

Lutetium-Hafnium isotope evidence for the co genesis of Neoproterozoic Veligallu and Gadwal greenstone belts, eastern Dharwar craton, India

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**This research contribution is dedicated to the memory of Dr. Sayed Mahmood Naqvi (S.M. Naqvi). Dr. Naqvi was the proponent of geochemistry in NGRI, who has contributed immensely to the existing knowledge in the field of Archean geodynamics of the Dharwar craton, till his last breath on 4th September 2009. He is an everlasting source of inspiration to me.*

ABSTRACT

This research contribution elucidates the genetic link between the Veligallu and Gadwal greenstone belts that are located to the south and north respectively, of the Proterozoic Cuddapah basin in Eastern Dharwar Craton, India. The metavolcanic sequences in both these Neoproterozoic belts are characterised by an identical initial isotopic composition. Recent study indicates field and petrological similarities, identical nature of magmatism and most significantly, the corresponding metavolcanic rocks from these two belts relate to the same initial $^{176}\text{Hf}/^{177}\text{Hf}$ isotope composition. Therefore, it is inferred that these two greenstone terranes form part of a linear N-S trending Neoproterozoic arc system, which is extensively obscured by the sedimentary cover of the Proterozoic Cuddapah basin, subsequent to post-accretionary geodynamic processes in the eastern Dharwar craton, India.

Key words: Lutetium-Hafnium, Veligallu, Gadwal, Greenstone belt, Dharwar craton, India.

INTRODUCTION

Lutetium-Hafnium isotope studies of juvenile magmatic rocks, in the recent past, have provided important constraints on the nature of magmatism and crustal growth processes in the Precambrian volcanic terranes (e.g. Blichert-Toft and Arndt, 1999; Polat and Munker, 2004; Hoffmann et al., 2010; Khanna et al., 2014). Unlike the Sm-Nd isotopic system, which is otherwise a very sensitive indicator of crustal recycling or assimilation during magmatic emplacement and post magmatic metamorphic processes that may cause ambiguity in the initial $^{143}\text{Nd}/^{144}\text{Nd}$ isotopic composition of the analysed bulk-rock samples, Vervoort and Blichert-Toft (1999) have evidently shown that the Lu-Hf isotope system is extremely robust and unperturbedly preserves the record of initial isotopic composition, even when the rocks are intensely deformed and metamorphosed under amphibolite facie conditions.

Khanna et al., (2014), presented the combined Hf-Nd isotope determinations in the bulk-rock metavolcanic samples from Gadwal greenstone belt. Recently, Khanna et al., (2016a) have presented the Lu-Hf isotope systematics of the metavolcanic rocks from the Veligallu greenstone belt.

The data has been compiled from the above published work and shown in Table 1. A comparative re-examination of the Lu-Hf isotope systematics for the corresponding metavolcanic rocks from these two belts has presented

an important revelation. Through a revisit of these two greenstone belts from an isotopic perspective, I present the initial $^{176}\text{Hf}/^{177}\text{Hf}$ isotope composition for the corresponding metavolcanic sequences in these greenstone belts and thus, propose their evolution from a common mantle source at ~ 2.7 Ga.

For a detailed account of the geology, geochemistry, petrogenesis, and isotopic aspects of the Veligallu and Gadwal greenstone belts the reader is referred to Srinivasan (1990); Manikyamba et al., (2005, 2007); Manikyamba and Khanna (2007); Khanna (2007, 2013); Khanna et al., (2014, 2015, 2016a).

