Chapter-2

GEOLOGICAL FRAMEWORK AND ANALYTICAL METHODS

2. 1. Geological Framework

2.1.1 General Description of the Vindhyan Supergroup

The Vindhyan Supergroup of rocks, deposited in the Vindhyan Basin, cover an aerial extent of ~ 178,000 km^2 (Tandon et al., 1991) spreading from Sasaram (Bihar) along the Son river Valley in the east to Chittorgarh, Kota, Bundi, Sawai Madhopur districts of Rajasthan in the west (Fig. 2.1). It is believed that about 78,000 km^2 of the area is concealed under Deccan Traps, and even a larger area is thought to be lying under the Indo-Gangetic alluvium (Venkatachala et al., 1996). The rocks of the Vindhyan Supergroup overlie unconformably on ~2500 Ma old basement rocks, which include the Bundelkhand Granite, the Bijawar Group, and the Berach Granite (Crawford and Compston, 1970; Mondal et al., 2002, Weidenbeck et al., 1996). The Bundelkhand craton (3.3-2.5 Ga; Mondal et al., 2002), located near the north-central margin of the basin, appears to divide the Vindhyan Basin into two parts: the eastern sector (Son Valley) and the western sector (Rajasthan). A geological map of the Vindhyan Basin, modified after Chakraborty et al. (2010), is given in Fig. 2.1.

In its present configuration, the Vindhyan Basin is bounded to the west by the Aravalli-Delhi orogenic belt (2500-900 Ma; Roy, 1988), to the south by the Satpura orogenic belt (1600–850 Ma; Verma, 1991) and to the east by the low-grade metamorphic rocks of the Mahakoshal Supergroup (2400 Ma; Das et al., 1990) and the Bijawar Supergroup (2100 Ma; Roy and Bandyopadhyay, 1990). The Son-

Narmada lineament (Fig. 2.1) marks the southern tectonic boundary of the Vindhyan Basin. It is believed that this tectonic structure came into existence during the Archean and has remained active throughout its geologic past (Naqvi and Rogers, 1987, Kaila et al., 1989). Further south of this lineament a southerly dipping reverse fault separates the Vindhyans from the Satpura mobile belt (Tewari, 1968, Rogers, 1986). This fault appears to have generated deformations in the sedimentary rocks occurring immediately to its north in the Son Valley, however, these deformations are untraceable to the west, which might be due to the cover of younger rocks (Rogers, 1986). It is believed that the mountain building activity in the Satpuras was underway during the early phases of deposition in the Vindhyan Basin and that at a later stage the folded rocks of the Satpuras were transported onto the Vindhyans (Radhakrishna and Naqvi, 1986, Narain, 1987, Naqvi and Rogers, 1987).

The Great-Boundary Fault (GBF) at the western margin, in Rajasthan, roughly separates the Vindhyans from the Archean/Paleoproterozoic Aravalli/Delhi Fold belt (Fig. 2.1). The strike-length of this fault is over 400 kilometers. Although it was earlier believed that the GBF was purely a pre-Vindhyan fault (Fermor, 1930, Iqbaluddin et al., 1978 and Banerjee and Singh, 1981) that bounded the Vindhyans from the pre-Vindhyan rocks (Murthy and Mishra, 1981, Kaila and Krishna, 1992), there exist ample field evidences which clearly suggest that it had numerous reactivations subsequent to the deposition of the Vindhyans (Sinha-Roy et al., 1986, Srivastava and Sahay, 2003). According to Verma (1996) the GBF started as a normal fault sometime around 2500 Ma and acquired a reverse geometry during the Delhi orogeny, ~1400 million years ago.

The Vindhyan rocks are largely undisturbed, or have gentle dips (~5°), however, deformation features are not uncommon in lower Vindhyans in western and southern margins (Naqvi and Rogers, 1987). The geometry of the basin is in the form of a gentle synclorium with the axis parallel to the arcuate thrust faults, which plunge to the west (Chakraborty and Bhattacharyya, 1996). The sedimentary successions of the Vindhyan Basin consist mostly of unmetamorphosed siliciclastic

and carbonate lithologies adding up to a total thickness of 4 km (Prasad 1984, Venkatachala et al., 1996). These rocks are generally believed to be of marine origin, which were deposited in an elongated basin striking East-West and was open to the west (Banerjee, 1974, Chanda and Bhattacharyya, 1982). Both shallow and deep water deposits are common in the basin. The Vindhyan Supergroup is divided into four groups, viz., the Semri, the Kaimur, the Rewa and the Bhander (Table 2.1; Prasad 1984; Sastry and Moitra, 1984; Soni et al., 1987). Each group is further subdivided into formations and members (Table 2.1). The Semri Group of rocks is generally known as the Lower Vindhyans, whereas the other three groups represent the Upper Vindhyans. Typical lithostratigraphic columns of the Vindhyans in the Son Valley and in Rajasthan are presented in Fig. 2.2. The Vindhyan Supergroup does not record any major igneous activity during its deposition except for some minor acidic volcanisms and volcaniclastic deposits related to them (see Venkatachala et al., 1996 and references therein).

The siliciclastic formations of the Vindhyan Supergroup are usually sandstone, shale, and minor conglomerate and volcaniclastic deposits. The carbonate formations (limestones and dolostones) are dominant in the Semri Group and in the Bhander Group. The rocks of the Vindhyan Supergroup in the Son Valley and in Rajasthan are believed to be laterally correlatable (see Table 2.1 and Bhattacharyya, 1996). A major regional unconformity is located between the Lower Vindhyans (Semri Group) and the Upper Vindhyans (Kaimur Group) in the Son Valley, whereas the same appears to be a minor discontinuity in Rajasthan (Oldham, 1893) (Table 2.1). Heron (1936) had suggested that the Lower Vindhyans had a gradational contact with the Upper Vindhyans in Rajasthan. Similarly, many studies carried out in Bundelkhand and Bhopal area also support the suggestion of a conformable relationship between the Lower and Upper Vindhyans (Soni et al., 1987). However, the occurrence of a very thick conglomerate horizon (known as Piparola Conglomerate) near Panna (Fig. 2.1) confirms the general view of a discontinuous relationship between the two groups of rocks (Soni et al., 1987). Furthermore, the intrusion of kimberlite diaterme within the Kaimur Group and its absence in the overlying Rewa Group has been

considered as an evidence for an additional depositional hiatus within the Vindhyans, between these two groups of the Upper Vindhyans (e.g., Soni et al., 1987).

The sandstone formations of the supergroup are believed to have been deposited in alluvial fan, braidplain, fan delta, eolian sandsheet, shallow marine and lacustrine environments, while the shale formations represent near shore or off shore deposits (Chakraborty, 2006). Carbonate formations of the supergroup represent various ramp settings (Bhattacharyya, 1996 and Chakraborty, 2006). Based on paleocurrent analysis in the Son Valley it has been suggested that the northerly paleocurrent direction in the southeast Vindhyans is indicative of sediment contribution from the evolving Satpura mountain range, whereas the southerly direction observed in northeast Vindhyans points to sediment sources in the north, to the basement rocks in the Bundelkhand craton (Bundelkhand Granite, Bijawar and Gwalior group of rocks) (Chakraborty, 2006) (Fig 2.1). Post-Vindhyan magmatic activities in the basin are not uncommon. Numerous dolerite dykes are known from the lower part of the Vindhyan Supergroup, and most of them are confined to and trend along the Narmada-Son lineament (Soni et al., 1987).

The Vindhyans of Rajasthan have an average total thickness of ~3.2 km and the basin occupies about 24000 km^2 of area, which is about one fourth of the entire basin and is comparable to its counter parts in the Son Valley (Prasad, 1984). Gokaran et al., (1995), however, suggested, based on magneto-telluric studies, that the Lower Vindhyans are ~3.0 km and the Upper Vindhyans are ~1.2 km in thickness. Therefore, considering this, a total thickness of the Vindhyans in the Rajasthan can be worked out to be ~4.2 km, which is comparable to the Vindhyans of the Son Valley. It is to be noted that some workers have included the Khairmalia volcanics within the Lower Vindhyans (e.g. Prasad, 1984). These volcanics have been considered to be equivalent of the Jungel volcanics in the Son Valley (Raza et al., 2009). However, others believe that the inclusion of the Khairmalia in the Vindhyan Supergroup does not have a geological basis (e.g., Roy and Jakhar, 2002), although

the depositions in both sectors appear to have started after the emplacements of the Khairmalia and the Jungel volcanics. These volcanics have been linked to the opening of the Vindhyan Basin by continental rifting (Raza et al., 2009).

The depositional model for the evolution of the Vindhyan basin is largely based on the work carried out at the margins, in particular on the studies carried out in the Son Valley. As of now, two models of basin evolution have been proposed. One of the models suggests that the Vindhyan Basin evolved with a rifting in an intracratonic setting (Jokhan Ram et al., 1996; Bose et al., 1997, 2001) and the second model advocates for an epicratonic foreland setting resulting from a southerly dipping subduction prior to the collision of Bhandara and Bundelkhand cratons (Chakraborty and Bhattacharya, 1996; Chakrabarti et al., 2007).

2.1.2 Lithostratigraphy of the Vindhyans

2.1.2.1 Vindhyans of the Son Valley

The rocks of the Vindhyan Supergroup in the Son Valley sector have been studied in great detail since the beginning of geological investigations in India (Oldham, 1856; Medlicott, 1859; Mallet, 1869). These rocks have been divided into groups and subgroups following the principles of superposition, lithological similarities and breaks in sedimentation. The general stratigraphic classification of the Vindhyans followed in this thesis is presented in Table 2.1, which is mainly based on the compilation by Bhattacharyya (1996), although some of the important features from other studies have also been included.

Medlicott (1859) defined the Semri Series (Group) of Lower Vindhyans on the basis of his work carried out on four formations exposed on the banks of the Semri River near Bijawar, Madhya Pradesh. There are nine formations in the Semri Group, which

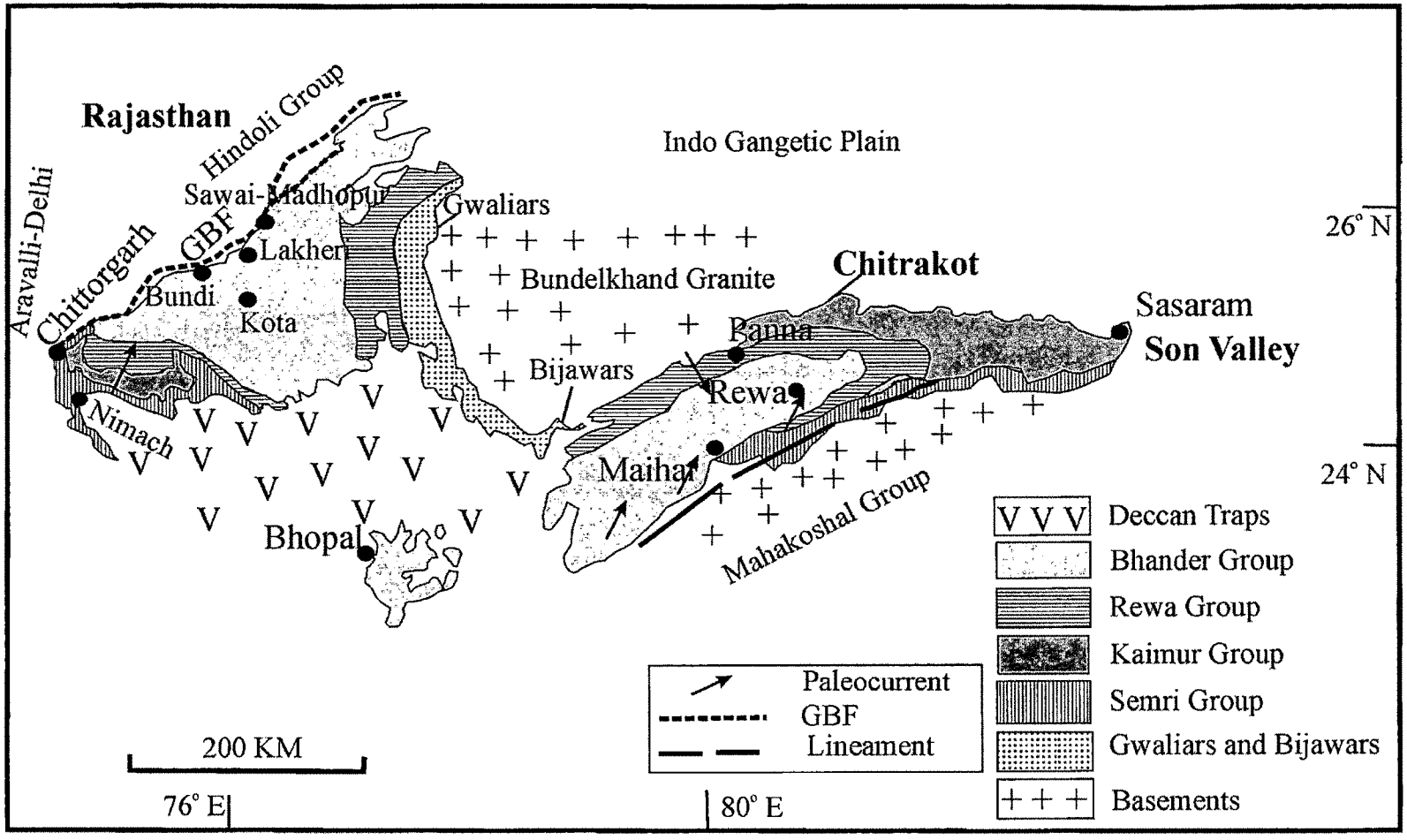

Fig. 2.1. The geological Map of the Vindhyan Supergroup (after Chakraborty et al., 2010). Paleocurrent directions are from Soni et al. (1987). GBF: Great Boundary Fault; Lineament: Son-Narmada Lineament.

