The Neoproterozoic Malani magmatism of the northwestern Indian shield: Implications for crust-building processes

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Malani is the largest event of anorogenic felsic magmatism (covering $\sim 50,000\,km^2$) in India. This magmatic activity took place at ~ 750 Ma post-dating the Erinpura granite (850 Ma) and ended prior to Marwar Supergroup (680 Ma) sedimentation. Malani eruptions occurred mostly on land, but locally sub-aqueous conditions are shown by the presence of conglomerate, grits and pillow lava. The Malani rocks do not show any type of regional deformation effects. The Malanis are characterised by bimodal volcanism with a dominant felsic component, followed by granitic plutonism and a terminal dyke phase. An angular unconformity between Malani lavas and basement is observed, with the presence of conglomerate at Sindreth, Diri, and Kankani. This indicates that the crust was quite stable and peneplained prior to the Malani activity. Similarly, the absence of any thrust zone, tectonic mélange and tectonised contact of the Malanis with the basement goes against a plate subduction setting for their genesis. After the closure of orogenic cycles in the Aravalli craton of the northwestern shield, this anorogenic intraplate magmatic activity took place in a cratonic rift setting under an extensional tectonic regime.

1. Introduction

In the region west of the Aravalli mountain range (a region called the trans-Aravalli), there is a change in the geological scenario from a typical mobile belt setting to that of a stable intracratonic platform lithopackage. The neighborhood of Sirohi Town (figure 1) is the region where such a changeover can be observed through some traverses in the east-west direction. Thus, Sirohi not only is a doorstep to the vast arid zone bordering the Thar desert (as described by Tod 1909), but its geological record is replete with evidences marking the transition from orogenic to anorogenic magmatism.

Blanford (1877) used the term 'Malani Beds' for the first time, after studying the volcanic rocks of the Malani district of erstwhile Marwar (Jodhpur) state. Coulson (1933) identified three phases of this igneous activity: **(a)** volcanism **(b)** plutonism and **(c)** hypabyssal phase, in Sirohi and Idar regions, and named them as Malani System. Coulson (1933) described (table 1) rhyolite, porphyries and granites from Sindreth, Angor, Dhanta, and Mirpur villages (Sirohi district). The Malani outcrops in western Rajasthan are scanty and generally covered with desert sand. There is controversy amongst the workers (Gupta *et al* 1980; Kochhar 1998; Bhushan and Chandrasekaran 2002; Roy and Jakhar 2002) regarding the nomenclature and duration of Malani magmatism, but unanimity exists on the following:

- The post-Erinpura granite (830 Ma) and pre-Marwar Supergroup (680 Ma) status of Malanis (table 2).
- The anorogenic character of the Malani magmatism.

Keywords. Neoproterozoic; Malani; Sindreth Group; felsic volcanism; crust building.

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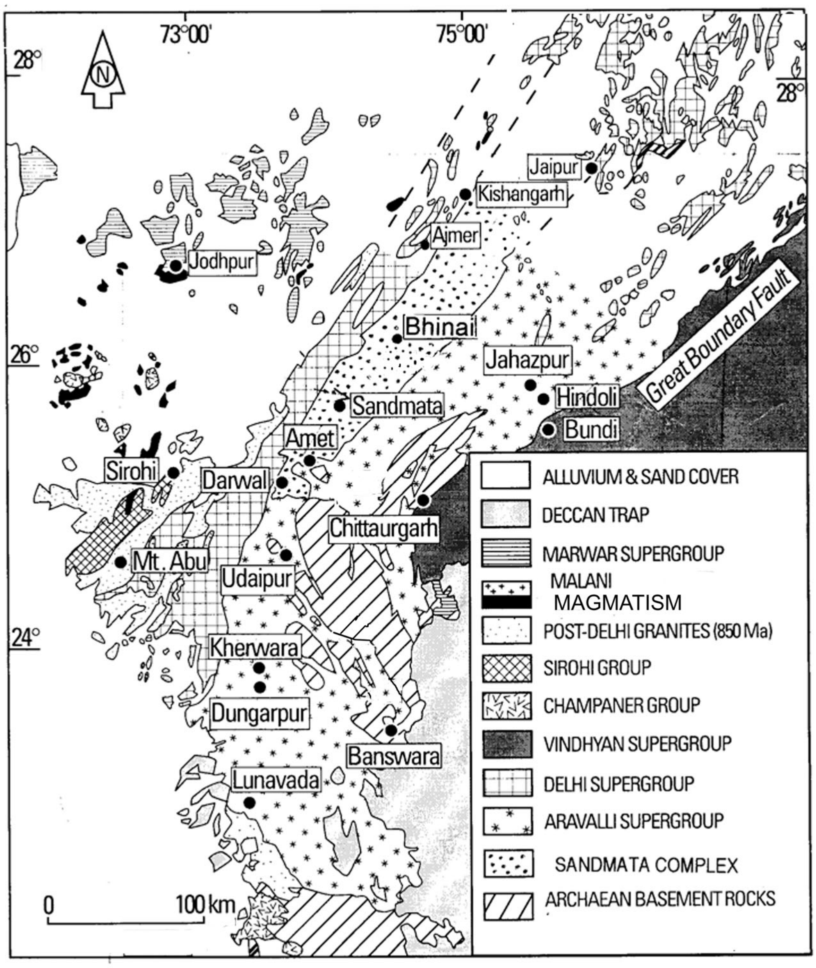

Figure 1. Geological map of northwestern India (modified after the Geological Survey of India map, 1969 and Roy and Jakhar 2002).

- Complete absence of penetrative deformation in Malani rocks.
- Three phases of igneous activity: **(i)** Bimodal volcanism with initial eruption of basic flows followed by voluminous felsic volcanism. **(ii)** Granite intrusions **(iii)** Emplacement of felsic and mafic dyke swarms.

To understand the tectonic and crust-building processes of all the three phases of Malani activity, the Sindreth-Angor outcrop (figure 2) is discussed here.