Regional Geology

The Dharwar proto-continent is subdivided into three distinct cratonic blocks: the western Dharwar craton, the eastern Dharwar craton, and the southern granulite terrane (Swami Nath and Ramakrishnan, 1981). The NNW-SSE trending shear zone extending along the eastern margin of the Chitradurga greenstone belt (Naqvi and Rogers, 1987) is considered as a marker that separates the eastern and western blocks. The western and eastern blocks of the Dharwar craton comprise laterally extensive and linearly arcuate Mesoproterozoic and Neoproterozoic greenstone terranes surrounded by younger granitoids. Basically, the greenstone belts located in the eastern Dharwar craton (EDC) are comparatively linear in appearance, mostly

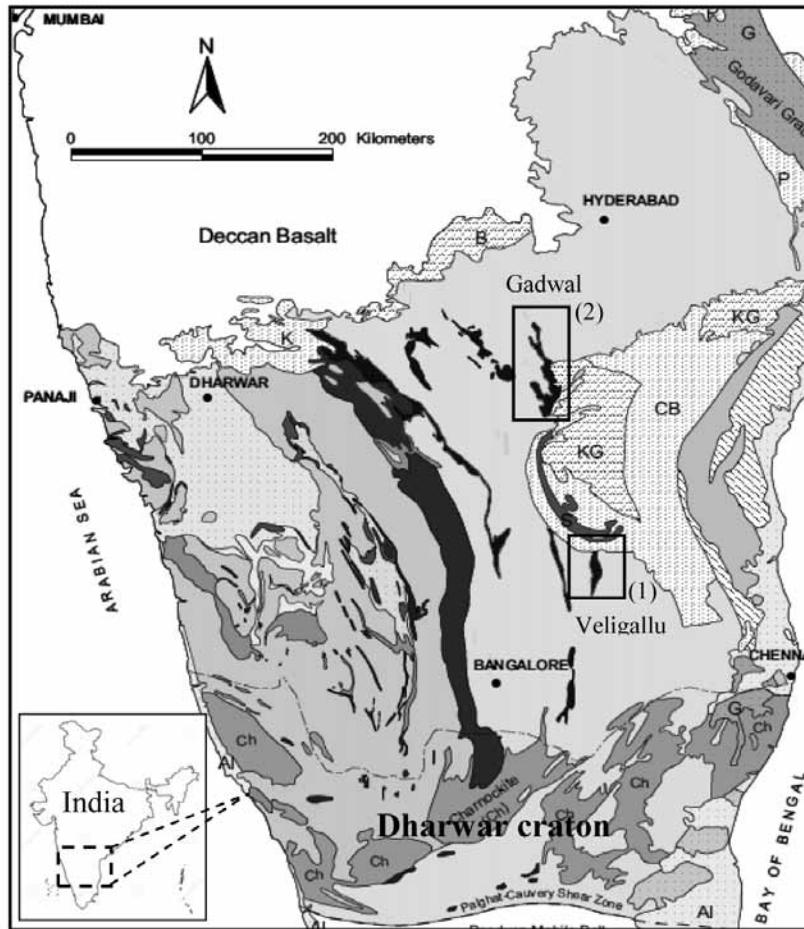


Figure 1. Generalized geological map of Dharwar craton, adapted from project Vasundhara of Geological Survey of India Records, 1994. Gadwal and Veligallu greenstone belts are also labeled and highlighted in rectangular boxes.

characterized by a north–south disposition, which are predominantly composed of metavolcanic rocks and minor metasedimentary components. The focus of this study are the Veligallu and Gadwal greenstone belts that are located on the southern and northern margins of the Proterozoic Cuddapah basin (Nagaraja Rao et al., 1987), in EDC, India (Figure 1).

The Veligallu greenstone belt (Figure 1) broadly exhibits N-S trend with an approximate strike length of ~ 60 km, and a maximum width of ~ 6 km in the central part (Srinivasan, 1990). The volcano-sedimentary sequence was subjected to greenschist to lower amphibolite grade metamorphism. The metamorphism of the volcanic units is presumed to be synchronous with the first generation (F1) folds preserved in the rocks (Ramam and Murty, 1997). The metavolcanic lithologies in the Veligallu belt are constituted of boninite-type ultramafics, basalt, high Mg-andesite and adakite suite of rocks that are associated with banded iron formations (BIFs) and metasediments (Khanna et al., 2015). The metaultramafic igneous rocks with distinctive boninite-like geochemical attributes,

occur as discontinuously interlayered conformable bands paralleling the mafic volcanic rocks in the Veligallu belt. The metavolcanic rocks in the Veligallu belt yielded a Lu-Hf isochron age of 2696 ± 54 Ma (Khanna et al., 2016a).

