Imaging mantle lithosphere for diamond prospecting in southeast India

Subrata Das Sharma* and Durbha Sai Ramesh
NATIONAL GEOPHYSICAL RESEARCH INSTITUTE (COUNCIL OF SCIENTIFIC & INDUSTRIAL RESEARCH), HYDERABAD 500007, INDIA

ABSTRACT
An understanding of the tectonic makeup of an area through study of surface geological features, together with depth information on the nature of the underlying lithosphere, forms the key to diamond exploration strategy. Although diamonds have been reported from the Indian craton for many centuries, the search for their carrier rocks dates back only to the beginning of the twentieth century. This study focuses on a wide area in southeast India, parts of which are sources of both diamondiferous and nondiamondiferous kimberlites and lamproites. Using Ps (SV and SH) and Sp receiver functions, we recovered depth images of the lithospheric mantle beneath southeast India encompassing the Eastern Dharwar–Bastar cratons and the adjoining Eastern Ghats mobile belt. These images reveal the presence of two significant velocity anomalies of contrasting nature at different depths beneath the study region. High-velocity features are observed between 160 and 220 km depth (Lehmann discontinuity depth, or L-depth), and a complex low-velocity contrast layer is delineated at ~80–100 km depth. Analyses of results from several other studies that include regional geology, geophysics, geochemistry, and geochronology allow us to infer that the positive velocity contrasts at L-depth represent preserved oceanic remnants of a ca. 1.6 Ga paleosubduction event. Consequent upon the reworking of these remnants with the Indian plate, a shallow lithosphere-asthenosphere boundary has developed. The diamond formation potential of the area is discussed in light of a working model that incorporates the Mesoproterozoic paleosubduction scenario (ca. 1.6 Ma event) and subsequent kimberlite and lamproite intrusions. Wide regions covering the Godavari graben and adjoining areas are identified as potential zones for diamond exploration.

INTRODUCTION
Diamonds originate within Earth’s mantle at depths in excess of 150 km and are transported to the surface by potash-rich high-magnesian volcanic rocks such as kimberlites and lamproites. It is well established that diamonds found in kimberlites and related rocks originate as xenocrysts. The actual genesis of diamonds is closely related to the presence of peridotite (both lherzolite and harzburgite) and eclogite, which are derived from the upper mantle below cratonic areas (see Kirkley et al., 1991). Apart from high pressures and temperatures, the formation of diamonds also requires suitable oxygen fugacity conditions (Meyer, 1985). Kimberlites and lamproites are brought to Earth’s surface through violent explosive emplacement of volatile-rich melts. Kimberlites typically form circular volcanic pipes ~40–50 m in diameter, while lamproites emerge at the surface as dikes or small intrusive bodies. Owing to their limited spatial dispersion, field detection of kimberlites and lamproites is often problematic. The fragile nature of these rocks further renders their field detection equivocal. For these reasons, in many cases, their surface expression may be cryptic. Therefore, geophysical detection of kimberlite and related rocks involving contrasts in physical properties such as magnetic susceptibility, electrical resistivity, density, dielectric permittivity, and seismic velocity contrast between kimberlites and their host rocks has been used (see, for example, Macnae, 1995; Palacky, 1993; Jones, 1999; Power et al., 2004; Pettit, 2009). Besides geophysical methods, in many cases geochemistry and heavy indicator mineral studies have proven to be rewarding (Gurney and Zweistra, 1995; Griffin and Ryan, 1995; Grütter et al., 2004).

The presence of kimberlite and related rocks in India is reported from four of its distinct Precambrian cratonic blocks, including the Bundelkhand, Singhbhum, Bastar, and Dharwar cratons (Fig. 1). Geophysical exploration for kimberlite and lamproite rocks employing magnetic and gravity methods (Murthy et al., 1998; Sarma et al., 1999) has been attempted in some of these cratonic areas. However, for diamonds to be present in kimberlite and lamproite, it is mandatory that the lithospheric thickness (i.e., pressure-temperature conditions) should fall within the diamond stability field (e.g., Mitchell, 1991), and the diamondiferous regions must have high concentrations of carbon. Deep-probing electromagnetic tools, such as natural-source magnetotelluric systems (Jones and Craven, 2004) have yielded a rapid and cost-effective method for identification of prospective diamondiferous regions in the Slave, Superior, and Rae cratons of North America. Recently, Snyder et al. (2004) mapped the upper-mantle stratigraphy in the Slave craton to understand seismic and other characteristics of the shallow mantle lithosphere with the ultimate aim of locating potential zones for diamond exploration. Their study reveals three shallow upper-mantle seismic discontinuities at depths of ~110, 140, and 190 km beneath the central Slave craton, indicating that the lithospheric thickness in this region falls within the diamond stability field. Such studies, when integrated with results from deep-probing magnetotelluric observations and xenolith petrology, can provide depth images of key physical properties within parts of the cratons that are known to host diamonds.

We mapped the upper-mantle stratigraphy beneath two well-recognized kimberlite- and lamproite-bearing cratonic regions of southeast India,
RESULTS show that the present-day lithosphere beneath southeast India is suitable to delineate prospective diamondiferous zones in the study. Our new seismic results to the cratonic blocks of southeast India. We also use these data, we present a comprehensive geodynamic model to illustrate diamond genesis in the cratonic blocks of southeast India. Based on these seismological results and available geological, geochronological, and thermobarometric data, we present a comprehensive geodynamic model to illustrate diamond genesis in the cratonic blocks of southeast India. We also use these results to delineate prospective diamondiferous zones in the study. Our results show that the present-day lithosphere beneath southeast India is indeed thick and extends beyond the well-defined diamond stability field.

