

Geochemistry and petrogenesis of mafic alkaline dike(s) to the east of Gadwal greenstone terrane: Implications for OIB – type magmatism in parts of the eastern Dharwar craton, India

Tarun C. Khanna¹, E.V.S.S.K. Babu¹ and Guochun C. Zhao²,

M. Satyanarayanan¹, A. Keshav Krishna¹, S. S. Sawant¹

¹CSIR – National Geophysical Research Institute, Hyderabad – 500 007, India.

²Department of Earth Sciences, The University of Hong Kong, Pokfulam Road, Hong Kong.

*Corresponding Author: khannangri@gmail.com

ABSTRACT

The Dharwar craton of southern India hosts a well preserved association of Archean granite - greenstone terranes and Proterozoic mafic dike swarms. Hitherto, the mafic dikes reported from the Dharwar craton, regardless of their occurrence in the eastern or western sector, are either tholeiitic or picritic and invariably contaminated by the Archean upper continental crust. In continuance to the previous study, this paper provides a rare account on the petrogenetic aspects of a Paleo-proterozoic crustally uncontaminated mafic dike "Dike 3" of alkaline affinity. Geochemically the rocks are basaltic in composition and mineralogically consist of clinopyroxene (Ti-augite), Na-rich plagioclase (oligoclase-andesine) as major silicate mineral phases while titaniferous magnetite \pm \ddot{u} lvospinel are the opaque mineral oxides. The samples are characterized by strongly fractionated rare earth element (REE) patterns with elevated light-REE (La/Yb)_N \sim 10 and depletion in the heavy-REE (Gd/Yb)_N \sim 2.5 consistent with a garnet signature. Geochemical modelling involving HFSE (Zr, Nb and Y) and REE indicates that the melts were generated by low degree (\sim 3-4 %) partial melting of a garnet facies mantle. The geochemical attributes of this dike are identical to the Phanerozoic ocean island basalts (OIB). La/Nb and La/Ba ratios in these samples indicate their derivation from an asthenospheric source, similar to the source of modern OIB. In contrast to the OIB, the Gadwal Dike 3 is characterized by an anomalous depletion in Nb relative to La in a primitive mantle normalized trace element variation diagram. This characteristic feature resembles with the unusual EM 1-type OIB from the Cretaceous, Site 525A of the Walvis Ridge, South Atlantic Ocean. Consequently, the anomalous behavior of Nb in the Gadwal Dike 3 samples is attributed to the addition of a small amount (\sim 2%) of ancient pelagic sediment recycled through an Archean subduction zone, in its mantle source. The occurrence of OIB-type magmas within the cratonic interior provide an essential link between the Archean sub-continental lithospheric mantle (SLM), and the EM1 mantle component in the Dharwar craton, India.

Keywords: Mafic dikes, Ocean island basalt, Sub-continental lithospheric mantle, Gadwal greenstone terrane, Dharwar craton

INTRODUCTION

Ocean island basalts are generated from anomalous thermochemical sources in response to upwelling of plumes originating from the deeper parts of the asthenospheric mantle, and are typically associated with hot-spots. Unlike that in the cratonic provinces, the magmas generated in the ocean basins are devoid of any contamination from crustal material, and hence provide significant insights into mantle composition, magma formation and evolution processes (Greenough et al., 2005a, b). It is uncommon to find crustally uncontaminated mafic magmatic rocks from intracontinental settings. Moreover, those with OIB-like geochemical attributes is very rare (e.g. Coish and Sinton, 1992; Liu et al., 1994; Cook et al., 2005; Manikyamba and Kerrich, 2011). This paper, and a study in the recent past (Khanna et al., 2013) is focused to constrain the intriguing geochemical aspects of previously undiscovered

crustally uncontaminated mafic dikes of alkaline to sub-alkaline nature. The objective is to constrain their petrogenesis within the Paleo-proterozoic Mahbubnagar Large Igneous Province (MLIP; Pandey et al., 1997), and similar occurrences elsewhere in the Precambrian cratonic terrane of the Dharwar craton, India.

Regional Geology

The Dharwar craton of southern India comprises of Archean granite - greenstone terranes, Proterozoic basins and granulite sequences (Ramakrishnan and Vaidyanadhan, 2010) that are extensively traversed by crustally contaminated Proterozoic mafic dike swarms. Hitherto, the mafic intrusions reported from the Dharwar craton, regardless of their occurrence in the eastern or western sector, are either tholeiitic (Srivastava et al., 2014) or picritic (Sesha Sai, 2011) in composition. The study

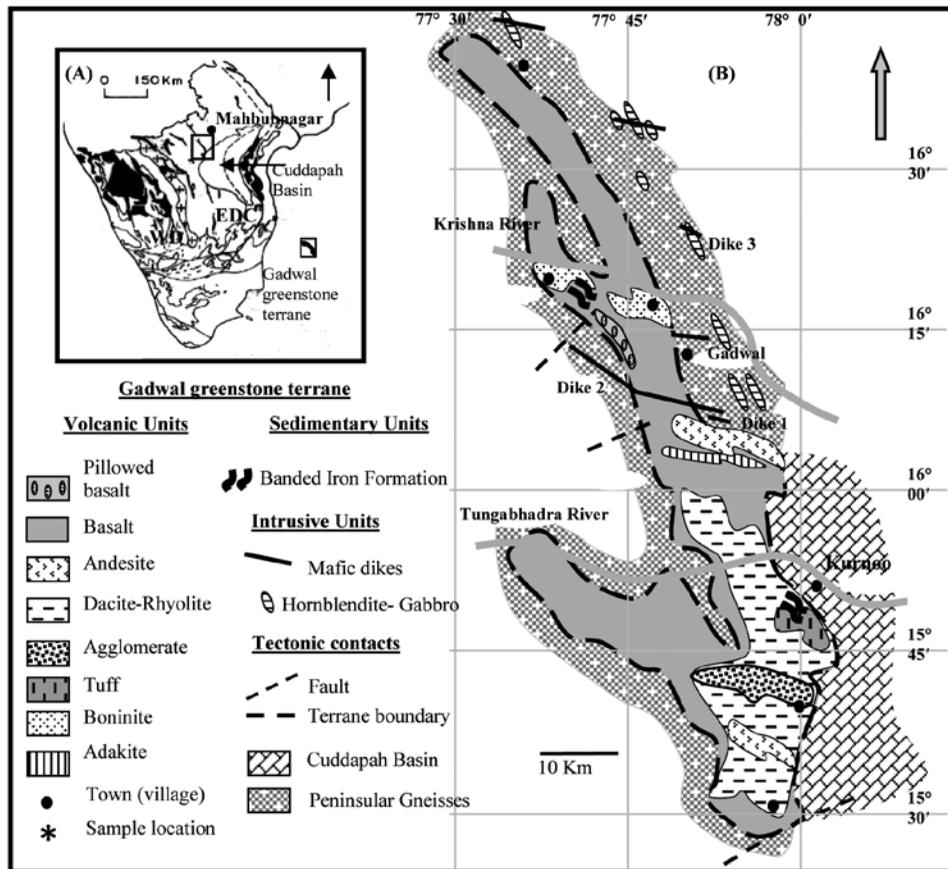


Figure 1. (A) Simplified geological map of the southern India comprising of three major tectonic blocks: the western Dharwar craton (WDC), the eastern Dharwar craton (EDC) and the southern granulite terrane (SGT). Also shown in the box is the location of Gadwal greenstone terrane in the eastern Dharwar craton. (B) Generalized geological map of the Gadwal greenstone belt, modified after Srinivasan (1990), showing the disposition of the Gadwal Dike 1 and 2; and Dike 3 sampled for this study.