The Gadwal belt (Figure 1) follows N-S trend in the southern part and NNW-SSE in the north, imparting an arcuate shape. The belt has an approximate strike length of ~ 90 km with a maximum width of ~ 5 km, as observed in the central part (Srinivasan, 1990). The rocks have been metamorphosed under greenschist to lower amphibolite facies conditions. The north-central part of the belt is composed primarily of basalts of both tholeiitic and calc-alkaline affinity (Khanna, 2013), and a geochemically distinctive group of boninitic rocks (Manikyamba et al., 2005). Dacites and rhyolites are also present in the north-central parts of the belt. Some of these felsic rocks are characterized by Phanerozoic adakite-like geochemical attributes (Manikyamba et al., 2007). The metavolcanic rocks in the Gadwal belt yielded identical Lu-Hf and Sm-Nd ages of 2700 ± 24 Ma and 2701 ± 28 Ma, respectively (Khanna et al., 2014).

Table 1. Bulk-rock Lu-Hf isotope data for the corresponding metavolcanics in the Veligallu and Gadwal schist belts, eastern Dharwar craton, India.

Location / rock type	Sample No.	$^{176}\text{Lu}/^{177}\text{Hf}$	$^{176}\text{Hf}/^{177}\text{Hf} (\pm 2\sigma)$
Veligallu			
<i>basalt</i>	TVK-67	0.0516	0.283870 ± 08
	TVK-68	0.0426	0.283435 ± 10
	TVK-72	0.0431	0.283423 ± 13
	TVK-74	0.0318	0.282865 ± 08
	TVK-77	0.0357	0.283047 ± 12
	TVK-81	0.0381	0.283192 ± 05
	TVK-87	0.0420	0.283398 ± 07
	TVK-137	0.0275	0.282580 ± 06
	TVK-155	0.0604	0.284252 ± 15
	TVK-156	0.0422	0.283328 ± 14
<i>boninitic rocks</i>	TVKR-2	0.0287	0.282679 ± 07
	TVKR-4	0.0356	0.283022 ± 14
	TVKR-12	0.0323	0.282814 ± 09
	TVKR-17	0.0345	0.282989 ± 06
	TVKR-20	0.0349	0.282942 ± 10
<i>adakitic rocks</i>	TVK-46	0.0029	0.281318 ± 08
	TVK-47	0.0024	0.281323 ± 04
	TVK-78	0.0024	0.281314 ± 05
Gadwal			
<i>basalt</i>	G-38	0.0273	0.282639 ± 06
	GWL-48	0.0292	0.282835 ± 06
	G-46	0.0356	0.283010 ± 05
	G-58	0.0325	0.282874 ± 05
	G-33	0.0284	0.282665 ± 06
	G-35	0.0298	0.282771 ± 08
<i>boninitic rocks</i>	TCK-35	0.1100	0.286863 ± 10
	TCK-36	0.1126	0.287112 ± 08
	TCK-40	0.1240	0.287505 ± 13
	TCK-43	0.1098	0.286957 ± 08
	TCK-44	0.0973	0.286207 ± 12
	G-21	0.0414	0.283345 ± 08
	G-22	0.0597	0.284277 ± 06
	G-23	0.0521	0.283842 ± 08
<i>adakitic rocks</i>	G-69	0.0068	0.281521 ± 04
	G-72	0.0054	0.281433 ± 04

Analytical Techniques

For bulk-rock geochemistry and Lu-Hf isotopes, the rocks were powdered manually using an agate mortar and pestle. An aliquot of the same sample was used for major and trace element analysis at CSIR – National Geophysical Research Institute, India. The major element oxides 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; 2016). For the determination of trace elements including large ion lithophile elements (LILE), high field strength elements (HFSE) and rare earth elements (REE), 50 mg of finely ground sample powder was digested in a freshly prepared mixture of ultrapure grade acids (HF + HNO₃)

taken in 3:1 ratio in screw top Teflon “Savillex” vessels, and heated on a hot plate at 160°C. The samples were analyzed by high resolution inductively coupled plasma mass spectrometry (HR-ICP-MS; Nu Instruments Attom³, UK). The detailed procedures relating to sample dissolution, analytical methodology and instrument parameters are described in Khanna et al., (2016b).