KIMBERLITE AND LAMPROITE OCCURRENCES IN CRATONIC REGIONS OF INDIA

The Bastar, Dharwar, and Bundelkhand cratons, using Ps (P-to-s conversions) and Sp (S-to-p conversions) receiver functions (Vinnik, 1977; Farra and Vinnik, 2000). Based on these seismological results and available geological, geochemical, geochronological, and thermobarometric data, we present a comprehensive geodynamic model to illustrate diamond genesis in the cratonic blocks of southeast India. We also use these results to delineate prospective diamondiferous zones in the study. Our results show that the present-day lithosphere beneath southeast India is indeed thick and extends beyond the well-defined diamond stability field.

In total, 47 occurrences of lamproites have been reported from the Cuddapah Basin and its northwestern and northeastern margins. They occur in three fields: (1) the Cuddapah lamproite field, consisting of occurrences at Chelima and Zangamarajupalle, (2) the Ramadugu lamproite field, and (3) the Krishna lamproite field (Naqvi, 2005, and references therein). Established diamond-bearing lamproite source rocks came to light from the Panna and Bundelkhand areas of Madhya Pradesh in the Bundelkhand craton. In the Bastar craton, presence of diamonds in kimberlites is reported from areas such as Bahradih, Payalikhand, Jangra, and Kodomal (Chatterjee et al., 1995; Mainkar and Lehmann, 2007). Diamond occurrences are also reported in the Wairagarh conglomerate (Sashidharan et al., 2002). In the eastern part of India, though lamproites are reported from the Damodar valley regions of the Singhbhum craton, to our knowledge, no diamonds have been reported from this cratonic segment.

METHODS AND DATA

We reanalyzed seismic data from four broadband stations, Kothagudem (KDM), Hyderabad (HYB), Cuddapah (CUD), and Dharwar (DHD), operated by the National Geophysical Research Institute, Hyderabad (Fig. 2). Several hundred clear records of P and S waves from earthquakes having magnitudes larger than 5.5 having relatively high signal-to-noise ratios (SNR ≥ 3) were selected. Among the band-pass filters tested, the range of band-pass periods from 1.5–3 s up to a maximum of 10–12 s was found best suited to process the recorded seismograms. To obtain the P receiver functions, earthquakes recorded in the distance range 30°–90° were utilized; for the S receiver functions, Wilson’s criteria (Wilson et al.,
RESULTS AND DISCUSSION

We demarcate two regions in southeast India within the Bastar and Eastern Dharwar cratons (marked as I and II) from whence the majority of diamond-bearing kimberlites and lamproites are reported (Fig. 1). Both these regions (I and II) are sampled rather densely by the Sp data (see Fig. 2). Additionally, though kimberlites and lamproites have yet to be reported from the intermediate region marked as III (Fig. 1), in view of its excellent sampling by the Sp receiver functions, this region was also analyzed. Each region was subdivided into 1° × 1° grids. Grids sampled generally by a minimum of 5 Sp data were considered for stacking. S receiver function stacks corresponding to the grids in each demarcated region are shown in Figure 5. Two Sp converted phases, corresponding to delay times at ~15 s (D15) and ~20 s (D20) marked in Figure 4, indicate the possible presence of interfaces with a positive velocity contrast located at upper-mantle depths between ~150 and 200 km. The presence of these signatures in all the demarcated regions (marked I, II, and III), as well as their delineation by data recorded at four seismic stations that are reasonably well separated, suggests that this velocity feature is present over a large spatial area of the study region. Besides these positive-velocity-contrast features, we also document the presence of a negative phase (low-velocity contrast layer) at ~10 s (Figs. 4 and 5), corresponding to 80–100 km depth beneath the study region.

Next, we investigated whether the observed shallow-mantle features delineated by Sp receiver functions were also visible in Ps data. The P receiver functions recorded at the four stations were transformed into the depth domain (Fig. 6) by back-projecting their energy to the corresponding conversion points along their paths, using the IASP91 standard velocity model. We used grid sizes of 2 × 2 km² and projected data onto roughly SW-NE profiles restricted to within one Fresnel zone around the incident ray. Though several other projection profiles were considered, coherent features were seen best along SW-NE profiles. A relatively high-resolution Ps migrated image along the SW-NE direction, i.e., along PQ (Fig. 2), starting at 14°N and 76°E and ending at 19°N and 83°E, is shown in Figure 6. The migrated P receiver function image (Fig. 6) shows the prominent D15 phase at ~150 km depth in the center of the image, deepening to the west. The D20 phase is clearly westerly dipping, starting at ~150 km (~82°E) in the east and deepening to ~200 km depth in the center (~77–80°E) of the profile. A coherent and relatively flat 410 km boundary can be seen in the Ps data image, while the 660 km interface is rather sporadic (Fig. 6).

