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A lithospheric mantle source for the proterozoic kimberlites and lamproites from the eastern Dharwar craton, India: Evidence from rare earth element inversion modelling

N. V. Chalapathi Rao*

Department of Earth Sciences, Downing Street, Cambridge CB2 3EQ, UK
*Present address: Department of Applied Geochemistry, Osmania University, Hyderabad 500 007, India

Inversion of rare earth element (REE) concentrations of a Proterozoic kimberlite (Maddur) and lamproite (Ramannapeta) from the eastern Dharwar craton, India is carried out to discover the partial melt distribution with depth that could have been responsible for producing their REE distribution patterns. In order to reproduce the observed REE patterns, the source regions of these rocks need to undergo an extensive initial depletion event (~ 20%) in the garnet stability field before being subjected to metasomatic enrichment and subsequent partial melting. The extensive initial depletion, probably represented by 'komatiitic type' melt extraction during the Archaean, necessitates the partial melting of the eastern Dharwar craton kimberlite and lamproite source regions to have taken place in lithospheric, but not convecting, mantle. This study rules out a 'transition zone' source recently invoked for such rock types from eastern Dharwar craton and elsewhere and therefore imposes important constraints as to the source regions of kimberlites and lamproites.

DESPITE great deal of research, the source regions of small-volume mafic potassic-ultrapotassic melts such as kimberlites remain controversial[1-3]. The presence of syngenetic inclusions of majoritic garnets within diamonds[4,5] and ultra-deep (> 400 km) xenoliths[6] in some southern African kimberlites with ocean island basalt (OIB) like isotope signature, i.e. group I type kimberlites[7] led some workers to suggest that such kimberlites were derived from a 'transition zone' source or even from the core-mantle boundary[8]. Invoking similar criteria, some of the kimberlites with group I type isotopic signature from the eastern Dharwar craton have been suggested[9] to be products derived from partial melting of sources in the 'transition zone'. The present paper, which arose from a detailed geochemical and isotopic study[10] of nearly 20 kimberlite and lamproite diatremes from the eastern Dharwar craton, aims to model the melting process responsible for the generation of these magmas so as to constrain their source region(s).

In the petrogenetic modelling of mafic and ultramafic rocks, peridotite mantle is assumed to be primary melt source of the magmas[11,12] and the partial melting processes may be represented by either batch melting or fractional melting[13]. Recent theoretical studies suggest that once formed, even small volumes of melt may separate rapidly from the matrix[14-16]. Hence, fractional melting may better represent mantle melt generation than the batch melting process[17], and so, given appropriate constraints on D_i (bulk partition coefficient), the mantle melting process may be modelled, using appropriate equations given by Shaw[13].

Based on this premise, McKenzie and O'Nions[17] developed an inversion technique to model the rare earth elements (REE) of mafic igneous rocks and to constrain the partial melt distributions with depth. The aim of the REE inversion modelling is to discover the model melt distribution with depth that could have been responsible for producing the observed REE pattern in the sample. In order to obtain the melt distribution, the REE composition of the sample has to be inverted, using the techniques similar to geophysical inverse theory[18]. The depth to top of the melting column is varied through plagioclase-, spinel- and garnet-stability fields to obtain a best fit to the observed REE concentrations. The inversion technique uses both the abundances of REE and the slope (La/Yb) of the normalized pattern to constrain the melt distribution with depth. REE are chosen in preference to major oxides and other trace elements as (i) their bulk partition coefficients in the upper mantle vary with depth from plagioclase through spinel to garnet stability fields, (ii) their concentrations may be precisely determined, (iii) the REE behave as chemically coherent series, and (iv) the partition coefficients for the REE between important mantle phases and melt are better known than many other elements. The mathematical expressions involved in REE inversion are described in McKenzie and O'Nions[19]. The inversion modelling carried out in this work was performed employing a FORTRAN program (INVMEL) developed by Dan McKenzie (Cambridge).

The observed REE concentrations of the kimberlites and lamproites can thus be modelled by varying the degree and depth of melting with a known source composition. However, in reality the source composition is unknown and this is a significant assumption in REE inversion modelling. Nevertheless, in the case of kimberlites and lamproites and in some alkali-basalts, where mantle xenoliths are present, it is justifiable to assume that source of their melts has the same composition as xenoliths[2,19].

