model ages <2.4 Ga (Pearson et al., 1998a; Janney et al., 1999). These model ages overlap the oldest Nd and Pb model ages for the Proterozoic crust south and west of the craton. The rough correspondence between crustal and mantle lithosphere ages in the off-craton xenoliths show that thick lithospheric keels are not unique to Archean cratons but also can be formed, and remain attached, beneath Proterozoic continental crust.

BENEATH THE ROOT?

The crystallization products of melts derived from deep in the lithosphere, or perhaps beneath the lithosphere, are widely believed to be represented by the Cr-poor megacryst suite commonly found in kimberlites (Gurney and Harte, 1980). The depth of megacryst crystallization varies across the craton into the surrounding mobile belts (MacGregor, 1975), and is reflected in the composition of megacrysts (Boyd and Nixon, 1980). Preliminary results from a new regional survey of megacryst compositions indicate a close correspondence to craton boundaries and significant variability within the craton. These variations correlate spatially with seismic velocity variations.

Megacrysts that precipitated before significant interaction with lithospheric mantle occurred can be used to fingerprint the compositional characteristics of the mantle at deep levels within, and perhaps below, the depleted root. Two isotopically and temporally distinct varieties of kimberlite, groups I and II of Smith (1983), contain megacryst suites with distinct major and trace element (Bell et al., 1995a, 1995b), radiogenic isotope (Smith et al., 1995), and $\delta^{18}O$ (Schulze et al., 1998) compositions. Rare examples of isotopically intermediate kimberlites host megacrysts of correspondingly intermediate and mixed attributes (Bell, 1997; Bell and Mofokeng, 1998). The Sr, Nd, and Pb iso-

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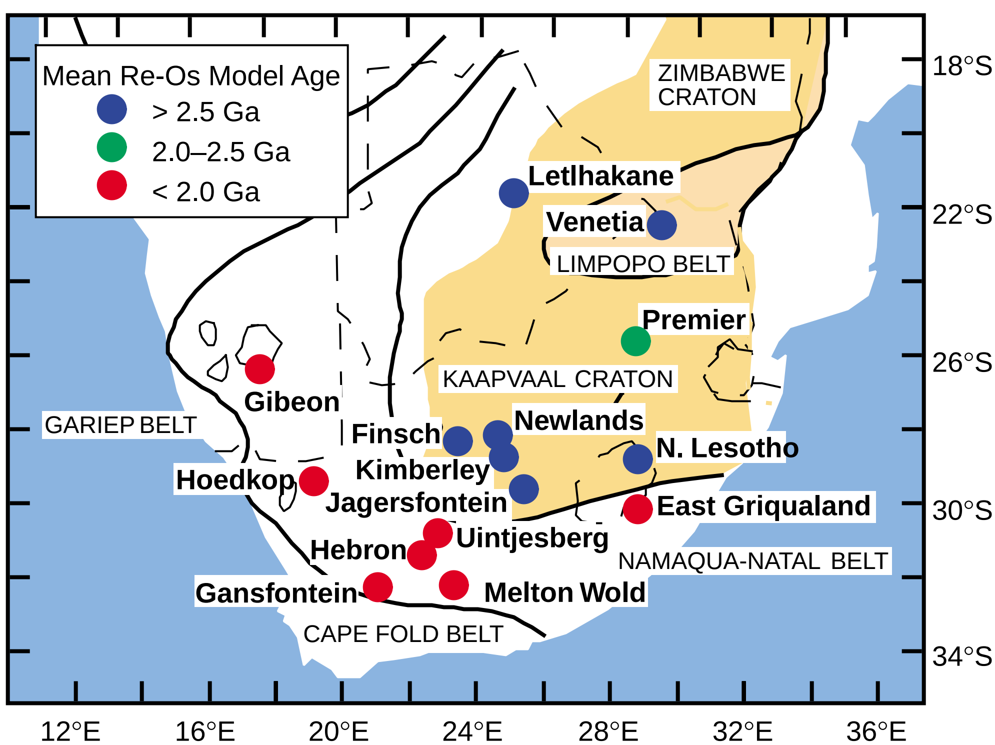

Figure 4. Map of southern Africa showing mean Re-depletion model ages measured for peridotite xenoliths from kimberlites erupted on- and off-craton. Each large circle is an individual kimberlite locality from which several xenoliths have been analyzed. Extent of Archean crust is outlined in yellow, brown is Limpopo metamorphic belt. Data from Pearson et al. (1995, 1998a), Carlson et al. (1999), Janney et al. (1999), and Pearson (1999).