2. Geological setting

The banded gneissic complex (BGC) includes the oldest supracrustal rocks of Archaean age in the western Indian shield. Several mobile belts viz., Aravalli, Delhi and Sirohi mobile belts traverse this region (figure 1). The beginning of the Neoproterozoic is marked by the intrusion of gabbro-diorite at Ranakpur (Volpe and Macdougall 1990). This magmatic event is part of the development of a narrow linear basin from Ras to Sirohi, named as the Sirohi basin (Roy and Sharma 1999). The granitoids and gneisses are the basement for Sirohi Group and Malani magmatism in the study area. The Sirohi Group contains rocks of fine shale-carbonate facies. There is a total absence of rocks with larger clasts (conglomerate, arkose and quartz arenite) as well as volcanics. The inversion tectonics took place under a compressional regime at the end of the orogenic cycle, which resulted in the development of strong penetrative deformation and intrusion of Balda granite in the axial zone of the Sirohi fold belt. The development of andualsite, garnet and biotite as hornfelsic minerals in the Sirohi mica schist around Balda granite indicates a perfect thermal metamorphic aureole. The Balda magmatism resulted in a fluorite and wolframite deposit in the Sirohi Group of rocks. The tungsten metallogeny, one phase of regional deformation up to greenschist facies and the absence of volcanics in Sirohi rocks make it different from the metasediments of Delhi mobile belt and unmetamorphosed Sindreth rocks (Sharma 1996).

Table 1. *Stratigraphic succession of the Sirohi state (Coulson 1933).*

Post-Tertiary and Recent	Wind-blown sand, talus, alluvium, and conglomerates, etc.
Post-Malani basic intrusives	Dolerites
Malani system (?Purana)	Idar granite, porphyries, rhyolites and dellenites.
Post-Erinpura-granite but pre-Malani basic intrusives	Dolerites, epidorites, gabbros, pyroxenites, picrites, basalts and sodalite-syenites.
Post-Delhi but pre-Malani granitic intrusives	Erinpura granite and accompanying quartz-reefs, pegmatites, and aplites.
Delhi and post-Delhi, but pre-Erinpura granite basic intrusives	Dolerites, epidiorites, amphibolites, hornblende- and actinolite schists.
Delhi system-Ajabgarh series	3. Limestones and calc-rocks, with associated basic rocks. 2. Mica-schists and thin quartzites, with abundant associated basic rocks. 1. Quartzites.
Unconformity	
Aravalli system	(Archaean) Mica-schists, phyllites, shales, crystalline limestones, quartzites, with ? contemporaneous tuffs and lavas.

Table 2. *The Precambrian stratigraphy of Rajasthan.*

Heron 1953		Gupta *et al* 1980		Roy and Jakhar 2002	
Malani series Erinpura granite		Proterozoic-III	Marwar Supergroup Malani suite Erinpura granite and gneiss Vindhyan Supergroup	Marwar Supergroup Malani Group = Sindreth Group 780–680 Ma Granite of Erinpura, Pali, etc. 835 Ma Sirohi Group Intrusion of gabbro, diorite 1000 Ma	Vindhyan Supergroup
Delhi system	Ajabgrh series Alwar series Railo series	Delhi Supergroup 2000–740 Ma Proterozoic-II	Punagarh Group = Sindreth Group Sirohi Group = Sendra, Ambaji granite ca. 800 Ma Kumbhalgarh Group = Ajabgarh Group Gogunda Group = Alwar Group	Synorogenic granite 1400 Ma Delhi Supergroup	
Aravalli system		Aravalli Supergroup 2500–2000 Ma Proterozoic-I		Darwal granite 1850 Ma Aravalli Supergroup	
Banded Gneissic Complex (BGC)		Bhilwara Supergroup Archaean		Untala, Ahar, Berach granitoids 2500 Ma Mewar gneiss (Heron's BGC) 2600–3300 Ma	

Coulson (1933) described igneous rocks present in Sindreth, Dhanta, Angor and Mirpur areas as part of the Malani system. He put a question mark before associated lavas and tuffs of Sindreth while assigning them to the Aravalli System (table 1). Gupta *et al* (1980), while reviewing the Precambrian stratigraphy of Rajasthan, considered the Sindreth rocks a part of Delhi Supergroup. For this, they stretched the time period of Delhi Supergroup from 2000 Ma to 740 Ma without giving any strong rationale for this revision. Bose (1989) questioned this revision and recommended a detailed