area is located in the eastern Dharwar craton (EDC) and embedded between the eastern margin of the Neoproterozoic Gadwal greenstone terrane (Khanna et al., 2014) and the northwest margin of the Proterozoic Cuddapah basin (Fig. 1A). It forms an integral part of the major ~2.18 Ga Mahbubnagar Large Igneous Province, consisting of short-lived magmatic events spanning the late-Archean and Proterozoic times. The focus of this study is the NW-SE trending newly identified mafic dike “Dike 3” of alkaline affinity. The dike has a surface exposure of ~500 meters in length and a few meters wide, which is located few kilometres east of Gadwal greenstone terrane (Fig. 1B). A detailed study in the recent past documented the occurrence of similar mafic alkaline dikes (Dike 1 and 2; Khanna et al., 2013), which are located ~20 km west of this newly identified dike (Dike 3; Fig. 1B). The longest dike (~20 km long Dike 2, Fig. 1B) transects the metabasalts in the adjacent Neoproterozoic Gadwal greenstone terrane, and therefore relatively younger than 2.7 Ga. The field relationships in conjunction with the radiometric ages of the dikes in the MLIP (Pandey et al., 1997), and the

palaeomagnetic studies endorse a Paleoproterozoic age (~2.2 Ga; Venkateshwarlu and Khanna, 2015) for the dike(s) in context.

Sample Collection:

The samples were collected from relatively fresh portions of the outcrop that is devoid of quartz veins and secondary mineralization. Petrographic screening was performed to rule out secondary carbonate and sulphide mineralization, or intense mineralogical alterations. Subsequently, the rocks were further screened for loss on ignition (LOI). A representative collection of 5 samples with LOI < 0.5 wt. % (e.g. Polat and Hoffmann, 2003), was then selected for further detailed petrological studies.

The laboratory studies including petrography, mineral chemistry and geochemical studies were carried out at the CSIR – National Geophysical Research Institute, Hyderabad, India. The mineral compositions were determined by electron microprobe analyzer CAMECA SX-100[®]. A 20 nA beam current and an accelerating voltage

Table 1. Instrument operating conditions of HR-ICP-MS (Nu Attom).

Plasma control parameters	
Coolant gas flow (L/min)	13.0
Auxillary gas flow (L/min)	1.05
Nebulizer gas flow (psi)	33.3
Forward RF Power (W)	1300
Peristaltic rate (RPM)	15.0
Peltier cooling temperature (°C)	5.0
Spray chamber	Glass-Cyclonic
Sample uptake (ml/min)	0.2
Detector	Ion counter and faraday
Sensitivity	1.1 x 10 ⁶ counts for ¹¹⁵ In 2.1 x 10 ⁶ counts for ²³⁸ U
Scan type	Magnet jumping with electric scan over a small mass range
Ion lens setting	Optimized for sensitivity and resolution peaks
Data acquisition parameters	
Dwell time per peak (ms)	3
Switch delay per peak (μs)	200
Number of sweeps	50
Number of cycles	3
Instrument resolution	300
Internal standard	¹⁰³ Rh

of 20 keV was maintained with a focused beam. Certified natural silicate standards were used for the instrument calibration. The corrections for ZAF were applied using SX control. For bulk-rock geochemistry, rocks were powdered manually using an agate mortar and pestle. Ten major element oxides, Cr, and Ni were analyzed using pressed powder pellets, on a Philips MagiX PRO PW2440; microprocessor controlled, wavelength dispersive sequential XRF. The relative standard deviation for the major element oxides is < 3% (Krishna et al., 2007). Trace elements including large ion lithophile elements (LILE), high field strength elements (HFSE) and rare earth elements (REE) were determined by high resolution inductively coupled plasma mass spectrometry (HR-ICP-MS, Nu Instruments Attom®, UK).

The sample solution introduction consisted of a standard Meinhard® nebulizer with a cyclonic spray chamber housed in Peltier cooling system. All quantitative measurements were performed using the instrument software (Attolab v.1), while the data processing was done using Nu Quant®, which uses knowledge-driven routines in combination with numerical calculations (quantitative analysis) to perform an automated/manual interpretation of the spectrum of selected elements. Instrumental parameters are given in Table 1. Instrument was optimized using 1ppb tuning solution and the sensitivity of ¹¹⁴In was about 1 million cps. Oxide and oxy-hydroxide ratios were low (< 0.2%) and the double charges ions ratio was < 3%. Mass bias fractionation and isobaric interferences were addressed by using certified geochemical reference materials. External

drift correction was performed by repeated analyses of a 1:5000 solution of BHVO-1 (Hawaiian Basalt reference standard). Instrument response was corroborated relative to two independent digestions of BIR-1 and BCR-1 (USGS standard). Precision and accuracy are better than RSD 3% for the majority of trace elements (Table 2). The dissolution method practiced at the University of South Carolina, was adopted at NGRI. For detailed sample dissolution procedure we refer to Khanna et al. (2015). The major element oxides were recalculated to 100% anhydrous for inter-comparison purpose. Mg# is calculated as the molecular ratio of Mg = Mg/ (Mg + Fe²⁺), where Fe²⁺ is assumed to be 90% for the total Fe. Chondrite (Sun and Mc Donough, 1989) and primitive mantle (Hofmann, 1988) normalizations are indicated by _(N) and _(pm), respectively. The mineral compositions, and the bulk-rock geochemical data of major element oxides, trace and rare earth elements for the representative samples is discussed below and given in Tables 3 and 4.

RESULTS AND DISCUSSION

Petrography and mineral chemistry

The Gadwal Dike 3 samples predominantly consist of clinopyroxene (Table 1a) and Na-rich plagioclase (Table 1b) as major silicate phases (~40% and ~50%, respectively), while titanomagnetite ± ulvöspinel (Table 1c) is present as accessory opaque mineral oxide (~8%; Fig. 2). Pyroxene is mostly fresh and unaltered. At few places, pyroxene

Table 2. Analytical data, standard deviations (SD) of BHVO-1 obtained by HR-ICP-MS.

Analyte	Mass No.	BHVO-1			
		A	B	SD	%RSD
Sc	45	31.162	31.8	0.797	2.559
V	51	307.884	317	9.166	2.977
Cr	52	283.847	289	7.251	2.555
Co	59	44.463	45	0.82	1.845
Ni	60	119.534	121	2.078	1.738
Cu	63	134.337	136	2.076	1.545
Zn	66	99.682	105	3.14	3.15
Ga	71	20.814	21	0.3	1.44
Rb	85	10.952	11	0.107	0.973
Sr	88	395.072	403	6.235	1.578
Y	89	27.324	27.6	0.352	1.287
Zr	90	177.386	179	3.166	1.785
Nb	93	18.941	19	0.27	1.424
Cs	133	0.124	0.13	0.003	2.407
Ba	137	139.481	139	2.5	1.792
La	139	15.711	15.8	0.35	2.228
Ce	140	38.9	39	0.865	2.223
Pr	141	5.708	5.7	0.142	2.482
Nd	146	25.402	25.2	0.55	2.166
Sm	147	6.343	6.2	0.259	4.088
Eu	151	2.059	2.06	0.066	3.21
Gd	157	6.353	6.4	0.117	1.84
Tb	159	0.961	0.96	0.032	3.286
Dy	163	5.202	5.2	0.177	3.406
Ho	165	0.994	0.99	0.032	3.206
Er	166	2.4	2.4	0.074	3.103
Tm	169	0.329	0.33	0.009	2.796
Yb	172	2.037	2.02	0.06	2.943
Lu	175	0.294	0.29	0.012	3.916
Hf	178	4.428	4.38	0.137	3.1
Ta	181	1.252	1.23	0.026	2.117
Pb	208	2.506	2.6	0.233	9.281
Th	232	1.075	1.08	0.044	4.114
U	238	0.429	0.42	0.022	5.204