The dipping features delineated in the migrated Ps image (Fig. 6) also appear as coherent inclined arrivals in the Sp receiver functions (Figs. 4 and 5). The corresponding inclined phases and the low-velocity contrast layer arrival (Figs. 4–6) are weakly recorded at appropriate windows in the radial (SV) receiver functions (Fig. 3). This is due to interference of the genuine Ps conversions from shallow-mantle boundaries by multiples (reverberations) that arrive in the same time window. Hence, unambiguous detection of shallow-mantle layers such as H-, X-, and L-boundaries in the general depth range 75–250 km using SV receiver functions alone becomes rather difficult (e.g., Bostock, 1998). Further, the presence of significant energy in the transverse (SH) component, corresponding to reasonably well-identified Ps converted phases on the radial (SV) component, signifies the presence of aspherical structure beneath a seismic station, possibly due to an anisotropic and/or a dipping layer (Bostock, 1998; Saul et al., 2000). Therefore, use of the SH (transverse) receiver functions that offer reverberation-free time windows in this context assumes importance.

Examples of the transverse receiver functions (SH) corresponding to stations HYB and KDM are shown in Figure 7. Good recordings at the Indian stations are limited to the back-azimuth range ~35°–120° (e.g., Saul et al., 2000; Ramesh et al., 2010a), so, SH component receiver functions from these back-azimuths were sorted by slowness (Fig. 7) to further authenticate the reported PLs phase in the radial receiver functions (see Fig. 3) centered on 20 s. At stations HYB and KDM, the respective SH components prominently register the PLs phase documented in the SV component, identified as a dipping interface in Figure 6. In addition to the PLs phase, arrivals with alternating polarities (sequential positive-negative-positive-sequence) centered on 10 s are seen on the SH component in our slowness plots (Fig. 7). A similar complex feature beneath station HYB is also visible in the SH response presented by Saul et al. (2000).

The combined results from Ps (SV and SH) and Sp data (see Figs. 3–7) can be summarized as follows: (1) The Moho is in the depth range of ~35–42 km; (2) two distinct seismic phases of opposing polarities (centered on ~10 s and ~20 s, respectively) can be identified at shallow upper-mantle depths covering all three regions (I–III) within the Eastern Ghats–Bastar–Dharwar cratons; (3) the shallower signal (~10 s) is characteristic of the presence of a complex low-velocity contrast layer at ~80 km depth; (4) the deeper images delineate the presence of westerly dipping positive-velocity-contrast features (PLs) in the depth range 160–220 km; (5) a relatively flat, undisturbed 410 km seismic boundary is clearly delineated; and (6) intermittent presence of the 660 km boundary is observed.

Our main interest is to identify areas for diamond prospecting in southeast India based on images of the underlying shallow mantle and constraints from various other studies in the region. Therefore, the following discussion
Figure 3. Sample Ps receiver functions in colored pixels, showing Ps move-out–corrected receiver functions with respect to epicentral distance and back azimuth at stations HYB and CUD. The top box in each panel shows the sum trace. Since the data recorded in back azimuths beyond 120° are rather sparse, the receiver functions up to 120° back azimuth are displayed. Various receiver function arrival phases are also labeled: Pms—phase converted at the Moho boundary; PLs—a converted phase from a boundary (marked by arrows) located at the Lehmann depth (L-depth) discontinuity (~150–250 km; Lehmann, 1959). Phases marked Pps and Pss correspond to crustal reverberation arrivals. All the data are move-out corrected, corresponding to a reference distance of 67°.
Figure 4. Sample Sp receiver function data in colored pixels, showing distance move-out–corrected S-receiver function individual traces at station CUD and distance stacks (binned using 2° interval) at station HYB. The corresponding sum traces are also shown in each panel. Arrivals from Lehmann depth (L-depth) range, marked as phases D15 and D20, are Sp conversions (indicated by arrows) from positive-velocity-contrast features located between ~150 and 200 km depth. Therefore, note that D15, D20, and PLs are used interchangeably to denote arrivals from the general L-depth range (~150–250 km) in the text and figures. The Sp arrivals recorded at ~10 s, corresponding to a low-velocity zone (LVZ) around 80–100 km depth, are interpreted to arise from a midlithospheric discontinuity (MLD) in the study region. See text for more details.

Figure 5. Sum traces of Sp receiver functions falling within ~1° × 1° grid squares corresponding to regions I–III. The binning strategy used for the Sp receiver function grid stacks is as follows: As a first step, ~1° × 1° grids were arranged row-wise from east to west. Grids sampled by 5 or more Sp data were considered. Later, data falling within each of such grids were stacked to obtain individual grid stacks. Quantities within parentheses denote the number of individual Sp receiver functions used to construct each grid stack. When the top row was completed, the next row was taken and arranged in a similar fashion. This exercise was carried out for all the three regions I–III shown in Figure 1. This was followed by obtaining the sum traces (shown in color) for each region. The grid stacks presented in the figure are arranged at equal distance. The labels used to denote the phases remain the same as discussed in Figure 4. However, we employ reversal of color convention in this figure compared to that of Figure 4 to denote low velocities in red. Note that the Sp phases originating from Lehmann depth (L-depth) show a progressive delay in time from region I to II through III. This becomes more conspicuous as an ~4 s delay and is better reflected in the corresponding sum traces. Incidentally, regions I–III have a NE-SW disposition to indicate that the documented delay in L-depth arrivals is due to the presence of westerly dipping features at ~160–220 km depth (see also Ramesh et al., 2010a). MLD—midlithospheric discontinuity.
Interpretation of the Low-Velocity Zones around 100 Km Depth

