Rb–Sr and Sm–Nd isotope systematics and geochemical studies on metavolcanic rocks from Peddavura greenstone belt: Evidence for presence of Mesoarchean continental crust in easternmost part of Dharwar Craton, India

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Linear, north–south trending Peddavura greenstone belt occurs in easternmost part of the Dharwar Craton. It consists of pillowed basalts, basaltic andesites, andesites (BBA) and rhyolites interlayered with ferruginous chert that were formed under submarine condition. Rhyolites were divided into type-I and II based on their REE abundances and HREE fractionation. Rb–Sr and Sm–Nd isotope studies were carried out on the rock types to understand the evolution of the Dharwar Craton. Due to source heterogeneity Sm–Nd isotope system has not yielded any precise age. Rb–Sr whole-rock isochron age of 2551 ± 19 (MSWD = 1.16) Ma for BBA group could represent time of seafloor metamorphism after the formation of basaltic rocks. Magmas representing BBA group of samples do not show evidence for crustal contamination while magmas representing type-II rhyolites had undergone variable extents of assimilation of Mesoarchean continental crust (>3.3 Ga) as evident from their initial ε_{Nd} isotope values. Trace element and Nd isotope characteristics of type I rhyolites are consistent with model of generation of their magmas by partial melting of mixed sources consisting of basalt and oceanic sediments with continental crustal components. Thus this study shows evidence for presence of Mesoarchean continental crust in Peddavura area in eastern part of Dharwar Craton.

1. Introduction

Study of Archean greenstone belts and surrounding granitoid terrains of Tonalite–Trondhjemite–Granodiorite (TTG) are important to understand processes responsible for crustal growth as they contain earliest records of the earth's history (e.g., De Wit and Ashwal 1995). The oldest rocks in the earth's continental crust were formed more than 4.2 Ga ago and rocks from Nuvvuagittug greenstone belt in Quebec, Canada were argued to represent such early crust (O'Neil *et al.* 2008). The Acasta gneiss complex (4.02–3.9 Ga) near Canada's Great Slave Lake also has zircons with a

U–Pb age of 4.2 Ga (Iizuka *et al.* 2006). Moreover, the finding of 4.4 Ga old detrital zircon from conglomerate unit of Jack Hills in the Narryer Gneiss Terrane of the Yilgarn Craton, western Australia (Wilde *et al.* 2001) indicates that the first continental crust formed within a few hundred million years after the formation of the earth. However, juvenile additions to continental crust in Archean took place mainly between 3.8 and 2.5 Ga ago in various cratons.

The greenstone belts and granitic rocks of the Pilbara craton formed episodically over an 800 Ma period, from ca. 3.6 Ga to younger than 2.8 Ga (Champion and Smithies 2001). The age of

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rocks in various granite-greenstone terrains of Yilgarn craton ranges between 3.0 and 2.6 Ga (Smithies and Champion 2000; Champion and Smithies 2001) signifying rapid growth of continental crust during this period. The North China Craton experienced a prolonged history of multiple metamorphic, magmatic, and deformation events from 3.0 to 2.4 Ga (Wu *et al.* 1991, 1998; Xu *et al.* 1992; Cao *et al.* 1996). The oldest rock types in this craton are 3.0–2.9 Ga old mafic to ultramafic granulites termed the Yishui group (Cao *et al.* 1996; Polat *et al.* 2006). The Slave craton is a complex mixture of volcano-sedimentary belts floored by older continental crust in the west and juvenile crust in the east, which are all intruded by late tectonic 2.5–2.6 Ga plutons (Covello *et al.* 1988; Kusky 1989; Isachsen and Bowring 1997; Mueller *et al.* 2005).

Greenstone belts in the Archean Superior Province are about 100 km scale terranes of volcanic-sedimentary supracrustal sequences and granitoid rocks with tectonic or intrusive boundaries (Thurston *et al.* 1991; Stott 1997). The granitoid rocks from various subprovinces range in age from 3.0 to 2.65 Ga, however, formation of most greenstone belts and accretionary amalgamation occurred over a relatively short period from 2.75 to 2.65 Ga diachronously from north to south (Percival *et al.* 1994; Polat and Kerrich 2001a; Izuka *et al.* 2006).

Some of the greenstone belts (e.g., Abitibi, Kolar, Hutti, and Kambala) host important mineral deposits (e.g., Au, PGE, Ni, Cu) and hence generated considerable interest among geologists to know the relationship between early crust formation and genesis of the ore deposits. The Dharwar Craton had significant addition of juvenile material and consequent crustal growth during 3.4–2.5 Ga ago (Balakrishnan *et al.* 1999; Krogstad *et al.* 1989; Jayananda *et al.* 2013; Maya *et al.* 2011). The western part of Dharwar Craton is dominated by greenstone belts and Tonalite-Trondhjemite-Granodiorite (TTG) gneisses, both ranging in age from 3.4 to 2.6 Ga (Beckinsale *et al.* 1980; Meen *et al.* 1992; Nutman *et al.* 1992, 1996; Peucat *et al.* 1993; Trendall *et al.* 1997a; Anil Kumar *et al.* 1996; Taylor *et al.* 1984; Naqvi and Rogers 1987; Jayananda *et al.* 2006, 2008, 2013; Maya *et al.* 2011). The Eastern Dharwar Craton (EDC) is dominated by a Neoproterozoic calc-alkaline complex of juvenile and anatectic granites, granodiorites, monzonites, and diorites that are interspersed with greenstone belts formed 2.7–2.5 Ga ago (Vasudev *et al.* 2000; Sarma *et al.* 2008; Bidyananda *et al.* 2011; Jayananda *et al.* 2013; Ram Mohan *et al.* 2013).

There are several linear greenstone belts occurring to east of Kolar and Hutti in the EDC, such

as, Gadwal, Kushtagi, Veligallu, and Peddavura greenstone belts. These greenstone belts need to be studied in detail to better understand the growth of Dharwar Craton during Neoproterozoic. The present study aims to determine petrogenesis and timing of emplacement of metavolcanic rocks of the Peddavura greenstone belt and integrate the results with earlier studies to understand whether there is any spatial variation in evolution of Archean continental crust in the Dharwar Craton.

2. Geological frame work

The Dharwar Craton contains TTG gneisses, a number of greenstone belts, and granites that intrude both gneisses and greenstone belts. The greenstone belts consist of rocks of sedimentary and volcanic origin subjected to greenschist to amphibolite facies metamorphism (Naqvi and Rogers 1987). The regional trend of foliations of granitoid gneisses and greenstone belt is NW–SE in the northern parts and N–S in the central and southern parts (figure 1a). Chadwick *et al.* (1992) suggested that a mylonitized zone on the eastern margin of the Chidradurga greenstone belt formed the boundary between the eastern and western parts of Dharwar Craton.

The presence of 3.38 Ga old TTG gneisses in the Western Dharwar Craton (WDC) has been well documented in the Gorur–Hasan area (Beckinsale *et al.* 1980; Meen *et al.* 1992; Nutman *et al.* 1992) and presence of granitic rocks as old as 3.8 Ga was inferred based on U–Pb dating of zircons from metasedimentary units of Sargur group and Bababudan group greenstone belts (Nutman *et al.* 1992; Hokada *et al.* 2013). Minor remnants of Mesoproterozoic continental crust were reported west of the Kolar greenstone belt while indirect evidences for existence of >3.1 Ga old granitoid rocks in the form of zircons in volcano-sedimentary units, such as, Champion gneisses have been reported from the eastern part of Kolar (Krogstad *et al.* 1991; Friend and Nutman 1991; Peucat *et al.* 1993, 2013; Balakrishnan *et al.* 1999; Chadwick *et al.* 2000, 2007; Jayananda *et al.* 1995, 2000; Moyon *et al.* 2003; Chardon *et al.* 2002, 2011; Vasudev *et al.* 2000; Rogers *et al.* 2007; Sarma *et al.* 2008, 2011).

