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Notes

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ABSTRACT

In situ Sr isotopic analyses of kimberlitic perovskite are more representative of primary magmatic compositions than conventional bulk-rock analyses of the same samples, because the latter are variably compromised by contamination and alteration processes. Bulk-rock Sr isotopic data obtained for 18 intrusions from the adjacent Narayanpet and Wajrakarur kimberlite fields of the Dharwar Craton, India, exhibit a high degree of scatter (~ 0.701 – 0.709) and have indistinguishable initial isotope ratios. In contrast, laser ablation perovskite results display strikingly uniform and distinct initial $^{87}\text{Sr}/^{86}\text{Sr}$ compositions for each field of 0.70312 – 0.70333 and 0.70234 – 0.70251 , respectively. The increased resolution provided by these new data permits the evaluation of key aspects of kimberlite genesis. It is argued that lithospheric and crustal contamination had a negligible impact on the perovskite Sr isotope compositions, and that these values are representative of the primary melt component in each field. The results cast doubt on models of kimberlite formation that invoke either the small degree melting of metasomatized subcontinental lithospheric mantle, or derivation from unusually enriched asthenospheric mantle. The data are more compatible with a source region for the Dharwar kimberlites that was similar to a common mantle component such as prevalent mantle (PREMA) or focal zone (FOZO).

Keywords: Dharwar Craton, kimberlite, perovskite, strontium, isotope, India, in situ Sr analysis.

INTRODUCTION

Kimberlites are ultramafic rocks that are thought to form via small-degree partial melting of the deep mantle (i.e., >150 km; Mitchell, 1986). As the primary source of diamonds, kimberlites have long been the focus for exploration and research, and provide a rare opportunity to study deep earth processes. Despite decades of research, however, many aspects of kimberlite petrogenesis, such as their depth of melting, the nature of their source rocks, and the involvement of the subcontinental-lithospheric mantle (SCLM) remain enigmatic. To a large extent progress has been hampered because magmatic kimberlites often contain a diverse assemblage of entrained mantle and crustal fragments, and are usually subject to extensive postemplacement alteration (Berg and Allsopp, 1972; Mitchell, 1986).

Radiogenic isotope techniques are powerful methods for studying deep earth processes, with the potential to “see through” the effects of partial melting and crystal fractionation. The use of Sr isotope ratios in this regard is well documented, and was integral in distinguishing group I and group II kimberlites, and the proposed relationship of the former to ocean island basalts (Smith, 1983; Le Roex, 1986). However, Sr isotope data for kimberlites are almost universally compromised by a high degree of scat-

ter, significantly limiting the resolution of results (e.g., Chalapatthi Rao et al., 2004; Becker and Le Roex, 2006). To date, only a small number of studies have yielded highly reproducible data through the careful separation of groundmass minerals in unusually pristine intrusions (e.g., Schmidberger et al., 2001; Maas et al., 2005). Thus there is considerable uncertainty regarding whether observed compositions have been affected by processes such as contamination and alteration, or instead preserve a true record of kimberlite magma variability.

Perovskite (CaTiO_3) is a common primary groundmass phase in kimberlites. Perovskite is also robust during weathering and typically contains several thousand $\mu\text{g/g}$ Sr and minimal Rb (Heaman, 1989; Chakhmouradian and Mitchell, 2000). These traits combine to make perovskite an ideal medium for recording the initial Sr isotope compositions (Sr_i) of kimberlites, a possibility first documented by Heaman (1989). In addition, magmatic perovskites may be largely immune to late-stage crustal contamination and alteration, which plague studies using bulk rock compositions. Despite these advantages, perovskite Sr isotopic analyses have received only limited attention, possibly due to their typically small grain size (5 – 150 μm), which renders the separation of grains for dissolution an

arduous task. In this study, in situ analysis of Sr isotope ratios in individual perovskite grains via laser ablation–multicollector–inductively coupled plasma–mass spectrometry (LA-MC-ICP-MS; Paton et al., 2007) has been used to overcome this difficulty and provide the first high-resolution Sr isotope study of kimberlitic rocks.

BACKGROUND AND SAMPLES

Samples were collected from the Narayanpet and Wajrakarur kimberlite fields, both located within the Archean Dharwar Craton of southern India (Fig. 1). We acquired 29 samples from 10 intrusions of the Narayanpet kimberlite field, spanning an area of 40×15 km, and 8 intrusions of the Wajrakarur kimberlite field, covering an area of 70×30 km. Specimens (1 – 2 kg) were collected from dark gray to black, visibly unaltered outcrops. Where multiple samples were taken, they were collected from separate outcrops, usually 25 – 50 m apart. All 29 samples were analyzed for their bulk-rock Sr isotope compositions with a subset of samples (from six and five intrusions of the Narayanpet and Wajrakarur fields, respectively), selected for LA-MC-ICP-MS Sr isotope analysis of perovskite.