together is about 1.3 km in thickness (Chakraborty, 2006). These nine formations have been grouped into three subgroups namely the Mirzapur, the Kheinjua and the Rohtas according to their order of superposition (Table 2.1). The Vindhyan sequences in the Son Valley starts with a locally developed ~3m thick diamictite at the base of Deoland Formation, which is believed to be of glacial origin by some previous workers (Bose et al., 2001 and references therein). The Mirzapur Subgroup includes the following formations: the Deoland Sandstone, the Arangi Shale, the Kajrahat Limestone and the Deonar Porcellanite. The Deoland Sandstone grades into Arangi Shale on which the Kajrahat Limestone is developed. The Kajrahat Limestone is stromatolitic and dolomitic in nature, and is believed to be shallow marine in origin, and could be correlated with the Bhagwanpura Limestone Formation in Rajasthan (Table 2.1). The Deonar (Porcellanite) Formation, which is made up of volcanic tuff, pyroclatstic surges and flow deposits, is about 500m in thickness. The Kheinjua subgroup is developed over the Porcellanite Formation starting with the dark coloured Koldaha shale consisting of recycled material from the underlying formation (Bose et al., 2001). The Salkhan Limestone which overlies the Koldaha shale is fine grained fawn coloured, dolomitic and cherty (Sharma, 2006). The Chorhat Sandstone Formation, in which fossils of early metazoan life forms have been reported by Seilacher et al. (1998) (see section on biostratigraphy later), is considered to be equivalent of the Salkhan Formation (Chakraborty, 2006). The Rampur Formation overlying the Salkhan Formation is comprised of greenish shale interbedded with sandstones (Chakraborty, 2006). The deposition of the Rohtasgarh Limestone which is massive, plane-laminated and generally devoid of stromatolities marks the beginning of the Rohtasgarh subgroup. The formation becomes a limestone-shale rhythmite towards top. Chakraborty (2006) reported ~ 30m thick volcaniclastic deposits at Jukehi, Satna District, and Madhya Pradesh that directly overlie the Rohtasgarh Limestone. The topmost unit of the Semri Group is called the Bhagwar Shale. The thickness of the Semri Group is estimated to be ~20m in Chandola (Soni et al., 1987) to as thick as ~1.3km (Chakraborty, 2006). This suggests

that there exist inherent irregularities on the floor of the Vindhyan Basin. A basin wide unconformity separates the Upper Vindhyans from the Lower Vindhyans (Table 2.1; Fig. 2.2).

The Upper Vindhyans comprising three groups (Kaimur, Rewa and Bhander) containing shale and sandstone formations with one major limestone formation close to the top. Kimberlitic pipes have intruded the Kaimur Group near Panna in the Son Valley. The observed maximum thickness of the Kaimur Group is 400m at the Rohtasgarh (Soni et al., 1987). The Kaimur Group is comprised of sandstones and shales forming six formations. The overlying Rewa Group consists of shales and sandstones appear to rest on the kimberlite pipes with a diamondiferous conglomerate zone in between (Vredenburg, 1906; Krishnan, 1968). The Rewa Group is best developed along the northern margin in the Son Valley. The thickness of this group varies from 109 to 296m (Soni et al., 1987). The Bhander Group, the uppermost division of the Vindhyan Supergroup, starts with the Ganurgarh Shale which grades into the Lakheri (or the Bhander) Limestone (> 100m thick) followed by the deposition of the Lower Bhander (Bundi Hill) Sandstone. This group of rocks is best developed in the central part of the basin. Another diamondiferous conglomerate separates the Rewa and Bhander Group near Panna. The Simrawal Shale marks the initiation of deposition of the Bhander Group in this area, which is considered equivalent to the Ganurgarh Shale (Soni et al., 1987). The Lakheri Limestone is stromatolitic in nature, which indicates that its deposition took place in a shallow shelf region (Sarkar et al., 1998). The Bundi Hill Sandstone overlying the Lakheri Limestone is the most impersistent formation (Soni et al., 1987). The Sirbu Shale which is best exposed in Sirbu hills near Rewa town is about 120 to 320m thick and occurs on the top of the Bundi Hill Sandstone. The Upper Bhander Sandstone or the Maihar Sandstone (or the Shikaoda Sandstone) that forms the topmost Vindhyan formation in the Son Valley is exposed along the central axis of the Vindhyan basin.

2.1.2.2 *Vindhyans of Rajasthan*

The Vindhyan Supergroup in Rajasthan commences with the eruption of the Khairmalia volcanics belonging to the lower part of the Sand subgroup, comprising of andesites and pyroclastics (Table 2.1). The total thickness mapped for the Sand subgroup is ~1000m thick which include the earlier classified Satola subgroup containing the lower 835m of sediments and volcanics (Prasad, 1984). A minor porcellanite formation which is considered to be equivalent to its counterpart in the Son Valley is mapped as part of the Palri Shale formation of the Sand subgroup (Table 2.1 and Prasad, 1984). The Kalmia Sandstone and the Binota Shale form the Lasrawan subgroup that overlies the Sand subgroup. The Khorip subgroup that marks the end of the deposition in the Semri is made up of three major formations: the Bari (or the Nimbahera) Shale, the Nimbahera Limestone and the Suket Shale (Table 2.1). The total thickness of the Khorip subgroup is ~475meter (Prasad, 1984). The cumulative thickness of the Semri Group is determined to be ~ 1.7 km , which is comparable to that in the Son Valley.

The Upper Vindhyans of Rajasthan start with the deposition of the Kaimur Group in which only one formation in the form of sandstone is present, in comparison to the six formations of different rock types in the Son Valley. The Badanpur Conglomerate below the Kaimur Group, in the Bundi district, which is about 8-10 meter thick, developed locally on the Pre Aravalli or the Hindoli Group of rocks (Prasad, 1984). The Rewa Group is comprised of four formations: the Panna Shale, the Indergarh Sandstone (or the Lower Rewa Sandstone), the Jhiri Shale and the Taragarh Fort Sandstone (the Upper Rewa Sandstone), with a maximum thickness of ~285m (Prasad, 1984). Deposition of the Bhander Group started with the Ganurgarh Shale (200m) followed by the Lakheri Limestone (150m). The Lakheri Limestone is not stromatolitic like its counterpart in the Son Valley. The Samaria Shale that overlies the Lakheri Limestone has patches of dolomite bearing stromatolitic limestones, and is found only in Rajasthan. The Bundi Hill Sandstone (or the Lower Bhander sandstones) overlies the Samaria Shale formation. These formations i.e. Ganurgarh,

Lakheri, Samria, Bundi Hill Sandstone and the Sirbu Shale constitute the lower portion of the Bhander Group (Prasad, 1984), whereas the Upper portion of the group is represented by the Maiher (or the Shikaoda) Sandstone, the Balwan Limestone, and the Dholpur (Bhavpura) Shale units marking the closure of the Vindhyan sedimentation in Rajasthan. Interestingly, the latter two formations are not observed/reported from the Vindhyans of the Son Valley. The Shikaoda Sandstone is best developed in Bundi area, and is about 780m thick (Soni et al., 1987). The Bhander Group shows thickening from east to west in Bundi. This group is best developed in Bundi- Ranthambhore-Sapotra-Karauli sector.

2.1.3 Biostratigraphy of the Vindhyans

Biostratigraphy of the Vindhyans are not well established for a simple reason that most of the supergroup is Paleo-Mesoproterozoic in age when life was not so well developed. However, the Vindhyans are famous for numerous interesting and controversial fossil discoveries. In this section I made an attempt to compile some of the important findings. A compilation of the fossil findings and their implications towards the age of the Vindhyan is presented in Table 2.2. In one of the earliest studies, Valdiya (1969) reported *Kussiella* type stromatolites from the Kajrahat Limestone in Son valley and the Bhgawanpura Limestone in Rajasthan that showed development of columnar-branching within the domal and laminated forms. According to this work, the stromatolites of Chitrakoot, which show passive branching and upward swelling columns, represent early forms of Lower Riphean (1650 -1350 Ma) stromatolites within *Kussiella* assemblage.

The *Chuaria* and *Tawuia* fossils have generally been reported from the upper Vindhyans, particularly from the Bhander and the Rewa groups (see Table 2.2), however, they are also known to occur in the Suket Shale of the lower Vindhyans (Kumar, 2001). The ages of these fossil assemblages are believed to be in the range of 1100-700 Ma (Hoffman, 2005). Seilacher et al. (1998) reported trace fossils of

Table 2.1: The stratigraphic classification of the Vindhyan Supergroup (after Bhattacharyya 1996).

			Typical Vindhyan Basin (adapted for Son Valley)		Vindhyan Basin in Rajasthan (used in the present work)
UPPER VINDHYAN	BHANDER GROUP		Shikaoda (Maihar) Sandstone		Bhavpura (Dholpur) Shale
					Balwan Limestone
					Shikaoda Sandstone
			Sirbu Shale		Sirbu Shale
			Bundi Hill Sandstone		Bundi Hill Sandstone
			Lakheri (Bhander) Limestone		Lakheri Limestone
			Ganurgarh Shale		Ganurgarh Shale
	REWA GROUP		Govindgarh Sandstone		Taragarh Fort Sandstone
			Dramondganj Sandstone		
			Jhiri Shale		Jhiri Shale
			Asan Sandstone		Indergarh Sandstone
			Panna Shale		Panna Shale
	KAIMUR GROUP		Dhandraul Sandstone		
			Mangesar Formation		
			Bijaigarh Shale		
			Ghaghar Sandstone		
			Susni Breccia		
			Sasaram Formation		Kaimur Sandstone with Conglomerate
LOWER VINDHYAN	SEMRI GROUP	Rohtas Subgroup	Bhagwar Shale	Khorip Subgroup	Suket Shale
					Nimbahera Limestone
			Rohtasgarh Limestone		Bari (Nimbahera)Shale
		Kheinjua Subgroup	Rampur Formation	Larsrawan Subgroup	
			Salkhan Limestone		Binota Shale
			Koldaha Shale		Kalmia Sandstone
		Mirzapur Subgroup	Deonar Formation	Sand Subgroup	Palri Shale (with Porcellanite)
			Kajrahat Limestone		Sawa Sandstone with Congolomerate
			Arangi Formation		Bhagwanpura Limestone
			Deoland Formation		Khardeola Sandstone
					Khairmalia Andesite
Aravalli/Bhilwara Supergroup/Berach Granite/ Bundelkhand Granite/Jungel volcanics/Bijawar Group of rocks					

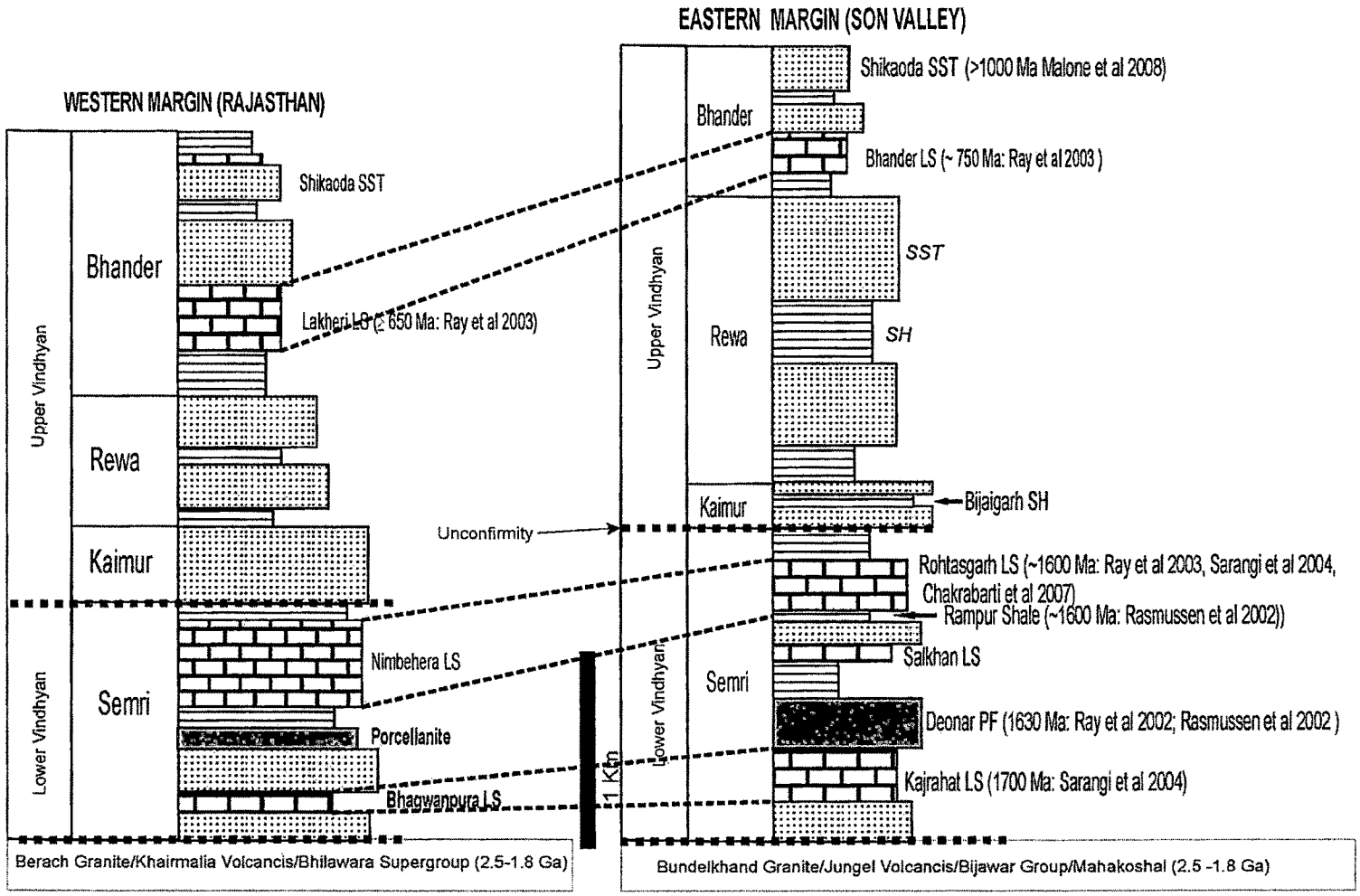

Fig. 2.2: Stratigraphic logs for the Vindhyan Supergroup in Rajasthan and in the Son Valley. The dashed lines connect correlatable limestone formations across the basin (Source: Ray et al., 2003). Recent radiometric ages and sources are given in the brackets. PF: Porcellanite Formation; SST: Sandstone; LS Limestone and SH: Shale.