In recent years, the possibly global presence of low-velocity contrast layers in the general depth range ~50–130 km within the cratonic lithosphere, centered on 100 km depth, has been reported, deriving mainly from Ps and Sp receiver functions (e.g., Abt et al., 2010; Rychert and Shearer, 2009). Some researchers have therefore inferred that the lithosphere beneath stable Archean–Proterozoic age cratons may be significantly thinner than expected. However, thin (~100 km) cratonic lithosphere or a shallow lithosphere-asthenosphere boundary beneath the cratons is in direct contradiction with many recent estimates based on other seismological, geophysical, and geochemical data and results (see Griffin et al., 2003; Lee, 2006; Fischer et al., 2010, and references therein; Romanowicz, 2009; Yuan and Romanowicz, 2010).

Given this discrepancy, we highlight the nature of the recorded sequential positive-negative-positive peaks centered on 10 s in the SH component receiver functions (Fig. 7), manifested as a complex low-velocity contrast layer in the Sp receiver functions (Fig. 5). Saul et al. (2000) interpreted this structure beneath station HYB, emphasizing only the negative polarity peak in this complex signal, and identified it as a converted phase arising from an anisotropic and/or a dipping layer at ~90 km depth. As we also observe this complex signature beneath the study region, we infer it to represent a genuine layering in the shallow lithosphere. The documented presence of this complex feature beneath southeast India encourages us to speculate that it originated as a pervasive mantle process that affected the study region. In a recent study, Hammond et al. (2012) adopted similar approaches to record the presence of multiple low-velocity layers in the depth range 50 and 190 km beneath the Seychelles. These low-velocity features, viewed as trapped sulfide melts and linked to episodic generation of the Deccan continental flood basalts, are interpreted as plume scars leading to the observed stratification at uppermost mantle depths. However, the presence of alternating velocity layers (Fig. 7) in a region such as southeast India, where both large numbers of potassic magma bodies and the absence of xenoliths containing sulfide melts are observed, indicates that the low-velocity contrast layer at ~10 s may not be associated with the Deccan flood basalt event.

Because kimberlite intrusions have been associated with CO$_2$ + H$_2$O fluid activities (Sleep, 2009), the related past mantle metasomatism could be a potential candidate to explain the observed complex low-velocity contrast layer feature (Fig. 7; see also Fig. 5). This possibility is supported by recordings of similar complex-natured seismic signals at variable depths in SH receiver functions beneath the Slave craton, Canada (Bostock, 1998; Snyder et al., 2004). Therefore, such lithospheric features could be linked to cratonic evolution through a mantle process tied to emplacement of diamonds in the study area. We therefore view the seismologically observed complex feature (low-velocity contrast layer; ~10 s) as a midlithospheric discontinuity developed in the cratonic lithosphere of southeast India by mantle metasomatism associated with emplacement of potassic magmas. The presence of low-velocity layers within the cratonic midlithosphere at depths of ~50–150 km is now increasingly viewed as relict features inherited from past geologic episodes that affected the region (e.g., Bostock, 1998; Hammond et al., 2012; Miller and Eaton, 2010; Yuan and Romanowicz, 2010).

Our interpretation of the observed shallow low-velocity contrast layer (80–100 km) beneath southeast India as a midlithospheric discontinuity, and not the lithosphere-asthenosphere boundary, differs from that of Kumar et al. (2007). Kumar et al. (2007) assumed that the existence of a high-velocity lithospheric lid would result in P410s wave speeds proportional to the lid thickness. Thus, they anticipated that P410s arrivals and times of the S-to-p conversions from the lithosphere-asthenosphere boundary (designated Sp$_{LAB}$ here) would anticorrelate. They used this anticipated anticorrelation between Sp$_{LAB}$ and P410s times as a diagnostic to validate their documented lithosphere-asthenosphere boundary depths globally.

Figures 8 and 9 suggest that the anticipated anticorrelation between Sp$_{LAB}$ and P410s times is poor (correlation coefficient $R^2 = 0.35$) in the dispersed Gondwanaland segments, and very poor ($R^2 = 0.11$) for the Indian cratonic stations. Thus, the Sp$_{LAB}$ arrivals and P410s times show no correlation, either positive or negative in the study region. We note that the P410s times are centered on the predicted IASP91 model arrival time of 44.1 s and show marginal variations on the order ±0.5 s (Fig. 9). This suggests that the 410 km boundary beneath southeast India is relatively flat on a regional scale (Fig. 9) and corroborates similar observations reported beneath most of India (Oreshin et al., 2011). In contrast to the observed uniform P410s times, the Sp$_{LAB}$ times beneath southeast India are scattered, varying from ~8 s to 12 s. This variation evidently cannot be attributed to changes that occur either at a specific depth or with tempera-
Imaging mantle lithosphere for diamond prospecting