Lutetium and Hf concentrations and Hf isotopes were determined for a total number of 34 metavolcanic rock samples consisting of a combined subset of 13 boninitic rocks [8_(Gadwal) + 5_(Veligallu)], 16 basalts [6_(Gadwal) + 10_(Veligallu)] and 5 adakites [2_(Gadwal) + 3_(Veligallu)] (Table 1), at the Center for Elemental Mass Spectrometry (CEMS), Department of Earth and Ocean Sciences, University of South Carolina, USA. A detailed description of the analytical methodology is given in Khanna et al., (2014, 2016a). In summary,

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Table 2. Comparisons between the ~2.7 Ga Veligallu and Gadwal greenstone belts, eastern Dharwar craton (EDC), India.

S. No.	Qualified component	Veligallu greenstone belt	Reference	Gadwal greenstone belt	Reference
1.	Location	South of Cuddapah Basin, eastern Dharwar craton	Srinivasan (1990)	North of Cuddapah Basin, eastern Dharwar craton	Srinivasan (1990)
2.	Structural disposition	North-South	Srinivasan (1990)	North-South	Srinivasan (1990)
3.	Deformation	3 generation folds (F1, F2 and F3)	Srinivasan (1990); Ramam and Murty (1997)	3 generation folds (F1, F2 and F3)	Srinivasan (1990); Ramam and Murty (1997)
4.	Metamorphic grade	Greenschist to amphibolite facies	Srinivasan (1990)	Greenschist to amphibolite facies	Srinivasan (1990)
5.	Foliation	NNE-SSW, sub-vertical foliation	Srinivasan (1990)	NNW-SSE, sub-vertical foliation	Srinivasan (1990)
6.	Volcanic units	Ultramafic (boninitic); Basalt – high-Mg-andesite – adakite	Khanna et al., (2015; 2016a)	Boninite-adakite; Basalt-andesite-rhyolite	Manikyamba et al., (2005, 2007); Manikyamba and Khanna (2007); Khanna (2007; 2013)
7.	Sedimentary units	Banded Iron Formations (prominent ridges); chromian muscovite quartzite*	Srinivasan (1990); Ramam and Murty (1997); *Khanna, T. C. (unpublished dataset)	Banded Iron Formation (thin lenses); devoid of clastic or non-clastic sediments.	Srinivasan (1990); Ramam and Murty (1997)
8.	Intrusive unit & age	mafic dikes, gabbro, pyroxenite, and granitoids	Srinivasan (1990); Ramam and Murty (1997)	Dolerite dikes, basaltic alkaline dikes (~2.2 Ga), and granitoids	Khanna et al., (2013; 2016b); Venkateshwarlu and Khanna (2015)
9.	Age of the schist belt & Radiometric dating method	2697 ± 5 Ma; 2696 ± 54 Ma; bulk-rock Lu-Hf.	Jayananda et al., (2013); Khanna et al., (2016a)	2586 ± 7 Ma; SIMS zircon U-Pb. 2700 ± 24 Ma, Lu-Hf; and 2701 ± 28, Sm-Nd. (bulk-rock)	Jayananda et al., (2013); Khanna et al., (2014)
10.	Nature of magmatism	Intraoceanic, subduction zone magmatism	Khanna et al., (2015);	Intraoceanic, subduction zone magmatism	Manikyamba et al., (2005, 2007); Manikyamba and Khanna (2007); Khanna (2007)
11.	Geodynamic setting & concluding evidence	Back-arc setting; Petrogenesis of basalts.	Khanna et al., (2015)	Back-arc setting; Petrogenesis of basalts.	Khanna (2013)