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topic compositions of megacrysts from group I kimberlites indicate a source for these magmas in a widespread, compositionally uniform reservoir with low $^{87}Sr/^{86}Sr$, high $^{143}Nd/^{144}Nd$ and $^{206}Pb/^{204}Pb$ similar to the isotopic component called HIMU that is found in ocean island basalts (Smith et al., 1995). Hf-Nd isotope systematics of these megacrysts indicate the influence of a unique component with a composition reflecting a long-term depletion in Lu/Hf relative to Sm/Nd (Nowell et al., 1999), possibly derived from the sublithospheric mantle.

SUMMARY

Results from the Kaapvaal craton project highlight both stable and dynamic aspects of the history of continents on Earth. These findings clearly show that continents consist not only of their crustal provinces, but also include a thick section of underlying mantle that formed during a time interval similar to that of the overlying crust. Several aspects of our data could relate to a common petrogenetic process reflecting craton formation in a convergent margin setting. These include:

- evidence that southern African komatiites derive from wet primary magmas;
- lithospheric peridotites with compositions indicative of extremely high degrees of melt removal, possibly the residues of komatiite extraction;
- Archean ages for melt depletion measured for the peridotites;
- the presence of subducted Archean oceanic crust in the deep lithospheric mantle as sampled by eclogitic xenoliths.

In the southern African case, this process continued sporadically over ~500 m.y. and resulted in the creation of a lithospheric block that has survived at Earth's surface for over 3 b.y.

Once formed, the history of this continental block was not yet complete. Accretionary belts were welded to its margins in the Proterozoic, increasing the crustal thickness of the craton around its margins as shown by geochronological results from crustal xenoliths. As before, this episode of continent growth was not restricted to the crust. Both the relative youth of some Kaapvaal diamonds and the Proterozoic ages obtained for off-craton peridotite xenoliths show that continent formation and/or modification involved the underlying mantle to depths extending at least into the diamond stability field. The presence and characteristics of the kimberlite-borne megacrysts extend this interaction to the very base of the lithosphere. The results demonstrate the dynamic nature of the whole continent, from top to bottom, as it has interacted with the surrounding crust and mantle over Earth history.

ACKNOWLEDGMENTS

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REFERENCES CITED

Armstrong, R. A., Compston, W., Retief, E. A., Williams, I. S., Welke, H. J., 1991, Zircon ion microprobe studies bearing on the age and evolution of the Witwatersrand triad: Precambrian Research, v. 53, p. 243–266.

Bell, D. R., 1997, Megacrysts in the Frank Smith kimberlite and the source regions of transitional kimberlites: Eos (Transactions, American Geophysical Union), v. 78, p. F749.

Bell, D. R., and Mofokeng, S. W., 1998, Cr-poor megacrysts from the Frank Smith Mine and the source region of transitional kimberlites: Cape Town, South Africa, 7th International Kimberlite Conference, Extended Abstracts, p. 64–66.

Bell, D. R., Gurney, J. J., LeRoex, A. P., Moore, R. O., and Shimizu, N., 1995a, Compositional evolution of the Monastery megacrysts and parent magma: Novosibirsk, Russia, 6th International Kimberlite Conference, Extended Abstracts, p. 50–51.

Bell, D. R., Schulze, D. J., Read, G. H., Mattioli, G. S., Shimizu, N., Moore, R. O., and Gurney, J. J., 1995b, Geochemistry of Cr-poor megacrysts from the Lace (Group II) kimberlite, South Africa: Novosibirsk, Russia, 6th International Kimberlite Conference, Extended Abstracts, p. 52–54.

Boyd, F. R., and McCallister, R. H., 1976, Densities of fertile and sterile garnet peridotites: Geophysical Research Letters, v. 3, p. 509–512.

Boyd, F. R., and Mertzman, S. A., 1987, Composition and structure of the Kaapvaal lithosphere, southern Africa, *in* Mysen, B. O., ed., Magmatic processes: Physicochemical principles: Geochemical Society Special Publication 1, p. 3–12.

Boyd, F. R., and Nixon, P. H., 1980, Discrete nodules from the kimberlites of East Griqualand, southern Africa: Carnegie Institution of Washington Yearbook, v. 79, p. 96–302.

Carlson, R. W., Grove, T. L., de Wit, M. J., and Gurney, J. J., 1996, Program to study the crust and mantle of the Archean craton in southern Africa: Eos (Transactions, American Geophysical Union), v. 77, p. 273, 277.