Figure 7. Transverse (SH) receiver function stacks at stations HYB and KDM. The presence of anisotropic and/or dipping layers beneath a seismic station is usually broadly reflected as back-azimuth dependence of the Ps conversions observed on the radial (SV) component. Further, the presence of significant energy in the transverse (SH) component corresponding to such identified Ps converted phases on the radial (SV) component becomes diagnostic of presence of a dipping/anisotropic layer beneath a seismic station. Prominent arrivals on the transverse component (SH) receiver functions corresponding to the PLs (centered on 20 s in the SV component) and a complex phase with positive-negative-positive peaks corresponding to ~10 s are seen. These energetic features on the SH component authenticate the claims of the possible presence of the dipping interfaces beneath both the stations. The complex signal at ~10 s on the SH component was also documented earlier by Saul et al. (2000) beneath station HYB. However, they discussed this feature only as a negative phase possibly arising from an anisotropic and/or dipping layer at ~90 km depth. Based on the results obtained here from Ps and Sp receiver functions, in addition to various other studies discussed in the text, we attribute the origin of this complex feature to a pervasive mantle metasomatic process during kimberlite intrusions in the geologic past.

Figure 8. Plot showing P410s times and corresponding SpLAB times reported in the literature at 35 stations distributed globally. The P410s times are arranged in increasing order. Vertical line refers to the predicted P410s arrival (44.1 s) corresponding to IASP91 standard earth model. The proclaimed diagnostic for presence of a lithosphere-asthenosphere boundary beneath several Gondwanaland cratonic stations in the form of anticorrelation between the P410s and corresponding SpLAB times proposed by Kumar et al. (2007) seems unfounded. A mere 35% of the data share the anticipated anticorrelation. The remaining 65% of data suggest that the observed/inferred low-velocity layer in S-receiver functions beneath the stations cannot be interpreted as the lithosphere-asthenosphere boundary. Note that station KDM is identical to KGD.
The presence of a thick lithospheric root beneath southeast India is the most plausible mechanism by which such distinct evidence of past tectonic events could be preserved. Our interpretation of a prominent mid-lithospheric discontinuity together with the occurrence of relict features preserved at L-discontinuity depths since the Mesoproterozoic collectively reinforce the idea that the lithospheric root beneath southeast India is thick and easily extends deeper than 200 km.

Given the fast ascent rates of kimberlites and lamproites (Mercier, 1979; Kelley and Wartho, 2000), the mantle xenoliths from the area provide a direct and model-independent means with which to constrain the thermal state of the continental lithospheric mantle at their time of ascent. Pressure-temperature (P-T) estimates from pyroxene compositions in mafic and ultramafic xenoliths associated with Proterozoic kimberlites (ca. 1.1 Ga) of the Eastern Dharwar craton (e.g., Ganguly and Bhattacharya, 1987; Nehru and Reddy, 1989; Brey and Köhler, 1990) yielded maximum equilibrium P-T conditions experienced by these xenoliths of 7.1 GPa and 1240 °C. When converted to equivalent depth, this P-T state suggests a lithosphere-asthenosphere boundary in excess of 200 km beneath the Eastern Dharwar craton. Chemical tomography on garnet xenocrysts associated with the kimberlites of the Dharwar craton (Griffin et al., 2009) also corroborates a thick depleted lithosphere of ~190 km. P-T estimates on garnet lherzolite xenoliths related to the 65 Ma kimberlite eruption from the Bastar craton of southeast India point to an equilibrium assemblage corresponding to a minimum depth of ~165 km (Babu et al., 2009). Observed average low heat-flow values of ~36 and 55 mW m⁻², respectively, in the Dharwar and Bastar cratons, with attendant low mantle heat-flow components (average ~17 mW m⁻²), indicate a deep, at least ~175 km, lithosphere-asthenosphere boundary beneath southeast India (Gupta, 1993; Roy and Mareschal, 2011). These observations agree well with the models derived from surface waves, which favor presence of a high-velocity mantle lid to at least 200 km depth beneath south India (Oreshin et al., 2011). The xenolith thermodiagnostic results and heat-flow data are therefore in excellent agreement with the Ps and Sp receiver function results obtained on southeast India and constrain well the inferred minimum lithospheric thickness of ~200 km for the region (see Fig. 10).

The presence of a thick tectospheric keel is also relevant to proposed causes of the anomalously fast drift of the Indian plate during the Cretaceous. Cande and Stegman (2011) related the “plume-push force” associated with a rising mantle plume impinging on the base of a tectonic plate to the acceleration of the Indian plate to velocities in excess of 10 cm/yr between 68 and 66 Ma, as the conjugate Africa plate slowed down. The evidence presented in this study, which overwhelmingly favors a thick Indian lithosphere, would be inconsistent with observed rapid drift or “supermobility” of the Indian plate during the Cretaceous as the geodynamic consequence of a thin Indian plate (e.g., Negi et al., 1986; Kumar et al., 2007).