100–150 mg of sample powder were digested in steel jacketed Parr Teflon bombs using HF–HNO₃ mixtures. The samples were then picked up in 10 ml of 1 M HNO₃ to ensure a visibly clear solution. 10–15% of that solution was aliquoted quantitatively in a separate Teflon beaker and spiked with mixed ¹⁷⁶Lu–¹⁷⁹Hf tracers for parent-daughter determination by isotope dilution following the method described in Khanna et al., (2014). Hafnium isotopes as well as Hf and Lu isotope dilution ratio measurements were determined on the Thermo Finnigan NEPTUNE MC-ICP-MS with the PLUS upgrade installed. The sample solutions were introduced with a 100 ul self-aspirating

Teflon nebulizer (ESI, USA) coupled to an APEX-Q (ESI, USA) system using a Jet-sampler cone and X-skimmer cone configuration. Isochrons were calculated with the ISOPLOT program (Ludwig, 2001), using the decay constants $\lambda^{176}\text{Lu} = 1.867 \times 10^{-11}$. The initial isotope compositions were calculated using the chondritic values: $^{176}\text{Hf}/^{177}\text{Hf} = 0.282785$, $^{176}\text{Lu}/^{177}\text{Hf} = 0.0336$ (Bouvier et al., 2008).

DISCUSSION

The Veligallu and Gadwal greenstone belts predominantly constitute of metavolcanic rocks with subordinate

Table 3. Representative geochemical mean composition of the metavolcanic rocks in the Veligallu and Gadwal green stone belts, eastern Dharwar craton, India.

	Veligallu ⁽¹⁾			Gadwal ⁽²⁾		
	basalt	boninitic rocks	adakitic rocks	basalt	boninitic rocks	adakitic rocks
SiO ₂	49.41	50.23	73.04	52.69	48.74	65.64
TiO ₂	1.10	0.22	0.19	0.81	0.28	0.50
Al ₂ O ₃	12.30	5.92	14.30	13.62	10.33	14.96
Fe ₂ O ₃	15.26	7.95	2.45	11.82	11.64	6.08
MnO	0.20	0.13	0.03	0.16	0.15	0.08
MgO	9.32	30.22	0.72	7.32	18.74	2.48
CaO	9.87	5.14	2.57	10.82	9.32	5.14
Na ₂ O	1.75	0.10	4.53	2.42	0.61	3.71
K ₂ O	0.68	0.05	2.12	0.25	0.15	1.10
P ₂ O ₅	0.12	0.03	0.05	0.10	0.03	0.15
Mg#	55	89	36	55	77	44
Cr	197	3346	19	115	2008	15
Ni	122	802	24	107	839	6
Rb	27	2	52	15	59	58
Sr	117	7	120	180	34	259
Cs	1.4	0.2	0.6	2	7	11
Ba	124	14	306	80	39	236
Sc	42	27	3.01	29	43	9
V	332	135	0.90	186	94	128
Ta	0.19	--	0.63	--	0.05	0.68
Nb	3.03	0.89	6.22	3.19	0.79	7.27
Zr	64	21	163	59	17	153
Hf	1.76	0.61	3.73	1.70	0.44	3.40
Th	0.37	0.54	4.30	0.73	0.27	9.18
U	0.14	0.22	1.58	0.24	0.14	2.11
Y	27	7	6	26	13	15
La	4.10	1.94	18.75	5.23	2.00	25.62
Ce	10.78	4.03	32.35	12.84	4.11	46.59
Pr	1.67	0.57	3.17	1.91	0.56	4.77
Nd	8.18	2.52	11.21	8.65	2.44	18.34
Sm	2.65	0.74	1.95	2.68	0.69	3.58
Eu	0.99	0.25	0.65	0.92	0.29	1.11
Gd	3.42	0.92	1.57	3.34	1.09	2.94
Tb	0.64	0.17	0.21	0.63	0.26	0.46
Dy	4.28	1.15	0.89	4.23	1.87	2.22
Ho	0.95	0.26	0.16	0.95	0.49	0.39
Er	2.61	0.74	0.46	2.64	1.44	1.24
Tm	0.40	0.12	0.07	0.42	0.47	0.19
Yb	2.74	0.81	0.44	2.81	1.49	1.21
Lu	0.43	0.13	0.07	0.43	0.24	0.19