Table 2.2: The fossil evidences with age connotation in Vindhyans.

Formation	Fossil Assemblages	Age Inferred (Ma)	References
	Upper Vindhyans		
Bhander Group			
Dholpur Shale	*Chuaria-Tawuia*		Srivastava, (2002)
Balwan Limestone	*cynobacterial affinity-algal mats*	late Neoproterozoic	Kumar & Pandey (2008)
Shikoada (Maihar) Sandstone	*Skolithos* and complex *Planolites* burrows		Maitra and De (1998)
Sirbu Shale	*Trachyhystrichosphaer*	Cryogenian (850–630 Ma)	Srivastava (2009)
Bundi Hill Sandstone			
Lakheri Limestone , Son valley	Sponge *spicule*		Kumar (1999)
Lakheri Limestone , Son valley	*Chuaria-Tawuia*	1100-700	Kumar & Srivastava (1997, 2003)
Lakheri Limestone, Rajasthan	*Ediacara* type	Ediacaran-Cambrian	De (2003, 2006)
Lakheri Limestone, Rajasthan	Stromatolites *Baicalia and Tungussia, Minjaria, Maslowviella & Linella*		Prasad (1980)
Lakheri Limestone, Maihar (Son valley)	Bioherm built Stromatolites (*Baicalia and Tungussia)*		Valdiya (1969)
Rewa Group			
Dramondganj Sandstone	*Planolites* burrows		Maitra and De (1998)
Jhiri Shale	Fossil*(Chuaria-Tawuia)*	1100-700	Rai et al. (1997)
Kaimur Group			
Kaimur Sandstone and Shale	*Skolithos* and Meandering traces *Planolites*		Kulkani & Borakar (1996); Maitra and De (1998)
	Lower Vindhyans		
Semri Group			
Rohtasgarh Limestone	Bedding planes of shales carbonaceous discs and filaments *Chuaria, Tawula, Sekwia*		Sahni (1936), Mishra (1969) Maithy and Babu (1988), Kumar (1995), Sharma (1996), Kumar (2001)
	annulated tubes, embryo like globules with polygonal surface pattern, and filamentous and coccoidal microbial fabrics similar to *Girvanella* and *Renalcis*	~1,650	Bengtson et al. (2009)
	Grypaenia spirals	~1600	Sarangi et al. 2004
	Small Shelly fossils		Azmi (1998), Azmi et al. (2006)
Chorhat Sandstone (Salkhan Formation)	*Triploblastic* metazoan burrows/worm like	> 1000	Seilacher et al. (1998)
	Horizontal Burrows		Sarkar et al. (1996)
	Planolites Serpens		Maitra and De (1998)
Salkhan Limestone	Conical Stromatolites (*Comophyton & Maslowviella*)		Mathur et al. (1958) Valdiya (1969)
	Obruchevella		Rai and Singh, (2004)
Koldaha Shale	*Acritarch*		Anbarasu (2001)
	Primitive no-vascular plant spores		Ghosh and Bose (1950)
Kajrahat Limestone, Son valley, Bhagwanpura Limestone in Rajasthan	Columnar branching Stromatolites (*Kussiella type)*	1650-1350	Valdiya (1969)

triploblastic animals in Chorhat Sandstone, which were believed to be worm-like metazoan. Azmi (1998) reported small shelly fossils (SSFs) from the Rohtasgarh Limestone from the Semri Group and claimed these to be similar to the fauna those are usually found near the Precambrian-Cambrian transition. These findings generated a debate among the workers about the age of the Vindhyan supergroup. Eventually, this led to a renewed interest among the various workers to settle the issue pertaining to the age of these rocks and the authenticity of the fossil discoveries. The main issue that needed to be resolved was that if the fossils were true then, these were the first ever finds of Ediacara in Mesoproterozoic rocks of the Vindhyans.

The renewed interest to date these sedimentary sequences by available geochronological tools resulted in publication of good age estimates of the Lower Vindhyans from the Son Valley (Rasmussen et al., 2002, Ray et al., 2002, Ray et al., 2003, Sarangi et al., 2004, Chakrabarti et al., 2007, Bengtson et al., 2009). The most recent work of Bengtson et al. (2009) re-ascertained the claims of fossil findings of Azmi et al. (2006) from the Lower Vindhyans and therefore has pushed back the age of metazoan evolution. These authors have also dated the fossilifeorus phosphorite horizons in Tirohan Dolostone (equivalent to Rohtasgarh Limestone) from Janaki Kund in Chitrakoot by Pb-Pb isochron technique, and reported an age of 1,650 ± 89 (2σ).

In the Upper Vindhyans of Rajasthan De (2003; 2006) reported 'Ediacaran-*like*' organisms with doubtful preservation characteristics in the Lakheri Limestone, suggesting that the age of this limestone could be younger than the latest Cryogenian (i.e. <620Ma). The authenticity of these findings further may be questioned by the recent study of Srivastava (2009), who reported 850-630Ma old fossils of *Trachyhystrichosphaer* an acritarch, in a dolomitic limestone member of the Sirbu Shale Formation. All these findings, although remains controversial, hint at the possibility that parts of the Upper Vindhyans in Rajasthan may actually have been deposited during the Cryogenian epoch of the Neoproterozoic.

2.1.4. Geochronology in the Vindhyans

The duration of the sedimentation within the Vindhyan basin is a controversy that has remained unresolved for over one hundred years (Venkatachala et al., 1996). The Table 2.3 presents a synoptic view on the existing reliable age information from the Vindhyan Supergroup. From the table it is evident that the age of the Lower Vindhyans i.e. Semri Group is well constrained compared to the Upper Vindhyans. From the existing age information it appears that the sedimentation in the Son Valley must have started prior to 1721 Ma (Sarangi et al., 2004), the oldest age estimate for the Kajrahat Formation based on Pb-Pb dating. Lack of robust age data restricts us to make such an inference for the Vindhyans of Rajasthan; however the upper age limit for initiation of the sedimentation could be put at 1850 Ma, the age of the underlying volcanic rocks (Deb et al., 2002).

The geochronological data for the Lower Vindhyan sequences (Table 2.3) are derived from U-Pb zircon ages from the Deonar Porcellanite Formation that yielded dates: 1628±8 Ma, and 1630.7±0.4 Ma (Rasmussen et al., 2002; Ray et al., 2002). The Rohtashgarh Limestone has been dated by various groups using Pb-Pb dating method, and the results fall in the range between 1514-1650 Ma (Ray et al., 2003, Sarangi et al., 2004, Chakrabarti et al., 2007, Bengtson et al., 2009). Unlike the Lower Vindhyans, the age of deposition for the Upper Vindhyan sequences has remained unresolved (see Table 2.2 and 2.3) due to lack of robust radiometric age data. A very poorly defined Pb-Pb age on the Bhander Limestone of 650±700 (2σ) Ma was reported by Ray et al. (2003) and this date has remained as the only direct radiometric age information for the Bhander Group. Based on the Sr-isotope stratigraphy Ray et al. (2003) suggested that the age of Bhander Limestone could be anywhere between 750 and 650 Ma, which the authors believe is consistent with the data for carbon isotope stratigraphy during this period.

Table 2.3 Radiometric Age data for the Vindhyan Supergroup

Formation	Method	Age (Ma)	Reference
		Upper Vindhyans	
Bhander Group			
Dholpur Shale	K-Ar	550	Vinogradov et al. (1964)
Shikaoda Sandstone	Detrital zircon (Pb-Pb)	>1000 ?	Malone et al. (2008)
Lakheri Limestone, Rajasthan	Sr Isotope stratigraphy	≤650	Ray et al. (2003)
Lakheri Limestone, Son Valley	Pb-Pb	650 ± 700 ?	Ray et al. (2003)
Lakheri Limestone, Son valley	Sr isotope stratigraphy	≤750	Ray et al. (2003)
Kaimur Group			
Kaimur Conglomerate	K-Ar	940	Vinogradov et al. (1964)
	F-T	1071 ± 169	Srivastava and Rajagopalan, (1986)
	F-T	1070 ± 160	Srivastava and Rajagopalan, (1986)
Bhagain (Kaimur)Sandstone	Rb-Sr	>1067	Based on the Age of Kimberlite intrusion (1067±31 Ma), Kumar et al. (1993)
		Lower Vindhyans	
Semri Group			
Rohtasgarh Limestone	Pb-Pb	1601 ± 130	Ray et al. (2003)
	Pb-Pb	1599±48	Sarangi et al. (2004)
	Pb-Pb	1514 ±120	Chakrabarti et al. (2007)
Tirohan Dolostone	Pb-Pb	1650 ± 89	Bengtson et al. (2009)
Rampur Shale (Rampur Formation), Son Valley	U-Pb	1599 ± 8	Rasmussen et al. (2002)
Deonar Porcellanites, Son Valley	U-Pb	1628 ±8	Rasmussen et al. (2002)
		1630 ± 1	Ray et al. (2002)
Glauconitic Sandstone, Chitrakoot	Rb-Sr	1504-1409	Kumar et al. (2001)
Kajrahat Limestone, Son Valley	Pb-Pb	1721± 90	Sarangi et al. (2004)
Basement Rocks			
Hindoli volcanics	U-Pb	1850	Deb et al. (2002)
Khairmalia	Rb-Sr	> 1000	Crawford & Compston, (1970)
Berach Granite	Pb-Pb	2440 ± 8	Wiedenbeck et al. (1996)
Bundelkhand Granite	Pb-Pb	2492 ± 10	Mondal et al. (2002)

A late Neoproterozoic or Cambrian age for the Bhander-Rewa was supported by a comparison of paleomagnetic directions found in the rocks with those from Late Proterozoic-Cambrian age sedimentary rocks in the Salt Ranges of Pakistan (McElhinny et al., 1978; Meert and Torsvik, 2003). Klootwijk et al. (1986) suggested that although the paleomagnetic poles from the Salt Range rocks are similar to the Bhander-Rewa directions, significant vertical axis rotation of units in the Salt Ranges during the Tertiary Era casts doubt on this proposed correlation. Additional evidences forwarded in support of a Neoproterozoic age for the Rewa and Bhander groups are generally indirect and inconclusive.

Recent attempt of Malone et al. (2008) using Pb-Pb dating of detrital zircon and paleomagnetic pole analysis in Bhander Group in the Son Valley as well as in Rajasthan suggests a lower age limit of ~1000 Ma for the topmost sandstone formation, the Shikoada (Maihar) Sandstone. This inference was based on the observation that the zircon population from the Shikoada Sandstone did not contain zircons younger than 1000 Ma. Using this evidence in the paleopole data that suggested identical pole position to the Majhgawan kimberlite intrusion, Malone et al. (2008) went on to infer that the deposition in Vindhyan Basin had seized much before 1000 Ma. However, we feel that the zircon data of Malone et al. (2008) is statistically insignificant (the 1000 Ma peak contains only 1 grain!), and hence, conclusions of this studies should not be considered seriously.

The findings of Malone et al. (2008) have made things more complicated because the uppermost Bhander Group is generally considered to be late Neoproterozoic (750-650 Ma; Kumar et al., 2002; Ray et al., 2003). Unfortunately, the most striking features of Late Neoproterozoic sequences worldwide - the presence of glacial diamictites (Evans, 2000) is not known from the Upper Vindhyans.

These are, however, some indirect (chemical) evidences which have been suggested to represent one or more of these Neoproterozoic glacial events. A large negative excursions in $\delta^{13}C$ of carbonates observed in the Lakheri Limestones of Rajasthan (by

Kumar et al., 2002) and in the Bhander Limestone (Ray et al., 2003) have been interpreted to represent one of the Neoproterozoic global glaciations. If true, then the age of the Lakheri/Bhander Limestones should lie between 750-635 Ma, which is supported by minimum ages obtained by Ray et al. (2003) from Sr-isotope stratigraphy.

2.2 Field Relationships and sampling

Since the focus of this work was the Vindhyans of Rajasthan, two localities were selected for sampling where all the groups of the supergroups were accessible in a small domain. After thorough field survey based on the existing geological maps and district resource maps prepared by Geological Survey of India (GSI), it was found that the Lower Vindhyans and the Upper Vindhyans were best exposed around Chittorgarh (Fig 2.3) and Bundi-Lakheri sectors (Fig. 2.4), respectively.

2.2.1 Field relationship

In the Chittorgarh district the general strike of the Vindhyan formations are N-S and these formations terminate against GBF, which runs NE to SW along the Berach River (Fig. 2.3 & 2.5). They are bounded by the Deccan Traps in the south, and by the Berach Granite in the north. The general stratigraphic younging direction is towards east from the contact with the Berach Granite and the Hindoli Group of rocks. In Chittorgarh region large scale folds occur in the Vindhyan formations, with synclines occupying the topographic highs and the anticlines forming the valleys (Srivastava & Sahay, 2003, Fig. 2.5). The axes of the numerous large scale folds, form parallel ridges and valleys, trend oblique to the GBF (Fig.2.5). Figure 2.6 represents eastern limb of such a folded anticline within the Nimbahera Limestone Formation that the topographic lows at Chittorgarh. Interestingly this folding pattern changes its orientation (axial) to NE-SW from N-S and becomes parallel to the GBF in the eastern sector towards Bundi and beyond, in Rajasthan. Near Chittorgrah the GBF

forms the boundary between the Vindhyans and the Berach Granite in the NW and western margins and traced through the Vindhyans in the northern margin (Fig. 2.3 & 2.5).