Observation of Mode-Converted Signals from the Lehmann Discontinuity Depth in the Study Area and Estimates of Minimum Thickness of Lithosphere beneath Southeast India

The mode-converted signals (D15 and D20) related to the Lehmann discontinuity depth (L-depth) identified in our work (Figs. 4–5) are germane to the tectonics, evolution, and lithospheric configuration of southeast India. In earlier publications (see Ramesh et al., 2010a, 2010b; Bapanayya et al., 2011), these positive-velocity-contrast seismic phases were interpreted as relict paleo-subduction features based on their present-day depth disposition, and on field geologic correlation and several other geophysical, geochemical, and age constraints. This interpretation is supported by: (1) the presence of nepheline syenites and carbonatites, which represent deformed alkaline rocks and carbonatites (DARCs), indicative of suturing in the study region (Leelanandam et al., 2006; Vijaya Kumar and Leelanandam, 2008); (2) 1.85 Ga sensitive high-resolution ion microprobe (SHRIMP) U-Pb ages of zircons separated from the Kandra ophiolite complex along the SE margin of India (Vijaya Kumar et al., 2010), suggestive of Wilson cycling; (3) documentation of a suite of rock occurrences in a particular sequence, along with their age constraints (Vijaya Kumar et al., 2011), reminiscent of the proposed subduction in southeast India; (4) a paired gravity anomaly in the region (Kaila and Bhatia, 1981), characteristic of suture zones; and (5) geophysically detected relict subduction features at depth from similar tectonic settings of Proterozoic age and younger Paleozoic times around the globe.

The presence of a thick lithospheric root beneath southeast India is the most plausible mechanism by which such distinct evidence of past tectonic events could be preserved. Our interpretation of a prominent mid-lithospheric discontinuity together with the occurrence of relict features preserved at L-discontinuity depths since the Mesoproterozoic collectively reinforce the idea that the lithospheric root beneath southeast India is thick and easily extends deeper than 200 km.

Given the fast ascent rates of kimberlites and lamproites (Mercier, 1979; Kelley and Wartho, 2000), the mantle xenoliths from the area provide a direct and model-independent means with which to constrain the thermal state of the continental lithospheric mantle at their time of ascent. Pressure-temperature (P-T) estimates from pyroxene compositions in mafic and ultramafic xenoliths associated with Proterozoic kimberlites (ca. 1.1 Ga) of the Eastern Dharwar craton (e.g., Ganguly and Bhattacharya, 1987; Nehru and Reddy, 1989; Brey and Köhler, 1990) yielded maximum equilibrium P-T conditions experienced by these xenoliths of 7.1 GPa and 1240 °C. When converted to equivalent depth, this P-T state suggests a lithosphere-asthenosphere boundary in excess of 200 km beneath the Eastern Dharwar craton. Chemical tomography on garnet xenocrystals associated with the kimberlites of the Dharwar craton (Griffin et al., 2009) also corroborates a thick depleted lithosphere of ~190 km. P-T estimates on garnet lherzolite xenoliths related to the 65 Ma kimberlite eruption from the Bastar craton of southeast India point to an equilibrium assemblage corresponding to a minimum depth of ~165 km (Babu et al., 2009). Observed average low heat-flow values of ~36 and 55 mW m⁻², respectively, in the Dharwar and Bastar cratons, with attendant low mantle heat-flow components (average ~17 mW m⁻²), indicate a deep, at least ~175 km, lithosphere-asthenosphere boundary beneath southeast India (Gupta, 1993; Roy and Mareschal, 2011). These observations agree well with the models derived from surface waves, which favor presence of a high-velocity mantle lid to at least 200 km depth beneath south India (Oreshin et al., 2011). The xenolith thermodiagnostic results and heat-flow data are therefore in excellent agreement with the Ps and Sp receiver function results obtained on southeast India and constrain well the inferred minimum lithospheric thickness of ~200 km for the region (see Fig. 10).

The presence of a thick tectospheric keel is also relevant to proposed causes of the anomalously fast drift of the Indian plate during the Cretaceous. Cande and Stegman (2011) related the “plume-push force” associated with a rising mantle plume impinging on the base of a tectonic plate to the acceleration of the Indian plate to velocities in excess of 10 cm/yr between 68 and 66 Ma, as the conjugate Africa plate slowed down. The evidence presented in this study, which overwhelmingly favors a thick Indian lithosphere, would be inconsistent with observed rapid drift or “supermobility” of the Indian plate during the Cretaceous as the geodynamic consequence of a thin Indian plate (e.g., Negi et al., 1986; Kumar et al., 2007).

Geodynamic Model for Genesis of Diamonds in Southeast India

Based on the proposed 1.6 Ga pre-Grenvillian subduction scenario in southeast India (Ramesh et al., 2010a), we attempt to provide a plausible model for diamond genesis within the study region. We note, however, that the ages of kimberlite intrusions at several locales in the study region are variable. In region II (see Fig. 1), as documented by the Rh-Sr and Sm-Nd isotope systematics, kimberlite intrusions are ca. 1.1 Ga (Anil Kumar et al., 2007). Limited data in region I suggest that kimberlites there are much younger, ca. 65 Ma, from Ar40Ar whole-rock and U-Pb perovskite ages of the Behradih and Kodomali pipes in the Mainpur area (Leemann et al., 2010). No attempt is made so far to evaluate either the compositions or ages of fluid/minor xenolith inclusions within diamonds.
The occurrence of this wide variety of mantle xenoliths from these regions (Karmalkar et al., 2009). The xenoliths associated with kimberlites from Dharwar and Bastar cratons are garnet harzburgites, lherzolites, wehrlite, olivine clinopyroxenites, and kyanite eclogites (Karmalkar et al., 2009). The occurrence of this wide variety of mantle xenoliths in the study area is itself sufficient to indicate that the diamonds brought to the surface by kimberlites owe their origin to both crustal (subduction-related isotopically light carbon) and mantle (primitive carbon) sources (see Wiens et al., 1990).