Data sources: (1) Khanna et al. (2015, 2016a);

(2) Manikyamba et al. (2005, 2007); Khanna (2007, 2013); Manikyamba and Khanna (2007)

metasediments (Srinivasan, 1990). Basalt-andesite-rhyolite series along with boninite-adakite geochemical variants in these Neoproterozoic belts indicate subduction zone magmatism (Srinivasan, 1990; Manikyamba and Khanna, 2007). Low incidence of gold mineralization has been recorded in both these Neoproterozoic greenstone belts of the EDC (Sesha Sai et al., 2001; Sahoo et al., 2009). Veligallu and Gadwal greenstone belts are located at the southern, and northern parts of the Cuddapah basin along its western

margin, respectively (Figure 1). The following comparative aspects between the two belts reveal significant similarities. These aspects are concisely presented in Table 2, and certain subtle features are comparatively discussed below.

The basalts are tholeiitic in composition ($\text{FeO}^*/\text{MgO} \sim 1.46$, $\text{SiO}_2 \sim 51$ wt. %; Miyashiro, 1974). They have a mean uniform narrow range in their SiO_2 (49 – 53 wt. %), MgO (7.3 – 9.3 wt. %), Fe_2O_3 (12 – 15 wt. %), and TiO_2 (0.81 – 1.10 wt. %), and identical Mg# (55) (Table 3). On

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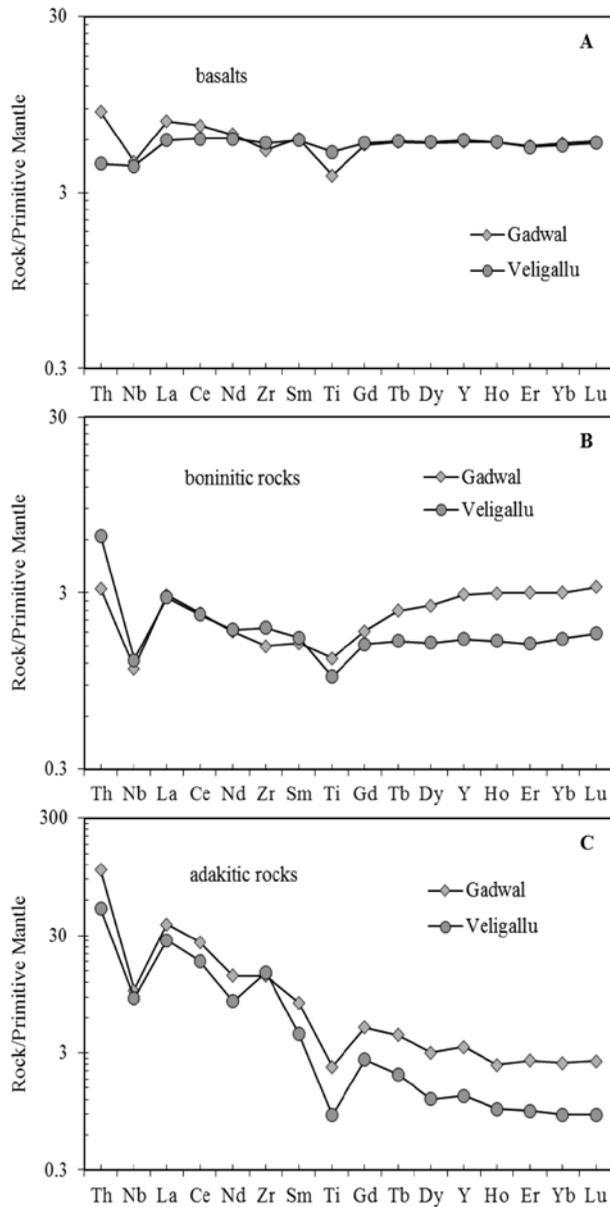