Structural analysis documents the contrasting responses of the Western Dharwar Craton (WDC) and Eastern Dharwar Craton (EDC) during late Archean (2.56–2.50 Ga) orogeny and associated partial melting and high temperature–low pressure metamorphism (Chardon and Jayananda 2008). The EDC is thought to have been an accreted terrane and the greenstone belts were considered as terrain boundaries (Krogstad *et al.* 1989;

Balakrishnan *et al.* 1999). The whole Archean continental crust in the Dharwar craton was affected by a major thermal event close to 2.51 Ga, followed by slow cooling up to 2.45 Ga (Peucat *et al.* 2013). According to Zachariah *et al.* (1996), the mafic to felsic volcanic rocks were emplaced in tectonic setting similar to present-day island arc volcanic suites.

Hutti, Ramagiri, Kolar, Kushtagi, Penakacherla, and Gadwal greenstone belts of the EDC (figure 1a) have been studied for their geochemistry. Kolar greenstone belt consists of komatiites, tholeiites, and dacites. Whereas, Hutti is made up of tholeiitic basalts, dacites, and rhyolite with

rare occurrence of ultramafic rocks (Basir and Balakrishnan 1999; Giritharan and Rajamani 2001). Association of rocks in various greenstone belts of EDC are given in table 1.

Ramagiri and Hungund greenstone belts consist of basalts, andesites, dacites, and rhyolites with minor units of banded iron formation (BIF), engulfed in extensive granitoid-gneiss terranes. At Ramagiri, ultramafic schists occur as a minor unit (Ghosh *et al.* 1970; Reddy *et al.* 1992; Zachariah *et al.* 1996, 1997), whereas in the Hungund region, pillow-basalts are extensively exposed with minor interflow carbonate units. Basalts have been dated at 2746 ± 64 Ma by Pb–Pb method

Figure 1. (a) Geological map of the Dharwar Craton. (b) Geological map of the Peddavura greenstone belt (after Srinivasan 1991) with sample locations marked.

Figure 1. (Continued.)

(Zachariah *et al.* 1995) which is consistent with U–Pb zircon age of 2707 ± 18 Ma reported for pyroclastic unit from the Ramagiri greenstone belt (Balakrishnan *et al.* 1999). Gadwal greenstone belt is made up of metabasalts along with felsic and intermediate volcanic rocks, thin band of pyroxenites, and minor banded iron formations. This belt has been intruded by granitoids of different phases namely:

- 1) tonalite–trondhjemite–granodiorite (TTG),
- 2) sanukitoid,
- 3) biotite granite, and
- 4) Closepet granite (high-Mg, high-HFSE type) (Manikyamba *et al.* 2005; Manikyamba and Khanna 2007).

Kushtagi greenstone belt consists of pillowed basalts actinolite-chlorite schist, banded ferruginous quartzite (BFQ), ferruginous argillite, quartzite, tuff, carbonates, phyllites, and granitic rocks. The volcanic and sedimentary rocks are intercalated with each other within the belt. Undeformed dolerite and pegmatite intrusions are

also present throughout the belt (Matin 2006; Naqvi *et al.* 2006). Granites in the southern part of the EDC between Kolar and Ramagiri is dated as 2552–2534 Ma by single zircon evaporation technique (Jayananda *et al.* 2000). An attempt has been made to determine U–Pb age of zircons separated from rhyolite of Peddavura greenstone belt using secondary ion microprobe technique by Jayananda *et al.* (2013) which yielded discordant ages with inferred minimum age of 2.4 Ga.

2.1 Field and petrographic studies

The NW–SE trending Peddavuru Greenstone Belt extends over 25 km with a width of 0.5–2 km (Srinivasan 1991) and is flanked on both sides by granitoid rocks whose ages are not known (figure 1b). The belt is well exposed near Vijayapuri-North all along the Krishna River, downstream of Nagarjuna Sagar Dam and consists of dark coloured basalts, fine-grained buff coloured felsic volcanic rocks and tuffs, and BIF that are interlayered with each other. Further south of Krishna River, the belt

Table 1. *Published geochronological data on the greenstone belts and granites of the Eastern Dharwar Craton.*

Greenstone belts in EDC	Rock types	Method	Time of formation	Authors
Sandur	Rhyolite	SHRIMP	2658 ± 14 Ma	Nutman <i>et al.</i> (1996)
	Rhyolite	SHRIMP	2691 ± 18 Ma	Nutman <i>et al.</i> (1996)
	Granite	SHRIMP	2570 ± 62 Ma	Nutman <i>et al.</i> (1996)
	Gneisses	SHRIMP	2719 ± 40 Ma	Nutman <i>et al.</i> (1996)
	Sandur belt	Sm–Nd	2706 ± 184 Ma	Naqvi <i>et al.</i> (2002)
Ramagiri	Chenna migmatitic gneisses	Sphene	2545 ± 1 Ma	Balakrishnan <i>et al.</i> (1999)
	Chenna migmatitic gneisses	Zircon	2650 ± 8 Ma	Balakrishnan <i>et al.</i> (1999)
	Central Ramagiri granitoid	Zircon	2614 ± 4 Ma	Balakrishnan <i>et al.</i> (1999)
	Central Ramagiri granitoid	Sphene	2613 ± 7 Ma	Balakrishnan <i>et al.</i> (1999)
	W. Gangam putonic complex	Zircon	2528 ± 1 Ma	Balakrishnan <i>et al.</i> (1999)
	Post-kinematic granite	Sphene	2468 ± 4 Ma	Balakrishnan <i>et al.</i> (1999)
	Pyroclastics, central ‘prong’ in the schist belt	Zircon, TIMS	2707 ± Ma	Balakrishnan <i>et al.</i> (1999)
	Meta basalt	Pb–Pb	2746 ± 64 Ma	Zachariah <i>et al.</i> (1995)
Hutti	Felsic volcanics	SIMS U–Pb	2569 ± 13 Ma	Jayananda <i>et al.</i> (2013)
	Felsic volcanics	SHRIMP	2543 ± 9 Ma	Rogers <i>et al.</i> (2007)
	Granodiorite	SHRIMP	2561 ± 21 Ma	Vasudev <i>et al.</i> (2000)
	Kavital granite intrusive	SHRIMP	2576 ± 12 Ma	Rogers <i>et al.</i> (2007)
	Kavital granite intrusive	SHRIMP	2543 ± 9 Ma	Rogers <i>et al.</i> (2007)
	North granitoids	Sphene	2574 ± 9 Ma	Anand (2007)
	North granitoids	Zircons	ca. 2.5 Ga	Anand (2007)
	North granitoids	Sphene	2531 ± 3 Ma	Anand (2007)
	Kardikal granitoids	Zircons	2559 ± 13 Ma	Anand (2007)
	Kardikal granitoids	Sphene	2555 ± 5 Ma	Anand (2007)
	Meta basalt	Pb–Pb	2637 ± 150 Ma	Anand and Balakrishnan (2010)
	Meta basalt	Rb–Sr	2706 ± 130 Ma	Anand and Balakrishnan (2010)
	Meta basalt	Sm–Nd	2662 ± 81 Ma	Anand and Balakrishnan (2010)
	Kavital granitoids	Zircons	2545 ± 7 Ma	Sarma <i>et al.</i> (2008)
Kolar	Felsic volcanics	SIMS U–Pb	2554 ± 10 Ma	Jayananda <i>et al.</i> (2013)
	Champion gneisses	Pb–Pb	>2844 Ma	Krogstad <i>et al.</i> (1991)
	Dod granodioritic gneisses	Zircons	2631 ± 7 Ma	Krogstad <i>et al.</i> (1991)
	Quartz monzonites	Pb–Pb	2540 ± 2 Ma	Jayananda <i>et al.</i> (2000)
	Dosa gneisses	Zircons	2610 ± 10 Ma	Krogstad <i>et al.</i> (1991)
	Patna granite	Zircons	2551 ± 3 Ma	Krogstad <i>et al.</i> (1991)
	Banded gneiss of W. KSB	Zircons	>3.14 Ga	Krogstad <i>et al.</i> (1991)
	Kamba gneiss	Zircons	2532 ± 3 Ma	Krogstad <i>et al.</i> (1991)
	Agmatite gneiss	Sphene	2501 ± 8 Ma	Krogstad <i>et al.</i> (1991)
	Western Quartz Monzonite	SHRIMP	2546 ± 9 Ma	Chardon <i>et al.</i> (2002)
	SE Trondhjemite Bisnattam Pluton	SHRIMP	2534 ± 6 Ma	Chardon <i>et al.</i> (2002)
	Komatiite	Sm–Nd	2696 ± 136 Ma	Balakrishnan <i>et al.</i> (1999)
	Tholeiite	Pb–Pb	2732 ± 155 Ma	Balakrishnan <i>et al.</i> (1999)
Jonnagiri	Granite intrusion SE part of belt	SHRIMP	2.55 Ga	Chadwick <i>et al.</i> (2000)
Gadwal	Felsic lava	SIMS U–Pb	2522 ± 54 Ma	Jayananda <i>et al.</i> (2013)
	Felsic lava	SIMS U–Pb	2586 ± 7 Ma	Jayananda <i>et al.</i> (2013)
	Felsic lava	SIMS U–Pb	2585 ± 7 Ma	Jayananda <i>et al.</i> (2013)
Kadiri	Felsic volcanics	SIMS U–Pb	2556 ± 13 Ma	Jayananda <i>et al.</i> (2013)
Veligallu	Felsic volcanics	SIMS U–Pb	2697 ± 5 Ma	Jayananda <i>et al.</i> (2013)
Peddavura	Rhyolite	SIMS U–Pb	Zircon ca. 2.4 Ga	Jayananda <i>et al.</i> (2013)
	Meta basalt, basaltic andesite, andesite (BBA group)	Rb–Sr	2551 ± 19 Ma	This work