A – values from HR-ICP-MS (average of 3 values)

B – values from Govindaraju (1994) and GEOREM (georem.mpch-mainz.gwdg.de)

is altered to greenish chlorite that constitutes ~2% in the rock. Relatively fresh and unaltered plagioclase laths (0.35 to 0.75 mm) exhibit characteristic lamellar twinning and show variation in their composition ranging from andesine to oligoclase ($An_{46-13}Ab_{86-51}Or_{12-0.3}$; Fig. 3A). Pyroxenes display perfect cleavage, and pale pink-green pleochroism. Under crossed polarized light they exhibit inclined extinction and interference colors of second order. The clinopyroxene is compositionally a Ti-augite ($En_{50-42}Wo_{43-37}Fs_{7-21}$; Fig. 3B; Table 1). Megascopically, the dike is porphyritic in appearance. Microscopically, two sets of clinopyroxenes are observed in the rock. The first set

consists of zoned euhedral phenocrysts (0.8 – 1.2 mm) that partially enclose tabular laths of plagioclase indicative of sub-ophitic texture (Fig. 2). The second set constitutes of euhedral clinopyroxene microphenocrysts (0.06 – 0.09 mm) in the groundmass, which occur as an intergranular phase amidst euhedral to subhedral, randomly oriented plagioclase laths. Compared to the second set, the first set is characterized by high MgO (~18 wt. %), Mg# (~95), low FeO (~6 wt. %), Al_2O_3 (~1.8 wt. %) and TiO_2 (~0.5 wt. %) contents (Table 1). On the contrary, the relatively low MgO (~14.8 wt. %), Mg# (~0.78), high FeO (~12 wt. %), Al_2O_3 (~2.6 wt. %) and TiO_2 (~1.1 wt. %) compositions

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Table 3a. Clinopyroxene compositions of the Gadwal Dike 3, eastern Dharwar craton, India

	macrophenocrysts					microphenocrysts				
	26	27	18	9		10	15	19	21	22
SiO ₂	50.87	51.14	50.27	49.32		48.89	48.46	48.03	48.00	48.72
TiO ₂	0.44	0.42	0.46	0.82		0.90	1.13	1.12	1.18	0.94
Al ₂ O ₃	1.38	1.35	1.60	2.83		2.14	2.65	3.19	2.70	2.30
Cr ₂ O ₃	0.78	0.73	0.45	0.12		0.06	0.02	0.04	0.02	0.00
FeO	4.86	4.77	6.75	8.60		11.48	11.98	13.00	11.92	12.09
MnO	0.10	0.05	0.15	0.17		0.25	0.18	0.34	0.20	0.29
MgO	18.08	17.73	17.15	16.73		15.05	14.75	14.46	14.56	15.14
CaO	21.22	21.35	20.94	19.69		18.01	18.41	17.51	18.55	17.99
Na ₂ O	0.19	0.24	0.29	0.31		0.27	0.31	0.44	0.31	0.31
K ₂ O	0.02	0.00	0.00	0.01		0.00	0.01	0.01	0.01	0.00
Total	97.94	97.79	98.05	98.61		97.05	97.90	98.13	97.44	97.79
<i>Number of ions on the basis of 6 oxygens</i>										
Si	1.91	1.92	1.90	1.86		1.90	1.87	1.86	1.86	1.88
Al	0.06	0.06	0.07	0.13		0.10	0.12	0.14	0.12	0.10
Al	0.00	0.00	0.00	0.00		0.00	0.00	0.00	0.00	0.00
Fe(iii)	0.13	0.10	0.16	0.17		0.12	0.14	0.17	0.16	0.15
Cr	0.02	0.02	0.01	0.00		0.00	0.00	0.00	0.00	0.00
Ti	0.01	0.01	0.01	0.02		0.03	0.03	0.03	0.03	0.03
Fe(ii)	0.02	0.04	0.05	0.09		0.25	0.24	0.25	0.23	0.23
Mn	0.00	0.00	0.00	0.01		0.01	0.01	0.01	0.01	0.01
Mg	1.01	0.99	0.97	0.94		0.87	0.85	0.83	0.84	0.87
Ca	0.85	0.86	0.85	0.80		0.75	0.76	0.72	0.77	0.74
Na	0.01	0.02	0.02	0.02		0.02	0.02	0.03	0.02	0.02
K	0.00	0.00	0.00	0.00		0.00	0.00	0.00	0.00	0.00
Total	4.04	4.03	4.05	4.05		4.04	4.04	4.05	4.05	4.05
Mg#	0.98	0.96	0.95	0.91		0.78	0.78	0.77	0.79	0.79
Wo	42	43	42	40		38	38	37	39	37
En	50	50	48	47		44	42	42	42	43
Fs	8	7	11	14		19	19	21	19	20
Note: Major element oxides in wt. % with total Fe as FeO;										
Wo, En, Fs = cation proportions of Ca, Mg and Fe (pyroxene) normalized to 100%.										

in the pyroxene microphenocrysts are noticed (Table 1). The zoned nature of the pyroxene macrophenocrysts and the bimodal variation in the composition, perhaps suggests disequilibrium conditions of crystallization.

GEOCHEMISTRY

Assessing trace element mobility

Trace element mobility is of critical concern in the petrogenetic interpretation of the rocks that occur in

the Precambrian cratonic provinces. The rocks may experience mobility of alteration sensitive trace elements. As such, petrological studies (e.g. Polat and Hofmann 2003) have resolved that trace elements (e.g. Al, Ti, Cr, Ni, Sc, V, Nb, Ta, Zr, Hf, Th, Y, and the heavy-REE), which are least susceptible to mobility during alteration and metamorphism up to amphibolite facies are suitable for petrogenetic interpretation. In principle, the robust correlations observed between Zr and the light-REE (e.g. La, Ce, Nd; note that all figures are not shown), HFSE (e.g. Th, Nb, Y) and heavy-REE (e.g. Gd, Yb) in the Gadwal Dike

Table 3b. Plagioclase compositions of the Gadwal Dike 3, eastern Dharwar craton, India.

	24	33	34	37
SiO ₂	53.88	55.33	62.44	58.91
TiO ₂	0.05	0.07	0.01	0.06
Al ₂ O ₃	26.24	24.54	20.54	23.00
Cr ₂ O ₃	0.00	0.00	0.04	0.02
FeO	0.58	1.08	0.80	0.53
MnO	0.03	0.00	0.02	0.01
MgO	0.04	0.08	0.06	0.04
CaO	9.41	5.60	2.90	5.45
Na ₂ O	5.84	6.42	10.43	8.82
K ₂ O	0.52	1.98	0.05	0.41
Total	96.60	95.11	97.29	97.24
<i>Number of ions on the basis of 32 oxygens</i>				
Si	10.10	10.50	11.40	10.86
Al	5.79	5.49	4.42	5.00
Mg	0.01	0.02	0.02	0.01
Fe(ii)	0.09	0.17	0.12	0.08
Na	2.12	2.36	3.69	3.15
Ca	1.89	1.14	0.57	1.08
K	0.12	0.48	0.01	0.10
Total	20.13	20.17	20.24	20.27
An	46	29	13	25
Ab	51	59	86	73
Or	3	12	0.3	2

3 samples (Fig. 4A, B, C) indicate essentially limited trace element mobility. The absence of negative Ce anomalies in conjunction with robust correlation between La and Zr, is taken as evidence that the light-REE were not significantly mobilised during post-magmatic emplacement. Therefore, the trace element depletion and enrichment relative to the primordial mantle or chondrite, in the Gadwal samples, are taken to reflect primary igneous source characteristics.