Figure 2. Primitive mantle normalized trace and rare earth element compositions of the corresponding metavolcanic rocks from the Veligallu and Gadwal greenstone belts. Normalized values are from Sun and McDonough (1989).

a primitive mantle normalized trace element variation diagram (Figure 2A), the basalts, collectively as a group, display flat rare earth element patterns with negative Nb [(Nb/La)_{pm} < 1] and Ti [(Ti/Gd)_{pm} < 1] anomalies. To first order, except for the slight differences in the magnitude of depletion in Nb and Ti, the high field strength element abundances (Nb, Zr, Hf and Y; Table 3) and the normalized REE patterns are remarkably identical to each other.

Unlike the basalts, the boninitic rocks are characterized by a broad range in their mean geochemical compositions

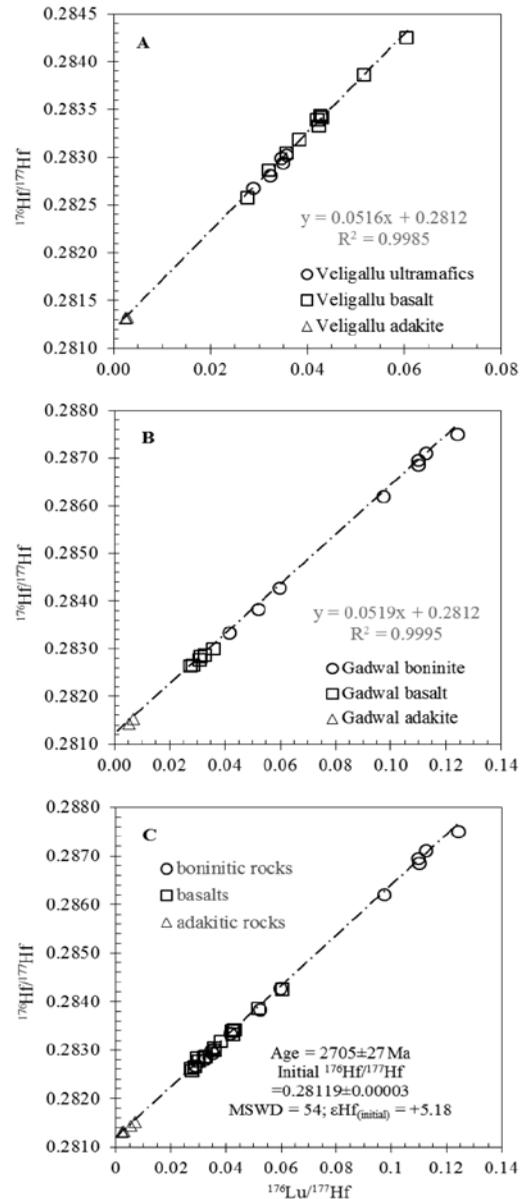


Figure 3. $^{176}\text{Lu}/^{177}\text{Hf}$ versus $^{176}\text{Hf}/^{177}\text{Hf}$ bivariate diagrams for the corresponding metavolcanic rocks in the (A) Veligallu belt, and (B) Gadwal belt. Note the identical intercept defined by these rocks. (C) Isochron derived for the entire sample population as shown in (A) and (B), and data given in Table 1.

(Table 3). For example, the MgO contents and Mg# significantly vary from ~18 to ~30 wt. %, and 77 to 89, respectively, over a narrow range of SiO₂ = 48.7 to 50.2 wt. %. Although, they are characterized by low TiO₂ (~0.25 wt. %) with higher than chondritic Al₂O₃/TiO₂ (> 22; Sun and McDonough, 1989) ratios with identical Nb and Ti anomalies on a primitive mantle normalized trace element variation diagram (Figure 2B), the high MgO and Mg# in the Veligallu samples compared to those sampled in the Gadwal sector, suggests that the Gadwal boninitic rocks

are comparatively more evolved. Conversely, the Veligallu adakitic rocks are characterized by higher contents of SiO₂ and Na₂O, and significantly lower concentrations in their TiO₂, Fe₂O₃, MgO, Mg#, Y and Yb (Table 3); and thus, on this basis appear to be relatively more evolved compared to those reported from the Gadwal sector. Accordingly, on a primitive mantle-normalized trace element variation diagram (Figure 2C) they display identical negative Nb and Ti anomalies, and contrasting positive Zr spikes.