Table 2. Major, trace and REE data of the Peddavura Basalt, Basaltic Andesite and Andesite (BBA group) and Rhyolite.

Rock type	BBA group					Rhyolites Type I					Rhyolites Type II				
	MV-2	MV-4	MV-5A	MV-5B		MV-3	MV-6	MV-8	MV-12	MV-13	MV-1	MV-7	MV-10/1	MV-11/1	
Sample no.															
SiO ₂	55.85	50.32	51.17	54.91	56.28	52.33	71.46	66.53	70.26	73.03	71.66	74.6	70.61	70.07	
TiO ₂	0.73	0.76	0.1	0.49	0.76	1.02	0.16	0.22	0.37	0.14	0.16	0.14	0.2	0.3	
Al ₂ O ₃	13.25	14.73	24.59	14.34	13.76	15	12.1	12.39	13.28	11.87	12.35	10.33	12.96	12.29	
Fe ₂ O ₃	9.41	13.63	2.01	7.65	8.45	13.06	1.61	2.35	3.62	1.47	1.4	1.27	1.78	3.39	
MnO	0.13	0.20	0	0.12	0.12	0.20	0	3.14	0.04	0	0	2.8	0	0.04	
MgO	4.74	6.05	1.65	5.12	4.28	5.54	1.61	1.34	2.45	1.30	1.35	0.92	1.23	1.42	
CaO	8.27	11.17	10.19	9.26	6.61	8.31	1.13	0.89	3.16	0.97	3.22	0.69	1.91	2.96	
Na ₂ O	2.35	2.59	1.07	1.70	2.93	3.52	4.61	0	3.35	4.62	4.29	0	4.48	2.17	
K ₂ O	1.18	0.26	3.58	1.04	1.5	0.64	1.88	3.33	1.72	1.60	0.57	3.55	1.33	2.22	
P ₂ O ₅	0.07	0.07	0	0	0.08	0.17	0	0	0.09	0	0	0	0.06	0.07	
LOI	1.54	0.96	4.61	2.06	2.61	1.28	2.01	1.45	2.57	1.11	1.53	0.96	1.36	1.45	
Total	97.53	100.74	98.97	96.68	97.37	101.06	96.57	96.81	97.17	98.53	96.54	95.26	95.92	96.38	
Mg#	33.51	30.73	45.13	40.11	33.61	29.79	50	36.33	40.38	46.98	49.11	42.1	40.85	29.53	
Concentration in PPM															
Cr	201	149	17	167	214	137	20	29	49	162	20	15	26	23	
Ni	73	80	39	81	80	53	43	52	52	59	58	59	59	58	
Rb	31	2	142	30	53	10	104	159	82	109	69	180	130	121	
Sr	116	114	144	126	129	159	146	154	270	103	338	144	256	197	
Ba	252	89	128	96	746	190	249	895	791	432	329	1227	340	500	
Sc	39.5	37	3.4	26.2	24.65	25.4	6.2	0.85	8.1	28.3	2.75	2.1	2.85	2.45	
Ta	0.29	0.19	0.18	0.26	0.19	0.32	0.56	0.07	0.52	0.38	0.36	0.23	0.49	0.38	
Nb	2.77	1.58	0.27	0.95	2.25	3.48	6.9	1.8	4.71	3.4	2.92	1.34	2.61	2.87	
Zr	55	32	6	32	63	85	153	240	176	100	107	218	88	97	
Hf	1.52	1.01	0.18	0.94	1.74	2.25	4.25	6.05	4.63	2.76	2.82	5.73	2.53	2.78	
Th	0	0	0	0	0	0	10.9	1.2	14.25	1.1	4.4	19.3	5.15	5.35	
U	0.25	0.2	0	0.1	0.25	0.6	2.7	3.6	2.55	0.75	2.9	4.8	1.55	2.2	
Y	20.8	16.5	1.1	9.15	14.25	19.95	29.55	2.7	18	27.05	3.8	15.9	4.15	4.95	
La	5.5	2.4	0	1.6	2.85	7.05	33.8	4.25	19.25	11.2	13.45	48.3	13.8	11.5	
Ce	14.26	7.895	0.52	5.06	8.01	16.885	74.12	8.995	47.675	23.605	22.825	82.92	23.11	22.94	
Pr	2.04	1.225	0.09	0.765	1.25	2.26	7.695	1.07	4.7	2.94	2.39	8.225	2.565	2.54	
Nd	9.43	6.225	0.44	3.73	6.225	10.14	27.405	3.935	18.135	12.375	8.34	27.875	9.035	9.15	
Sm	2.78	2.085	0.2	1.21	2.155	2.795	5.525	0.935	4.355	3.495	1.6	4.975	1.685	1.955	
Eu	1.01	1.675	0.16	0.68	0.9	1.385	1.135	0.255	2.545	0.92	0.69	1.145	0.73	0.695	
Gd	3.28	2.615	0.24	1.46	2.365	3.315	6.505	0.795	4.405	4.27	1.71	5.515	1.855	1.995	
Dy	4.285	3.775	0.33	1.98	3.175	3.955	6.155	0.61	3.665	6.155	0.935	3.385	0.98	1.16	
Ho	0.905	0.815	0.075	0.42	0.665	0.82	1.23	0.125	0.68	1.33	0.15	0.615	0.16	0.195	
Er	2.73	2.455	0.22	1.255	1.99	2.455	3.845	0.415	2.055	4.025	0.44	1.955	0.48	0.565	
Yb	2.645	2.39	0.22	1.205	1.8	2.27	3.79	0.455	1.925	3.685	0.37	1.77	0.4	0.475	
Lu	0.395	0.355	0.035	0.18	0.255	0.32	0.56	0.07	0.28	0.52	0.055	0.255	0.055	0.07	
Eu/Eu*	1.02	2.19	2.23	1.56	1.22	1.39	0.58	0.9	1.78	0.73	1.28	0.67	1.26	1.08	