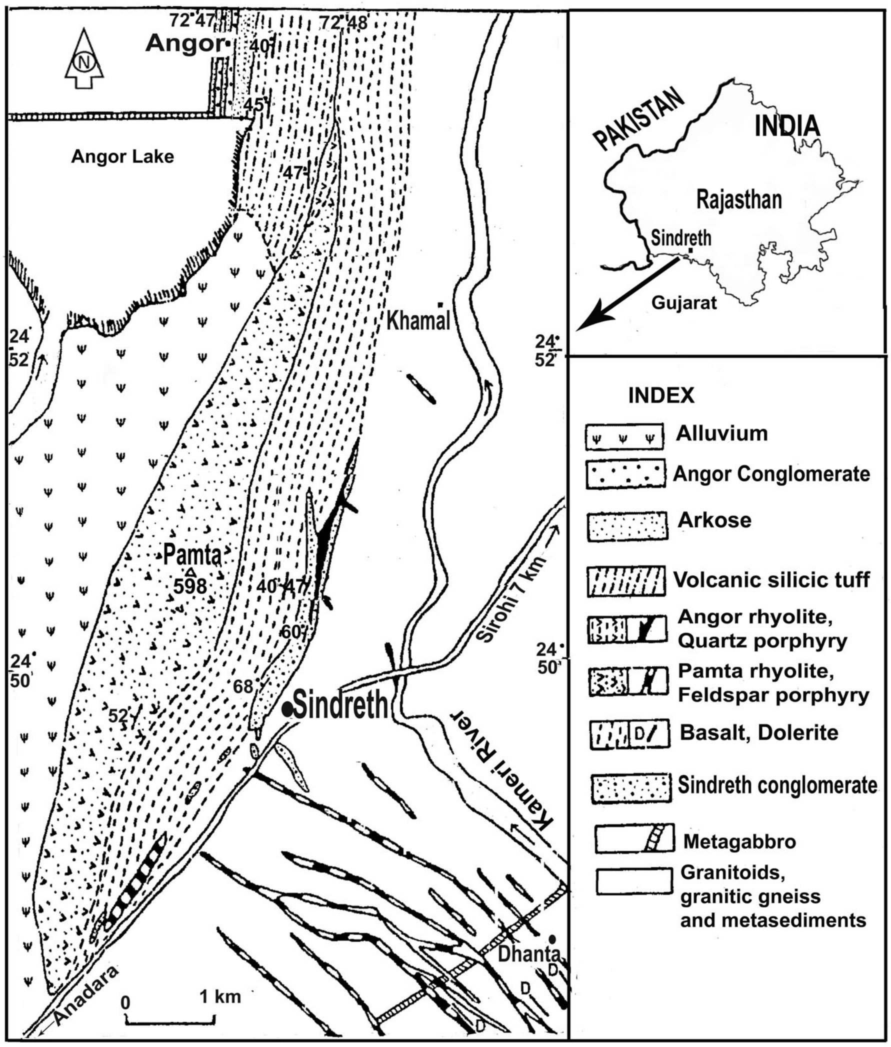

Figure 2. Geological map of the Sindreth region showing the linear rift basin structural setting of the Malani rocks (Sharma 1996).

study before any final conclusion was made. The Sindreth volcano-sedimentary rocks are totally unmetamorphosed and undeformed and comprise conglomerates, arkose, basalt, tuffs, rhyolites, and silicic tuffs. Interestingly, the age and stratigraphic status of the dellenite (rhyolite), porphyry dykes and granites of Sindreth region have never been ascertained. These rocks neither resemble the Delhi Supergroup nor the Sirohi Group but nicely match the other anorogenic Malani magmatic rocks (Sharma 1996; Roy and Sharma 1999; Roy and Kataria 1999).

3. Lithology

Different lithological associations that outcrop in the area around Sindreth may be conveniently grouped under the following heads from oldest to youngest:

- Basement rocks.
- Metasediments of the Sirohi Group.
- Malani Magmatism—unmetamorphosed volcanics (flows and tuffs), and sediments.
- Mirpur Granite.
- Dyke rocks.

3.1 *Basement rocks*

3.1.1 *Granitoids and granite gneiss*

The basement granites of the Sindreth region are popularly described as Erinpura Granite (after Coulson 1933). Although described as granite, the Erinpura Granite rock actually comprises a variety of lithologic types ranging from massive granitoids to strongly contorted banded gneisses and mylonitic varieties. The overall character of the Erinpura Granite is gneissic, showing alternation of quartz-feldspar and mafic-rich bands. Folding, contortion and transposition of the gneissic banding is a common feature notable in different outcrops of the Erinpura Granite. In coarse grained varieties, feldspar megacrysts occur as large oval or tabular grains measuring over 10 cm^2 along their length in some cases. These megacrysts commonly occur parallel to the foliation. Rapakivi structure is observed in massive, less foliated, granitoids in which the cores of potassium feldspar have rims of sodic plagioclase feldspar. Most of the rocks of the region are characterized by the presence of large megacrysts of K-feldspar. The other important minerals in the rock are plagioclase feldspar, quartz and biotite. Muscovite, garnet, magnetite, chlorite occur as minor constituents. K-feldspar grains are of variable sizes ranging from about an mm to over 10 cm in length. Most of the grains are subhedral in shape. Plagioclase feldspar grains are fine to coarse grained, and are subhederal in shape. Lamellar twinning is a characteristic feature. Quartz grains are of variable shapes and sizes. Polygonal and strain-free grains are quite common. There are also few stretched grains, which occur as ribbons parallel to the mylonitic foliation.

3.1.2 *Metagabbro*

A large body of gabbro, which grades to amphibolite along its margins, occurs as a linear outcrop about 10 km in length. The maximum width of the body is approximately 300 metres. The outcrop is traceable from Sirohi to Dhanta and is bounded by shear zones. Deformation along with synkinematic growth of hornblende and chlorite has led to the development of a foliation at the margins whereas the central portion has remained more or less massive. At several places, smaller bodies (about one metre in length) of granitic gneissic occur as enclaves within the mafic unit. Massive gabbro occurs in the central part of the linear body, particularly where the body becomes wider. In altered varieties of the gabbro, hornblende occurs as a medium to coarse grained mineral, hexagonal or prismatic in shape, replacing augite. Prismatic grains of hornblende show an alignment parallel to the direction of schistosity. Plagioclase occurs in amphibolite and appears cloudy due to kaolinisation. Calcite, chlorite and epidote occur as secondary minerals. Opaque minerals are also present.

3.2 *Metasediments of Sirohi Group*

3.2.1 *Mica schist*

The mica schist of the Sirohi Group outcrops in the river cutting in the southern part of the Sindreth village. The mica schist is silvery grey coloured, showing development of pervasive schistosity planes defined by prisms of muscovite and biotite, and flattened grains of quartz, these three being the major minerals. Garnet and andalusite occur as porphyroblasts. Epidote, chlorite, microcline, tourmaline and some opaque minerals occur in minor quantities.

3.2.2 *Calc-silicate rock*

It forms a small, oval-shaped enclave within the granitic gneiss near Khamal (figure 2). The rock is off-white to dark grey in colour and, at places, grades into small crystalline marble bands. Locally, the calc-silicate body appears brecciated and powdery. The heterogeneity of rock types suggests compositional variation of the calc-silicate rock.