Carlson, R. W., Pearson, D. G., Boyd, F. R., Shirey, S. B., Irvine, G., Menzies, A. H., and Gurney, J. J., 1999, Re-Os systematics of lithospheric peridotites: Implications for lithosphere formation and preservation: Cape Town, South Africa, 7th International Kimberlite Conference, Proceedings, p. 99–108.

Dawson, J. B., Harley, S. L., Rudnick, R. L., and Ireland, T. R., 1997, Equilibration and reaction in Archaean quartz-sapphirine granulite xenoliths from the Lace kimberlite pipe, South Africa: Journal of Metamorphic Geology, v. 15, p. 253–266.

de Wit, M. J., Roering, C., Hart, R. J., Armstrong, R. A., deRonde, C. E. J., Green, R. W. E., Tredoux, M., Peberdy, E., and Hart, R. A., 1992, Formation of an Archaean continent: Nature, v. 357, p. 553–562.

Eales, H. V., and Cawthorn, R. G., 1996, The Bushveld Complex, *in* Cawthorn, R. G., ed., Layered intrusions: Amsterdam, Elsevier, p. 181–229.

Grove, T. L., Gaetani, G. A., and Parman, S. W., 1996a, Origin of olivine spinifex textures in 3.49 Ga komatiite magmas from the Barberton Mountainland, South Africa: Eos (Transactions, American Geophysical Union), v. 77, p. 281.

Grove, T. L., de Wit, M.J., and Dann, J. C., 1996b, Komatiites from the Komati type section, South Africa, *in* de Wit, M. J., and Ashwal, L. D., eds., Greenstone belts: Oxford, UK, Oxford University Press, p. 435–450.

Gurney, J. J., and Harte, B., 1980, Chemical variations in upper mantle nodules from southern African kimberlites: Royal Society, London, Philosophical Transactions, v. A297, p. 273–293.

Gurney, J. J., Moore, R. O., Otter, M. L., Kirkley, M. B., Hops, J. J., and McCandless, T. E., 1991, Southern African kimberlites and their xenoliths, *in* Kampunzu, A. B., and Lubala, R. T., eds., Magmatism in extensional structural settings—The Phanerozoic African plate: Berlin, Springer-Verlag, p. 495–535.

Hart, R. J., Andreoli, M. A. G., Tredoux, M., and de Wit, M. J., 1990, Geochemistry across an exposed section of Archean crust at Vredefort: With implications for mid-crustal discontinuities: Chemical Geology, v. 82, p. 21–50.

James, D. E., VanDecar, J., van de Lee, S., Fouch, S., Gao, S., Nguuri, T., and Gore, J., 1999, Tomographic and depth phasing imaging of mantle structure beneath the southern African seismic array: Eos (Transactions, American Geophysical Union), v. 80, p. F712–713.

Janney, P. E., Carlson, R. W., Shirey, S. B., Bell, D. R., and LeRoex, A. P., 1999, Temperature, pressure and Re-Os age systematics of off-craton peridotite xenoliths from the Namaqua-Natal belt, western South Africa, *in* Ninth Annual V. M. Goldschmidt Conference: Houston, Texas, Lunar and Planetary Institute Contribution 971, p. 139.

Jordan, T. H., 1988, Structure and formation of the continental tectosphere: Journal of Petrology, v. 29, p. 11–37.

Kamo, S., Reimold, W. U., Krogh, T. E., and Colliston, W. P., 1996, A 2.023 Ga age for the Vredefort impact event, and a first report of shock metamorphosed zircons in the pseudotachylitic breccias and granophyre: Earth and Planetary Science Letters, v. 144, p. 369–388.

Kramers, J. D., 1979, Lead, uranium, strontium, potassium and rubidium in inclusion-bearing diamonds and mantle-derived xenoliths from southern Africa: Earth and Planetary Science Letters, v. 42, p. 58–70.

MacGregor, I. D., 1975, Petrologic and thermal structure of the upper mantle beneath South Africa in the Cretaceous: Physics and Chemistry of the Earth, v. 9, p. 455–466.

MacGregor, I. D., and Manton, W. I., 1986, Roberts Victor eclogites: Ancient oceanic crust: Journal of Geophysical Research, v. 91, p. 14,063–14,079.

Menzies, A. H., Carlson, R. W., Shirey, S. B., and Gurney, J. J., 1999, Re-Os isotope systematics of peridotite xenoliths: Implications for diamond and lithosphere formation: Cape Town, South Africa, 7th International Kimberlite Conference, Proceedings, p. 566–573.

Moser, D., 1997, Dating the shock wave and thermal imprint of the giant Vredefort impact, South Africa: Geology, v. 25, p. 7–10.