Extensive studies on the lherzolite and harzburgite nodules recovered from the southern African kimberlite pipes have revealed that they were subjected to extreme depletion by 'komatiitic' type melt extraction during the Archaean craton-forming events[20–22]. Hence, the underlying sub-continental lithospheric mantle in the Kaapvaal craton of southern Africa is generally considered to represent a residue of 'komatiitic' melt extraction. Only such a residue which has melted in the garnet stability field can account for the high amounts of heavy rare earth elements (HREE) in the peridotite nodules, even though their light rare earth element (LREE) contents may be very low[23,24].

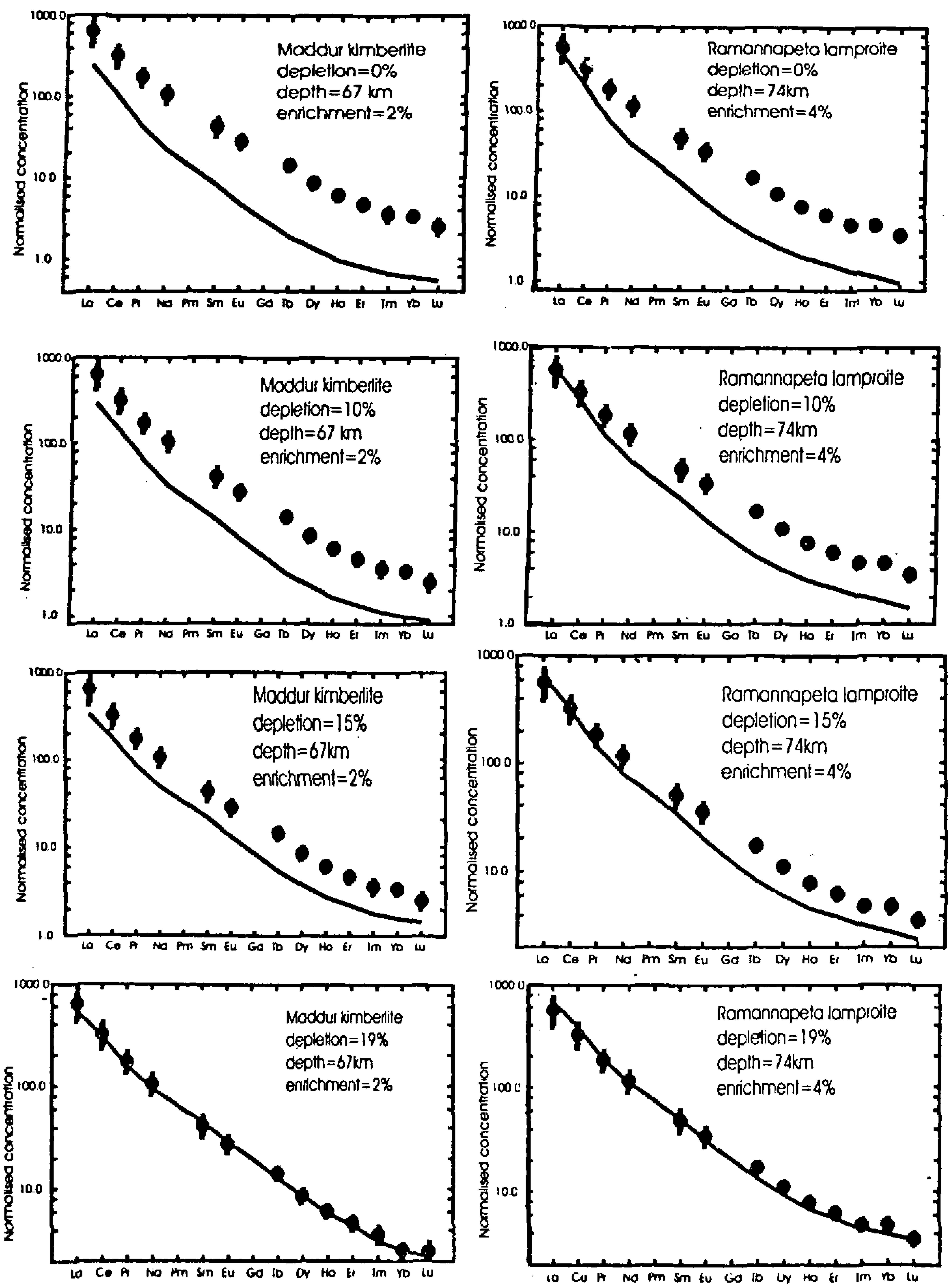

Figure 1. Plots to demonstrate that both enrichment and depletion (~ 20%) are necessary to reproduce the observed rare earth elemental (REE) abundances in kimberlites (e.g. Maddur kimberlite) and lamproites (e.g. Ramannapeta lamproite) from southern India. Dots show observed REE concentrations normalized with respect to MORB[17] with error bars corresponding to 1 SD. The continuous solid lines are the best fits required to reproduce the observed REE abundances. The amount and depth of depletion as well as metasomatic enrichment required to generate the observed REE are also shown at the top in all the REE normalized distribution plots.

Nodule data from the eastern Dharwar craton kimberlites are sparse compared to those from southern Africa. Nevertheless, the available data[25,26] suggest that they are similar to the 'depleted' garnet peridotite xenoliths derived from southern African kimberlites. Furthermore, there is general agreement based on palaeomagnetic[27] as well as tectonic[28] criteria that India and Africa were in close proximity to each other during the Proterozoic, forming essentially adjacent regions of