3.3 *Malani magmatism*

The Malani magmatism of the Sindreth region represents a sequence of unmetamorphosed and undeformed rocks (table 3). The following are the different members of the Group:

- Sindreth conglomerate
- Basalt and pyroclasts
- Pamta rhyolite
- Angor rhyolite
- Volcanic silicic ash
- Arkose
- Angor conglomerate

3.3.1 *Sindreth conglomerate*

This basal unit forms a north-south trending hill near Sindreth. It is a red coloured polymictic conglomerate comprising unsorted angular pebbles of carbonaceous phyllite, phyllite, quartz mica schist, quartzite and granite, cemented in siliceous and ferruginous matrix. Fine to medium grained lithic matrix is present in a few cases. The pebbles are generally of large sizes and unsorted in the lower part. Upward in the succession, the rock changes to grit, and exhibits graded bedding, a feature that indicates a westward younging direction. The quartz porphyry dykes, intrusive into the conglomerate, are observed at various places. The pebbles in the conglomerate have been drawn from the rocks of the Sirohi Group as well as from the basement granites. The unsorted and sub-angular character of pebbles signifies that the provenance was close by.

3.3.2 *Basalt and pyroclastics*

Basalt occurs in the valley between hills composed of the Sindreth conglomerates and Pamta

Table 3. *Tectono-stratigraphy of the Precambrian rocks of western Rajasthan.*

Age	Reference	Tectono-stratigraphy	Events
680 Ma	Rathore *et al* (1999)	Marwar Supergroup	Maximum age of Marwar Supergroup (Roy and Jakhar 2002)
~ 750 Ma	Crawford and Compston (1970)	Malani Magmatism	Emplacement of Dyke swarms at Dhanta, Sankara and other places Anorogenic granitic intrusion in Sirohi, Jalore, Siwana and Barmer region Opening of the Sindreth-Kankani rift basin (and other parallel rift basins) with basal conglomerates and bimodal volcanics
~ 850 Ma	Choudhary *et al* (1984)	Sirohi Group	Granitic intrusion in Sirohi, Abu and Pali region. End of Sirohi orogenic cycle
~ 1000 Ma	Volpe and Macdougall (1990)		Opening of the Sirohi-Ras basin
~ 1480 Ma	Choudhary *et al* (1984)	Delhi Supergroup	Granitic intrusion in the Delhi Supergroup of rocks. End of Delhi orogenic cycle

rhyolites. It lies conformably over the Sindreth conglomerate, but also includes a few lenses of conglomerate as intertrappean beds. Field study suggests several phases of volcanic activity. The periods of quiescence are marked by cherts and jaspelites. There are also beds of pyroclastics interlayered with sediments. The basalt is a fine grained rock with amygdaloidal and vesicular structure. The colour varies from almost black to dark green; the latter colour is an indication of epidotisation. The presence of green epidote in amygdales of uniform size in a dark groundmass imparts an attractive look to the basalt in hand specimens. Augite and plagioclase feldspar are the two essential minerals, with glass and ore-minerals forming the accessories. Epidote and chlorite form minor constituents. In some samples the amount of epidote-chlorite is around 5%. The amygdales vary in size, and are chiefly made up of epidote, calcite, quartz, chalcedony and zeolite. Augite is fine grained and surrounded by plagioclase laths. Opaque minerals, mainly iron minerals, are euhedral to anhedral in shape, and are fine to medium in size. Chlorite and epidote occur as alteration products. Under microscope, the amygdales do not show any type of deformation features.

Pyroclastic rocks are observed in some nalla cuttings. These are volcanic tuffs and agglomerates. The tuff is light green in colour, fine grained and shows a finely bedded character. Beds strike north south and have a moderate westerly dip. Agglomerates are observed locally to the west of Khamal. The rock is fine to coarse grained, red colored, and includes angular fragments of basalts.

3.3.3 *Pamta rhyolite*

The Pamta rhyolite, called dellenite by Coulson (1933), constitutes the highest physiographic feature in the form of a north-south running hill, known as Pamta hill. The rhyolite conformably overlies the basalt. The rock is fleshy red in colour, fine grained, showing phenocrysts of quartz and plagioclase. At places, it shows ignimbritic texture of quartz and feldspar, indicating welding of these grains at high temperature. In thin sections, the rock shows a fine grained microcrystalline or glassy groundmass enclosing phenocrysts of quartz and plagioclase feldspar. Quartz is anhedral in shape and sometimes exhibits well rounded corroded margins and fracturing. Feldspar (oligoclase) grains are anhedral and subhedral in shape, and shows lamellar twinning. Chlorite, epidote and calcite occur as secondary minerals. In the southern part of the Pamta hill, the colour of rhyolite becomes light pink. The change is gradual and no sharp boundary exists within the rhyolite.

3.3.4 *Angor rhyolite*

It forms a small outcrop at the northern extremity of the Pamta hill near the village Angor, conformably overlying the Pamta rhyolite. It is a green coloured, fine grained, silica-rich ultrapotassic rock in which quartz and feldspar occur as phenocrysts and appear as large anhedral grains with smoothly corroded margins. Orthoclase feldspar is subhedral to anhedral. The groundmass is made up of cryptocrystalline to microcrystalline material as well as glass.

3.3.5 *Volcanic silicic tuff*

Conformably overlying the Angor rhyolite occurs a thick (about 400 metres) formation of silicic tuff. The outcrop runs for several kilometers northward from Angor. The formation comprises a number of units; the thickness of individual units varies from a fraction of a cm to about 20 cm. These are well bedded rocks separated from one other by thin layers of clayey material. The entire sequence appears to be hydroclastic in nature (Fisher 1979). Penecontemporaneous structures like folding, faulting, disrupted bedding, intraformational cherty conglomerates, etc., are preserved in these rocks. Aqueous conditions during ash deposition caused chertification of the siliceous material. Under microscope the rock shows a fine groundmass of glassy to microcrystalline materials with a few phenocrysts of quartz, orthoclase and plagioclase. In some cases, the individual grains are angular.