is covered by Proterozoic Cuddapah Basin. The strike and dip of the layers are nearly north–south and dip 70° – 85° towards west. The rocks are fine grained, dark green, brown, and black coloured and some exhibit porphyritic texture. Based on field observations these rocks are classified as basalt, basaltic andesite, andesite, dacite, and rhyolite. Pillow structures with cherty layers along the margin of the pillows of the basaltic rocks were found in the field area (figure 2a and b). Quartz veins were seen intruding along the fractures of the felsic rocks (figure 2c). The sharp contact relationships between the mafic and felsic rock types are clearly

observed (figure 2d). One of the basaltic rock sample (sample no. 5A) shows glomeroporphyritic texture with very coarse, tabular, light coloured phenocrysts of plagioclase ranging in size from 1 to 10 cm set in fine grained ground mass (figure 2e). Several layers of banded iron formation (BIF) are also interlayered with volcanic rocks (figure 2f). Hence it is inferred that these basaltic and felsic rocks originated as lava flows that formed under subaqueous (submarine) condition.

The basaltic rocks are mostly fine grained and mainly made up of hornblende and calcic-plagioclase feldspar. X-ray Diffraction (XRD) studies were also

Figure 2. Field photographs of rocks of the Peddavuru greenstone belt exposed along the northern bank of Krishna River. (a) Basalts and basaltic andesites show pillow structure. (b) Cherty layer is seen along the margin of the pillow structure found in basalt. (c) Quartz veins are seen in the felsic volcanic rocks. (d) Sharp contact between basaltic and felsic volcanic rocks is seen in the greenstone belt. (e) Basaltic rocks had undergone seafloor metamorphism which has resulted in formation of light green patches made up of prehnite and chlorite. (f) Banded Iron Formation unit found in between the mafic and felsic rocks in the Peddavuru greenstone belt.

carried out to aid in the mineral identification. The basaltic rock samples, except MV-5A, consist of hornblende and calcic-plagioclase feldspar, whereas, MV-5A contains calcic-plagioclase feldspar, clinopyroxene, sericite, and prehnite. Based on the mineral assemblage in the sample MV-5A and its association with rocks that were formed under submarine condition, it is suggested that this outcrop represents rock that was close to a hydrothermal vent. The felsic volcanic rocks show porphyritic texture with quartz occurring as phenocrysts surrounded by fine grained matrix of quartz and feldspar. Quartz phenocrysts are elliptical in shape indicating partial resorption. All the felsic volcanic rocks show quartz and albite as the major constituents.

3. Analytical methods

From least weathered outcrops of Peddavura greenstone belt exposed along river Krishna 15 samples, around 2–3 kg each, were collected for laboratory studies. Out of these six were basalts and other nine were felsic rocks. Major and trace element analysis was done using Wavelength Dispersive X-ray Florence Spectrometry (WD-XRF) on glass-beads and pressed pellets, respectively at Central Instrumentation Facility, Pondicherry University. USGS standards BHVO-2, BCR-2, AGV-2, SDC-1 were used for calibrating the XRF.

Rare Earth Elements (REE), Nb, Ta, Hf, Th, and U were analysed using ICP-MS (Thermo Scientific X-SERIES 2) at the Department of Earth Sciences, Pondicherry University. About 0.2 g of rock powder was precisely weighed into 7 ml Savillex® vial and HF, HNO₃, and HCl added and

kept in Teflon® lined steel bomb (Parr®) for digestion for three days at 150°C. After drying, the fluorides in the samples were removed by repeated addition of concentrated nitric acid and heated to dryness three times to completely break down fluoride complexes. Finally the samples were dissolved in 5 ml of 2N HCl and made up to 100 ml and a 10 ml aliquot of the solution was taken and dried and passed through the cation exchange column (HCl) to separate Rare Earth Elements (REE) from the other elements. A series of REE multielement standard solutions containing 0.4–21 ppb of each REE were used for calibration of the ICP-MS. USGS standards AGV-2 and BCR-2 were digested and REE separated and used as reference to monitor accuracy of analysis. Isobaric interferences on heavier REEs were corrected using procedure given in Rajamanickam and Balakrishnan (2013). Trace element abundances on chondrite and primitive mantle given by Sun and McDonough (1989) were used for normalizations.

Rb–Sr and Sm–Nd isotope analysis was carried out using HCl and HDEHP ion exchange columns following separation method outlined in Anand and Balakrishnan (2010). The Sr and Nd isotopic ratios were measured using the Thermal Ionisation Mass Spectrometer (TRITON, Thermo-Finnigan) at the Department of Earth Sciences, Pondicherry University. In the course of work, Sr and Nd isotope standards SRM-987 and AMES were analyzed repeatedly and their average ⁸⁷Sr/⁸⁶Sr and ¹⁴³Nd/¹⁴⁴Nd ratios were 0.710261 ± 8 ($n = 33$) and 0.511969 ± 7 ($n = 31$) respectively. The reported values for Sr and Nd were 0.710240 and 0.511969, respectively, and hence ⁸⁷Sr/⁸⁶Sr ratios alone were corrected by subtracting 0.000021 from the measured values.

Figure 3. Total alkali vs. silica (TAS) diagram of Le Maitre *et al.* (1989) with samples from Peddavuru greenstone belt plotted. Basalts, basaltic andesites and andesites (BBA) form one group while dacites and rhyolites form another group.

4. Result

4.1 Major and trace elements

Major and trace element abundances of metavolcanic samples of the Peddavura greenstone belt (table 2) show a wide range and are plotted in total alkali ($\text{Na}_2\text{O} + \text{K}_2\text{O}$) vs. SiO_2 diagram (figure 3) of Le Maitre *et al.* (1989) to classify them. One sample falls in basalt, two in basaltic andesite, three in andesite, one in dacite, and eight in rhyolite fields.

The dacite sample also plots close to the field of rhyolite and hence all felsic volcanic rocks are considered as rhyolite. The basalt, basaltic andesite, and andesite (BBA) can be considered as a group and there is a significant gap in SiO_2 content (10%) between this group and rhyolites. Basaltic andesite samples MV-5A and MV-5B were collected from the same location, but MV-5A represents more altered part of the basaltic andesite outcrop. It shows much higher Al_2O_3 , K_2O , Rb, Sr, and loss on ignition (4.61%) and lower FeO, MgO, Cr, Ni, Sc,

Figure 4. Chondrite normalized REE patterns of the BBA group and rhyolites from the Peddavura greenstone belt, Eastern Dharwar Craton. (a) BBA group shows flat to slightly LREE enriched REE patterns with positive Eu anomaly. MV-5A is an altered sample showing very low concentration of REE with positive Eu anomaly compared to the other samples of BBA group. (b) Rhyolites show two types of REE patterns, type I is enriched in HREE with higher REE abundances and type II is HREE depleted and fractionated.

Zr, Y, and REE compared to MV-5B. Interestingly alkali and large ion lithophile elements K, Rb, Sr, and Ba are all enriched in MV-5A and this could be attributed to seafloor hydrothermal alteration.