Perovskite is present as a groundmass phase in all intrusions from the Narayanpet kimberlite field, and all but two intrusions from the

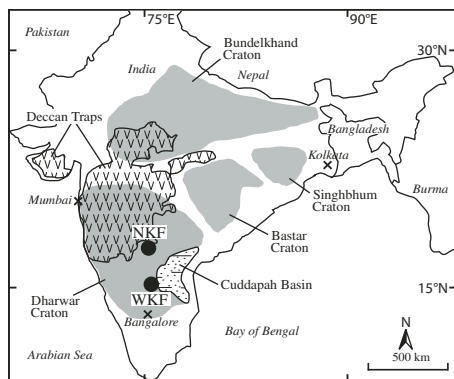


Figure 1. Regional map of India showing location of Narayanpet kimberlite field (NKF) and Wajrakarur kimberlite field (WKF) within Dharwar Craton and relevant geological features.

Wajrakarur kimberlite field, occurring as subhedral pseudo-cubic grains (Fig. 2). Crystals are consistently dark brown with a submetallic luster. Grain size and abundance vary considerably between intrusions, from rare grains, 5–20 μm in diameter, to samples with ~3% modal abundance and grain sizes of 50–150 μm diameter. Compositionally, perovskites of the Narayanpet field approach the ideal formula with <2% substitution by other elements (predominantly light rare earth elements [LREE], some Nb_2O_5), while those of the Wajrakarur field have higher and more variable abundances of substituting elements (Nb_2O_5 0.15%–1.85%, total LREE 1.4%–5.4%; Chalapathi Rao et al., 2004; Paton et al., 2007). These compositions are similar to those of kimberlites from Africa, Asia, and North America (Chakhmouradian and Mitchell, 2000).

Bulk-rock geochemical data indicate that alteration processes affected at least some elements, including Sr isotope compositions (Haggerty and Birkett, 2004; Chalapathi Rao et al., 2004). All intrusions exhibit extreme LREE

enrichment (La to 700 times chondritic), low SiO_2 (28%–40%), high MgO (18%–29%), and La/Yb ratios of ~70–175 (Chalapathi Rao et al., 2004). Relative to intrusions worldwide, the chemistry of elements that are less mobile during weathering (i.e., the high field strength elements [HFSE] and REE) is similar to the group I bodies of southern Africa. Although many intrusions contain abundant groundmass phlogopite, they differ chemically from micaceous group II kimberlites (Haggerty and Birkett, 2004; Chalapathi Rao et al., 2004). Compared to the Wajrakarur kimberlite field, samples of the Narayanpet kimberlite field have higher TiO_2 , $\text{FeO}_{\text{total}}$, and HFSE, and lower K_2O , Ni, and LREE abundances (Chalapathi Rao et al., 2004). In addition, ~80% of Wajrakarur kimberlites are diamondiferous, while those of the Narayanpet field are barren. Previous isotopic analyses conducted on three Narayanpet and five Wajrakarur kimberlites yield a range in Sr_i from ~0.702–0.708 and ϵNd_i of +0.5 to +4.5, with no clear distinction between the fields (Chalapathi Rao et al., 2004).

Existing geochronological data for the two kimberlite fields are ambiguous. There is general consensus that the Wajrakarur field was emplaced ca. 1090 Ma based on Rb–Sr dating of phlogopite (Kumar et al., 1993). However, ages for the Narayanpet field are less clear. K–Ar and Ar–Ar data of the Kotakonda kimberlite indicate emplacement ca. 1400 Ma, similar to ages obtained for lamproites of the nearby Cuddapah Basin (Chalapathi Rao et al., 2004, and references therein). In contrast, Rb–Sr phlogopite ages of the Kotakonda and Mudalabidi intrusions suggest emplacement ca. 1090 Ma, contemporaneous with the neighboring Wajrakarur kimberlite field (Kumar et al., 2001). As kimberlitic phlogopite often contains excess ^{40}Ar (Phillips et al., 1999), the younger Rb–Sr ages are favored, and thus we conclude that the Narayanpet and Wajrakarur kimberlite fields are likely to be broadly contemporaneous.