Berach Granite (Fig. 2.7) forms the basement of the Vindhyan Basin at Chittorgarh, and the Bhagwanpura Limestone represents the beginning of the deposition of the Vindhyan Super group. The topmost Vindhyan formation in this area is Panna Shale which occupies the ridges atop the Kaimur Sandstone of the Upper Vindhyans. The contact between the Suket Shale (Semri Group) and Kaimur Sandstone (Kaimur Group) has been observed in the Chittorgarh Fort Hill where it appears to be conformable, in contrast to the observations elsewhere in the basin. Near the contact zone of GBF and the Vindhyans, the rocks of the supergroup have been deformed as a result of the reactivatiuon of the fault (Sahay & Srivastava, 2005). Multiphase deformations in the Nimbahera Shale at Berach river section (Fig. 2.8) is an evidence of the post Vindhyan reactivation of the GBF.

In the Bundi-Lakheri sector only the upper Vindhyans are exposed in the form of hills and ridges, those run parallel to the ENE-WSW strike of the GBF. These ridges many of which are anticlines are affected by secondary faults parallel to and at an angle to the GBF (Fig. 2.4). A majestic fault scarp that runs for > 60 km from Bundi to Lakheri within the Vindhyans provides a testimony for the reactivation of the GBF subsequent to the filling of the Vindhyan Basin. Further towards Sapotra in NE the GBF bifurcates into two major faults. The main fault of the GBF marks the boundary between the Hindoli supracrustals and the Vindhyans, however, patches of Kaimur sandstone are emplaced onto the Hindolis through secondary faults (Fig. 2.9). The GBF is displaced about 1.5km near Satur. The continuity of the GBF is truncated and displaced for ~ 2km towards SSE near Mohanpura south of Indergarh town, by a right lateral cross fault. An example of cross fault cutting across the Bundi-Indergarh ridge near Khatgarh is shown in Fig 2.8. One can observe that the formations of the Bhander Group occur in repetitive manner all along the Bundi-Indergarh road in form of linear ridges below the fault scarp. The Lakheri limestone formation

occupies most of the linear anticlines and also deformed at a smaller scale too, an example of which is shown in Fig. 2.10. The Vindhyan formations continue further towards north parallel to the GBF in Sawai-Madhopur and the Sapotra-Karauli sub-basin, where some formations of the Lower Vindhyans are also exposed.

The top three formations of the Bhander Group, which are not exposed along the Bundi-Lakheri section, are exposed along a 15 km long patch, south-east of Lakheri near Indergarh (Fig. 2.4). The topmost formation of the Vindhyans in Rajasthan, the Dholpur Shale outcrops along a faulted contact with the Sirbu Shale-the most extensive formation below the alluvium in the Bundi District of Rajasthan. The Shikaoda (Maihar) Sandstone formation occurs on a ridge (Fig. 2.4). The Balwan Limestone formation, which is ~100-120m thick, forms a necklace around the sandstone ridge in the north east and disappears along with two other formations in the south west. The Balwan Limestone is stromatolitic at the base and at the top with a conglomerate horizon in between. Interestingly the Balwan Limestone is not exposed in the Balwan Village, which is situated almost at the centre of the ridge. A detailed geological map of this region is given in Fig. 2.11.

It is believed that the Vindhyan Supergroup of rocks was deposited on peneplained Archeans and Paleoproterzoic basements with irregular topography. The occurrence of a conglomerate as an outlier (named Badanpur Conglomerate) of the Kaimur Group directly over the folded Pre-Aravallis, north of the GBF, between Bundi and Indergarh (see Fig 2.4) and absence of the Lower Vindhyans in this sector while partial presence of the Lower Vindhyans in Karauli-Sapotra region, indicate the irregularities in the basement topography. The transition of Suket Shale (Lower Vindhyans) to the Kaimur sandstones (Upper Vindhyans) at Chittorgarh fort suggests a conformable nature. These observations indicate that the non deposition of Lower Vindhyans at the margins could be due to the highland and ridges like topography. This could have been a result of Pre-Vindhyan geological events such as the formation of Aravalli-Delhi mountain ranges.

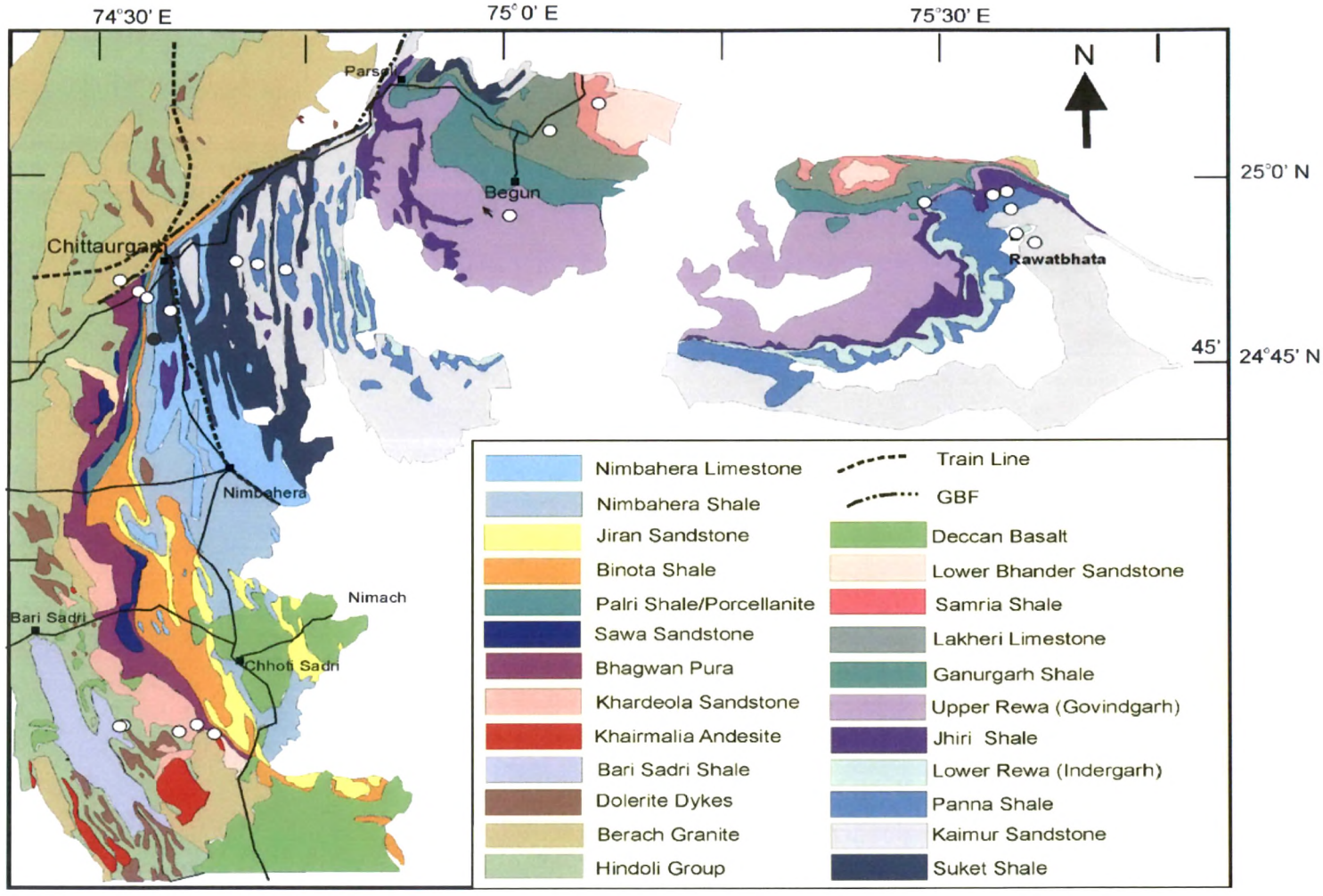

Fig. 2.3: The Geological map of the Chittorgarh district (after DRM, courtesy: GSI). Samples collected from Vindhyan formations and the basement rocks are marked as white circles.

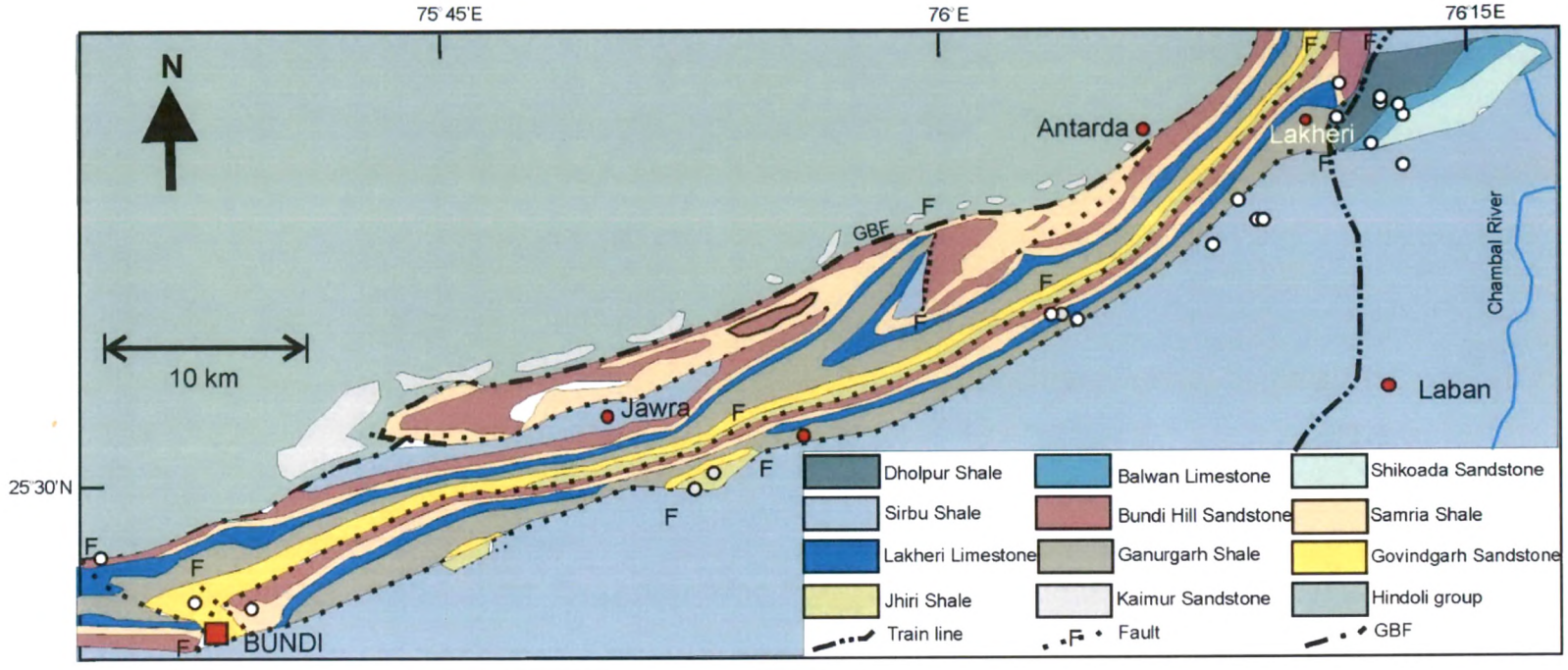

Fig.2.4: Geological map of Vindhyans in the Bundi-Lakheri sector (after DRM: courtesy GSI). Samples collected from various formations are marked as white circles.

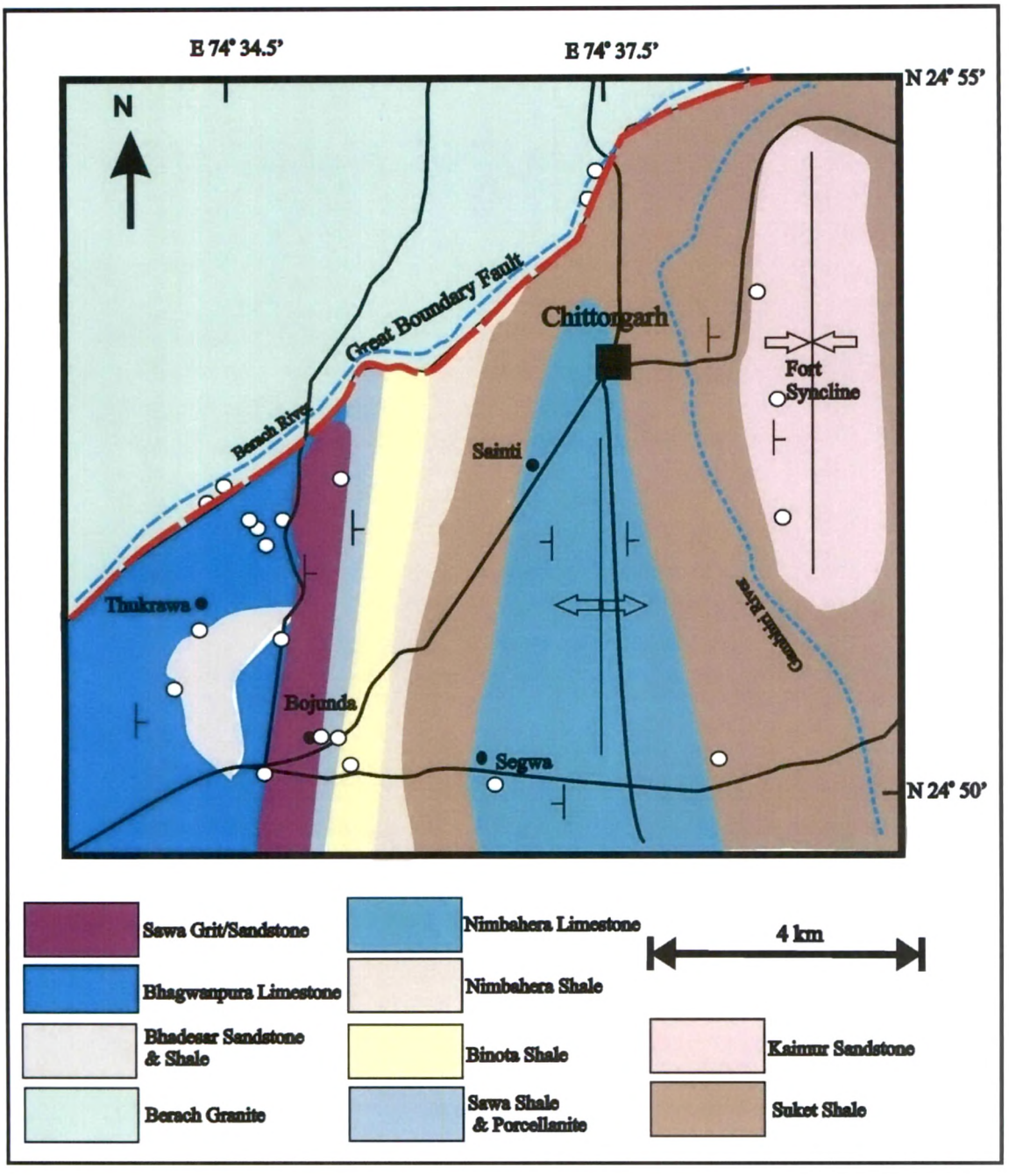

Fig. 2.5: Detailed geological map around Chittorgarh modified from Srivastava and Sahay (2003).