3.3.6 *Arkose*

Well-bedded arkose showing sedimentary features is well exposed in the western part of the map area. The total thickness of the unit is about one hundred metres. The individual beds are up to 15 cm or more in thickness. There are partings of shales separating beds of arkose. The arkose is pink coloured, consists chiefly of quartz, altered feldspars, and fragments of granite. In some cases, smaller fragments of the above minerals and rocks make up the matrix. The grains are generally well rounded and sorting relatively poor. Graded bedding has been observed in some thicker beds showing coarser clasts at the base, which gradually become finer at the top. In some cases flat pebbly conglomerates occur at the top of beds.

3.3.7 *Angor conglomerate*

This is a transgressive conglomerate deposited during the concluding stage of the Sindreth basin. It is a polymictic, grey coloured conglomerate, and in no way has it any resemblance with the Sindreth conglomerate. It is composed of subrounded, poorly sorted, quartz pebbles and granitic fragments in a lithic matrix.

3.4 *Mirpur granite*

The plutonism associated with Malani magmatic event is seen at Mirpur (approximately 3 km south of Sindreth village, figure 2). This granite is correlated with the Jalore granite (Coulson 1933; Bhushan and Chandrasekaran 2002). The granite preserves magmatic fabric perfectly and there is no indication of later deformation. It is red coloured, non-foliated and coarse-grained granite, which can easily be distinguished from the basement granitic gneisses and the foliated Erinpura granite and Balda granite. It contains pink feldspar up to 1.5 cm in size, medium grained quartz and minor amounts of biotite. The granite is intruded by later felsic and dolerite dykes.

3.5 *Dyke rocks*

There are dyke swarms extending from Dhanta to Sindreth in an ESE-WNW direction, intruding through the Erinpura granite, which constitutes the country rock and Malani volcanic rocks of Sindreth region (figure 2). The dykes also intersect the NNE-SSW running metagabbro body near Dhanta village. The dykes are almost parallel to each other, and form linear hills of low relief. The dykes can be divided into three categories. The chemistry of dyke rocks closely resemble the volcanic counterparts (sample no. 13–18, table 6A).

3.5.1 *Feldspar porphyry*

These are light pink to grey coloured and have feldspar phenocrysts in fine grained groundmass. Rocks consist of plagioclase feldspar, orthoclase and quartz as essential minerals. Chlorite and calcite occur as secondary minerals. These dykes vary in thickness from 2 to 15 m. The maximum length is approximately 4 km.

3.5.2 *Quartz porphyry*

It is a greenish looking fine grained rock, showing phenocrysts of quartz. The silica percentage is higher (79.98%) in these rocks, which gives them compactness. The dyke intrudes the Sindreth conglomerate and Angor rhyolite.

3.5.3 *Dolerite*

These are of smaller dimensions compared to the porphyry dykes. These are fine to medium grained and composed of augite, hornblende and plagioclase as major constituents, and trend parallel to the feldspar porphyry dykes. Biotite and opaque minerals occur as accessory minerals.

4. Stratigraphic status of Sindreth rocks

Coulson (1933) described the conglomerate and associated lava flows and tuffs of the Sindreth area as part of the Aravalli system with a question mark on the status of the associated basic volcanics (table 1). The rhyolites of Pamta Hill, overlying

Table 4. *Startigraphic succession of rocks present in the Sirohi region.*

	Hypabyssal intrusion	Dhanta porphyry and dolerite dykes
Malani magmatism	Plutonism	Mirpur granite
	Volcanism and associated sedimentary units	Angor conglomerate
		Arkose
		Volcanic silicic tuff
		Angor rhyolite
		Pamta rhyolite (dellenite)
		Basalt and pyroclasts
		Sindreth conglomerate
Angular unconformity		
Sirohi Group	Balda granite	
	Carbonaceous phyllite (local)	
	Calc-silicates and marble	
	Mica schist	
Basement rocks	Granitoids, granitic gneiss, and meta gabbro	

the Sindreth basalts, were considered by Coulson (1933) to be typical Malani volcanics. Gupta *et al* (1980) considered the volcanic sequence of the Punagarh and Bambholai region to be part of the Punagarh Group (the youngest component of Delhi Supergroup) and equated them with the Sindreth Group (table 2). The rocks of the Punagarh and Sindreth Groups comprise subaqueous bimodal volcanics with pillow-lava structures, cherts, jaspelites and hydroclastic deposits. These do not show any kind of penetrative deformation and thus post-date the Delhi orogeny (tables 3 and 4).

Bose (1989) agreed on the bimodal character of the Sindreth and Bambholai rocks and their strong resemblance to anorogenic Malani volcanics. He opined that these rocks formed during the time gap between the Delhi orogeny and formation of the Malanis. Bhushan (1999) described two continual episodes of Neoproterozoic magmatism; the first of the syn- to late-tectonic magmatism resulting in Erinpura, Mt. Abu granitoids and Sindreth-Punagarh bimodal volcanics at 900–800 Ma, and the second, of anorogenic bimodal Malani magmatism, at 750–730 Ma.

Chore and Mohanty (1998) included the Malani rhyolites of Pamta Hill in the Sindreth area into the Sindreth Group (740 Ma, Gupta *et al* 1980) without giving any clear reason for this. However, they made no comment on the hypabyssal and plutonic phases described by Coulson (1933) from the same area. Chore and Mohanty (1998) opined that **(a)** although the Punagarh and Sindreth Groups strongly resemble the adjacent MIP (Malani Igneous Province), the two groups indicate a subaqueous depositional environment unlike the subaerial environment of the Malani volcanics, **(b)** The Punagarh and Sindreth rocks occur in linear graben and record a single deformational history with pervasive foliation, unlike the Malani rocks, and **(c)** the chemical characteristics of these are distinct from the anorogenic effusives of the MIP.