a supercontinent. Therefore, a garnet peridotite with 70% olivine, 22% orthopyroxene, 3% clinopyroxene and 5% garnet, phlogopite and apatite, corresponding to the composition of 'depleted' garnet phlogopite peridotite xenoliths[29] from Kaapvaal craton, is employed in this work as source composition.

Intensely fractionated nature (Figure 1) of REE distributions of kimberlites and lamproites (La/Yb = 70–160) with strong enrichment in LREE implies that partial melting occurred in the presence of garnet[1,2]. As melting takes place entirely in the garnet stability region, the depth to the top of the melting column cannot be predicted in the case of kimberlites and lamproites. However, as these magmas sample diamond their melt source must originate in the diamond stability field. Hence, in the inversion modelling adopted in this work, the top of the melting column is placed at 150 km, which is the appropriate depth of intersection of diamond–graphite transition with the cratonic geotherm[2]. This assumption is supported by the pressure–temperature estimates[25,26] made on mantle xenoliths from the kimberlites in the eastern Dharwar craton which suggests that the lithosphere in these parts was at least 185 km thick during the Mid-Proterozoic.

Using these input parameters, the REE concentrations (Table 1) of a Proterozoic kimberlite (Maddur: 16°51′54″: 77°37′2″) and lamproite (Ramannapeta: 16°43′: 80°7′) from the eastern Dharwar craton are inverted. It is well established from geochemistry and isotope systematics that kimberlites and lamproites are extreme products of mantle enrichment processes[30–32]. Both the isotopic and trace element data also suggest that the source of kimberlite and lamproite metasomatic melt is a mid oceanic

Table 1. Major oxide and rare earth elemental abundances of Ramannapeta lamproite and Maddur kimberlite