The basalt, basaltic andesites and andesite (BBA) group are characterised by SiO_2 : 50.32–56.28 wt%, TiO_2 : 0.49–1.02 wt%, Fe_2O_3 : 7.65–13.63 wt%, MgO : 4.28–6.05 wt%, Al_2O_3 : 13.25–15 wt% and $\text{Mg\#}$: 29.89–40.1 (table 2). MgO , Fe_2O_3 , CaO , Al_2O_3 are negatively correlated with SiO_2 , whereas, K_2O shows positive correlation. BBA group yields light REE enriched to nearly flat chondrite normalized REE patterns with REE abundances ranging from 8X to 20X that of

chondrite (figure 4a) La_N/Yb_N ratios range from 0.72 to 2.23 with positive Eu anomaly. In multi-element diagram the BBA group of samples shows distinct negative Nb anomaly and much higher enrichment of Ba, Rb, and U compared to neighbouring elements (figure 5a).

The rhyolites are characterised by SiO_2 : 66.53–74.60 wt%, TiO_2 : 0.14–1.09 wt%, Al_2O_3 : 10.33–13.28 wt%, Fe_2O_3 : 1.27–4.18 wt%, MgO : 0.92–2.45 wt%, $\text{Mg\#}$: 29.5–50.0. Rhyolites normalized to primitive mantle show less Ba compared to Rb, less Th compared to Rb and U and Nb negative anomaly, and both positive and negative Sr anomalies in multi-element diagram (figure 5b). Negative

Figure 5. Primitive mantle normalized multi-element patterns for the samples of Peddavura greenstone. (a) Samples of BBA group show negative Nb anomaly. (b) Rhyolites of type I and type II are showing variable abundances of trace elements with negative Ba, Th and Nb anomalies and negative and positive anomalies of Sr.

and positive Sr anomalies in rhyolites are possibly due to fractional crystallization or accumulation of feldspar.

A wide range in REE enrichment, heavy REE depletion, and LREE and HREE fractionation with (La_N/Yb_N) ratios ranging from 2.18 to 26.07 is observed in rhyolites (figure 6a). Based on (La_N/Yb_N) and (Gd_N/Yb_N) ratios they were considered to form two types (figure 6b), type I has lower (La_N/Yb_N) and (Gd_N/Yb_N) ratios than type II rhyolites (figure 6b). Both types of rhyolites show minor positive and negative Eu anomalies (figure 4b). Higher extent of HREE fractionation ($Gd_N/Yb_N > 2.5$) observed in type II rhyolites could be a result of their magma equilibrated with residue consisting of significant fraction of garnet.

4.2 Rb–Sr and Sm–Nd isotope systems

The Rb–Sr and Sm–Nd isotope analyses are given in table 3. When BBA group and rhyolites of Peddavura greenstone belt were plotted in the Rb–Sr isochron diagram, they show considerable scatter (figure 7a). The rhyolites are highly scattered and show little correlation in the Rb–Sr isotope evolution diagram. Samples of BBA group, except MV-5B and the altered sample MV-5A define a collinear array in the Rb–Sr isochron diagram (figure 7b) which corresponds to an age of 2551 ± 19 Ma (MSWD = 1.16). It may be noted that samples MV-5A and MV-5B were collected from the same outcrop that was inferred to have been close to a hydrothermal vent. These four samples do not show any correlation when plotted in $1/Sr$

Figure 6. (a) The two types of Peddavura rhyolites are distinctly grouped with variable REE abundance and La_N by Yb_N ratio. (b) The type I rhyolites have low $(La/Yb)_N$ ratios while type II have distinctly higher ratios. Magmas representing type II rhyolites equilibrated with a residue consisting significant proportion of garnet.

Table 3. Rb–Sr and Sm–Nd data of the Peddavura Basalt, Basaltic Andesite and Andesite (BBA group) and Rhyolites..

Sample name	Rb(ppm)	Sr(ppm)	$^{87}\text{Rb}/^{86}\text{Sr}$	$^{87}\text{Sr}/^{86}\text{Sr}$ (± 2 Sigma $\times 10^{-6}$)	$^{147}\text{Sm}/^{144}\text{Nd}$	$^{143}\text{Nd}/^{144}\text{Nd}$ (± 2 Sigma $\times 10^{-6}$)	T_{DM}	$f_{\text{Sm}/\text{Nd}}$	$\varepsilon^{2600}\text{Nd}$	$\varepsilon^{2600}\text{Sr}$
BBA group										
MV-2	47	138	0.9801	0.737211 ± 9	2.7	0.512268 ± 4	3322	-0.12	0.5	-15
MV-4	5	133	0.1059	0.705291 ± 8	1.9	0.512707 ± 5	4783	0.02	0.3	-2
MV-5A	194	95	5.9693	0.793813 ± 18	0.4	0.512533 ± 8	5356	0.00	-2.0	-1884
MV-5B	54	139	1.1277	0.730749 ± 10	1.3	0.512644 ± 5	3767	-0.02	1.2	187
MV-10/2	78	131	1.7375	0.765512 ± 10	2.4	0.512506 ± 4	4425	-0.03	-0.9	-18
MV-11/2	19	219	0.2533	0.710621 ± 8	3.3	0.512069 ± 4	3438	-0.16	-0.9	-5
Rhyolite										
MV-1	69	338	0.1592	0.709866 ± 10	1.0	0.511152 ± 7	2842	-0.45	1.0	35
MV-3	104	146	2.1886	0.80915 ± 16	6.6	0.511295 ± 5	3002	-0.39	-0.6	362
MV-6	159	154	4.3059	0.728229 ± 12	5.2	0.510927 ± 6	3005	-0.48	-1.6	-1927
MV-7	180	144	12.1239	0.834677 ± 9	5.4	0.510843 ± 6	2941	-0.52	-1.0	-4601
MV-8	82	270	0.5539	1.023596 ± 12	4.9	0.511315 ± 4	3598	-0.31	-5.7	4296
MV-10/1	130	256	0.6618	0.734834 ± 9	1.9	0.511151 ± 6	2818	-0.46	1.3	121
MV-11/1	121	197	1.8392	0.741163 ± 6	1.7	0.511277 ± 5	2811	-0.43	1.5	-420
MV-12	43	225	0.55341	0.726299 ± 8	3.7	0.512065 ± 4	3449	-0.3553	-0.9	58
MV-13	105	256	1.1194	0.724018 ± 9	0.9	0.511371 ± 4	3224	-0.34	-2.5	-278

vs. $^{87}\text{Sr}/^{86}\text{Sr}$ and hence, the correlation in Rb–Sr isotope evolution diagram is not due to two component mixing (figure 7c). The initial $^{87}\text{Sr}/^{86}\text{Sr}$ ratio of BBA group is 0.70128 ± 27 which corresponds to mantle sources.

In Sm–Nd isochron diagram Peddavura volcanic samples were plotted (figure 8a). The BBA group and rhyolites plot as two separate groups with a distinct break. The combined slope corresponds to an imprecise age of 2621 ± 250 Ma (MSWD = 1611) (figure 8a). The samples of BBA group and rhyolites were derived from different sources, they would have had different initial Nd isotope ratios at the time of their formation and therefore, this age has no geological significance. Samples of BBA group when plotted separately yield an errorchron corresponding to 2782 ± 860 Ma (MSWD = 405) (figure 8b) which could not be treated as a reliable age due to large uncertainty.