RESULTS

All isotopic analyses were conducted using a Nu Instruments MC-ICP-MS at the University of Melbourne, Australia. For in situ Sr isotope analyses, the mass spectrometer was coupled to a Helix laser ablation system utilizing a 193 nm Excimer laser. A CetacTM Aridus desolvating nebulizer was employed for solution analyses. Bulk-rock powders were prepared from fragments free of visible alteration and contamination, and were leached prior to dissolution in warm 1 mol/L acetic acid for 10 min in an attempt to remove secondary carbonate. Details of the bulk-rock analytical procedures were given in Maas et al. (2005). Laser ablation analyses were conducted in situ on thick sections polished to a 1 μm finish; these were cleaned ultrasonically in ultrapure H_2O , and again with analytical reagent

grade methanol immediately preceding analysis. A full description of the technique is provided by Paton et al. (2007), with instrumentation details provided in Woodhead et al. (2004). Laser spot sizes were constrained by grain size and varied from 120 to 55 μm diameter, with corresponding internal precisions (2 standard error, S.E.) from 0.006% to 0.035%. Sr and Rb concentrations for perovskites from this study are ~3500 ppm and ~5 ppm, respectively, while levels of the minor interfering elements Er and Yb are <50 and 20 ppm, respectively (see Paton et al., 2007). All data are normalized to a value of 0.71023 for the NBS 987 Sr standard.

After age correction to 1090 Ma, the bulk-rock analyses from both kimberlite fields display a wide range in Sr_i ratios (0.701–0.709; GSA Data Repository Table DR1¹), with the majority of samples preserving values in the lower end of this range, and no apparent distinction between the Narayanpet and Wajrakarur fields (Fig. 3A). The range in bulk-rock ϵSr_i values overlaps southern African group I kimberlites (Becker and Le Roex, 2006), and extends to higher values.

In marked contrast, perovskite results for each field indicate uniform compositions (Fig. 3B; Table DR1), and reveal a clear distinction between the Narayanpet field intrusions, which exhibit Sr_i ratios of ~0.70321, and the Wajrakarur field intrusions, which have significantly lower values of ~0.70246. These ratios equate to average ϵSr_i values of +0.9 and –9.8 for the Narayanpet and Wajrakarur fields, respectively. Owing to the extremely low Rb/Sr ratios observed in perovskite, uncertainties associated with the choice of age used in the corrections are less than the in-run precision of the measured ratios.

DISCUSSION AND IMPLICATIONS FOR KIMBERLITE PETROGENESIS

The Sr_i results obtained via in situ analysis of perovskite display remarkably uniform values within each kimberlite field, strongly contrasting with the data collected via bulk-rock solution analysis. The observed scatter in bulk-rock data is attributed primarily to alteration processes, which have been shown to adversely affect the Sr isotope systematics of other kimberlites (Berg and Allsopp, 1972), although crustal contamination may also have played a minor role.

Overall, the Indian kimberlites yield in situ ϵSr_i values that are entirely within the field defined by southern African group I kimberlites (~–18 to +18; Becker and Le Roex, 2006, and references therein); however, a distinct difference is appar-

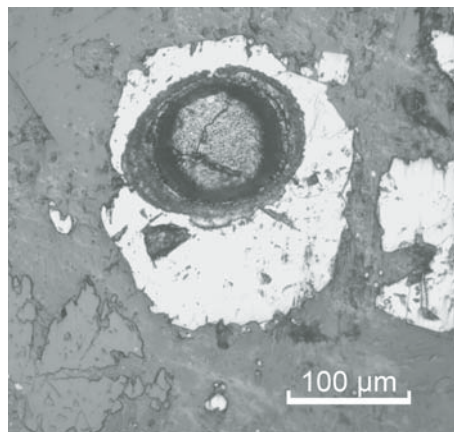
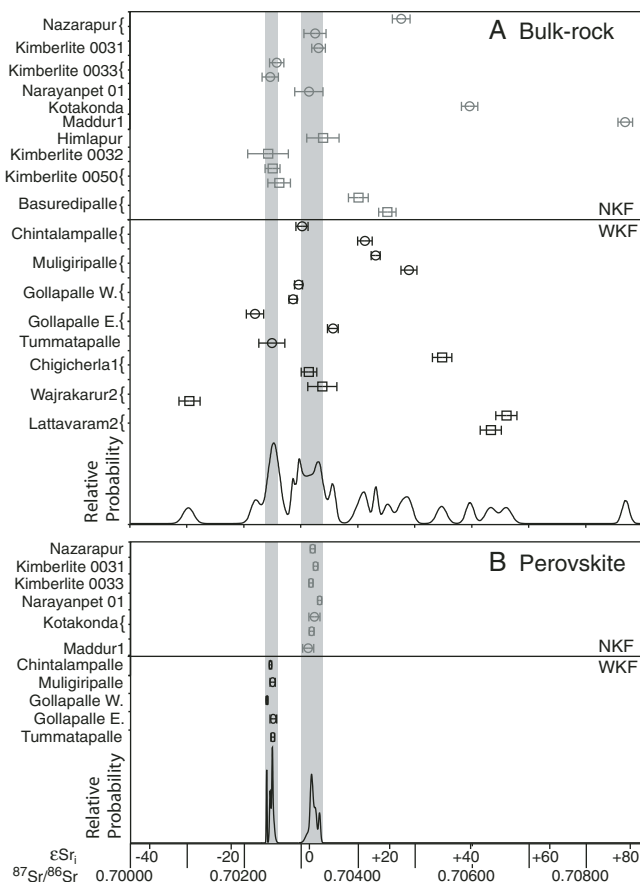