	Ramannapeta lamproite			Maddur kimberlite			
	RU1	NR1	NR/7	MD/11	MD-7	MD/11A	MD-5
Major oxides (wt%)							
SiO_2	44.95	47.14	46.81	36.62	34.90	36.72	35.99
Al_2O_3	6.93	7.02	7.09	4.53	4.40	4.52	4.47
Fe_2O_3*	11.82	11.58	11.69	14.30	13.70	14.40	13.67
MgO	14.40	14.09	13.99	21.20	21.17	21.35	20.93
CaO	10.29	8.51	8.72	12.96	12.96	12.98	13.49
Na_2O	0.35	0.47	0.47	0.37	0.55	0.31	0.59
K_2O	2.55	2.68	2.67	4.27	4.36	4.31	4.05
TiO_2	3.33	3.00	2.96	0.20	0.19	0.20	0.19
MnO	0.17	0.15	0.16	0.57	0.50	0.59	0.53
P_2O_5	0.90	0.72	0.95	0.57	0.50	0.59	0.53
LoI	3.86	3.46	3.58	4.10	6.46	3.71	5.04
Total	99.54	98.81	99.09	99.27	99.30	99.24	99.16
REE (ppm)							
La	105.67	124.30	120.10	70.80	66.47	70.83	61.63
Ce	233.67	237.30	231.60	138.70	128.70	136.70	122.20
Pr	26.77	25.70	26.50	15.53	14.43	15.3	13.67
Nd	96.33	92.23	95.67	56.10	51.80	57.10	51.80
Sm	15.03	13.60	15.11	9.16	8.49	9.57	8.84
Eu	4.22	3.48	4.17	2.67	2.44	2.84	2.38
Gd	13.93	13.57	13.62	11.97	9.90	9.70	8.37
Tb	1.38	5.74	5.73	3.94	3.35	4.19	3.77
Dy	5.98	5.74	5.73	3.94	3.35	4.19	3.77
Ho	0.96	0.95	0.91	0.65	0.53	0.64	0.61
Er	2.21	2.23	2.08	1.54	1.16	1.51	1.47
Tm	0.26	0.26	0.26	0.19	0.14	0.17	0.15
Yb	1.59	1.77	1.60	1.09	0.77	1.07	0.91
Lu	0.19	0.22	0.20	0.15	0.12	0.13	0.11

Total iron is expressed as Fe_2O_3*. Major oxides were determined on a Phillips PW 1480 automatic XRF spectrometer at Edinburgh. Typical uncertainties for major oxides are < 5%. REE were measured using a VG PLASMAQUAD PQSTE machine at the NERC ICP-MS facility at Silwood Park, Ascot, London. The difference in concentrations for individual REE is < 10%.

ridge basalt (MORB) source[7,33], i.e. which has already been depleted by the removal of a small melt fraction. In order to reproduce the REE abundance of typical asthenospheric melts such as OIB, which share the same isotopic signature as group I kimberlites, a simple enrichment without any depletion is adequate[19]. In case of continental magmas such as alkali basalt, the observed REE can only be modelled if the source is initially depleted by ~ 10% and subsequently enriched[34]. However, in case of kimberlites and lamproites unless the peridotite source is first depleted by extraction of ~ 20% melt in garnet stability field before being subjected to metasomatic enrichment with a MORB type melt, their observed REE cannot be reproduced (Figure 1). Extensive initial depletion event (~ 20%) is required to produce observed low concentrations of Tm, Yb and Lu in equilibrium with melt since any subsequent metasomatic enrichment can produce only observed LREE abundances. The calculated REE abundances in kimberlite as well as lamproite fit the observed values (Figure 1) and their amounts of depletion and enrichment are almost indistinguishable. Calculated source rock compositions (Table 2) obtained from the melting models of REE inversion for kimberlites and lamproite are indistinguishable from each other and also from the depleted garnet phlogopite peridotite nodules[29]. Similar observations are obtained from inversion modelling of nearly 20 kimberlites and lamproites from the eastern Dharwar craton[10] and these will be published elsewhere.

The most important conclusion of this study is that extensive depletion (~ 20%) of the source is pre-requisite for the generation of kimberlites and lamproites of the eastern Dharwar craton. Tainton and McKenzie[2] showed that melt distribution obtained from the inversion of a komatiitic REE composition, but not that of a tholeiite, can satisfy the extraction of ~ 20% melt from a region in which garnet is stable. Tainton and McKenzie[2] also calculated that komatiitic melting results in the thickening of the lithosphere by a factor of 2 ($\beta = 2$), thereby leading the depleted source well within the graphite–diamond transition, i.e. 150 km. Therefore, the strong

Table 2. Calculated source rock composition for Ramannapeta lamproite and Maddur kimberlite compared with that of a depleted garnet peridotite nodule[29]

Major oxides (weight %)	Maddur kimberlite	Ramannapeta lamproite	Depleted garnet phlogopite peridotite xenolith
SiO_2	44.70	44.80	45.70
Al_2O_3	0.48	0.83	0.98
Fe_2O_3	4.85	4.79	5.14
MgO	42.70	43.24	43.77
CaO	0.74	0.97	1.03
Na_2O	0.05	0.09	0.17
K_2O	0.01	0.03	0.20
TiO_2	0.05	0.09	0.06

initial depletion of the source necessitated by this study is attributed to 'komatiitic' type melt extraction during the Archaean times. Neither the metasomatic enrichment of a source depleted by the extraction of a basalt, as in the case of continental alkali volcanics[34], nor a simple metasomatic enrichment of a source without any depletion, as in case of ocean island basalts[19] can account for the observed REE abundances of eastern Dharwar craton kimberlites and lamproites.