Fig. 2.6: East dipping beds of the Nimbahera Limestone at Chittorgarh. These beds represent the eastern limb of a regional anticlinal fold.

Fig 2.7: Outcrop of the Berach Granite exposed along the banks of the Berach River near Chittorgarh.

Fig. 2.8: Complexly folded Nimbahera Shale Formation along the Great Boundary Fault Zone at Chittorgarh.

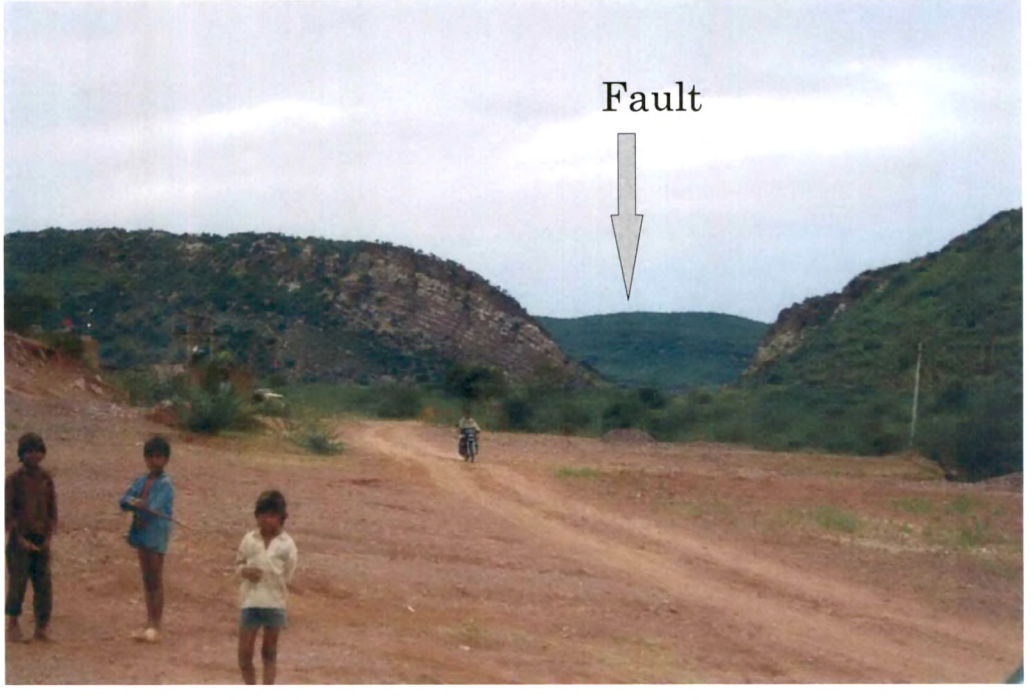

Fig.2.9: A fault within the upper Vindhyans at Khatgarh that cut across the GBF at an angle.

Fig.2.10: Folding in the Lakheri Limestone near Gandoli Village on the Bundi-Indergarh road.

2.2.2 Sampling Strategy and Sample details

Our work required sampling of siliciclastic formations for provenance study and therefore one or two representative samples from each formation were considered sufficient. For sampling the Lower Vindhyans the area south and south west of Chittorgarh town was selected. The samples were collected starting from the Berach River with the Berach Granite and following an east-west transect towards the Chittorgarh Fort, where the Kaimur group (Kaimur Sandstone) is exposed. This total transect is about 5 km across the general strike. Also to determine the chemistry of possible source rocks for the Vindhyan sediments we collected samples of various Pre-Vindhyan rocks near Chittorgarh. These include the Berach Granite and several meta-volcanic rocks of the Hindoli supracrustals. Our sampling locations are marked

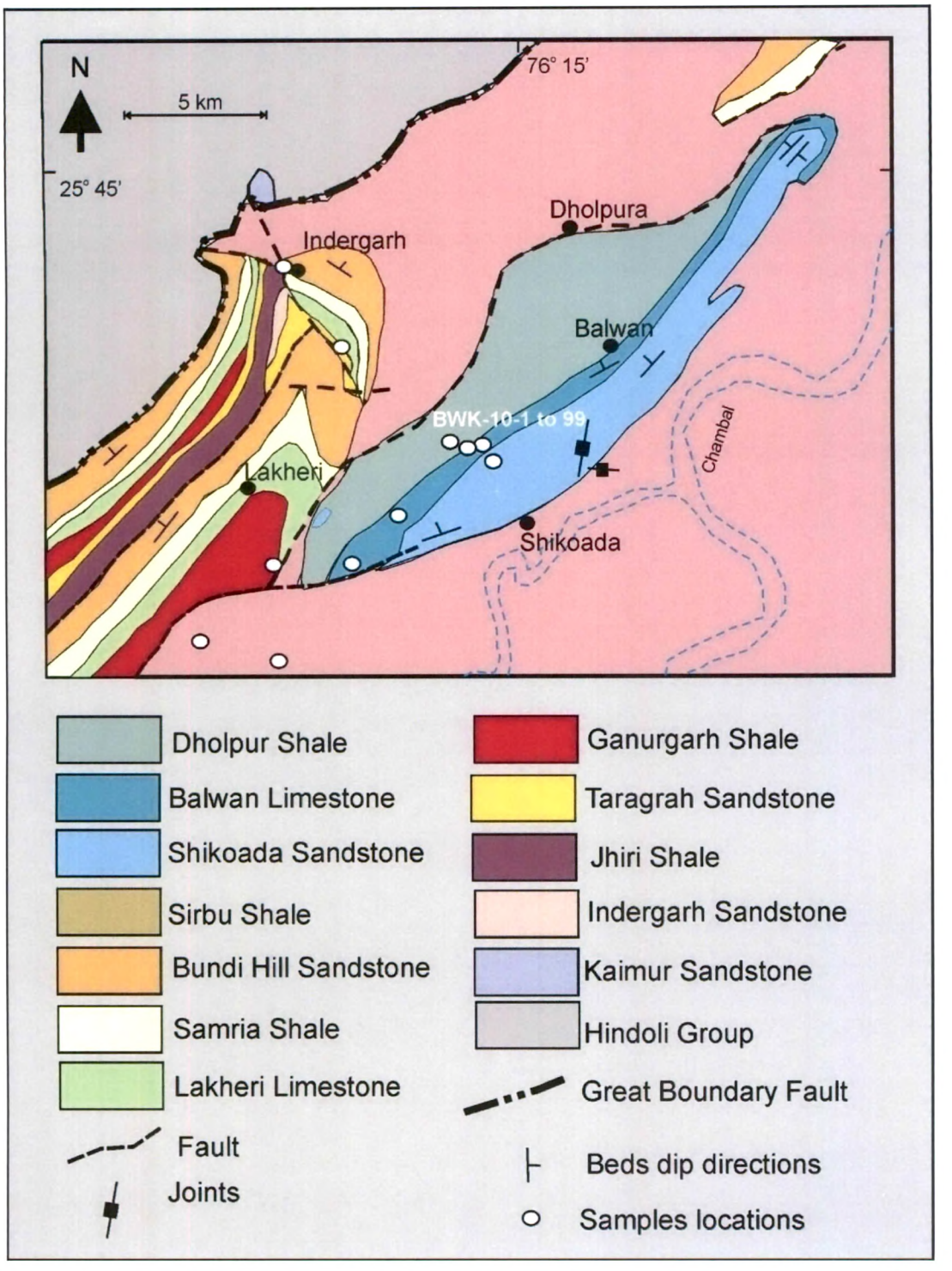

Fig. 2.11: Detailed map of the Lakheri-Indergarh area, after Prasad (1984).

in Fig. 23. & 2.5. Furthermore, some of the lowermost formations of the Lower Vindhyans including Khairmalia Andesites were sampled near Chhoti Sadri (Fig 2.3). Sample of various formations of the upper Vindhyans were collected in Begun, Rawatbhata, Bundi and Lakheri sectors (Fig 2.3, 2.4). As discussed earlier stratigraphic correlations between various formations of the Vindhyans of Rajasthan and those in the Son Valley remains problematic. In an attempt to shed some light on these issues we took the help of detrital zircon geochronology. Considering the fact that the Lower Vindhyans of Chittorgarh contains a formation (Sawa Sandstone) that is believed to be equivalent of the ~1630 Ma Deonar porcellanite Formation of the Son Valley (Prasad, 1984) an attempt was made to date this formation using the above method. For this purpose samples were collected from this formation near Bojunda (N24°50.434′E74°35.528′ Table 2.5). As has been demonstrated by many workers (e.g. Ray et al., 2003), Sr-isotope stratigraphy is a useful tool to determine minimum depositional ages of limestone formations in cases where direct dating methods and biostratigraphy either are absent or fail. In an effort to establish the chronology of the topmost limestone unit of the Vindhyans in Rajasthan, the Balwan Limestone, we employed this method and for this purpose careful sampling was done to reduce least altered samples. We also worked on C and O isotope compositions of these limestone formations in order to understand their depositional environments/diagenetic history. For C and Sr isotope stratigraphy high resolution sampling was done, with ~ 5cm sampling interval, in the Balwan Limestone from two transects across the strike (Fig.2.4 & 2.12).

Our samples were collected from the large exposures of various formations after selecting fresh outcrops to avoid the weathered domains. Lists of the samples with their locations and other relevant information are presented in Tables 2.4, 2.5, and 2.6. Table 2.4 presents samples collected from the Vindhyan formations exposed in the Chittorgarh district, whereas Table 2.5 deals with the samples collected from Bundi district. The samples collected from the Balwan Limestone near Lakheri town in Bundi district are presented in Table 2.6. The locations of the samples are marked on the geological maps in Figs. 2.3, 2.4, 2.5 &2.12.

Table 2.4: Samples collected from the Vindhyan formations and pre-Vindhyan rocks exposed in Chittorgarh district.

Sample	Location	Formation	Description/Remarks
CHITTOR-09-12	N25°07.207'; E75°07.954' Near Menaal on NH 76	Bhander Shale	Fine grained, yellow color with sandy intercalations
CHITTOR-09-9	N25°02.877'; E75°08.880'	Ganurgarh Shale (Black Shale)	Thinly laminated black shale, from a well
CHITTOR-09-8	N24°57.587'; E75°04.410'	Ganurgarh Shale (Black Shale)	Hard, thinly laminated, black colour, from a well
CHITTOR-09-13	N25°08.099'; E75°07.304'	Samaria Shale	Greenish-gray thinly laminated
CHITTOR-09-07	N24°58.916'; E75°29.689' Rawat Bhata	Ganurgarh Shale	Compact, greenish colour
CHITTOR-09-06	N24°57.934'; E75°33.434'	Jhiri Shale	Green color, thinly laminated, fissile
CHITTOR-09-05	N24°57.188'; E75°33.714'	Jhiri/Panna Shale	Purple & greenish colour, thinly laminated
CHITTOR-09-03	N24°55.562'; E75°35.667'	Indergarh Sandstone	Light colour with brown bands
CHITTOR-09-17	N24°54.512'; E74°46.706' Gorasiya village	Panna Shale (Black Shale)	Black shale with evident pyrite crystal
CHITTOR-09-15	N24°54.465'; E74°42.044'	Panna Shale	Greenish-yellow with sandy intercalations
CHITTO-09-02	N24°58.074'; E75°35.064'	Panna Shale	Brownish, thinly laminated, fragile
CHITTOR-09-16	N24°54.913'; E74°42.130'	Panna Shale	compacted, laminated with sandy layer, dark green colour
CGB07-20	N24°51.914'; E74°38.719'	Kaimur Sandstone	White hard, quartz-feldspar bearing rock
CGB07-21	N24°52.437'; E74°38.752'	Kaimur Sandstone	White, hard, quartz-feldspar, bearing fine grained rock
CGB07-22B	N24°53.305'; E74°38.524'	Suket Shale	Banded, yellowish shale, with lenticular structure
CGB07-22A	N24°53.305'; E74°38.524'	Suket Shale	Red bands in yellowish shale

Table 2.4 continued...