5. Petrogenesis

The petrogenesis of volcanic rocks can be understood through quantitative modelling of major and trace elements and initial $^{87}\text{Sr}/^{86}\text{Sr}$ and $^{143}\text{Nd}/^{144}\text{Nd}$ ratios. Predominantly, at low grade metamorphism the HFS elements and REE are immobile. However, during extreme level of alteration the REE are leached by the carbonate-rich and K-rich metasomatic fluids. Rb and Ba are mobilized to a lesser extent during alteration while Sr is mobile at all levels of alteration (Ludden *et al.* 1982). The major elements, REE, and other trace element data are basis for modelling the formation of the crust by partial melting of basalts and mantle sources at various pressures and fluid contents (Shirey and Hanson 1986). Archaean rocks are invariably metamorphosed and some trace elements may have been mobilized from these rocks. The rocks of the Peddavura greenstone belt were subjected to upper greenschist facies metamorphism. Hence, abundance of least mobile elements such as, Ti, Al, Mg, Fe, REE, and other HFSE abundances may not have been changed significantly except in sample MV-5A. These least mobile elements were utilized to model extent of melting and to understand the nature of sources for the BBA group of rocks and rhyolites of the Peddavura greenstone belt.

5.1 BBA group

O'Hara (1968) constructed a phase diagram in the form of tetrahedron with $\text{CaO-MgO-Al}_2\text{O}_3\text{-SiO}_2$ (CMAS) as the components. Takahashi and Kushiro (1983) carried out experiments on

Figure 7. (a) All samples BBA group and rhyolites of Peddavura greentone belt were plotted in Rb–Sr isotope evolution diagram and they are highly scattered. (b) The samples of BBA group, except the altered samples MV5A and MV5B, define a colinear array in Rb–Sr isotope evolution diagram which corresponds to an age of 2551 ± 19 Ma (MSWD = 1.16). (c) Samples of BBA group do not show any mixing trend in the $1/\text{Sr}$ vs. $^{87}\text{Sr}/^{86}\text{Sr}$ plot.

melting of dry peridotite at various pressures and provided major element composition of melts generated. For these melt compositions, C, M, A, and S values calculated and plotted into the plane of C_3A –M–S projected from diopside to represent melt compositions generated at the respective pressures (Rajamani *et al.* 1993). Similarly, basaltic samples of Peddavura greenstone belt were plotted in the CMAS projection (figure 9) and they fall in the pressure range of 0–1 GPa. Thus magma representing the BBA group might have been generated at depths <30 km (figure 9).

Samples of the BBA group are variably enriched in Ba, Rb, and U and markedly depleted in Nb and to lesser extent in Y relative to the neighbouring elements in the primitive mantle normalized plot (figure 5a). Negative Nb anomaly is considered as a characteristic feature of subduction zone magmatic rocks (Polat and Kerrich 2001b). Multi-element plots of the BBA group of rocks are similar to basalts and basaltic andesites of Tocopilla (221S), North Chilean Coastal Cordillera, and Kermadec Arc reported by Kramera *et al.* (2005), Maurice *et al.* (2012) and Ewart *et al.* (1977) (figure 10). Hence, magmas representing the BBA group of Peddavura greenstone belt could have formed in island arc type tectonic settings.

The samples of BBA group, except MV-2, show variable positive Eu anomaly in chondrite normalized REE patterns (figure 4a). On fractional crystallization of plagioclase, residual magma will be depleted in Eu and display a negative Eu anomaly, whereas, if magma accumulates plagioclase then positive Eu anomaly will be found. If the magma undergoes fractional crystallization of pyroxene, then the residual magma will have positive Eu anomaly. Plagioclase accumulation will result in increase in Sr and pyroxene fractional crystallization will lead to depletion of Ni and Cr in the magma. The sample MV-2 does not show any Eu anomaly whereas samples MV-5B, MV-10/2, and MV-11/2 have higher Sr abundances, as well as, show positive Eu anomaly. Hence, plagioclase accumulation could have caused positive Eu anomaly in these samples. The sample MV-4 shows lower Cr than MV-2 and this sample could represent residual magma formed after fractional crystallization of pyroxene.

Ni and Zr abundances in basaltic magmas formed by different extents of partial melting and fractional crystallization were modelled using mass balance equations (Hanson 1978). Low extents of partial melting (up to 20%) of primitive mantle with 2000 ppm Ni and 7.8 ppm Zr will result tholeiitic magma having about 82–194 ppm Ni (Rajamani *et al.* 1985). Whereas, Peddavura BBA group has 39–81 ppm Ni and hence may not represent magma derived from the partial melting of

Figure 8. (a) All Peddavura greenstone belt samples consisting of BBA group and rhyolites were plotted in the Sm–Nd isotope evolution diagram where they plot as two separate groups. (b) BBA group of rocks in the Peddavura greenstone belts show a large scatter in the Sm–Nd isotope diagram.

Figure 9. The BBA group of Peddavura greenstone belt samples were plotted in the CMAS. They fall in between 1 and 10 k bar pressure.

Figure 10. Samples of BBA group of Peddavura greenstone belt were compared with similar rock types formed in island arc tectonic settings, basaltic andesite of the Tocopilla (221S), North Chilean Coastal Cordillera and Kermadec Arc after Kramera *et al.* (2005), Ewart *et al.* (1977). The multi-element patterns of the BBA group are matching with the grey shaded region defining the above island-arc volcanic rocks.

the primitive mantle (figure 11). Samples of the BBA group show a wide variation in Zr and Ce contents but less variation in Ni content. This variation could be explained as a result of different extents of partial melting of a mixed source. Mantle wedge containing 80% primitive mantle and 20% of island arc basalts with Ni and Zr contents of 1612 and 16.6 ppm, respectively is assumed as the source and trace element concentrations in melts formed by different extents of melting (0–100%) was calculated and plotted in figure 11. Comparing the Zr abundance in MV-2, MV-10/2, and MV-11/2 it is inferred that they formed by 15–30% partial melting of the mixed source (80% primitive mantle and 20% of island arc basalts) leaving 60% olivine, 20% clinopyroxene, and 20% orthopyroxene in a residue. The samples MV-4 and MV-5B have lowest Zr content and may represent magmas that were generated by higher extent of partial melting, ~40%. Alternatively, their magma could have been generated from a source highly depleted in Zr. The olivine only fractional crystallization has been plotted in the same diagram. Magmas representing BBA group could have undergone 5–10% fractional crystallization of olivine from their parent magmas (figure 11). Samples MV-4 and MV-5B represent magmas that had undergone olivine fractional crystallization to similar extents.

REE abundances in magmas that represent different extents of partial melting of mixed mantle sources consisting of primitive mantle and island arc basalt was considered. It was assumed that on partial melting the melt equilibrated with residue consisting of 50% olivine, 30% clinopyroxene, and 20% orthopyroxene. Chondrite normalized REE pattern of the Peddavuru basalts compare well with the calculated ones (figure 12) and therefore,

it is suggested that the magmas representing BBA group were formed by 5–20% partial melting of the mixed sources, usually found in the mantle wedge above the subducting slab.

5.2 Rhyolites

Strong depletion of Nb, Sr, Ta, and Y indicates that the rhyolites of Peddavura greenstone belt might have been formed in island arc tectonic setting. Mostly, the felsic magmas with high silica content could have been formed by partial melting of basalt or basaltic andesite. Based on chondrite normalized REE patterns and LREE and HREE fractionation, the rhyolites of the Peddavura greenstone belt have been grouped into type I which is fractionated to lesser extent than rhyolite type II (figure 6).