Classification

Greenough et al. (2005a, b) gave an explicit account on the two magma series, tholeiitic and alkaline, which occur in the oceanic islands. On the basis of mineralogy and mineral chemistry, bulk-rock geochemistry and isotopes, they have shown that rocks occurring in the ocean islands can be appreciably distinguished and categorized into either of the two series. For example, alkali basalts are essentially nepheline normative; on the contrary, the tholeiitic basalts are generally quartz or olivine normative. Although, olivine, augite and plagioclase appear as common phenocryst

Table 3c. Oxide compositions of the Gadwal Dike 3, eastern Dharwar craton, India.

	Titaniferous magnetite			Titaniferous magnetite + ùlvospinel		
	11	16	23	17	20	30
SiO ₂	0.13	0.17	0.24	2.63	0.22	0.62
TiO ₂	21.99	30.30	21.54	20.95	26.35	27.17
Al ₂ O ₃	0.00	0.00	0.00	0.63	0.22	0.32
Cr ₂ O ₃	0.38	0.02	0.04	0.14	0.07	0.07
FeO	72.65	65.25	73.94	66.62	68.25	67.31
MnO	0.81	1.24	0.81	0.75	0.99	1.10
MgO	0.02	0.00	0.05	0.27	0.01	0.14
CaO	0.08	0.13	0.06	1.35	0.13	0.26
Na ₂ O	0.00	0.03	0.08	0.04	0.05	0.00
K ₂ O	0.00	0.00	0.01	0.01	0.02	0.01
Total	96.06	97.15	96.77	93.39	96.33	96.98
<i>Number of ions on the basis of 32 oxygens</i>						
Si	0.04	0.05	0.07	0.81	0.07	0.19
Al	0.00	0.00	0.00	0.23	0.08	0.11
Cr	0.09	0.00	0.01	0.03	0.02	0.02
Fe(iii)	5.72	2.00	6.02	4.34	3.64	3.11
Ti	5.06	6.95	4.91	4.88	6.06	6.19
Mg	0.01	0.00	0.02	0.12	0.00	0.06
Fe(ii)	12.85	14.63	12.72	12.92	13.82	13.95
Mn	0.21	0.32	0.21	0.20	0.26	0.28
Ca	0.03	0.04	0.02	0.45	0.04	0.08
Total	24.00	24.00	24.00	24.00	24.00	24.00

phases in both the series rocks, the augites in the alkali basalts are characteristically pleochroic and zoned. Unlike the alkali basalts, the tholeiites are characterized by the presence of low Ca-pyroxene (pigeonite or orthopyroxene) either in the norm or mode. Comparatively, the Gadwal samples appear to be transitional between the two types. For instance, the Gadwal samples are slightly Q-normative (~1% normative quartz), although, quartz is essentially absent in the rock. Augite is not strongly pleochroic, but it is typically zoned (Fig. 2). The rocks do not consist of modal pigeonite or orthopyroxene, as expected in tholeiitic OIBs. The SiO₂, Al₂O₃, Na₂O and MnO contents in the augites are transitional to those observed in the tholeiitic and alkaline types (see Fig. 6 in Greenough et al., 2005a, for a review), and plot in the intersection defined by both the types. Similarly, the titanium concentration in these clinopyroxenes overlaps with basalts derived from tholeiitic and calc-alkaline lineage (Fig. 4D). However, the samples plot distinctly above the dividing line and hence, exhibit alkaline affinities. Geochemically, the rocks consist of uniform major element oxide concentrations

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Table 4. Major (wt %) and trace (ppm) element composition for the Gadwal Dike 3, eastern Dharwar craton, India; and the average composition of EM 1-type OIB from the literature.

	GTG-8	GTG-9	GTG-10	GTG-11	GTG-12		Gadwal Dike 3 (average) ¹	Walvis Ridge (Site 525A) ²	Gadwal Dike 2 (average) ³	Gadwal Dike 1 (average) ³
SiO ₂	46.26	45.98	45.42	46.12	45.59		45.87	51.28	47.96	49.76
TiO ₂	3.25	3.13	3.20	3.26	3.16		3.20	2.87	1.75	1.69
Al ₂ O ₃	11.34	10.94	10.82	11.31	11.11		11.10	15.82	14.12	8.16
Fe ₂ O ₃	16.58	16.96	17.66	16.96	17.40		17.11	11.49	12.97	12.25
MnO	0.17	0.17	0.19	0.17	0.17		0.17	0.11	0.16	0.16
MgO	8.52	9.30	9.19	8.58	9.36		8.99	4.58	10.32	16.15
CaO	10.20	9.64	9.77	9.32	9.43		9.67	8.58	8.43	8.34
Na ₂ O	2.34	2.28	2.26	2.28	2.33		2.30	3.55	2.57	1.95
K ₂ O	0.94	1.25	1.16	1.72	1.09		1.23	0.92	1.42	1.24
P ₂ O ₅	0.38	0.34	0.33	0.39	0.35		0.36	0.46	0.30	0.29
Mg#	50	52	51	50	52		51	-	61	72
Cr	111	149	151	112	138		132	139	130	989
Ni	63	74	73	66	75		70	53	154	468
Rb	44	64	57	81	62		62	9	104	70
Sr	471	452	424	428	414		438	447	391	317
Cs	3.0	3.9	3.9	12.3	3.3		5.3	0.11	2.3	3.6
Ba	393	408	443	469	455		434	364	248	427
Sc	22	22	23	20	22		22	44	23	28
V	376	405	392	353	373		380	353	224	234
Ta	1.57	1.56	1.54	1.57	1.58		1.56	1.7	1.4	2.1
Nb	28	26	26	25	27		26	29	16	27
Zr	248	225	223	219	231		229	265	121	150
Hf	6.4	5.8	5.7	5.6	6.0		5.9	7.0	3.0	3.6
Th	4.4	3.6	3.6	3.5	4.0		3.8	4.1	1.4	2.4
U	0.74	0.58	0.58	0.57	0.64		0.62	1.1	0.3	0.5
Y	34	32	31	31	33		32	41	18	20
La	39.10	35.54	35.13	34.43	36.32		36.10	32.75	15.86	26.45
Ce	89.86	80.85	81.88	79.94	84.15		83.34	71.31	35.50	55.14
Pr	10.09	9.16	9.11	8.92	9.42		9.34	10.18	4.78	6.86
Nd	42.45	39.17	38.45	38.19	40.54		39.76	41.14	19.62	26.56
Sm	9.90	9.08	9.15	9.01	9.73		9.37	8.95	4.36	5.39
Eu	2.82	2.72	2.77	2.76	2.92		2.80	2.85	1.62	1.63
Gd	9.21	8.43	8.60	8.12	8.76		8.62	9.45	4.39	5.21
Tb	1.16	1.06	1.12	1.05	1.13		1.10	1.40	0.63	0.72
Dy	6.63	6.08	6.09	5.99	6.44		6.24	7.88	3.33	3.77
Ho	1.09	0.99	1.00	0.98	1.04		1.02	1.58	0.63	0.71
Er	2.81	2.62	2.63	2.60	2.72		2.68	4.26	1.57	1.78
Tm	0.39	0.37	0.37	0.35	0.39		0.37	-	0.22	0.25
Yb	2.59	2.39	2.40	2.36	2.48		2.44	3.46	1.34	1.57
Lu	0.35	0.33	0.33	0.32	0.35		0.34	0.50	0.20	0.22
Nb/Th	6.5	7.1	7.1	7.2	6.7		6.9	7.1	11.3	11.4
Nb/Y	0.8	0.8	0.8	0.8	0.8		0.8	0.7	0.9	1.3
Zr/Y	7.2	7.1	7.1	7.1	7.0		7.1	6.5	6.9	7.4
Ba/Th	90	112	123	134	115		114	90	179	182
Ba/Nb	14	16	17	19	17		16	13	16	16
Ba/La	10	11	13	14	13		12	11	16	16
Zr/Nb	8.7	8.7	8.7	8.7	8.7		8.7	9.2	7.7	5.6
K/Nb	274	401	375	564	340		387	266	750	386
La/Nb	1.37	1.37	1.37	1.36	1.36		1.37	1.14	1.01	0.99
La/Ba	0.10	0.09	0.08	0.07	0.08		0.08	0.09	0.06	0.06
Th/Nb	0.15	0.14	0.14	0.14	0.15		0.14	0.14	0.09	0.09