Nowell, G. M., Pearson, G. D., Kempton, P. D., Carlson, R. W., Bell, D. R., and Zartman, R. E., 1999, Hf isotope analysis of kimberlite megacrysts by laser ablation and solution mode plasma ionization multicollector mass-spectrometry (PIMMS): Evidence for a contribution from a deep mantle component in kimberlites and megacryst magmas?, *in* Ninth Annual V. M. Goldschmidt Conference: Houston, Texas, Lunar and Planetary Institute Contribution 971, p. 212–213.

Parman, S. W., Grove, T. L., Shimizu, N., Dann, J., and de Wit, M. J., 1996, Magmatic trace and minor element abundances in Barberton komatiites inferred from augite composition: Eos (Transactions, American Geophysical Union), v. 77, p. F848.

Parman, S. W., Dann, J. C., Grove, T. L., and de Wit, M.J., 1997, Emplacement conditions of komatiite magmas from the 3.49 Ga Komati Formation, Barberton Greenstone Belt, South Africa: Earth and Planetary Science Letters, v. 150, p. 303–323.

Pearson, D. G., 1999, Evolution of cratonic lithospheric mantle: An isotopic perspective, *in* Fei., Y., et al., eds., Mantle petrology: Field observations and high pressure experimentation: Geochemical Society Special Publication 6, p. 57–78.

Pearson, D. G., Carlson, R. W., Shirey, S. B., Boyd, F. R., and Nixon, P. H., 1995, Stabilization of Archean lithospheric mantle: A Re-Os isotope study of peridotite xenoliths from the Kaapvaal craton: Earth and Planetary Science Letters, v. 134, p. 341–357.

Pearson, D. G., Carlson, R. W., Boyd, F. R., Shirey, S. B., and Nixon, P. H., 1998a, Lithospheric mantle growth

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Karlstrom Appointed *GSA Today* Science Co-Editor

Karlstrom on Nankoweap Butte, Grand Canyon.

Karl E. Karlstrom, University of New Mexico, is the new science co-editor of *GSA Today.* He replaces Suzanne M. Kay (Cornell University), whose term ended December 31, 1999. Karlstrom joins Molly F. Miller, Vanderbilt University, who was appointed in 1998.

Karlstrom received his M.S. and Ph.D. degrees at the University of Wyoming and taught at North Carolina State University and Northern Arizona University before accepting his current post at New Mexico. His main research interests involve the Proterozoic (and younger) tectonics of the western United States and processes of interaction of deformation, metamorphism, and plutonism in the deep crust. He has conducted field studies of Proterozoic rocks in the Arizona Transition Zone, Eastern Mojave desert, Grand Canyon (both Paleoproterozoic basement and the Mesoproterozoic-Neoproterozoic Grand Canyon Supergroup), and southern Rocky Mountains. He has been a member of GSA since 1982.

"Molly Miller and I hope to carry on the fine tradition set by Eldridge Moores and Sue Kay in making the lead articles of *GSA Today* some of the most visible papers in earth sciences," Karlstrom said. "*GSA Today* papers need to be both cutting-edge research (for the specialists in the field) and also understandable to the wider earth science community. We offer an important challenge to authors of lead articles: Can you effectively communicate important new ideas to a wide community?"

Proposals for "hot topic" papers for *GSA Today* must go to either Miller (Molly.F. Miller@Vanderbilt.edu) or Karlstrom (kek1@unm.edu) before a paper is submitted for consideration. All science articles for *GSA Today* are peer-reviewed. ■

GSA President Named to Committee on National Medal of Science

Mary Lou Zoback, 2000 president and Fellow of the Geological Society of America, will soon be appointed by President Bill Clinton to the Committee on the National Medal of Science. The Medal of Science is awarded to individuals who have made outstanding contributions to science and engineering. The President's Committee on the National Medal of Science selects the recipients of the award, as many as 20 people per year. Geologist and geophysicist Mary Lou Zoback is currently chief scientist of the Earthquake Hazards program attached to the U.S. Geological Survey in Menlo Park, California.

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around cratons: A Re-Os isotope study of peridotite xenoliths from East Griqualand: Cape Town, South Africa, 7th International Kimberlite Conference, Extended Abstracts, p. 658–660.

Pearson, D. G., Shirey, S. B., Harris, J. W., and Carlson, R. W., 1998b, Sulfide inclusions in diamonds from the Koffiefontein kimberlite, S. Africa: Constraints on diamond ages and mantle Re-Os systematics: Earth and Planetary Science Letters, v. 160, p. 311–326.