CGB07-19	N24°50.037'; E74°37.569'	Suket Shale	Yellowish
CGB07-18	N24°50.049'; E74°36.328'	Nimbahera Limestone	Fine, grayish
CGB07-23	N24°53.597'; E74°36.855'	Nimbahera Shale	Dark gray
CGB07-24	N24°54.226'; E74°37.364'	Nimbahera Shale	Light gray
CHITTOR-09-21	N24°26.510'; E74°37.692'	Palri (Binota) shale	Gray/greenish, yellow ting, finely laminated
CGB07-17	N24°50.205'; E74°35.453'	Binota Shale	Greenish
CGB07-01	N24°52.1'; E74°35. 6' Bojunda	Sawa Grit	Coarse grained, grayish with weathered material.
CGB07-02	N24°52.1'; E74°35. 6'	Sawa Grit	Fine grained, grayish with white infillings
CGB07-09	N24°51.75; E74°34.96'	Sawa Shale	Buff colour compact
CGB07-10	N24°51.662'; E74°34.903'	Sawa Shale	Grayish ,hard
CGB07-15	N24°50.434'; E74°35.528'	Sawa Sandstone/	Coarse grained, Black
CGB07-16	N24°50.496'; E74°35.515'	Sawa sandstone	Coarse, quartz, feldspar(pink)
CGB07-13	N24°51.00'; E74°35'	Bhagwanpura Limestone	Fine grained, grayish, stromatolitic, silicified
CGB07-14	N24°50.257'; E74°35.019'	Bhagwanpura Limestone	Fine grained, grayish, hard, stromatolitic
CGB07-05	N24°52.051'; E74°34.554'	Bhagwanpura Limestone	Grayish, fine grained, hard.
CGB07-04	N24°52.051'; E74°34.554'	Quartzite	Grey granite with quartzite bands.
CHITTOR-09-20	N24°25.399'; E74°40.002'	Khardeola Sandstone	Fine grained, purple with brown solution features
CGB07-08	N24°51.8'; E74°34.8'	Metabasalt	Coarse grained, black
CHITOR-09-24	N24°16.606'; E74°36.678'	Khairmalia Andesite	Coarse grained, black
CHITOR-09-25	N24°16.606'; E74°36.678'	Light colored basic rock	Green colour
CHITOR-09-26	N24°16.606'; E74°36.678'	Khairmalia Andesite?	Gray colour rock

Table 2.4 continued...

CHITOR-09-23B	N24°16.850'; E74°35.827'	Mafic rock	Black in colour, very fine grained
CGB07-07	N24°51.12'; E74°34.33'	Bhadesar Quartzite	Yellowish white
CGB07-11	N24°50.71'; E74°34.21'	Bhadesar Quartzite	White with yellow and black bands
CGB07-12	N24°51.8'; E74°34.8'	Bhadesar Quartzite	Coarse grained, quartz & feldspar bearing
CGB07-6	N24°52.051'; E74°34.554'	Berach Granite	Coarse, quartz with pink feldspar
CGB07-3	N24°51.99'; E74°34.48'	Berach Granite	Coarse, gray with quartz-feldspar

Table 2.5: Samples collected from Vindhyan formations exposed in Bundi District.

Sample	Location	Formation	Descriptionn/Remarks
BUNDI-09-06	N25°41.175'; E76°14.512' Kavarpura	Dholpur Shale	Thinly laminated, yellowish brown in colour
BUNDI-09-07	N25°41.345'; E76°14.568'	Dholpur Shale	Laminated yellow in colour
BUNDI-09-03	N25°40.993'; E76°14.602'	Balwan Limestone	Stromatolitic, pinkish white calcites
BUNDI-09-04	N25°40.993'; E76°14.602'	Balwan Dolomite	Light pink, coarse grained
BUNDI-09-05	N25°40.821'; E76°14.722'	Upper Bhander Sandstone	Purple colour fine grain with dark brown bands
BUNDI-09-10	N25°40.701'; E76°12.433'	Sirbu Shale	Thinly laminated, yellowish colour
LAK07-02	N 25°37.06'; E 76° 07.46'	Black shale (Sirbu)	From a well dump
LAK07-08	N 25°38.577'; E 76°9.093'	Gray shale ~22feet thick below the soil in the well (Sirbu)	Gray colour from a fresh dump from a well
LAK07-09	-do-	Black shale (Sirbu)	Dull Black in occurs below the above inside the well
LAK07-10	-do-	Black shale (Sirbu)	Black Shale below occurs below the above inside the well
LAK07-11	N 25°38.297'; E 76° 08.893'	Black shale (Sirbu)	Black shale from a well
LAK07-12	N 25°38.009'; E 76° 08.538'	Black shale (Sirbu)	Black shale from a well
LAK07-13	N 25°37.023'; E 76° 07.438'	Black shale (Sirbu)	Black shale from a well
LAK07-14	N 25°36.554'; E 76° 06.882'	Black shale (Sirbu)	Black shale from a well
SAT-07-23	N 25°28.260'; E 75° 33.133'	Bundi Hill Sandstone	Maroon colour ferruginous with solution features
BUNDI-09-08	N25°43.450'; E76°11.421'	Bundi Hill Sandstone	Purple colour with light brown bands, fine grained
SAT-07-22	N 25°28.260'; E 75° 33.133'	Dolostone (Samaria)	Stromatolitic yellow colour
SAT-07-21	N 25°28.260'; E 75° 33.133'	Samaria Shale	Thinly laminated yellow colour
BUNDI-09-13	N25°27.178'; E75°38.510'	Samaria Shale	Purple, compact
BUNDI-09-01	N25°32.639'; E75°58.274'	Samaria Shale	Compact, thinly laminated, creamish
BUNDI-09-02	N25°32.639'; E75°58.274'	Samaria Shale	Purple, pinkish, thinly laminated

Table 2.5 continued...

BUNDI-09-09	N25°42.983'; E76°11.461'	Shale (Samria) below sandstone	Sandy horizon within shale, yellow colour
SAT-07-01	N 25°28.260'; E 75° 33.133'	Samaria Shale	Thinly laminated yellow colour
SAT-07-02 to SAT-07-20 and SAT-07-25 & 26	N 25°28.260'; E 75° 33.133'	Lakheri Limestone	Pinkish /purple/grey colour
Gandoli-1 to Gandoli-23	N 25°32.65'; E 75° 58.33'	Lakheri Limestone	Pinkish /purple/gray colour
LAK07-07	N 25°28.260'; E 75° 33.133'	Ganurgarh shale	Thinly laminated grey colour
LAK07-01	N 25°35.389'; E 76° 4.928'	Ganurgarh shale	Yellowish, grey friable
BUNDI-09-10	N25°40.701'; E76°12.433'	Ganurgarh Shale	Yellowish, grey friable
BUNDI-09-14	N25°27.140'; E75°38.007'	Taragarh Fort Sandstone	Light pink fine grained compact
LAK07-16	N 25°30.520'; E 75° 52.072'	Taragarh Fort Sandstone	Reddish, compact, ferruginous
BUNDI-09-11	N25°32.086'; E75°56.161'	Upperr Rewa Sandstone	Reddish, compact, ferruginous
BUNDI-09-12	N25°32.086'; E75°56.161'	Jhiri Shale	Reddish brown laminated with folding

Table 2.6: Samples from the Balwan Limestone Formation near Lakheri town in Bundi district.

Sample	Relative Position	Description/Remarks
Transect-1		
	Towards older formation	(~ 2km from Kavarpura Village towards east on the Bagishwar Mahadev road left side) N25°40.993'; E 76 °14.602'
BWK-10-1	0 m	Stromatolitic, in contact with Dholpur Shale
BWK-10-2	15 m	pink coloured, stromatolitic
BWK-10-3	30 m	-do-
BWK-10-4	35 m	-do-
BWK-10-5	40 m	-do-
BWK-10-6	50 m	-do-
BWK-10-7	52 m	Colour change from pink to yellowish Limestone
BWK-10-8	55 m	intraclastic limestone
BWK-10-9	57 m	intraclastic limestones with chert
BWK-10-11	58.5 m	intraclastic limestone
BWK-10-12	61.5 m	Limestone Clast-1
BWK-10-13	61.5 m	Limestone Clast-2
BWK-10-14	64.5 m	intraclastic limestone
BWK-10-15	69.5 m	dolomitic, grainy
BWK-10-16	79.5 m	dolomitic, with intraclasts
BWK-10-17		Black ,sandy, clast bearing limestone
BWK-10-18		Limestone with large intraclasts
BWK-10-19		Limestone conglomerate
	N 25° 40.938'; E 76 °14.580'	
BWK-10-38		Light pink coloured
BWK-10-39		A limestone clast
BWK-10-42		Limestone conglomerate
BWK-10-41	1m	pink coloured
BWK-10-40	0m	Stromatolitic, pink coloured dolostone
N 25° 41.047'; E 76°, 14.559'		
BWK-10-90	Close to the contact with Shikaoda Sandstone	
BWK-10-91	Limestone in contact with Dholpur Shale (~30m above BWK-10-1)	
Transect-2		
N 25° 41.064'; E 76°; 14.727'		
(~200 m north of the Transect -1 along the strike)		
BWK-10-34	0m	Stromatolitic –top of the formation
BWK-10-33	5m	No Stromatolites
BWK-10-32	6.5m	Pink colour
BWK-10-31	7.6m	Pink colour
BWK-10-30	8.5m	Pink colour

		Table 2.6 continued...
BWK-10-29	10m	Pink colour
BWK-10-28	11m	Limestone with chert pebbles
BWK-10-27A	11.6m	Stromatolitic, with chert pebbles
BWK-10-27B	11.6m	Stromatolitic , with chert pebbles
BWK-10-26	13.1m	Limestone with chert clasts
BWK-10-25	14.1m	Limestone with chert clasts
BWK-10-24	15.9m	Intraclastic
BWK-10-23	17.4m	Intraclastic
BWK-10-22	19.9m	Intraclastic
BWK-10-35	44.9m	Cherty horizen
BWK-10-36	59.9m	Abundant Molar Tooth structures
BWK-10-37	67.9m	Pinkish, molar tooth structures
N 25° 41.064'; E 76° 14.727'		
(Re-sampling at same location with high resolution)		
BWK-10-67	0m	With stromatolitic intraclasts
BWK-10-66	0.7m	Non stromatolitic
BWK-10-65	1.2m	Stromatolitic
BWK-10-64	2m	Stromatolitic
BWK-10-63	2.1m	Stromatolitic
BWK-10-62	2.8m	Stromatolitic
BWK-10-61	3.9m	Limestone with sandy pebbles
BWK-10-60	4.8m	Intraclastic (=BWK-10-27)
BWK-10-68	9.6m	Intraclastic
BWK-10-69	11.1m	Intraclastic
BWK-10-70	26.1m	Intraclastic
BWK-10-71	29.6m	Intraclastic
BWK-10-72	30.6m	Intraclastic
BWK-10-73	31.1m	Intraclastic
BWK-10-74	32.1m	Cherty horizen
BWK-10-75	34m	Without stromatolites
BWK-10-76	35m	Without stromatolites
BWK-10-77	43m	Without stromatolites
BWK-10-78	45m	Stromatolitic
BWK-10-79	47.5m	Stromatolitic
BWK-10-80	48.5m	Stromatolitic
BWK-10-81	51.5m	Stromatolitic
BWK-10-82	53.5m	Stromatolitic
BWK-10-83	54.5m	Stromatolitic
BWK-10-84	56.5m	Stromatolitic
BWK-10-85	60m	Stromatolitic
BWK-10-86	62m	Stromatolitic
BWK-10-87	68m	Stromatolitic
BWK-10-88	69m	Stromatolitic
BWK-10-89	79m	Molar Tooth structures
Transect-3		
N 25° 40.195'; E 76° 12.880'		
Along the left side of the Lakheri- Shikaoda road, near ACC quarry		
BWK-10-45	0 m	Stromatolitic

Table 2.6 continued...

BWK-10-46	3m	Stromatolitic
BWK-10-47		Stromatolitic at same position of BWK-10-46
BWK-10-44	5 m	Stromatolitic
BWK-10-43	7.5 m	Above the chert intercalated horizon
BWK-10-53	8 m	Limestone with cherty intercalations
BWK-10-54	10 m	Limestone Conglomerate
BWK-10-55	12 m	Chert bearing horizon
BWK-10-56	17 m	yellow colour
BWK-10-57	27m	Yellowish colour
BWK-10-48	30m/100m	compacted
BWK-10-20		Pink color, stromatolitic from the near-by quarry
BWK-10-21		Black color, stromatolitic from the near-by quarry
N 25° 40.278'; E 76° 12.874'		
BWK-10-49	Cherty horizon below the pink stromatolitic top unit	
BWK-10-50	Below sandy horizon	
BWK-10-51	Pink Limestone above sandy BWK-10-50	
BWK-10-52	same at BWK-10- 51 level ~ 15 m away	
N 25°40.220'; E 76° 12.876'		
BWK-10-92	0m	Stromatolitic, pink colour
BWK-10-93	0.5m	Above the sand intercalated horizon
BWK-10-94	2.0m	Limestone with sandy intercalation
BWK-10-95	3.5m	Clast bearing unit of the limestone (=BWK-10-56)
BWK-10-96	9.5m	Chert bearing
BWK-10-97	11.5m	Chert bearing
BWK-10-98	12.5m	Chert bearing (=BWK-10-57)
N 25° 40.938'; E 76° 14.580'		
BWK-10-99	Cherty Limestone on the left side of the Shikaoda road (Dip of the beds are changing)	
N 25° 24.584'; E 75° 35.229'		
BWK-10-100	Limestone within Sirbu Shale Formation at 6 km milestone Bundi- Bijolia	

2.3 Experimental Methods

The objectives of the current work were achieved by carrying out necessary field studies, collecting suitable rock samples and performing various analyses petrographic and chemical in the laboratory. Petrography was done on all the samples and subset of these was selected for geochemical and isotopic studies. Care was taken to avoid weathered and altered materials. Petrography was done on thin sections, where as geochemical studies were performed on powder samples. Powdering was done using an Agate mortar and an automated milling system (Fisher-Type). Major element analyses were carried out using X-ray Fluorescence (XRF) method and trace element content were measured using Inductively Coupled Plasma Mass Spectrometry (ICPMS). Sr and Nd isotopic ratios were analyzed with the help of Thermal Ionization Mass Spectrometer (TIMS) and the stable C-O isotope analyses for carbonates, were done using gas source mass spectrometry. In the next sections detailed description of these methodologies are given.