1 = This study;

2 = Salters and Kocher (2010), the values in italics are from Humphris and Thompson (1983);

3 = Khanna et al. (2013)

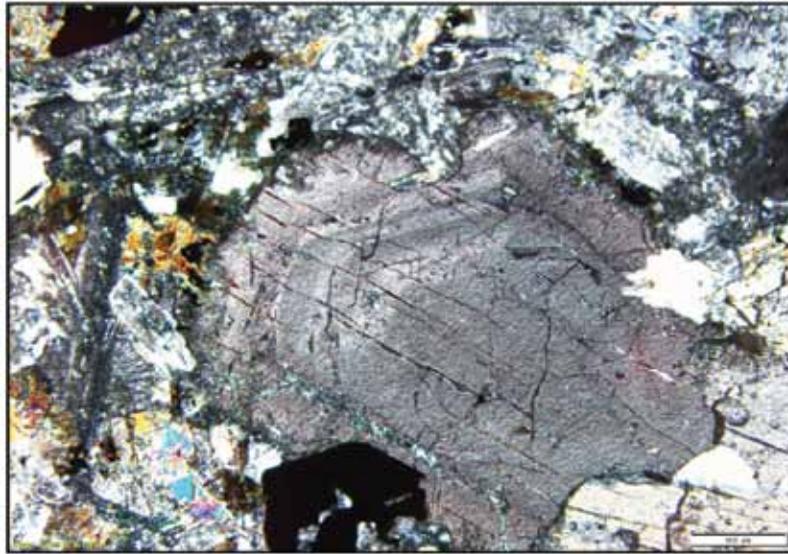


Figure 2. Photomicrograph of Gadwal Dike 3 sample showing the zoned macrophenocryst of pyroxene, surrounded by tabular to subhedral plagioclase laths and euhedral microphenocrysts of pyroxene. Note the partially enclosed lath of plagioclase in the pyroxene indicative of sub-ophitic texture.

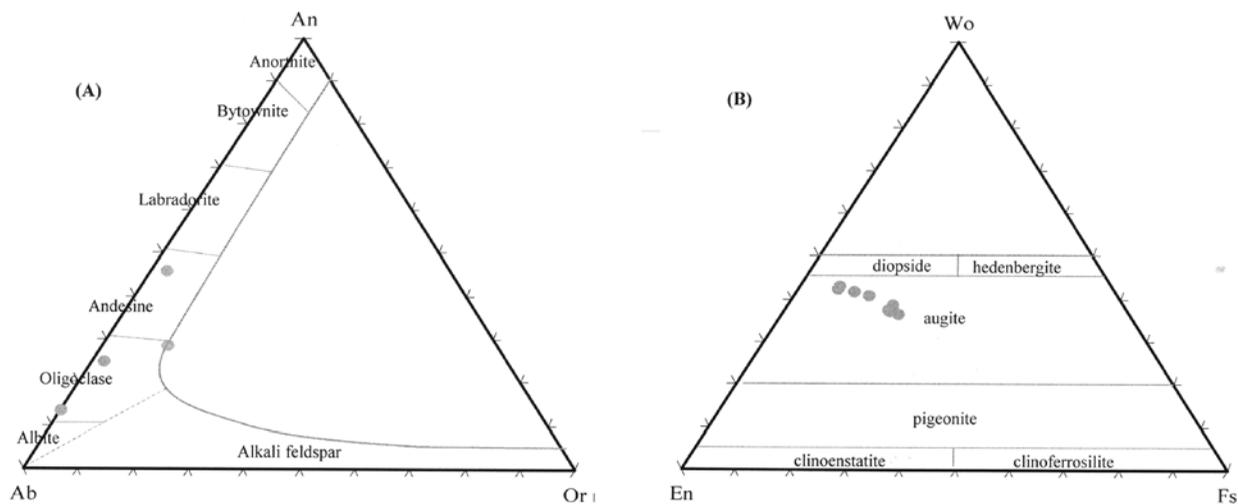


Figure 3. (A) Ab-An-Or (Deer et al., 1966), and (B) En-Di-Fs (Morimoto, 1988), ternary diagrams for the plagioclase and pyroxene compositions, respectively, in the Gadwal Dike 3 samples.

(Table 2). $FeO^*/MgO \sim 1.71$ ratio at a mean concentration of ~ 46 wt% SiO_2 in these samples suggests a tholeiitic composition (Miyashiro, 1974). In contrast to the normal tholeiitic basalts e.g. Khanna (2013), the Dike 3 samples are characterized by high TiO_2 (~ 3.2 wt. %), Nb (~ 26 ppm) and Zr (~ 229 ppm) contents, and high Zr/Y (~ 7.11), Nb/Y (~ 0.82) and Ti/Y (~ 592) ratios. These geochemical attributes are transitional to tholeiitic and alkaline basalts that are typically generated in within plate oceanic and continental settings (Fig. 4E, F; Pearce, 1982). The compatible and incompatible trace element concentrations in the Gadwal dike samples are comparable to the moderately alkaline basalts that are generated in

ocean islands e.g. Moorea Society Islands (Greenough et al., 2005a).

Testing for crustal contamination

Titanium and Zr are not significantly fractionated during MORB melting, and hence the Ti/Zr ratio in the mantle lavas should closely reflect that of their source (Hatton and Sharpe, 1989). Further, during formation of the continental crust, Ti behaves as a compatible element in a Ti-bearing oxide phase (e.g. rutile; Rudnick et al., 2000). In contrast, Zr behaves as an incompatible element. Therefore, melting or assimilation of crustal rocks should