Mitchell (1991), based on compositional and morphological differences in diamonds, realized that the diamond-forming process is not unique, although the presence of a thick lithospheric root is a prerequisite for diamond genesis. A generalized schematic model, presented in Figure 11, shows extrusion/transport of diamonds formed by varied processes to the surface carried by the two different groups of kimberlites (groups I and II). The occurrence of diamonds in the Slave (Canada), Kaapvaal (southern Africa), and Siberian cratons is in conformity with such a model and the associated tectonic settings therein (see Simandl, 2004).

Based on the results from this study, a similar model can be extended to explain presence of diamonds in southeast India. The Archean Eastern Dharwar craton and the Proterozoic Eastern Ghats mobile belt, shown in the cross section, are clearly underlain by a feature, interpreted as a relict subducted slab, within the upper mantle at 160–220 km depth. The depth of this feature also coincides with the diamond stability field (Fig. 11). The graphite-diamond stability boundary originates within the keel (referred to as the diamond stability field in the literature; see also Fig. 10). Kimberlite intrusions through such domains can carry both peridotitic (K1 and K2 in Fig. 11) and eclogitic (K2 and L in Fig. 11) diamonds. The origin of the transported diamonds is determined by the way in which kimberlites or lamproites intrusives sample subregions of the tectonic keel below the graphite-diamond stability boundary that contain eclogitic (e.g., originating from subducted slabs) or peridotitic (mantle source) xenoliths. Additionally, the carrier rocks may be devoid of diamonds, as shown in Figure 11 (note that K3 will be barren), because they sample diamond-barren subregions. Diamonds and associated xenoliths of varied origin that are reported from southeast India can therefore be explained. Interestingly, the limited number of data obtained on diamonds from southeast India remarkably show δ13C compositions covering a wide range, starting from heavy (~4‰) and moving to light (~26‰) values (Wiens et al., 1990), suggesting that both crust and mantle sources of carbon (distinct source reservoirs) were responsible for the generation of diamonds in this region. In light of the established age relationship between the Mesoproterozoic (ca. 1.6 Ga) subduction event (Vijaya Kumar and Leelamandam, 2008; Ramesh et al., 2010a) and eruption of kimberlites and lamproites in region II at ca. 1.1 Ga (Anil Kumar et al., 2007) and in region I at ca. 65 Ma (Lehmann et al., 2010), a subduction-related mechanism can be suggested for the origin of some of the diamonds in southeast India (Fig. 11).

Delineation of Prospective Diamond Zones in the Study Area

From the previous discussion, it is apparent that the geotectonic controls for diamond formation and their ascent to the surface through kimberlites and lamproites are governed by different mechanisms (see also Helmstaedt and Gurney, 1995). Therefore, Helmstaedt and Gurney (1995) provided some useful guidelines to select sites for diamond exploration: (1) identification of lithospheric regions where diamonds could potentially form and remain stable for sufficiently long time to be sampled by younger kimberlites or lamproites; and (2) an overall comprehension of the local and regional structural controls for the intrusion of potash-rich high-magnesian magmatic rocks like kimberlites and lamproites. Southeast Indian receiver functions delineate positive-velocity-contrast features within the subcontinental lithospheric mantle at 160–220 km depth. These features are inferred to be remnants of a paleosuturing event related to the Eastern Ghats orogeny in southeast India; they dip approximately...
NE-SW and have been preserved at a depth where diamonds are stable (see Figs. 10 and 11). The tectonics of the Eastern Dharwar craton and Eastern Ghats mobile belt can therefore be compared to the subduction and collision related to the diamondiferous Kimberley and Witwatersrand blocks, which represent the western and eastern domains of the Kaapvaal craton, respectively (e.g., Schmitz et al., 2004). Both peridotitic as well as eclogitic diamonds have been reported from the cratonic regions of southeast India and South Africa. Therefore, our results are consistent with high diamond-forming potential in the subcontinental lithospheric mantle in all three regions (I–III) demarcated in Figure 1, in view of existence of thick tectonic roots that preserve relic subducted slabs within the diamond stability at depths in excess of ~150 km. Thus, identification of kimberlites or lamproites that potentially transport the resident diamonds to the surface remains crucial for diamond exploration in the study region.