Partial melting of the Peddavura BBA group (sample no. MV-11/2) with the residue of 58% olivine + 25% clinopyroxene + 17% amphibole produced magma which is similar to the rhyolite type I of the Peddavura greenstone belt (figure 13a). Magmas representing rhyolite samples (type I) with lower REE abundances could have been generated by partial melting of basaltic samples with low REE abundances, such as, MV-5B (figure 13a) leaving residue consisting of orthopyroxene 21%, clinopyroxene 27%, amphibole 25%, and plagioclase 27%. Magma of rhyolite composition can be also generated by partial melting or assimilation of TTG suite of rocks as shown by Rapp *et al.* (1991). Hence, modelling of partial melting of a mixed source of 20% Champion gneiss and 80% of MV-11/2 basaltic andesite has been carried out to estimate REE contents in magma thus generated. The results of the modelling show

Figure 11. Samples of BBA group are plotted along with the calculated paths of melting Ni and Zr contents of mixed source (80% Primitive mantle and 20% of Island arc basalts) with 1612 and 16.6 ppm, respectively (Sun and McDonough 1989). Magmas representing Peddavura BBA group MV-2, MV-10/2, and MV-11/2 were formed by 15–30% partial melting of mixed source leaving 60% olivine, 20% clinopyroxene and 20% orthopyroxene in residue. Comparison with the olivine fractional crystallization trends suggest that magmas representing BBA group were formed by 5–10% crystallization of olivine from their parent magmas.

Figure 12. Partial melting of the IAB and primitive mantle in equal proportion from 1% to 20% melting leaving a residue consisting of 50% olivine, 30% clinopyroxene and 20% orthopyroxene. Magmas compositionally similar to BBA group samples could have been formed by the 5 to 20% partial melting of mixed source made up of IAB and Primitive mantle.

that chondrite normalized REE pattern of rhyolites of Peddavura are similar to those modelled for partial melting of mixed sources leaving 37% orthopyroxene, 29% clinopyroxene, 12% amphibole, and 22% plagioclase in the residue (figure 13b). Thus magmas parental to rhyolites can be generated by either partial melting of basaltic rocks or a mixed source made up of Archean continental crust predominated by TTG and basaltic rocks.

Assuming different extents of partial melting of source similar in composition to basaltic andesite (sample no. MV-11/2) leaving a residue consisting

of 47% orthopyroxene, 15% amphibole, 11% garnet, and 28% plagioclase produced magma similar to the type II rhyolites of Peddavura greenstone belt (figure 13c). Hence, magma representing Peddavura type II rhyolites could have been formed by partial melting of sources compositionally similar to the basaltic andesites. Presence of about 10% garnet in the residue indicates that melting had taken place at pressures where garnet can occur as a stable phase, and such conditions are possible close to subduction zone. Magmas representing type I rhyolites unlike that of type II rhyolites did

Figure 13. **(a)** Partial melting of the basaltic andesite (sample MV-11/2) from 0% to 28% leaving a residue consisting of 58% olivine+25% clinopyroxene+17% amphibole matches with high REE patterns of the Peddavuru rhyolite type I and low REE patterns of the rhyolite were formed by the partial melting of the MV-5B (BBA group) with a residual composition of 27% clinopyroxene, 21% orthopyroxene, 25% amphibole, and 27% plagioclase. **(b)** Partial melting of the mixed source of 20% Champion gneiss and 80% of the basaltic andesite (MV-11/2) from 0% to 27% leaving a residual composition of 29% clinopyroxene, 37% orthopyroxene, 12% amphibole, and 22% plagioclase also results in REE patterns that match with that of type I rhyolites. **(c)** Partial melting of the Peddavura basaltic andesite (sample MV-11/2) from 0% to 27% leaving a residue consisting of 47% orthopyroxene, 15% amphibole, 11% garnet and 28% plagioclase matches with REE patterns of the Peddavuru rhyolite type II.

not equilibrate with garnet and thus the depth of melting must have been much shallower compared to that of type II rhyolites.

Rhyolites do not yield an isochron in the Rb–Sr isotope evolution diagram due to large scatter. This scatter may be due to low temperature alteration, because the Rb–Sr system could not remain as completely closed system even at low temperatures. In rhyolites, Rb–Sr isotope system was not completely reset, rather it was partially reset, therefore does not yield isochron in the Rb–Sr isotope evolution diagram.

However, four samples of BBA define an isochron (figure 7b) in Rb–Sr isotope evolution diagram which is not due to mixing as evidenced from scatter observed in $1/\text{Sr}$ vs. $^{87}\text{Sr}/^{86}\text{Sr}$ diagram (figure 7c). This could be explained if the Rb–Sr isotope system was completely reset during this low temperature seafloor metamorphism of the BBA group of rocks as evidenced from petrographic observations. Samples MV-5A and MV-5B collected from an outcrop that was close to hydrothermal vent also had Rb–Sr system reset but with initial $^{87}\text{Sr}/^{86}\text{Sr}$ ratio different from other samples of BBA group and therefore are not collinear with them in the isochron diagram. Hence, the Rb–Sr isochron age of 2551 ± 19 Ma (MSWD = 1.16) potentially corresponds to time of resetting of Rb–Sr isotope system in BBA during seafloor metamorphism.

The initial ratio obtained is also similar to the depleted mantle sources at 2551 Ma ago. It is possible that the BBA volcanic rocks might have undergone seafloor metamorphism soon after their formation as they exhibit pillow structures and are interlayered with banded ferruginous chert. Seafloor metamorphism occurs relatively close to either mid-ocean ridge along axial zone or submarine volcanic centres where hot volcanic rocks interact with seawater (Honnorez 2003; Terabayashi *et al.* 2003). The seafloor metamorphism must have taken place within few million years after eruption before the rocks became cold ($<100^\circ\text{C}$). Therefore, the Rb–Sr isochron age of 2551 ± 19 Ma could represent time of crystallization of BBA group of rocks, assuming that the Rb–Sr isotope system was reset during seafloor metamorphism.

The above Rb–Sr age is the only precise age available on the rocks of the Peddavura greenstone belt and similar ages were reported from other greenstone belts of the EDC by several workers. Jayananda *et al.* (2013) obtained a less precise 2.4 Ga U–Pb age based on Secondary Ion Mass Spectrometry (SIMS) analysis of zircons from a rhyolite of Peddavura. The Rb–Sr age obtained from the Peddavura greenstone belt volcanic rock were similar to the felsic volcanic rocks from the

Hutti greenstone belt that have U–Pb zircon age of 2587 ± 7 Ma (Sarma *et al.* 2008), SIMS U–Pb age of 2569 ± 13 Ma (Jayananda *et al.* 2013) and SHRIMP age of 2586 ± 56 Ma and 2543 ± 9 Ma (Roger *et al.* 2007). Jayananda *et al.* (2013) reported similar SHRIMP zircon age of 2554 ± 10 Ma for felsic volcanic rocks (Champion Gneiss) from Kolar greenstone belt, and SHRIMP zircon age of 2556 ± 13 Ma for felsic volcanic rocks of Kadiri greenstone belt.

Sm–Nd isotope system does not yield any age for both BBA group and rhyolites due to the large scattering. This scatter could be attributed to source heterogeneity in terms of initial Nd isotope composition which, unlike Sr isotope, could not be obliterated during the seafloor metamorphism. To understand the source characteristics, initial $^{87}\text{Sr}/^{86}\text{Sr}$ and $^{143}\text{Nd}/^{144}\text{Nd}$ ratios were calculated for an age of 2600 Ma. ε_{Nd} values were calculated using the equation after DePaolo and Wasserburg (1976).