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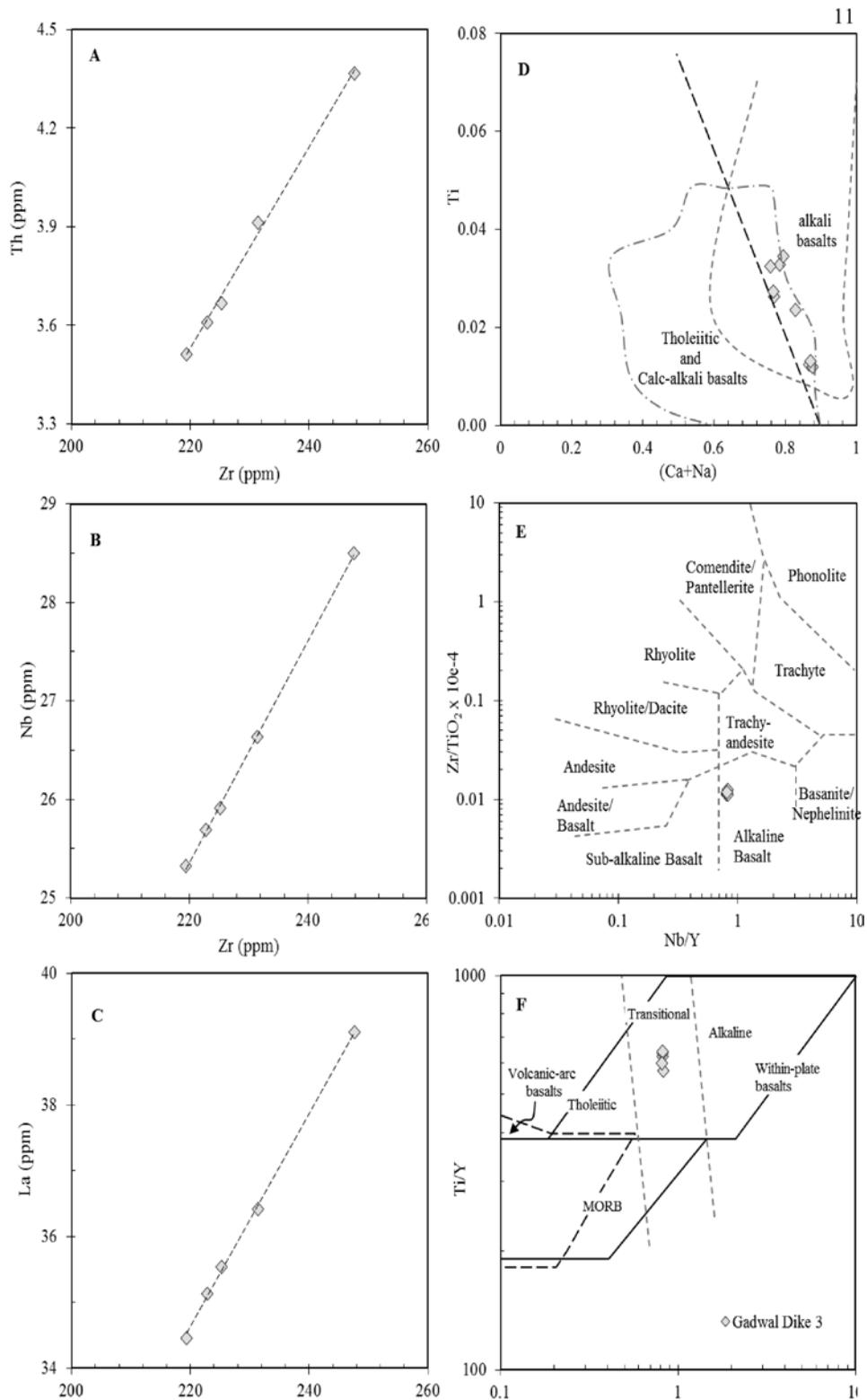


Figure 4. Zr versus (A) Th, (B) Nb and (C) La bivariate plot for the Gadwal Dike 3 samples. See text for details. (D) Discrimination diagram for clinopyroxene phenocrysts in Gadwal Dike 3, composition expressed in cations per six oxygens. Figure adopted from Leterrier et al. (1982). (E) Nb/Y versus Zr/Ti immobile element discrimination diagram after Winchester and Floyd (1977), in which the Gadwal Dike 3 samples plot in the alkaline basalt fields. (F) Nb/Y versus Ti/Y immobile element discrimination diagram after Pearce (1982), in which the samples distinctly plot in the within-plate basalt field, and they are of transitional type.

lead to an enrichment of Zr relative to Ti in the melt, and consequently low Ti/Zr ratios. The Gadwal Dike 3 samples, however, have a mean value of Ti/Zr (~ 83), which is slightly lower than the normal MORB (~ 93 ; Hofmann, 1988), but significantly higher than that in the Archean upper continental crust (AUCC ~ 20 ; Rudnick and Gao, 2004), and hence, inconsistent with the involvement of a low Ti/Zr crustal component in its mantle source. Further, the Gadwal samples do not plot on a mixing trend between normal MORB and the Archean upper continental crust as would be expected in the case of magmas that may have assimilated crustal material during emplacement e.g. siliceous high-Mg basalts (Fig. 5A; Sun et al., 1989; Srivastava and Singh, 1999). Moreover, contamination of magma by assimilation of crustal material will significantly lower the Nb/Th ratio of the erupted melt compared to a pristine melt derived from the upper mantle. The Dike 3 samples, however, are characterized by Nb/Th ~ 6.94 , although it is slightly lower than the primitive mantle value (~ 7.6 ; Hofmann, 1988), it remains significantly higher than the Archean upper continental crust (~ 1.1 ; Rudnick and Gao, 2004). Further, the high Nb contents coupled with consistently high Nb/U ratio (39 - 45) in these samples is unlike that in the continental crust (Fig. 5B); on the contrary, the relatively high Zr/Th and low Th/Ce in the Gadwal samples (Fig. 5C), compared to the Archean upper continental crust, are identical to the range observed in the ocean island basalts (37 - 47; Hofmann et al., 1986). Therefore, we infer that the geochemical attributes of the Gadwal Dike 3 reflect the nature of their mantle source.

Nature of the mantle source

The relatively high Gd/Yb and CaO/Al₂O₃ coupled with low Al₂O₃/TiO₂ ~ 3 , in the Gadwal samples, suggests partial melting of a peridotitic mantle source under moderate pressure conditions with residual garnet in the source (e.g. Arndt, 2003). Unlike the alkali OIB, tholeiitic OIBs form below relatively thin lithosphere at lower pressures from high percentage partial melting (see Fig. 3 in Greenough et al., 2005b, for a review). Given the transitional nature of the Gadwal Dike 1 and Dike 2 samples, and moderate temperature, pressure and depth conditions of melt generation ($\sim 1390^\circ\text{C}$, $\sim 2.2\text{ GPa}$ and $\sim 70\text{ km}$; Khanna et al., 2013), we presume that perhaps Dike 3 samples were also generated under similar conditions by low percentage partial melting at depth, in the garnet stability field. To quantify this observation, geochemical modelling involving HFSE and REE (Fig. 5D, E; Zr, Nb, Y and Ce) was performed. The modelled parameters for source composition, melt proportions, and partition coefficients have been adopted from McKenzie and O'Nions (1991) and Thirlwall (1994) and given in the figure caption. A non-modal partial melting

model (after Shaw, 1970) was used to constrain the nature of the partial melting curve spanning the degree of partial melting (1% - 20%) from the theoretically assigned mantle source i.e. a garnet peridotite source. The primitive mantle composition of Hofmann (1988) was taken as the starting material. The geochemical modelling essentially indicates that the rocks were generated by low degree ($\sim 3 - 4\%$) partial melting in the garnet facies mantle. Moreover, partial melting of a depleted spinel peridotite source cannot generate melts that can significantly fractionate Y and /or Yb from other HFSE or REE resulting in high La/Yb, Zr/Y, Nb/Y and Ce/Y ratios. Therefore, a convecting depleted asthenospheric mantle, which is the source of MORB magmas, cannot be the source of Gadwal Dike 3 samples.

The Gadwal Dike 3 samples are characterized by high Nb ($\sim 26\text{ ppm}$), Zr (~ 229), and slightly lower Y ($\sim 32\text{ ppm}$) and Yb ($\sim 2.44\text{ ppm}$) contents relative to the average N-MORB (3.5 ppm, 105 ppm, 36 ppm and 3.9 ppm, respectively; Hofmann, 1988). The significantly high Nb/Yb (~ 11), Zr/Y (~ 7.1) and extremely low Zr/Nb (~ 8.7) ratios in these rocks, relative to the average N-MORB (Nb/Yb = 0.9, Zr/Y = 2.9 and Zr/Nb = 30; Hofmann, 1988), suggests that these samples were generated from partial melting of a relatively enriched mantle source. These ratios are comparable to EM 1-type OIB (e.g. Salters and Kocher, 2010; Nb = 29, Zr = 265, Y = 41, Yb = 3.46, Nb/Yb = 8.3, Zr/Y = 6.5 and Zr/Nb = 9.2; Table 2).