Evidence for at least one episode of extensive melting of the eastern Dharwar craton during the Archaean comes from the widespread occurrences of komatiites and metavolcanics in the greenstone belts[35,36]. Positive εNd isotopic values of the mafic units of these schist belts also indicate a long term LREE depletion in their mantle source[37]. Early Proterozoic dykes with komatiitic affinity are also recently reported around the Cuddapah Basin[38], thereby supporting the initial depletion event invoked in this work. Nd isotope systematics[10] of kimberlites and lamproites of eastern Dharwar craton are also consistent with this argument.

The depleted OIB type isotopic signature of group I type kimberlites led many workers to suggest that the latter are predominantly convecting mantle melts[1,3]. However, large scale depletion (~ 20%) of the source regions of southern Indian kimberlites and lamproites, as shown in this work, necessitates partial melting of their source to have taken place in a lithospheric, but not convecting, mantle. This is because such a strong (~ 20%) depletion is characteristic of many depleted xenoliths characteristic of continental lithosphere[20]. Furthermore, such an extensively depleted signature cannot be preserved indefinitely if the source is a convecting asthenosphere. This is supported by the recent observation from REE inversion modelling that the convecting mantle melts like ocean island basalts does not require any depletion prior to their enrichment[19].

Similarity of calculated source composition (Table 2) suggests that difference in chemistry between kimberlites and lamproites may not be due to difference in the depths of melting. Hence, their observed petrological and compositional differences are attributed to the differences in the content and nature of volatiles in their source regions which would have undoubtedly influenced the low pressure crystallization of these magmas[10].

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Estimation of tectonic stress in NW Himalaya region using IRS-1B data

Pradeep K. Sahoo, Sandeep Kumar and Ramesh P. Singh*

Department of Civil Engineering, Indian Institute of Technology, Kanpur 208 016, India

Earthquake records, landslide and recent changes in geomorphological features indicate that area between Main Boundary Thrust (MBT) and Main Frontal Thrust (MFT) is tectonically active. Spectral and spatial enhancement techniques have been employed for the digital data of IRS-1B LISS-I to delineate the lineaments and major faults of the area. Based on Mohr's theory failure criteria and statistical analysis of remotely sensed lineament data, the horizontal compressive stress (S_{Hmax}) has been estimated at various sites of the study area. These data are found to be consistent with the published S_{Hmax} orientation determined from earthquake focal mechanism solution.

SATELLITE remote sensing has emerged as a powerful tool for seismic hazard assessment and mapping[1-3]. The synoptic overview of a wide area and digital nature of the remote sensing data can be utilized suitably to map the active tectonic features. In the present study, the area around Dehradun lying between the lat. 29.52°–31.18°N and long. 76.89°–78.55°E (Figure 1), NW Himalaya, has been chosen for the study of the present tectonic stress using remote sensing data. This area is part of the active tectonic zone of the Indian and Eurasian plate collision 40 million years ago. This area has experienced devastating earthquakes like Kangra (1905) and Uttarkashi (1991) due to the recent earth movements or stress deformations. Analyses of the catalogue of past earthquakes have revealed that these earthquakes are not isolated events, but only the latest expression of diffuse seismic activities.

We have taken IRS-1B LISS-I digital data covering path 29 and rows 46 of October 20, 1994 for detailed analysis. The data consists of 2500 rows and 2350 columns. The whole scene shown in Figure 2 is divided into 19 windows of size 512×512 pixels depending upon the morphology of the area. We have made efforts to enhance the edges using numerous filters in horizontal, vertical and two diagonal directions. For mapping of

*For correspondence. (e-mail: ramesh@iitk.ernet.in)