Subaqueous emplacement conditions for some of the Malani volcanics are represented by conglomerates and other depositional features observed at Manihari, Kankani, Siwana, Jasol, Lava etc. (La Touche 1902; Pareek 1984; Bhushan 2000). Shyam Naryan (1988) established that the slate/phyllites of the Punagarh group (Gupta *et al* 1980) are fine grained tuffaceous rocks (ash beds) associated with lava flows and suggested that the geochemistry and undeformed nature of the Punagarh rocks resembles the Malani rocks. Roy and Sharma (1999) described the perfectly undeformed and unmetamorphosed character of the Sindreth rocks and the absence of any penetrative deformation in the Sindreth and Punagarh rocks. There is total absence of any type of secondary pervasive foliation in the Sindreth region (Sharma 1996). The different volcano-sedimentary rocks of the Sindreth region do not show any kind of recrystalisation or development of deformational foliation planes. The volcanic fabric of the mafic and felsic flows is well preserved and there is no evidence for later deformation. Chore and Mohanty (1988), on the basis of minor flow warps and flow fold bands in basalts, assumed one phase of deformation. However, they gave no detail of schistosity or deformation and no photomicrograph depicting the nature of the foliation of the Sindreth flows.

Therefore, the Sindreth and Bambholai rocks are neither part of the Delhi Supergroup nor can be accommodated in a separate time slot of post-Delhi and pre-Malani magmatism. These form a part of the Malanis, indicating the initiation of polyphase Malani magmatism. Malani magmatism

Table 5. *Average trace element content (in ppm) and elemental ratios in the different rocks of Diri-Gurapratap Singh region. After Srivastava et al (1989).*

Sample no.	1 Andesite	2 Dacite	3 rhyodacite	4 Rhyolite	5 High silica rhyolite	6 Rhyolite and High silica rhyolite	7 Ultrapotassic rhyolite	8 Rhyolite porphyry
Li	20	16	11	11	8	10	12	8
Rb	55	109	144	192	181	187	269	205
Co	15	5	2	6	7	6	4	6
Cu	12	12	3	7	6	7	11	10
Ni	150	34	6	14	17	16	15	16
Ba	287	1095	969	771	610	697	740	362
Sr	243	226	101	54	40	48	24	29
Zn	82	81	83	67	67	67	69	85
Cr	52	55	15	14	12	13	14	13
K/Rb	229	260	212	207	184	198	222	188
K/Ba	44	29.09	32	63.29	62.18	62.77	86	109
Ca/Sr	143	79.38	133	140.6	151	145.4	157	179
Ba/Rb	5	9.87	7	4.21	3.51	3.89	2.9	1.88
Ni/Co	10	7.06	2	2.47	2.36	2.42	3.62	2.3
Ba/Sr	1.18	4.95	10	14.23	15.68	14.9	35	13.29
Mg/Li	515.7	265.2	166	77.79	89.75	83.32	65.83	73.69

commenced with effusive basalt – rhyolite flows in most of these areas.

5. Geochemistry

Srivastava (1988), on the basis of total alkali vs. silica and total iron vs. alumina plus calcium diagrams, described different chemical associations of magmatic rocks from western Rajasthan:

- Basalt-andesite-dacite-rhyolite association from the Diri-Gurapratap Singh and Manihari area, which represents the oldest rocks of the Malani series. A similar association is also reported from Sindreth, Barmer and Siwana.
- Normal rhyolites, rhyodacite and dacite from Pali, Barmer and Siwana.
- Mildly alkaline trachybasalt-trachyandesite-trachyte-alkali rhyolite of the Tavider, Karara and Sarnu-Dandali.
- Alkaline and hyperalkaline rocks including alkali pyroxenite, ijolite, essexite, syenite and carbonatite from Mundwara and Sarnu-Dandali.

The first two associations belong to the Neoproterozoic Malani magmatic event, while the third and fourth, occurring at Tavider, Karara, Mundwara, Sarnu and Dandali, are related to the Cretaceous-Tertiary period. Srivastava *et al* (1989) opined that the basalt, dolerite, andesite, dacite, rhyodacite, rhyolite and ultrapotassic rhyolite association of the Diri and Gurapratap Singh region is a result of progressive differentiation from andesite to rhyolite (table 5) and their trace-element chemistry suggests a crustal origin.

On the basis of geochemistry Bhushan (2000) divided Malani rhyolites into two—the peraluminous rhyolites, which are characterized by more K_2O than Na_2O, and the peralkaline rhyolites, which show a marked increase in Na_2O compared with K_2O. The average trace-element data indicate enrichment of Zr, Nb, Hf and Ta, which is a diagnostic feature of alkaline magmas. The relative enrichment of Th, La, Ce, Zr and Y suggests a crustal component in the melt.

There is close resemblance of the volcanic rocks of Sindreth to those of Gurapratap Singh and Diri (Sharma 1996; Maheshwari *et al* 1996; tables 6A and 6B). The basalt-rhyolite-ultrapotassic rhyolite association is reported from both the localities. The volcanics show SiO_2 ranging between 50 and 76%. MgO, CaO, Fe_2O_3 and TiO_2 decrease gradually with increase of SiO_2. Less than 1 wt% Na_2O but more than 5 wt% K_2O characterizes the ultrapotassic rhyolites of Sindreth and Diri. The ultrapotassic rhyolites have more than 75% silica and thus a unique chemistry. The comparison of geochemical data from Sindreth and Diri and Gurapratap Singh confirms that their tectonic evolution took place along the north-south running Undwaria-Kankani lineament. The high oxygen isotopic ratio for quartz mineral separates of the rhyolites indicates the role of crustal melting in the formation of Malani rhyolites (Maheshwari *et al* 1996). The elevated initial $^{87}Sr/^{86}Sr$ ratio of Malani rhyolites (Crawford and Compston 1970) also explains the

Table 6A. *Chemical composition of Malani volcanics and dykes of Sindreth region. (After Sharma (1996).) Oxides in weight percent, trace elements in ppm.*