Implications

Ocean island basalts vary from tholeiitic to alkaline in composition and are characterised by extremely diversified geochemical and radiogenic isotope signatures, even within the intra-island volcanic groups (Weaver et al. 1986). Accordingly, distinct end-member components have been recognised to explain the isotopic heterogeneity of the OIB derived from a particular source. These are depleted MORB mantle (DMM), high- μ (HIMU: high ²⁰⁸U/²⁰⁴Pb), enriched mantle I (EM I) and enriched mantle II (EM II). The end-member components are rarely unique and often represent mixtures between the end-members. Nevertheless, the end-member components can also be appreciably distinguished based on the trace element relationships in terms of incompatible element enrichments and their inter-element ratios that can be invariably interpreted to characterize their origin from a particular source (Saunders et al., 1988; Greenough et al., 2007; Manikyamba and Kerrich, 2011). Although, the chondrite normalized REE and primitive mantle normalized incompatible trace element characteristics in the Gadwal Dike 3 superficially resemble the geochemical composition of normal ocean island basalts (Fig. 6A, B; Sun and McDonough, 1989), the interelement ratios between the incompatible elements i.e. Zr/Nb=8.7, La/Nb=1.37, Th/Nb=0.14 and Ce/Nb=3.2, however, are

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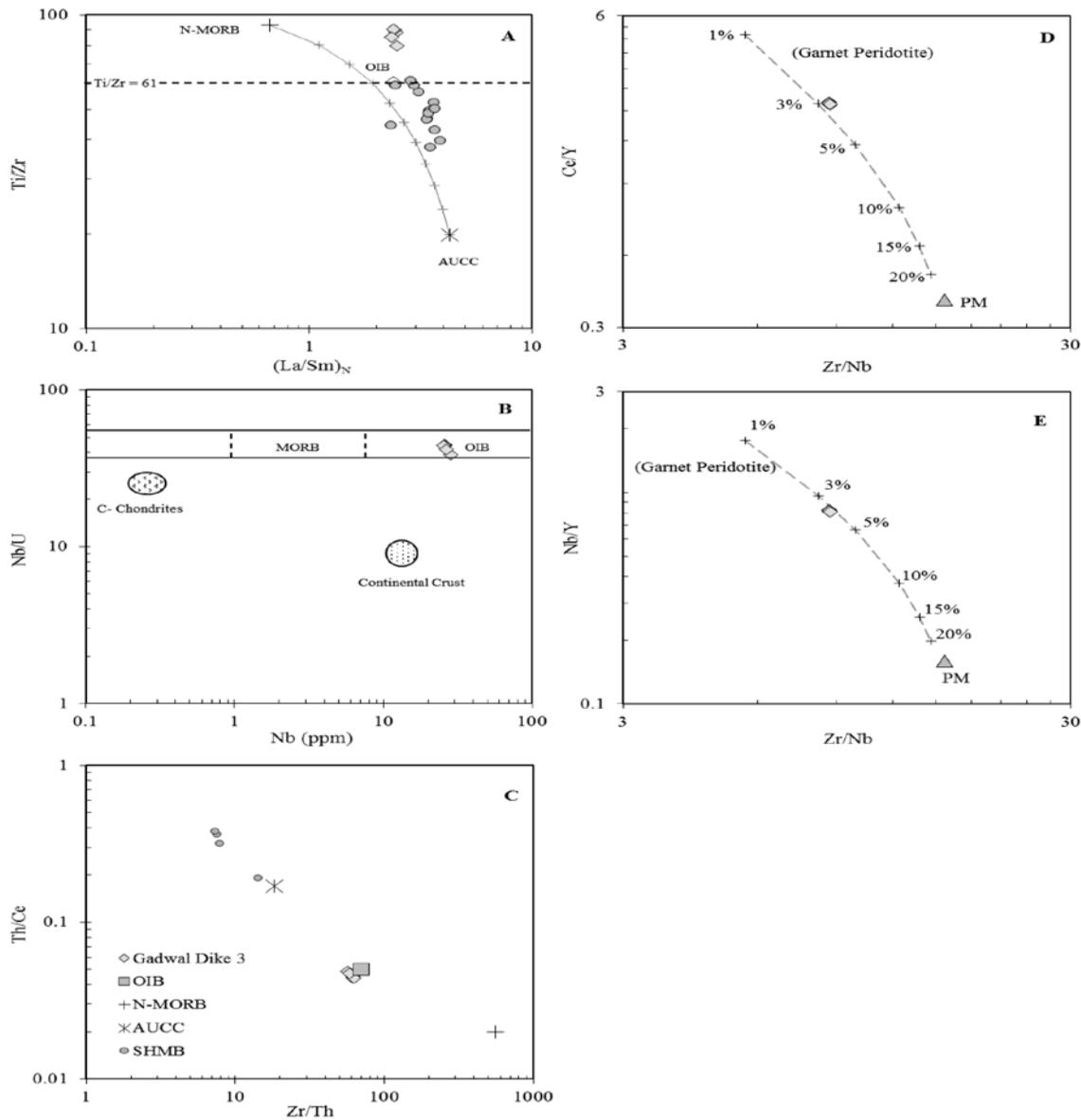


Figure 5. Bivariate ratio-ratio and element-ratio discrimination diagrams for the Gadwal Dike 3 samples. The fields in (B) are from Hofmann et al. (1986). The Gadwal samples are inconsistent with any crustal contamination. See text for details. Siliceous high-Mg basalts (SHMB; Sun et al., 1989; Srivastava and Singh, 1999) are also shown for comparison. The values for OIB (Sun and McDonough, 1989), N-MORB (Hofmann, 1988) and AUCC (Rudnick and Gao, 2004) are also shown for comparison. Zr/Nb versus (D) Ce/Y and (E) Nb/Y ratio-ratio partial melt modelling diagram for Gadwal Dike 3 samples. The source mineralogy (Ol = 0.598, Opx = 0.211, Cpx = 0.076, and Gt = 0.115), melt proportions (Ol = 0.05, Opx = 0.20, Cpx = 0.30, and Gt = 0.45) are from Thirlwall et al. (1994), and partition coefficient data is from McKenzie and O’Nions (1991). See text for details.

distinct and higher than those in the normal OIB (5.8, 0.8, 0.1 and 1.7, respectively; Sun and McDonough, 1989). Compared to the HIMU-type or EM II-type OIB, the high average values of Ba/Th >80, Ba/Nb >7, Ba/La >9, Zr/Nb >5 and K/Nb >250 in the Gadwal Dike 3 are consistent with an EM 1-type OIB signature (Weaver et al., 1986). In contrast to the EM I-type OIB e.g. Gough ocean island (Willbold and Stracke, 2006), the Dike 3 exhibits negative

Nb anomaly relative to the La (Fig. 8B). This atypical behaviour is not a ubiquitous feature of an OIB (Weaver et al., 1986). This characteristic feature, however, is identical and comparable to that observed in the EM1-type OIB from Site 525A of the Walvis Ridge. This is discussed further later.