Figure 2. Groundmass perovskite containing 93- μm -diameter laser ablation pit. Polished thick section in reflected light.

¹GSA Data Repository item 2007249, Table DR1, results of in situ perovskite analyses and bulk-rock analyses, is available online at www.geosociety.org/pubs/ft2007.htm, or on request from editing@geosociety.org or Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301, USA.

Figure 3. Initial $^{87}\text{Sr}/^{86}\text{Sr}$ isotope data for Narayanpet (gray) and Wajrakarur (black) kimberlite fields obtained using (A) bulk-rock methods and (B) in situ perovskite analysis. Circles indicate those data analyzed using both methods; squares represent those analyzed using only bulk-rock methods. Error bars on bulk-rock data include magnification resulting from age correction. Note the clear division between perovskite results from Narayanpet and Wajrakarur kimberlite fields, and the remarkable uniformity of these values within each field (as illustrated by relative probability curves generated using Isoplot; Ludwig, 2001). All data are corrected to emplacement age of 1090 Ma. In situ perovskite values of each sample are weighted averages (calculated using Isoplot; Ludwig, 2001) of 10–25 individual laser ablation analyses. Uncertainties are plotted as 2 standard error.



ent between intrusions of the Narayanpet (−0.4 to +2.6) and Wajrakarur fields (−11.5 to −9.1).

Three models are proposed that might account for the observed offset in Sr isotope compositions between the Wajrakarur and Narayanpet kimberlite fields.

1. All kimberlites derive from a single source, with melts for the Wajrakarur and Narayanpet fields forming at different times, allowing radiogenic in-growth within the source to produce the higher Sr_i ratios of the second (Narayanpet) kimberlite pulse.

2. Magmas of the Wajrakarur and Narayanpet kimberlite fields were generated from a common source with identical isotopic characteristics, and the difference between the fields reflects variable assimilation of material en route through the SCLM or continental crust.

3. Each kimberlite field originated from source rocks of differing isotopic composition, and the magmas derived from these sources preserve distinct $^{87}\text{Sr}/^{86}\text{Sr}$ ratios.

In order for the first model to produce the observed results, the Narayanpet field would need to have intruded after the Wajrakarur field. Even if the bulk-rock $^{87}\text{Rb}/^{86}\text{Sr}$ ratio of the kimberlites is assumed to mirror the source region, the average $^{87}\text{Rb}/^{86}\text{Sr}$ ratio for the two fields (−0.4) would require more than 130 m.y. of isotopic evolution to generate the observed isotopic offset. Even an

unusually high $^{87}\text{Rb}/^{86}\text{Sr}$ ratio of 1.0 would require an accumulation period of >50 m.y. As existing geochronology unanimously indicates that bodies from the Narayanpet kimberlite field were either contemporaneous with or preceded those of the Wajrakarur field by as much as 300 m.y. (Kumar et al., 1993, 2001; Chalapathi Rao et al., 2004), this explanation appears untenable.

Although the entrainment of xenolithic material from the SCLM and/or continental crust is a universal feature of kimberlite formation (Mitchell, 1986; Becker and Le Roex, 2006), the degree to which such material is chemically assimilated and might thereby affect Sr_i values, as proposed in model 2, is less certain. As the lithosphere is known to be chemically heterogeneous (e.g., Schmidberger et al., 2003), a composition can certainly be chosen to explain the observed variations in Sr_i , using plausible quantities of assimilation. However, in order to produce the uniformity of Sr_i values within each field, this model requires that the magmas, supplying dozens of individual intrusions, are mixed in equal proportions with a contaminating component of homogeneous composition. Furthermore, the deviation between the two fields would require different, but uniform amounts of assimilation (or a change in the Sr isotopic composition) of this component. Such a model is at odds with numerous studies of mantle xenoliths that have demonstrated that the SCLM