Sample no.	1 Basalt	2 Basalt	3 Basalt	4 Basalt	5 Basalt	6 Rhyolite	7 Rhyolite	8 Rhyolite	9 Rhyolite
SiO_2	51.34	52.34	51.85	51.96	52.69	68.18	71.97	74.62	75.24
TiO_2	1.40	1.45	1.25	1.42	1.01	0.29	0.15	0.10	0.10
Al_2O_3	15.07	15.17	14.92	14.09	16.07	13.92	12.60	12.70	12.84
Fe_2O_3	4.62	6.76	2.54	2.53	3.07	4.39	2.94	2.05	1.68
FeO	7.48	6.12	9.40	10.60	9.60	1.80	0.60	0.32	0.20
MnO	0.16	0.11	0.17	0.16	0.13	0.01	0.01	0.01	0.00
MgO	5.38	4.89	5.28	5.29	3.65	0.64	0.12	0.14	0.20
CaO	4.75	6.10	6.93	7.54	4.79	1.54	1.69	1.26	1.26
Na_2O	3.51	2.60	1.66	1.80	6.26	3.00	3.28	2.85	3.12
K_2O	0.73	0.70	1.19	0.83	0.02	6.73	7.01	6.33	5.63
P_2O_5	0.78	0.79	1.03	0.69	0.38	0.18	0.04	0.02	0.04
Total	95.22	97.03	96.22	96.91	97.67	100.68	100.41	100.40	100.31
Sr	296	371	217	321	164	51	21	14	35
Rb	37	35	54	56	7	154	282	374	237
Ni	57	65	68	84	37	15	15	9	12
Co	17	16	14	15	13	7	6	5	8
Cr	25	26	26	31	23	9	15	12	16
Li	54	52	70	80	20	8	7	7	2
Ba	148	168	169	433	29	154	382	79	293
Cu	16	25	17	24	25	4	5	9	18
Zn	130	97	133	152	87	27	9	2	10

Table 6A. *(Continued)*

Sample no.	10 Ultra-potassic rhyolite	11 Ultra-potassic rhyolite	12 Ultra-potassic rhyolite	13 Feldspar porphyry	14 Feldspar porphyry	15 Feldspar porphyry	16 Feldspar porphyry	17 Quartz Porphyry	18 Feldspar Porphyry
SiO_2	77.86	81.86	77.91	72.9	66.23	71.12	71.46	79.98	65.43
TiO_2	0.10	0.14	0.09	0.17	0.18	0.18	0.19	0.05	0.46
Al_2O_3	10.81	10.31	10.96	14.18	14.32	13.78	13.86	13.07	14.27
Fe_2O_3	1.84	0.98	2.49	1.54	3.22	2.07	2.2	1.05	3.59
FeO	0.40	0.56	0.56	1.64	2.21	2.16	1.84	0.16	4.8
MnO	0.05	0.01	0.02	0.01	0.04	0.03	0.05	0.38	0.07
MgO	0.08	0.10	0.31	0.32	0.42	0.27	0.11	0.38	0.54
CaO	0.13	0.04	0.36	0.71	1.01	0.61	0.81	0	3.06
Na_2O	0.11	0.04	0.05	3.58	4.31	2.47	3.65	0	2.19
K_2O	7.75	5.10	6.35	5.79	7.86	7.17	6.01	3.88	6.03
P_2O_5	0.00	0.00	0.00	0.09	0.07	0.16	0.05	0.13	0.31
Total	99.13	99.14	99.10	100.9	99.87	100.02	100.23	99.08	100.75
Sr	10	9	8	32	47	65	41	5	132
Rb	242	245	295	238	270	290	276	450	186
Ni	15	19	11	25	32	15	17	17	25
Co	12	7	4	9	11	8	10	5	10
Cr	15	19	18	2	3	5	18	10	15
Li	13	16	17	4	5	16	11	23	30
Ba	450	276	258	102	181	220	92	14	943
Cu	7	7	8	6	9	8	9	9	12
Zn	15	17	29	21	48	94	65	8	69

Note: Sample number 13 to 18 are dyke rocks.

Table 6B. *Chemical composition of Malani volcanics from Diri & Gurapratap Singh areas. (After Maheshwari et al (1996).) Oxides in weight per cent, trace elements in ppm.*

Sample no.	1 Basalt	2 Andesite	3 Dacite	4 Dacite	5 Rhyolite	6 Rhyolite	7 Rhyolite	8 Rhyolite	9 Ultra-potassic Rhyolite	10 Ultra-potassic Rhyolite	11 Ultra-potassic Rhyolite
SiO_2	50.86	61.41	64.42	69.60	71.57	73.08	75.11	75.11	76.56	76.56	75.76
TiO_2	1.57	1.22	0.82	0.42	0.25	0.20	0.22	0.17	0.03	0.13	0.19
Al_2O_3	16.79	15.91	16.67	15.30	14.64	14.85	12.91	14.30	13.44	13.58	13.54
Fe_2O_3	2.26	3.83	2.57	1.72	1.35	1.14	1.63	1.64	0.57	1.55	1.08
FeO	7.40	2.60	2.52	2.12	0.74	0.72	0.20	0.12	0.40	0.16	0.12
MnO	0.17	0.16	0.11	0.11	0.07	0.05	0.03	0.01	0.01	0.03	0.02
MgO	5.04	1.71	1.28	0.44	0.11	0.08	0.20	0.19	0.19	0.10	0.04
CaO	8.75	4.85	3.50	2.05	0.85	0.80	1.30	0.85	0.32	0.39	0.88
Na_2O	2.46	4.06	2.68	2.74	2.30	3.05	2.70	2.35	0.55	0.76	0.34
K_2O	0.98	1.52	3.00	3.56	6.08	5.00	4.40	3.65	7.00	6.80	6.75
P_2O_5	0.33	0.66	0.46	0.26	0.14	0.09	0.03	0.02	0.00	0.07	0.13
LOI	2.60	1.60	1.20	0.08	0.80	0.80	1.20	0.60	0.00	0.00	0.80
Total	99.21	99.53	99.23	98.40	98.90	99.86	99.93	99.01	99.07	100.13	99.65
Sr	367	272	286	248	79.00	85.00	63.00	41.00	14.00	53.00	33.00
Ni	55	7	6	4	6	13	9	7	7	6	11
Co	52	15	1	8	5	7	2	3	3	9	4
Cr	70	17	14	9	9	13	15	9	8	8	14
Li	7	20	20	19	1	18	12	5	20	10	5
Ba	754	728	617	1201	864	502	402	949	582	1282	665
Cu	10	12	11	23	24	7	1	7	0	12	10
Zn	87	82	81	82	82	73	57	85	60	107	56
Zr	145	207	193	270	218	242	196	158	65	186	129
Th	0.7	15	14	17	14	28	26	17	18	13	18
Y	27	38	34	47	59	79	111	66	112	63	56
Nb	5	10	10	15	21	19	19	15	17	14	10
La	5	33	29	44	69	56	68	32	29	67	35
Ce	13	64	57	65	136	139	138	65	47	93	61
V	227	79	84	6	4	5	15	7	6	5	5

involvement of continental crust in the formation of Malani volcanics. The absence of a substantial volume of basic component in the dominantly felsic Malanis does not support a mantle origin for Malani magmatism.