Fitton et al. (1991) have shown that La/Nb and La/Ba ratios can be used successfully to constrain the nature of

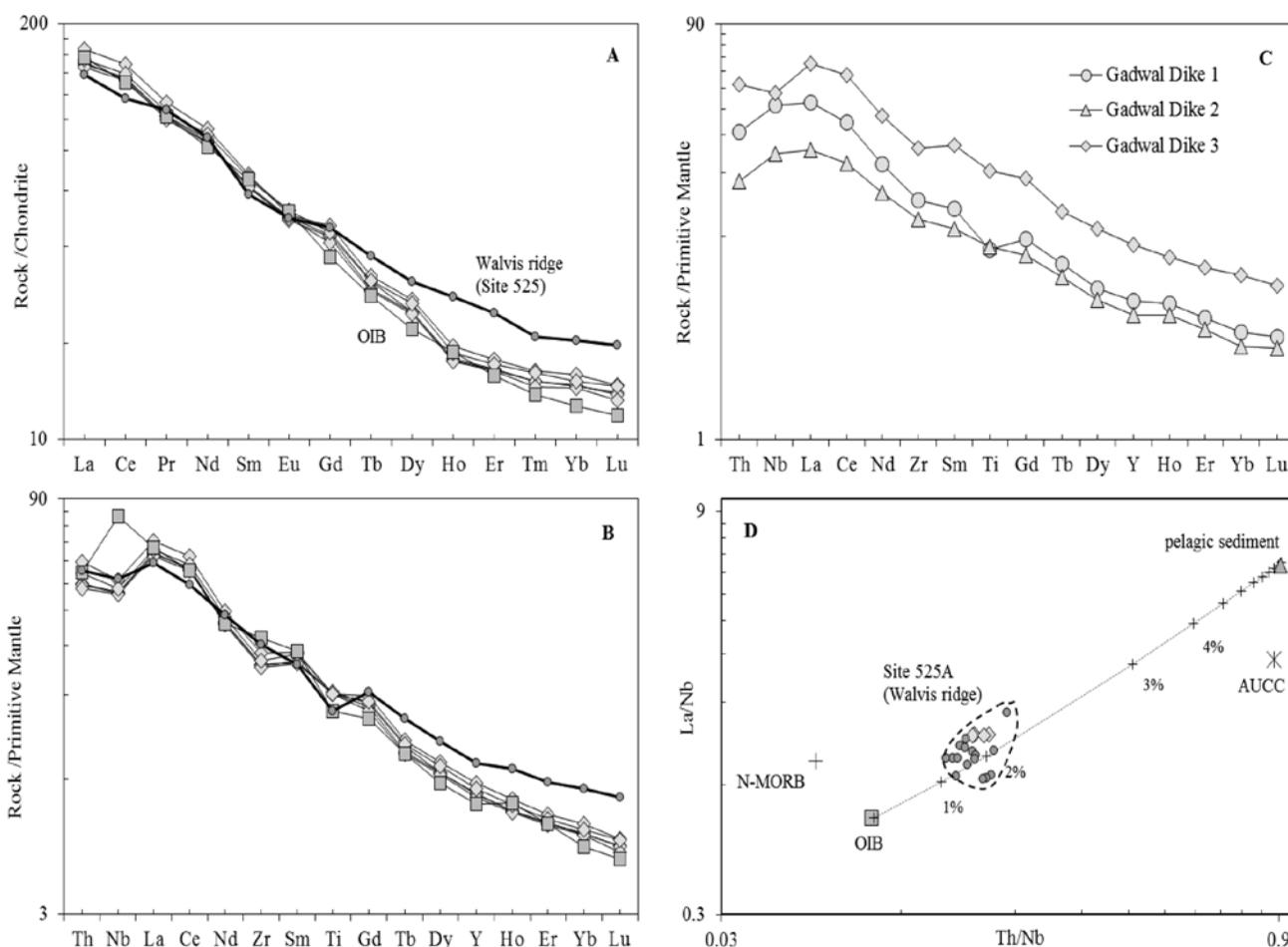


Figure 6. (A) Chondrite normalized REE, and (B) and (C) Primitive mantle normalized trace element variation diagrams for Gadwal Dike 3 samples. The normalizing values are from Sun and McDonough (1989) and Hofmann et al. (1988), respectively. The values for normal OIB are from Sun and McDonough (1989), and Site 525A Walvis Ridge EM1-type OIB is from Salters and Kocher (2010). Note the identical patterns in Gadwal Dike 1, 2 and 3 samples, except for the Nb depletion in Gadwal Dike 3. See text for details. (D) Th/Nb vs. La/Nb diagram for Gadwal Dike 3 is shown for mixing between two end-member components. The ratios for OIB and calculated average composition of an ancient pelagic sediment are from Weaver et al. (1986). The mixing hyperbola between the two end-member components was calculated using the equation from Langmuir et al. (1978).

the magmatic melts originating beneath the continent from a sub-continental lithospheric mantle or an asthenospheric mantle source. In contrast to the enriched sub-continental lithospheric melts, the asthenosphere derived melts are essentially characterized by $La/Nb < 2$ and $La/Ba < 0.3$. The La/Nb and La/Ba ratio in the Gadwal Dike 3 samples is ~ 1.37 and 0.09 , respectively, which is similar to the basalts derived from asthenospheric EM1 OIB sources (e.g. Gough Islands $La/Nb = 0.82 - 1.28$, $La/Ba \sim 0.06$, Weaver, 1991; Walvis Ridge $La/Nb = 0.80 - 1.65$, $La/Ba = 0.06 - 0.12$, Salters and Kocher, 2010). Further, the samples from Gadwal Dike 1 and Dike 2 (Fig. 6C), which are geochemically identical and comparable to Dike 3, consists of La/Nb ratio ~ 1 and $La/Ba \sim 0.06$, and hence consistent with their derivation from an asthenospheric source similar to EM1-type OIB (Khanna et al., 2013). In contrast to the

Dike 3, the Dike 1 and Dike 2 samples, however, are not characterized by Nb depletion relative to La in a primitive mantle normalized diagram (Fig. 6C). This perhaps suggests that albeit the Dikes 1, 2 and 3 were generated from the same subcontinental asthenospheric mantle source, the Dike 3 inherited localized heterogeneity that might have developed due to contribution from crustal recycling in its mantle source region.

The interelement ratios of highly incompatible elements with similar bulk partition coefficients are least affected by partial melting and low pressure fractional crystallization processes during mantle melting. Consequently, the uniform ratios of Zr/Nb , La/Nb and Th/Nb in the Gadwal Dike 3 samples essentially indicate that the melt experienced only mild geochemical fractionation subsequent to segregation from the parental source region.

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As such, fractional crystallization and partial melting is unlikely to be the cause of this heterogeneity. On the basis of similar geochemical attributes, identical trace element ratios and mantle normalized trace elemental abundances, we propose that the anomalous depletion in Nb in the Gadwal Dike 3 samples is ascribed to the involvement of a small amount (~2%) of ancient subducted pelagic sediment recycled into its mantle source region (Fig. 6D). This assertion is in accordance with the explicit account provided by Weaver et al. (1986) for the anomalous depletion of Nb in the OIB from Site 525A of Walvis Ridge.

CONCLUSIONS

The depletion in Nb relative to the neighboring REE need not always potentially implicate crustal contamination. The persistent occurrence of pristine mafic alkaline dikes in this sector of the Dharwar craton provides a significant window to fingerprint the trace element systematics and constrain the heterogeneous nature of the subcontinental lithospheric mantle, beneath the Dharwar craton. The grossly identical OIB-type geochemical attributes of the Gadwal Dike 3 and those from the Site 525 OIB of the Walvis Ridge provide a compelling evidence that the Earth's geodynamic processes that operated at ~2.2 Ga in the Dharwar craton were most probably similar in nature with those that took place ~70 Ma in the South Atlantic Ocean (Humphris and Thompson, 1983). This intracratonic magmatic event appears to have significantly contributed to the growth and evolution of the continental crust in the eastern Dharwar craton at ~2.2 Ga.

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