is isotopically heterogeneous on a scale from individual grains (Schmidberger et al., 2003) to tens of kilometers (Hawkesworth et al., 1990), particularly in regard to the Sr isotope system. In addition, large Sr isotope variations are observed between xenoliths within a single kimberlite intrusion, and it has been demonstrated that these heterogeneities existed at the time of kimberlite formation (Hawkesworth et al., 1990). Therefore, the uniform mixing required to explain the Narayanpet and Wajrakarur kimberlite field data could only occur if two magma chambers were formed after ascent through the SCLM (or deep crust), allowing the homogenization of magmas in each field before further ascent to the surface as a series of individual pipes. Such magma chambers are incompatible with kinetic modeling results (Spera, 1984), which suggest that kimberlite melts ascend rapidly (10–30 m s^{−1}) through the SCLM along fracture systems, accelerating to transonic speeds through the upper crust. Thus the implication is that the amount of SCLM or continental crust entrained by magmas of the Narayanpet and Wajrakarur fields was either small, or was incorporated via a purely mechanical process that did not alter the composition of the kimberlite magma from which the perovskites precipitated. Alternatively, we must hypothesize that the SCLM beneath the area was isotopically homogeneous over very large distances, a possibility at odds with the study of Nehru and Reddy (1989) that implies significant compositional heterogeneity of the mantle below the Wajrakarur field.

We therefore propose that the observed offset in Sr_i between the Wajrakarur and Narayanpet kimberlite fields is best explained by their derivation from two distinct, yet internally homogeneous mantle sources. Current models suggest that three potential mantle source regions exist, namely the SCLM, the convecting upper mantle (i.e., a mid-oceanic ridge basalt [MORB] source), and the deep mantle (transition zone or lower).

Although the source of kimberlite magmas remains unconstrained, many authors favor small-degree melting of metasomatized SCLM (Tainton and McKenzie, 1994; Chalapathi Rao et al., 2004; Becker and Le Roex, 2006). However, it is likely that the SCLM is heterogeneous in Sr isotope composition, as noted above. Thus, while the Sr isotope variability of bulk-rock analyses is compatible with the formation of kimberlites via the small-degree melting of an SCLM source, it is difficult to reconcile the unprecedented homogeneity of the in situ Sr isotope results of this study with such a model. Melting within the SCLM is further challenged by the presence of diamonds containing majoritic garnet inclusions in kimberlites of the Wajrakarur field, which are best explained by the direct transport of xenocrysts from as deep as the transition zone (Ringwood et al. 1992; Patel et al., 2006).

A direct derivation from asthenospheric depths may best explain the within-field homogeneity, perhaps via a diapiric mode of formation. Based on numerical modeling, Grégoire et al. (2006) argued that small-degree partial melts (i.e., <1%) could pool at melt concentrations of up to 7% beneath a roof of metasomatized material within a diapir of upwelling mantle. In this model, melt accumulates over ~10 m.y. as the diapir rises from its origin within the transition zone to sublithospheric depths, whereupon the pressure of the melt pool is sufficient to rupture the diapir roof, allowing kimberlite magmas to escape to the surface via brittle fracturing processes. A similar process was proposed by Janney et al. (2002) to explain melilitite formation. In their model, domains (predominantly composed of subducted oceanic crust) rise to the top of the asthenosphere before undergoing partial melting. The diapiric model of Grégoire et al. (2006) is favored here, as it allows for the production of each kimberlite field from a single pool of homogenized melt, and is thus in excellent agreement with the results of this study.

What are the likely candidates for such a source? In order to make comparisons between the 1.1 Ga kimberlites and potential mantle components, it is necessary to correct present-day ratios back to this time. For example, the present-day range in $^{87}\text{Sr}/^{86}\text{Sr}$ for normal (N) MORB of 0.7023–0.7027 (Workman and Hart, 2005) yields corresponding values at 1.1 Ga of 0.70201–0.70241 ($\epsilon\text{Sr} -16.1$ to -10.4). Thus although in situ ϵSr results of the Wajrakarur kimberlite field potentially overlap with N-MORB at 1.1 Ga, those of the Narayanpet field cannot have been generated from an N-MORB source and require a more enriched source, perhaps similar to prevalent mantle (PREMA) or focal zone (FOZO) (Stracke et al., 2005). An important conclusion is that, based on the Sr isotope data presented here, magmas of the Wajrakarur and Narayanpet kimberlite fields do not require a unique or unusually enriched mantle source. Given the presence of eclogite xenoliths containing retrogressed majoritic garnet within kimberlites of the Wajrakarur field (Patel et al., 2006), however, we suggest that this source originated within or below the transition zone.

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