Richardson, S. H., Gurney, J. J., Erlank, A. J., and Harris, J. W., 1984, Origin of diamonds in old enriched mantle: Nature, v. 310, p. 198–202.

Richardson, S. H., Harris, J. W., and Gurney, J. J., 1993, Three generations of diamonds from old continental mantle: Nature, v. 366, p. 256–258.

Richardson, S. H., Chinn, I. L, and Harris, J. W., 1999, Age and origin of eclogitic diamonds from the Jwaneng kimberlite, Botswana: Cape Town, South Africa, 7th International Kimberlite Conference, Proceedings, p. 709–713.

Schmitz, M. D., and Bowring, S. A., 1999, The significance of U-Pb zircon ages from lower crustal xenoliths of the southwestern margin, Kaapvaal Craton, southern Africa: Chemical Geology.

Schmitz, M. D., and Bowring, S. A., 2000, The evolution of cratonic geotherms: U-Pb thermochronometric constraints from lower crustal xenoliths, Lesotho, southern Africa [abs.], *in* Ninth Annual V. M. Goldschmidt Conference: Houston, Texas, Lunar Planetary Institute Contribution 971, p. 263.

Schmitz, M. D., Bowring, S. A., Robey, J. v. A., 1998, Constraining the thermal history of an Archean craton: U-Pb thermochronology of lower crustal xenoliths from the Kaapvaal craton, southern Africa: Cape Town, South Africa, 7th International Kimberlite Conference, Extended Abstracts, p. 766–768.

Schulze, D. J., Valley, J. W., Bell, D. R., Spicuzza, M., 1998, Significance of oxygen isotope variations in the Cr-poor megacryst suite: Cape Town, South Africa, 7th International Kimberlite Conference, Extended Abstracts, p. 769–771.

Shirey, S. B., Wiechert, U., Carlson, R. W., Gurney, J. J., and Heerden, L. V., 1999a, Re-Os and oxygen isotopic systematics of diamondiferous and non-diamondiferous eclogites from the Roberts Victor kimberlite, South Africa, *in* Ninth Annual V. M. Goldschmidt Conference: Houston, Texas, Lunar and Planetary Institute Contribution 971, p. 273–274.

Shirey, S. B., Harris, J. W., and Carlson, R. W., 1999b, Re-Os systematics of sulfide inclusions in diamonds from the Orapa kimberlite, Botswana: Implications for multiple generations of diamond growth: Eos (Transactions, American Geophysical Union), v. 80, p. F1191.

Smith, C. B., 1983, Pb, Sr, and Nd isotopic evidence for sources of southern African Cretaceous kimberlites: Nature, v. 304, p. 51–54.

Smith, C. B., Schulze, D. J., Bell, D. R., and Viljoen, K. S., 1995, Bearing of the subcalcic, Cr-poor megacryst suite on kimberlite petrogenesis and lithospheric structure: Novosibirsk, Russia, 6th International Kimberlite Conference, Extended Abstracts, p. 546–548.

Tankard, A. J., Jackson, M. P. A., Eriksson, K. A., Hobday, D. K., Hunter, D. R., and Minter, W. E. L., 1982, Crustal evolution of southern Africa: 3.8 billion years of Earth history: New York, Springer-Verlag, 523 p.

Tredoux, M., Hart, R. J., Carlson, R. W., and Shirey, S. B., 1999, Ultramafic rocks at the center of the Vredefort structure: Further evidence for the crust on edge model: Geology, v. 27, p. 923–926.

Walker, R. J., Carlson, R. W., Shirey, S. B., and Boyd, F. R., 1989, Os, Sr, Nd, and Pb isotope systematics of southern African peridotite xenoliths: Implications for the chemical evolution of subcontinental mantle: Geochimica et Cosmochimica Acta, v. 53, p. 1583–1595.

Wilson, A. H., and Carlson, R. W., 1989, A Sm-Nd and Pb isotope study of Archaean greenstone belts in the southern Kaapvaal Craton, South Africa: Earth and Planetary Science Letters, v. 96, p. 89–105.

Wilson, A. H., and Versfeld, J. A., 1994a, The early Archaean Nondweni greenstone belt, southern Kaapvaal craton, South Africa, Part I. Stratigraphy, sedimentology, mineralization and depositional environment: Precambrian Research, v. 67, p. 243–276.

Wilson, A. H., and Versfeld, J. A., 1994b, The early Archaean Nondweni greenstone belt, southern Kaapvaal craton, South Africa, Part II. Characteristics of the volcanic rocks and constraints on magma genesis: Precambrian Research, v. 67, p. 277–320.

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