6. Tectonic evolution

The Neoproterozoic crustal building process in western Rajasthan is marked with the intrusion of 1000 Ma old diorite and gabbro in the south Delhi fold belt (Volpe and Macdougall 1990). Following this, a narrow linear Sirohi-Ras-Makarana basin (Sirohi Group), similar to 'aulacogen' (Milanovsky 1987), evolved in the silicic crust. This basin is characterized by the linearity over a long distance, and presence of ductile shear zone at the contact of sediments and the basement rocks (Roy and Sharma 1999). The fine clasts (shale and carbonate sediments) deposited in the basin indicate subdued topography of the provenance region. This indicates, that crust during the Sirohi sedimentation was thick and stable. The intrusion of granites at 850 Ma (Choudhary *et al* 1984) marks the culmination of Sirohi cycle and closure of orogenic events in the Aravalli craton of northwestern Indian shield.

The Sirohi basin became thermally stabilised-rifted lithosphere (cf. Morgan and Ramberg 1987) prior to the opening of Sindreth volcano-sedimentary basin. The Malani volcanicity as recorded at Sindreth as well as at Gurapratap Singh and Diri, Pali district is bimodal in character. Sedimentary association of the volcanics includes conglomerate and arkose along with tuffs is suggestive of local aqueous conditions. An angular unconformity is present between basement and eastern margin of the Sindreth basin. This is marked by the presence of north-south trending undeformed polymictic conglomerate with poorly sorted pebbles. The north south Sindreth basin clearly transects the NNE trending inverted basin of the Sirohi Group. This indicates change in structural grain from NNE to almost N-S, is also suggestive of rotation of the stress system. The basement cover relationship of Sindreth rocks with the presence of undeformed conglomerate does not show any type of plate subduction setting. The evolution of dykes transverse to the Sindreth basin margin were possibly along secondary rift fractures transverse to the main basin boundary (cf. Morgan and Ramberg 1987).

Pareek (1984) considered that the main trend of Malani outpouring is fissure controlled and there is relationship between volcanism and tectonic lineament. Srivastava (1988) also proposed that weak lines developed parallel to Aravalli Mountain range during it's upliftment in late Proterozoic time, which further reactivated during epirogenic rise and resulted in outpouring of the Malani volcanism. Sinha-Roy and Mohanty (1988) considered that Malani volcanism resulted due to a low angle subduction of the Delhi oceanic\transitional crust below the western Marwar craton under distensional tectonic regime. Bhushan and Chittora (2000) rejected the plate model after presenting the set up at Kankani (Jodhpur), where Malani unconformably overlying the basement and well defined unconformity plane is present. Kochhar (1984) attributed Malani magmatism to hotspot activity. He argued that there was no movement of the Indian plate relative to the hotspot between 1,500 Ma and 750 Ma. Bhushan (1999, 2000), Raval (2000) and Roy (2001) also suggested hotspot model for the evolution of Malani magmatism. The Moho, as shown by the Deep Crustal Reflection Study (DCRS) below the Marwar and Malani rocks, is an almost horizontal reflective horizon and indicates a uniform crustal thickness (Tiwari *et al* 1998). There is no evidence for marginal sea subduction, collision of the Mewar craton below Marwar or similarities with the Tibetan plateau as proposed by Sinha-Roy (1988, 1999). Field study also indicates that the basement rocks do not have a tectonised/sheared/ductle contact with Malani rocks. Considering the DCRS profile and the basement cover relationship, a Tibet-like Neoproterozoic history for western Rajasthan and a plate-subduction model for the origin of Malani magmatism is not viable (Sharma 2003).

Similar to Malani magmatism, bimodal magmatic activities are also well developed in the Seychelles (Tucker *et al* 2001; Torsvik *et al* 2001) and in Madagascar (Handke *et al* 1999; Kröner *et al* 1999; 2000). The Seychelles islands and the Indian subcontinent have been found to be located at 30° and 32° north, respectively towards the western margin of Rodinia supercontinent at 750 Ma (Torsvik *et al* 2001; Pooranchandra Rao *et al* 2003). Handke *et al* (1999) and Tucker *et al* (2001) interpreted these igneous rocks, together with the Malani igneous suite in northwestern India, are of island arc origin because of their possible continental margin location in Rodinia, facing the Mozambique Ocean. Kröner *et al* (2000) argued that they were developed in an extensional environment rather than island arc setting. Devey and Stephens (1992) and Stephens *et al* (1997) also proposed an intra-plate extensional setting for Seychelles magmatism.

The Malani magmatism of northwestern Indian shield has its bearing on the Rodinian tectonics. Rodinia splitting resulted into widespread Neoproterozoic anorogenic, commonly bimodal, magmatism on most of the continents under extension tectonic regime. After the assembly of Rodinia (~ 1000 Ma), the crust was thick and remained thermally insulated for a long time. Prolonged heat build up in silicic crust resulted extensional tectonics and intraplate anorogenic magamtism. The splitting of Rodinia supercontinent led to the development of new ocean floor, and cratonic fragmentation, which ultimately led to the development of intraplate anorogenic rift magamtism on the northwestern Indian shield, Madagascar, Seychelles and other landmasses.

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