Kimberlites and lamproites generally appear in the field as outcrop clusters occurring along parallel sets of corridors. These corridors are usually distributed across large parts of a subcontinent. The Narayanpet, Raichur, Tongabhadra, and Wajrakarur kimberlite fields within the Eastern Dharwar craton represent examples of such occurrences distributed over an area of ~9500 km² (Fig. 1). Focused efforts for diamond exploration should therefore be planned in hitherto unexplored regions, such as all of region III (Fig. 1), the Godavari graben and its adjoining areas. Likewise, the Nallamalai fold belt and areas between the northeast corner of the Cuddapah Basin and the Pakhal Basin within region II and major areas in the Eastern Ghats mobile belt near the Bastar craton in region I (Fig. 1) are amenable to further exploratory work. Since region III covers an extensive area that includes the Godavari graben, it is important to inquire whether diamonds could be preserved and transported in such a rift-related tectonic setting: (1) The lithospheric root established in this study extends beyond the diamond stability field and encompasses all the regions I–III. (2) The recorded ages of kimberlites and lamproite intrusions that emplaced diamonds in the study region span a wide range from ca. 1.1 Ga to ca. 65 Ma (see Anil Kumar et al., 2007; Lehmann et al., 2010). This result, together with lack of records of major magmatic episodes succeeding the Deccan flood basalt eruption (67–64 Ma; Courtillot et al., 1988; Duncan and Pyle, 1988), suggests no thinning of the lithosphere in the study area. (3) The association of major deep faults or shears that traverse the entire crust/lithosphere and kimberlite emplacement observed globally across major grabens (White et al., 1995) is also likely valid in the Godavari graben, and suggests the mechanism of diamond transport to the surface. Linear grabens represent important structural settings favored by Mesozoic and younger kimberlite intrusives controlled by reactivation of structures such as rift system faults inherited from past orogenic cycles (de Boorder, 1982; Pereira et al., 2003; White et al., 1995). Classic examples come from the Archean Congo craton and Lucapa corridor in Angola, which show similarities with the tectonic setting of the Godavari graben with an inferred Precambrian ancestry.

Diamondiferous kimberlites are found even in the North China craton, which, paradoxically, today has an abnormally thin lithosphere of ~100 km. A recent study on xenocrysts of kimberlites from the North China craton by Li et al. (2011) suggests that diamondiferous kimberlites were emplaced in the region ca. 480 Ma (Paleozoic). Other studies on Hf isotopic compositions of the subcontinental lithospheric mantle–derived material beneath the North China craton, and Cenozoic basalt-transported peridotite xenoliths in the region suggest that the lithospheric thickness to ~100 km occurred sometime between Early Ordovician and Cenozoic times (Li et al., 2011). Together, these results imply that delamination beneath the North China craton postdated the kimberlite emplacement age of 480 Ma, though the precise timing of this destructive thinning event is unclear. It is evident from the previous discussion that, although the present-day lithospheric thickness has no bearing on the diamond prospects in a region, thick lithosphere is a prerequisite for diamond formation and preservation until emplacement.

Diamond Prospecting in Southeast India—A Historical to Current Perspective

Diamonds found in the Indian subcontinent prior to the nineteenth century were either associated with alluvial or conglomeratic sources. They were obviously eroded from kimberlite or lamproite source rocks and transported and deposited at new sites. Systematic exploration for new sources by the Geological Survey of India and the State Mining Departments only began during the twentieth century. A major boost to the diamond exploration activities began with the introduction of the “open exploration” policy by the Government of India during 1991. Recent efforts have identified a large number of kimberlite fields in the Bastar craton (Lynn, 2005; Lehmann et al., 2010), and large numbers of new finds are reported at different locations in the Eastern Dharwar craton within our demarcated region II (see Fig. 1). The Anumpalle cluster occupies an area of ~60 ha (Rao et al., 1997). A diamond-bearing carbonatite-kimberlite association was discovered in the Ramagiri gold field area of the Anantapur district (Radhakrishna, 2007). New discoveries of kimberlites occupying an extensive area of ~400 km² are also reported from the Madhur-Mahboobnagar sector of the Eastern Dharwar craton. These intrusives are centered around the villages of Madkur (10 pipes), Kotakonda (7 pipes), Vanjamur and Narayanpet (6 pipes) (Devaraju et al., 2009). Likewise, three pipes are also reported from a few areas around Gurumatkal, and four in the neighborhood of Bewanahalli villages within the Gulbarga district of Karnataka in the Eastern Dharwar craton. In addition, a cluster of intrusions (referred to as the Bhima cluster) containing 29 intrusive bodies borders the area of Raichur and Gulbarga districts of the Eastern Dharwar craton (Devaraju et al., 2009). Although recognition of lamproite dikes from the Chelima and Zangamarajupalle areas is longstanding, 28 new dikes were recently found. In addition, 8 kimberlite pipes within the Cuddapah Basin, designated the “Gooty cluster,” are also reported (Radhakrishna, 2007). All these newly discovered locales fall within region II demarcated in Figure 1. It is, however, important to note that the diamond potential of these freshly discovered kimberlites and lamproites remains to be assessed.

Our results and those of other studies discussed herein collectively reaffirm that theshield areas/cratons beneath southeast India have deep keels associated with low geothermal gradient, which are indeed potential regions where diamonds remain stable (Figs. 10 and 11). Kirkley et al. (1991) referred to such a P-T environment as the diamond “storage area.” A search for new indicator minerals that are stable within the stability field of diamond and dominantly defined by subduction-related process that possibly operated over an area in excess of 2 × 10⁹ km² (Ramesh et al., 2010a) holds the key to realize the unrealized potential of the study region in terms of diamond exploration.

CONCLUSIONS

Results obtained primarily from passive seismological studies within southeast India, together with constraints from several other geophysical, geological, and geochronological studies, reveal preservation of relic subducted oceanic slab material at ~160–220 km depth related to suturing of the Eastern Dharwar craton and Eastern Ghats mobile belt possibly during the Mesoproterozoic (ca. 1.6 Ga). This strongly suggests that a thick lithospheric root (keel) that extends beyond ~200 km underlies southeast India, which is conducive to diamond stability. The recorded presence of many diamond-bearing kimberlite and lamproite fields that cover the Eastern