2.3.1 Petrography

The major objectives of this study were to identify various minerals present in sandstone (e.g. quartz, feldspar etc.), determine the carbonate mineralogy in limestones/dolostones, determine the degree of alteration, determine the micro structures generated by biology and most importantly select a region of least alteration in limestones for micro sampling for C-O-Sr isotope analyses.

Calcite and dolomite phases and their variants (e.g. Fe/Mn rich varieties) were identified in limestone samples using the standard staining procedure on thin sections. The staining solution was prepared following the standard protocol using Potassium Ferricyanide and Alizarine Red S (Tucker et al. 1990) in the following manner:

- A 500 ml 0.5% HCl solution was prepared, and divided into two parts: a 300ml solution -Part A and a 200ml solution-Part B.

- 1.5g of Potassium Ferricyanide was added to Part A and thoroughly mixed and left for 24 hours.
- 0.2gm Alizarine Red S to Part B thoroughly mixed and left for 24 hours.
- After 24 hours both the solution were mixed and used for staining a portion of a thin section.

In general, calcites are stained to pink or purple (Fe-rich), while dolomites remain either colourless or stained blue. After identifying carbonate minerals on thin section the same were sampled from a polished slab, which represents the counterpart (mirror image) of thin section, using a micro drill. This sample powders were then processed for C, O and Sr isotopic ratio analyses. Preference was given to least altered calcite minerals for the geochemical work. Petrographical studies of sandstones were also carried out to understand the mineral composition that was expected to help in understanding the geochemical variations and ultimately deciphering the provenances. All the petrographical studies of thin sections of sandstones and carbonates were done using a Nikon Eclipse LV100POL microscope and Stereo Microscopes at PRL.

2.3.2. Major element analysis

Major element concentrations were measured by X-ray Fluorescence (XRF) Spectrometry method in an automated Philips AXIOS X-ray Spectrometer fitted with an Rh X-ray tube, operated at 50 kV and 55 mA, of 4kW power. The instrument is a National Facility for Planetary Science and Exploration Program (PLANEX) of Indian Space Research Organisation (ISRO) housed at Physical Research Laboratory, Ahmedabad. This instrument was set-up and installed and calibrated for routine measurements of rock samples under this research activity (Ray et al., 2008). The analyses for this work were done on pressed pellets of sample powders. For calibration purpose several international rock standards, as listed in Table 2.7, were used. Appropriate set of standards were used for a given set of samples to avoid interferences and absorptions caused by matrix. For example, sedimentary samples

were analyzed using sedimentary rock or sediment standards, while igneous rocks were analyzed with calibration using igneous rock standards. Fig 2.12 gives typical calibration curves for major element oxides and two trace elements.

Pressed Pellets of our samples and rock standards were prepared using wax binder. A finely powdered sample (2.0 gm) was mixed homogeneously with 0.5 gm of wax binder in an agate mortar. The mixture was then transferred into 37 mm standard aluminum cups and subjected to 150kN pressure using a hydraulic press for about a minute. The pressure was removed slowly and pellets were recovered for analysis. The precision of measurements at 2σ level, based on repeated analyses of sample/standard, for major oxides is better than 5% and for trace elements it is better than 15%, except for Ni for which it is ~25%.

During the analyses one of the sedimentary standards Cody-Shale (SCo-1), which was not part of the calibration, was used as unknown for accuracy check (Table 2.8). The measured values (average of 20 measurements) are in good agreement with the reported values within the 2σ level of error.

2.3.3 Loss on Ignition (LOI) analysis

The concentration of volatile matter (e.g. water in the form of hydrates or labile hydroxyl ions; carbon dioxide from the carbonates etc.) in rocks or sediments is reported as Loss on Ignition (LOI). For this purpose, ~ 2 gm of a sample powder was taken in a silica crucible after drying down at 110°C for 4-5 hours. The silica crucible was inserted into a furnace preheated to 1070°C and sample was ignited. After igniting the sample for an hour, furnace was switched off, and was allowed to cool down to room temperature. The difference in the weight (in% loss) of sample powder before and after ignition is determined and tabulated as LOI.

Table 2.7: International rock standards used in various analytical techniques during the generation of major and trace elements data.

Name of Standard	Rock Type	Supplier
AGV-1	Andesite	USGS*
BCR-2	Basalt	USGS
BHVO-2	Hawaiian Basalt	USGS
COQ-1	Carbonatite	USGS
G-2	Granite	USGS
JB-2	Japanese Basalt	GJS**
JG-2	Granite	GJS
JGb-1	Gabbro	GJS
JGb-2	Gabbro	GJS
JLS-1	Limestone	GJS
JDO-1	Dolomite	GJS
JMS-2	Marine Mud	GJS
MAG-1	Marine sediments	USGS
SCO-1	Cody-Shale	USGS
SDO-1	Shale	USGS
W-2	Diabase	USGS

**USGS= United State Geological Survey & **GJS= Japanese Geological Survey*

Table 2.8: A comparison of measured and reported concentrations for various elements in SCo-1 standard.

	Measured (n=20)		Reported*	
		±2σ		±2σ
Al_2O_3 (wt %)	14.0	0.65	13.7	0.42
CaO (wt %)	2.79	0.02	2.62	0.4
Fe_2O_3 (wt %)	5.06	0.11	5.13	0.36
K_2O (wt %)	2.72	0.01	2.77	0.16
MgO (wt %)	2.83	0.02	2.72	0.36
MnO (wt %)	0.05	0.00	0.053	0.008
Na_2O (wt %)	0.99	0.02	0.9	0.12
P_2O_5 (wt %)	0.20	0.01	0.21	0.04
SiO_2 (wt %)	63.1	0.22	62.8	1.32
TiO_2 (wt %)	0.66	0.01	0.63	0.12
Rb (ppm)	117	5.36	110	8
Sr (ppm)	180	2.10	170	32
Zr (ppm)	163	1.59	160	60
Ni (ppm)	28.1	7.00	27	8
Y (ppm)	24.5	1.50	26	8
Cr (ppm)	84.1	11.77	68	10

*(*Certificate of Analysis supplied by USGS: Abbey, (1983), Flanagan, (1976); Gladney & Roelandts (1988); Govindaraju, (1994)).*

2.3.4 Analysis of Trace Elements including Rare Earth Elements (REE)

Inductively coupled plasma-mass spectrometry (ICP-MS) is a well established rapid and precise method for the determination of concentration of trace elements including rare earth elements (REEs) in geological samples (Lichte et al., 1987; Jarvis, 1988; Longerich et al., 1990). Trace elements Sc, V, Cr, Co, Ni, Zn, Rb, Sr, Zr, Nb, Ba, Hf, Ta, Th and 14 REEs (La, Ce, Pr, Nd, Sm, Eu, Gd, Tb, Dy, Ho, Er, Tm, Yb and Lu) in our samples were measured using a Thermoelectron X-Series^{II} ICPMS, which is installed recently at the National Facility for Planetary Science and Exploration Program (PLANEX) of ISRO at Physical Research Laboratory, Ahmedabad. This instrument was set-up and installed and calibrated for routine measurements for rock samples during this work (Ray et al., 2008).

Samples and a couple of rock standards (G2 and BHVO-2) (~50mg each) were dissolved using ultra-pure acids following standard HF-HNO3 dissolution technique in Savillex Teflon vials. Care was taken for complete dissolution of rock powders. The stock solutions were prepared in 2% HNO_3 with ~1000 dilution factor. The analyses were performed on highly diluted samples prepared from the stock solution, to avoid matrix effect. Calibration curves were generated using blank and various dilutions of G-2 and BHVO-2 standards. Normally calibration curves are drawn in the range of 0 to 50 ppb concentrations. A few typical calibration curves are presented in Figure 2.13. The isotopes ^{139}La, ^{140}Ce, ^{141}Pr, ^{146}Nd,^{147}Sm, ^{153}Eu, ^{157}Gd, ^{159}Tb, ^{163}Dy, ^{165}Ho, ^{166}Er, ^{169}Tm, ^{172}Yb, ^{175}Lu,^{45}SC, ^{51}V, ^{52}Cr, ^{59}Co, ^{60}Ni, ^{66}Zn, ^{85}Rb, ^{88}Sr, ^{90}Zr, ^{93}Nb, ^{137}Ba, ^{178}Hf, ^{181}Ta, and ^{232}Th, were analyzed for their respective elements. Reproducibility (external precision) of our measurements, based on repeated analyses of a sample, were better than 2% at 2σ level, for all trace elements reported here. For accuracy check analyses of various dilutions of the international standard BHVO-2 were performed at regular intervals. As can been seen in Table 2.9, the measured data agree well with the reported values (within the reproducibility) for all the elements analyzed.

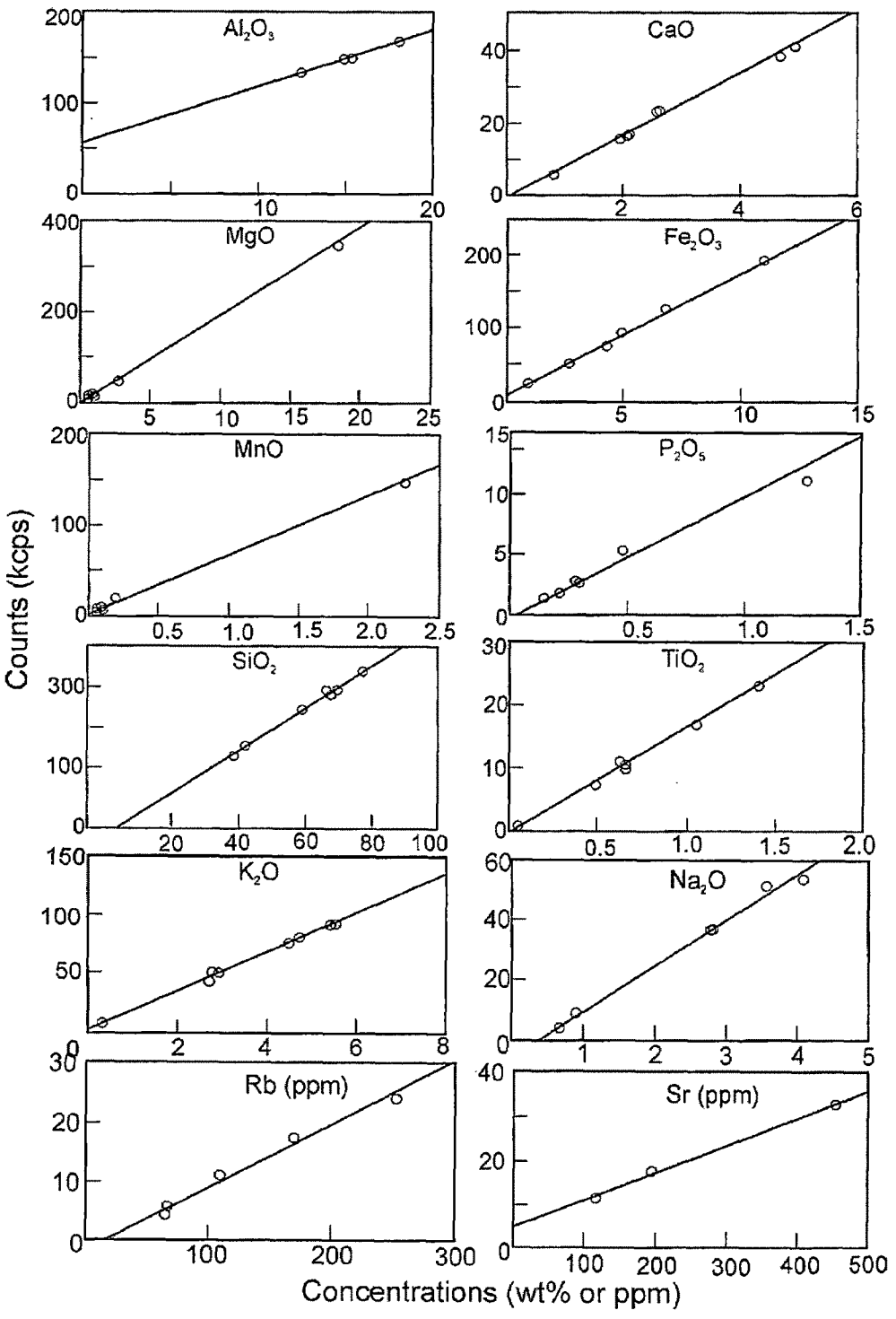

Fig. 2.12: Typical calibration curves generated using XRF for 10 major element oxides and two trace elements using several international rock standards.