The BBA group of Peddavuru greenstone belt showing small variations in ε_{Nd} values could be a result of heterogeneity in their sources with respect to initial Nd isotope composition. Fluids and melts generated at subduction zone move upward and add to overlying mantle wedge. Such additions could have involved Nd and Sr derived from old continental crust. The samples MV-10/2 and MV-11/2 have negative ε_{Nd} suggesting long term enrichment of LREE in the source. The positive ε_{Nd} for the three basalt samples suggest the long term LREE depletion of the source of their magma. Whereas, the negative $f_{\text{Sm}/\text{Nd}}$ values indicate enrichment of LREE in the magma due to low extents of partial melting of the LREE depleted sources as suggested based on trace element modelling (figure 9) which resulted in lower Sm/Nd ratios than the CHUR. No evidence of old continental crustal contamination to significant levels of magmas represented by BBA is found (figure 14).

The Rb–Sr isotope system in BBA group of rocks and rhyolites has been disturbed to various extents. Seafloor hydrothermal alteration has totally reset the Rb–Sr isotope system in four samples of the BBA group MV-2, MV-4, MV-10/2, and MV-11/2 which form a collinear array in Rb–Sr isotope evolution diagram (figure 7b), whereas, other samples do not show any correlation in the above diagram (figure 7a). This could have been as a result of partial resetting of the Rb–Sr isotope system in these rocks. For example, if Rb is gained and/or Sr is lost, much after its formation, the sample will show unrealistically low Sr initial ratio. Alternatively, if Rb was lost and/or Sr is gained, after formation, that will result in low Rb/Sr ratio and $^{87}\text{Sr}/^{86}\text{Sr}$ initial ratio much higher than what was originally

Figure 14. Epsilon Nd ($t = 2600$ Ma) *vs.* $f_{\text{Sm/Nd}}$ plots for the BBA group and rhyolites from the Peddavuru greenstone belts. Samples of BBA group do not define crustal contamination trend and their magmas could have been derived from LREE depleted to enriched mantle sources. Some of the BBA samples are slightly enriched in LREE, resulting in negative $f_{\text{Sm/Nd}}$ values, as a result of low extents of partial melting. The rhyolites plot along a mixing line between primitive magma and Champion gneiss. The magmas that represented the rhyolites were contaminated from 20 to 40% by continental crust similar to granitoid gneiss inclusions in the Champion gneiss except sample number MV-8 which has $\sim 80\%$ crustal contamination or their sources had significant proportion of Mesoarchean evolved continental crustal component.

present in the sample. Partial exchange of extraneous Sr with different isotope composition with the samples could have also taken place. In view of this, the Rb–Sr system is not useful in understanding the petrogenesis of these rocks.

Melts, representing the rhyolites, if generated by partial melting of a source similar to basaltic andesite should have inherited Nd isotopic ratios similar to the source. However, the initial ratios of type I rhyolites are negative, unlike the basaltic andesite source, indicating assimilation of older continental crust by the magma or contamination of the source (figure 14). Partial melting of the mixed source (80% basaltic andesite and 20% champion gneiss) composition will produce negative $f_{\text{Sm/Nd}}$ value similar to that of these rhyolites and variable involvement of Mesoarchean upper continental crustal rocks similar in composition to the Champion Gneiss ($\varepsilon_{\text{Nd}} \leq -7$; >3.3 Ga) in generation of magmas representing type I rhyolites is suggested. The MV-8 has high negative ε_{Nd} value (-5.7), which suggests that magma representing this sample might have been formed by partial melting of mixed source with about 80% contribution from Champion Gneiss and 20% from basaltic rock. The other samples of MV-3 were also formed by partial melting of a mixed source of subducting basaltic rocks and Champion gneiss which can explain their Nd isotope characteristics (figure 14).

Whereas, type II rhyolites show ε_{Nd} values ranging from $+1.5$ to -1 and thus their magmas could have been derived from short-lived basaltic sources similar to the BBA group that were derived from mantle sources. Therefore, it appears that both types of rhyolites of Peddavura may have originated by partial melting of basaltic andesites similar to the BBA group at different depths, however, type I rhyolites sustained higher crustal contamination/assimilation compared to the type II rhyolites.

Bidyananda *et al.* (2011) have also found evidences for existence of granitic gneisses of Mesoarchean age based on Pb–Pb isotope studies on zircon from EDC. Similarly, Jayananda *et al.* (2013) also reported evidence of older (3.3 Ga) continental crust from the Kolar and Kadiri greenstone belt based on SHRIMP U–Pb isotope studies on zircons.

Available geochronological data of the EDC (table 1) indicates that the ultramafic and mafic rocks are older than the felsic volcanics occurring in various greenstone belts such as Sandur, Ramagiri, Hutti, and Kolar. The age of the meta basalts is ca. 2700 Ma whereas, the age of felsic volcanics ranges from 2697–2543 Ma. The greenstone belts that occur in western part of the EDC consist of dominantly tholeiitic rocks and subordinate amount of komatiites and felsic volcanic rocks. Whereas those in the eastern part

of EDC dominantly consist of high-Mg andesite, boninites, andesite, dacites, rhyolites and komatiites are not reported from these greenstone belts. The compositional variations of rocks present in the greenstone belts from west to east of the EDC could be related to tectonic settings. The mafic and ultramafic rocks of the Ramagiri, Hutti, and Kolar may have formed in oceanic island arc setting (Balakrishnan *et al.* 1990, 1999; Krogstad *et al.* 1991; Zachariah *et al.* 1996; Anand and Balakrishnan 2010) and these rocks occurring in greenstone belts in the eastern part of EDC could have been formed in continental arc setting. Felsic volcanic rocks from this greenstone belt also exhibit evidences for significant involvement of old continental crust, which supports their origin in continental arc setting. The difference in tectonic settings could either reflect maturing of arc with time during a single protracted subduction event, or could mean simultaneous presence of distinct micro-terranes which later got juxtaposed together.

Plate tectonic style of continental growth during Neoarchean was proposed by Krogstad *et al.* (1989) based on geochemical and geochronological studies of a Kolar schist belt and adjacent granitoid rocks. Balakrishnan *et al.* (1999) and Anand and Balakrishnan (2010) suggested that greenstone-granite terrain in eastern Dharwar craton was assembled by plate tectonic processes. Whereas, Jayananda *et al.* (2000) suggested that geochemical and geochronological features of granites of Closepet in EDC could be explained by mantle plume. However, it has been recognised that komatiite and high-Mg tholeiites could have been formed by plume activity. The major rock types such as basalts, basaltic andesites, dacites, rhyolites, adakites reported from greenstone belts of EDC were formed by subduction processes (Kerrick and Manikyamba 2012; Manikyamba and Kerrich 2012; Sukanta Dey 2013; Ram Mohan *et al.* 2013). More precise geochronological data from different greenstone belts are required to have a better understanding of the evolution the Dharwar Craton with time.

6. Conclusion

The presence of pillow structure, Banded Iron Formation (BIF) and cherty layers along with basalt, basaltic andesite and andesite (BBA) group of rocks indicates that they were formed under submarine condition. Major and trace element abundances show a bimodal distribution with basalt, basaltic andesite, andesite (BBA) forming a group and rhyolite another group. Rb–Sr whole-rock isochron age

of 2551 ± 19 Ma for BBA group of rocks represents timing of seafloor metamorphism event which could have occurred soon after the formation of these rocks. Magmas parental to the BBA group of rock were formed by partial melting of mixed source consisting of primitive mantle and island arc basalts. These magmas had undergone small extents of olivine fractional crystallization. Type-I rhyolites were formed by partial melting of mixed sources made up of basalts and oceanic sediments at shallow depths where garnet is not stable. Type-II rhyolites were formed by partial melting of the basaltic andesite and these magmas were contaminated with older, Mesoarchean continental crustal rocks, such as, granitoid gneiss inclusions in Champion gneiss and banded gneisses from the Kolar greenstone belt. Thus the rocks of the belt preserve evidences for existence of >3.3 Ga old continental crust in the eastern parts of the Dharwar Craton.

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