Khanna et al., (2016a) have shown that the Veligallu basalts and the boninite-like ultramafics are cogenetic in nature, and that the ultramafics represent cumulates derived from the associated basaltic melt instantaneously after their separation from the mantle source (e.g. Szilas et al., 2015). Similar petrogenetic model is applicable for the Gadwal basalt – boninite association. In the ¹⁷⁶Lu/¹⁷⁷Hf versus ¹⁷⁶Hf/¹⁷⁷Hf bivariate diagram, the Veligallu metavolcanics describe a consistently linear trend with an intercept of 0.2812 (Figure 3A) on the y-axis. The intercept is identical to the one described by the corresponding metavolcanic rock sequence in the Gadwal sector (Figure 3B). This necessarily indicates that besides the geochemical attributes, the volcanic sequences in the two belts have the same initial isotopic composition, and hence it provides a compelling evidence for their derivation from a common mantle source. Collectively, the volcanics yield an age of 2705 ± 27 Ma with an initial ¹⁷⁶Hf/¹⁷⁷Hf = 0.28119 ± 03 and εHf_(t) = +5.18 (Figure 3C). The positive initial isotopic compositions obtained for the Veligallu – Gadwal metavolcanics is consistent with their derivation from a depleted mantle source relative to chondritic mantle at ~2.7 Ga.

CONCLUSIONS

Geochemical compositions determined for the metavolcanic rocks in the Veligallu and Gadwal greenstone belts indicate identical trace and rare earth element attributes. (2) the boninitic rocks, in these two belts, are spatially associated with the arc basalts; (3) the arc basalt and boninite-like ultramafic suite represents corresponding melt and derivative cumulate; (4) based on the trace element attributes of the corresponding basalt sequences in the individual belts, a palaeo-back arc tectonic setting has been proposed (Khanna, 2013; Khanna et al., 2015); (5) the metavolcanic sequences in the Veligallu and Gadwal belts are characterized by an identical initial ¹⁷⁶Hf/¹⁷⁷Hf isotopic composition, which provides a compelling evidence of cogenesis from a common mantle source; (6) therefore, it is proposed that these two greenstone belts form part of a linear N-S trending Neoproterozoic arc system, which is obscured by the sedimentary cover of the Proterozoic Cuddapah Basin.

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Compliance with ethical Standards

The author declare that he has no conflict of interest and adhere to copyright norms.

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Yellowstone's Last Super-eruption

Geologists suggest that mixing of magma melt pockets could have caused the explosion a little more than 600,000 years ago. Yellowstone National Park is renowned for more than just its hot springs and Old Faithful. The area is famous in the volcanology community for being the site of three explosive super eruptions, the last of which was 631,000 years ago.

During that eruption, approximately 1000 cubic km of rock, dust, and volcanic ash blasted into the sky. Debris rained across the continental United States, spanning a rough triangle that stretches from today's Canadian border down to California and over to Louisiana. In places, ash reached more than a meter thick. Hannah Shamloo, and Christy Till, examined two crystals of feldspar that they found embedded in the tuff. These crystals, called phenocrysts, form as magma cools slowly beneath the volcano. Temperature information locked in a phenocryst's outer rims can be extracted using a technique called feldspar thermometry. The technique relies on the fact that certain minerals vary their compositions in known ways as temperatures change. Thus, scientists can work backward from the exact compositions of minerals present in these outer rims to estimate the surrounding temperature when the crystal rim formed. The duo found signatures in the rims that point to an increase in temperature and uptick in the element barium in the magma just before the eruption. (**Citation:** Woodward, A. (2017), Pinpointing the trigger behind Yellowstone's last supereruption, *Eos*, 98, doi:10.1029/2017EO065953.