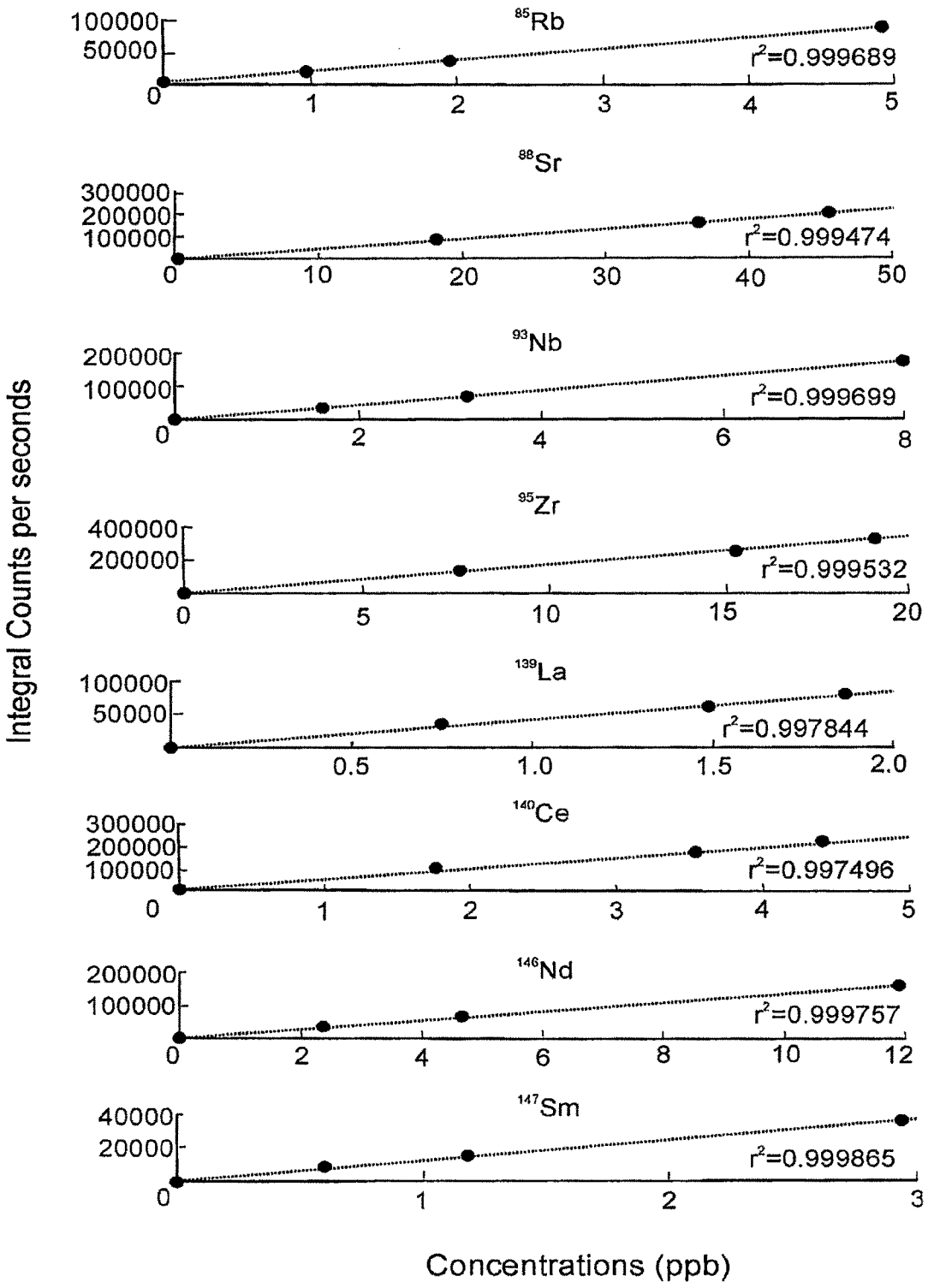

Fig. 2.13: Typical calibration curves generated by diluting the BHVO-2 USGS rock standard for analyzing the trace elements by ICPMS.

Table 2.9: Measured Trace element concentrations in BHVO-2 compared with their reported values.

Elements	Measured (n=10) (ppm)		Reported* (ppm)	
		±2σ		±2σ
Sc	31.6	3.6	31	2
V	330	36	329	18
Cr	290	31	285	28
Co	48.1	5.4	47	4
Ni	114	13.8	112	18
Rb	10.5	1.1	10.1	1.2
Cs	0.11	0.02	0.11	0.02
Sr	383	36	382	20
Y	23.0	2.4	23	2
Zr	159	17	160	16
Nb	16.3	1.9	16.4	0.1
Ba	129	1.0	128	8
La	15.1	1.5	15.6	0.1
Ce	37.3	3.6	37	2
Pr	5.35	0.86	5	0.6
Nd	24.4	3.3	24	2
Sm	6.10	0.76	5.8	1.0
Eu	2.06	0.23	2.0	0.2
Gd	6.24	0.78	5.9	0.8
Tb	0.82	0.17	0.86	0.06
Dy	5.37	0.58	4.9	0.8
Ho	0.93	0.07	0.91	0.12
Er	2.59	0.27	2.3	0.2
Tm	0.31	0.03	0.3	0.1
Yb	1.95	0.24	2.0	0.4
Lu	0.29	0.01	0.26	0.08
Hf	4.13	0.39	4.1	0.8
Ta	0.93	0.12	0.94	0.14
Pb	1.61	0.10	1.4	0.4
Th	1.12	0.19	1.18	0.18
U	0.41	0.07	0.44	0.06

**Gao et al. (2002); Kent et al. (2004); Raczek et al. (2003)*

2.3.5 Analysis of Radiogenic Isotope Ratios

Sr and Nd isotopic ratios ($^{87}Sr/^{86}Sr$ and $^{143}Nd/^{144}Nd$) were measured in selected samples from all the siliciclastic formations of the Vindhyan Supergroup from Chittorgarh as well as Bundi area. The sample powders were dissolved in 17 ml Savillex^R teflon vials using the standard HF-HNO_3-HCl acid dissolution protocol (see Table 2.10). Sr and REE were separated from other elements by standard cation exchange chromatography using 2N HCl as elutant (Table 2.11). Nd was separated from the rest of the REE fraction using Ln -specific resin from Eichrom^R and diluted (0.18N) HCl acid as elutant (Table 2.12).

Table 2.10: The dissolution procedure for silicate rocks.

Step 1: About 50-100mg sample powder weighed into pre cleaned Savillex^R Teflon vials
Step 2: ~1.5ml of HF: HNO_3 (3:1) mixture was added to the sample
Step 3: Samples were agitated through ultrasonication
Step 4: After 24 hours of dissolution- samples were completely dissolved. After complete dissolution samples were dried down at slow heat (~80°C) and taken back in ~ 1ml of 8N HNO_3
Step 5: Dissolution in 1ml HNO3 and drying down were repeated 3 times to oxidize the elements completely.
Step 6: 2ml of 6N HCl was added and dried down to convert the elements to chloride.
Step 7: Final solution was prepared in 1ml in 2N HCl and kept for column chemistry.

Table 2.11: Protocol for Sr and REE separation from sample solution.

Step 1: The primary columns (~15 cm length) were filled with Dowex 50 cation exchange resin
Step 2: Columns were conditioned with 6ml 2N HCl
Step 3: 1ml of the dissolved sample in 2N HCl was loaded on to a column
Step 4: 1ml of 2N HCl passed to allow complete loading
Step 5: 36 ml of 2N HCl was passed and discarded-(removal of Fe, K, Na, Ca, Rb etc)
Step 6: Collect 12ml of 2N HCl was passed and collected for Sr
Step 7: 18ml of 2N HCl passed and collected for REE-dried down and taken up in 100μl of 0.18N HCL-ready for REE column chemistry
Step 8: The collected Sr cut (12ml) was dried down-ready for mass spectrometry
Step 9: columns were cleaned 2 times with full volume of 6N HCl and regenerated with water

Table 2.12: Protocol for Nd separation from rest of the REE.

Step 1: Setting up of REE columns using Ln-specific resin (~9cm length)
Step 2: Columns were conditioned with 2ml 0.18N HCl each. The REE cuts from the primary columns were loaded (100μl of sample in 0.18N HCl)
Step 3: Another 100μl of 0.18N HCl was loaded after washing the vial for each sample
Step 4: Wash- 19 ml of 0.18 N HCl was passed (removal of La, Ce, Pr)
Step 5: Collection - 7ml of 0.3N HCl was eluted for collection of Nd
Step 6: Columns were washed with 6N HCl to remove other REEs and full column volume with water to regenerate the resin
Step 7: The collected 7ml Nd cut was dried down and stored for Nd- analysis

Sr-isotopic ratio analyses in the selected carbonate samples from the limestone formations were also carried out. For these Sr was separated from other elements by

Sr- Sr-Specific resin from Eichron^R. In brief, the selected carbonate sample powders were leached with 40μl Acetic Acid (glacial) and 3ml of Milli-Q water, in a clean 15ml centrifuge tube. These tubes were ultrasonicated for 30 minutes and centrifuged for 15 minutes to separate the solution from residue. 2ml each of the solutions were collected in a clean 7ml Savillex^R Teflon vials and dried down. The samples were then converted into nitrate by adding 0.5 ml of 3N HNO_3 twice and drying down. The final solution was prepared in 2ml 3N HNO_3, which was then processed for Sr preconcentration through column chemistry using the Sr-Specific resin as shown in Table 2.13.

Table 2.13: Protocol for Sr-separation using Sr-specific resin column chemistry.

Step 1: Specific Resin (100-150μm) cleaned with MilliQ water and was stored in MilliQ water
Step 2: The 2ml BioRad polypropylene disposable columns (with frits) were cleaned with warm HNO_3 (3N) and MilliQ water before use
Step 3: About 200 μl resin was loaded onto each column
Step 4: Columns were conditioned with 1ml of 3N HNO_3
Step 5: Samples in 3N HNO_3 were loaded onto the resin
Step 5: Wash -columns were washed 3 times with 0.5ml of 3 N HNO_3
Step 6: Sr collection: Elution of Sr with 4 times of 0.5ml of MilliQ water
Step 7: The collected Sr was dried down and proceeds for mass spectrometry

The mass spectrometric analyses for Sr and Nd isotopic ratios were carried out on a new generation solid source, thermal ionization mass spectrometer (TIMS) Isoprobe-T, at PRL. Sr samples were loaded on pre-degasses, oxidized single Ta filaments and analyzed in static multi collection mode. Small samples were loaded on single Re filaments and a Ta activator. Mass fractionation correction was done by normalizing $^{86}Sr/^{88}Sr$ to 0.1194. Typical Sr loads were 2-4 μg, yielding ^{88}Sr beams of 2-3 V. The 4 years average (n=40) of $^{87}Sr/^{86}Sr$ for international standard NBS 987 is 0.71023

±0.00001 (2σ). Nd samples were loaded on the outer Ta filament of the triple (Ta-Re-Ta) filament settings. Data collection was done in a static mode. Typical Nd loads were 500-1000 ng yielding ^{146}Nd beams of 0.5-2V. Mass fractionation correction was done by normalizing 144Nd/146Nd to its natural ratio of 0.7219. The 2 year average (n-20) of $^{143}Nd/^{144}Nd$ for an international standard is 0.512104±0.000008 (2σ). This corresponds to a value of 0.511847 for much commonly used La Jolla Nd-standard (Tanaka et al., 2000). In addition to running international isotopic ratio standards on mass spectrometer a rock standard, BHVO-2 from USGS, was also processed regularly with samples and analyzed for Sr and Nd isotopic ratios. The average values for $^{87}Sr/^{86}Sr$ and $^{143}Nd/^{144}Nd$ for 12 runs during the course of this work respectively are 0.703458 ± 0.00003 (2σ) and 0.512975 ± 0.000010(2σ). These are well in agreement with the reported values of 0.703462 and 0.512983 respectively (Raczek et al., 2003).

2.3.6 Stable C and O isotopic ratio analysis

Carbon and oxygen isotopic ratios of limestone samples, microdrilled from the slabs were carried out in PRL and the analyses were performed by Dr. J. S. Ray. Samples were weighed (~10 mg) into side-arm (35 cc) vessels with the arm filled with ~2 cc of 100% H_3PO_4. After evacuation, vessels were kept in a constant-temperature water bath at 25°C for a couple of hours and then reacted. In case of pure calcite samples, CO_2 was extracted after 12 hours of reaction at 25°C, while in case of pure dolomites, CO_2 extraction was carried out after 72 hours of reaction. CO_2 extraction was done using in-house fabricated glass system. During the extraction the vessels were kept at 25°C using small water baths.

The $\delta^{13}C$ and $\delta^{18}O$ of CO_2 were measured on a Europa-2020 mass spectrometer against a pre-calibrated laboratory standard CO_2 (prepared from foraminifers) and then converted to PDB and SMOW, respectively. The 25°C acid fractionation factors used for $\delta^{18}O$ of calcite and dolomite were from Friedman and O' Neel (1977) and Rosenbaum and Sheppard (1986) respectively. Reproducibility measured as 1σ for

eight analyses of NBS-19 ($\delta^{13}C_{PDB}$ = 1.95 and $\delta^{18}O_{PDB}$ = −2.3‰) and a local dolomite standard ($\delta^{13}C_{PDB}$ = 0.7 and $\delta^{18}O_{PDB}$ = −9.2‰), during the course of the measurements, was better than 0.1‰ for both $\delta^{13}C$ and $\delta^{18}O$. The analyses were carried with respect to pre-calibrated internal laboratory standard CO_2 and then converted to PDB and SMOW respectively.

2.3.7. Detrital Zircon Geochronology

The detrital zircon geochronology on the zircons separated from the Sawa Sandstone Formation was carried out by Dr. J. S. Ray at Geological Survey of Canada at Ottawa using a Sensitive High Resolution Ion Micro Probe (SHRIMP) following the analytical protocol described by Stern (1997), with standards and U-Pb calibration methods following Stern and Amelin (2003). Zircons were mounted in a 2.5cm diameter epoxy mounts along with fragments of the GSC laboratory standard zircon (z6266, with $^{206}Pb/^{238}U$ age = 559 Ma). The zircon grains were exposed by polishing using 9, 6, and 1-μ diamond compound. The mount surfaces were evaporatively coated with 10nm of high-purity Au. All the analyses were carried out using a $^{16}O^-$ primary beam. The area on the zircon grains used for analysis was between 15 to 25μ. The data was processed off-line using customized in-house software. The characterizations of the zircons were carried out using scanning electron microscopy (SEM) for the clean and unaltered areas which were used for analyses. The Pb-isotope data was not subjected to fractionation correction. The common Pb correction was taken account the Pb composition of the surface blank (Stern, 1997). The Isoplot v. 3.00 (Ludwig, 2003) was used to calculate weighted means and cumulative probability diagrams were generated using the Age-Display workbook for MS-Excel (Sircombe, 2004). The 1σ external errors of $^{206}Pb/^{238}U$ ratios reported in the data table incorporate a minimum ±1.0% error in calibrating the standard zircon.