# CHAPTER 2. REGIONAL GEOLOGY AND PREVIOUS WORK

## 2.1 General

The 'Aravalli Mountain Belt' (AMB) is an arcuate-shaped mobile belt having NE-SW orographic trend and runs for over 700 km through the States of Gujarat, Rajasthan, Haryana and Delhi. It is a major mountain belt of north-western India and is made up of Proterozoic supracrustal rocks of the Aravalli and Delhi Supergroups, which are diverse from each other in their depositional environment as well as deformational and metamorphic history. These rocks are a. The Bhilwara Supergroup has an age > 2500 Ma. b. The Aravalli Supergroup from 2500-2000 Ma. c. The Delhi Supergroup ranging up to the period of 700 Ma. The metasediments and associated intrusive as well as extrusive rocks corresponding to these three Proterozoic sequences have been identified as the Bhilwara, the Aravalli and the Delhi Supergroups.These three Supergroups are divided into several Groups and Formations (Gupta et al., 1980; 1992; 1995; 1997).

These Proterozoic supracrustals were deposited on the Archaean basement gneiss complex, called as Banded Gneissic Complex (BGC) which is predominantly a polymetamorphosed, multideformed rock-suite of tonalite-trondhjemite gneiss, amphibolite, migmatite and granitoid, most of which are Archaean (3.4–2.6 Ga old). To the west of the BGC occurs the Delhi fold belt while the Aravalli fold belt made up of the Aravalli Supergroup is located to the east of the Delhi fold belt and also amidst the BGC terrain. The width of the fold belt in the north is about 40 km and it increases up to 150 km toward the south, especially north of Banswara district of Rajasthan.

The AMB of Rajasthan and north-eastern Gujarat comprises several fold belts of the early and middle Proterozoic age. These folds evolved through the development of a series of basins in which sediments and volcanics were laid down in several successive groups bounded by unconformities.

The eastern margin of the Aravalli rocks rests with an erosional unconformity over the underlying Bhilwara Supergroup of rocks, whereas the western margin is bounded by the overlying Delhi Supergroup of rocks. However, its southern extremity is obscured by the cover of Deccan traps and recent sediments. The Aravalli Supergroup is characterized by greenschist facies metamorphism and shows evidences of multi-deformational events, associated with syn-tectonic acidic intrusives (Fig. 2.1).

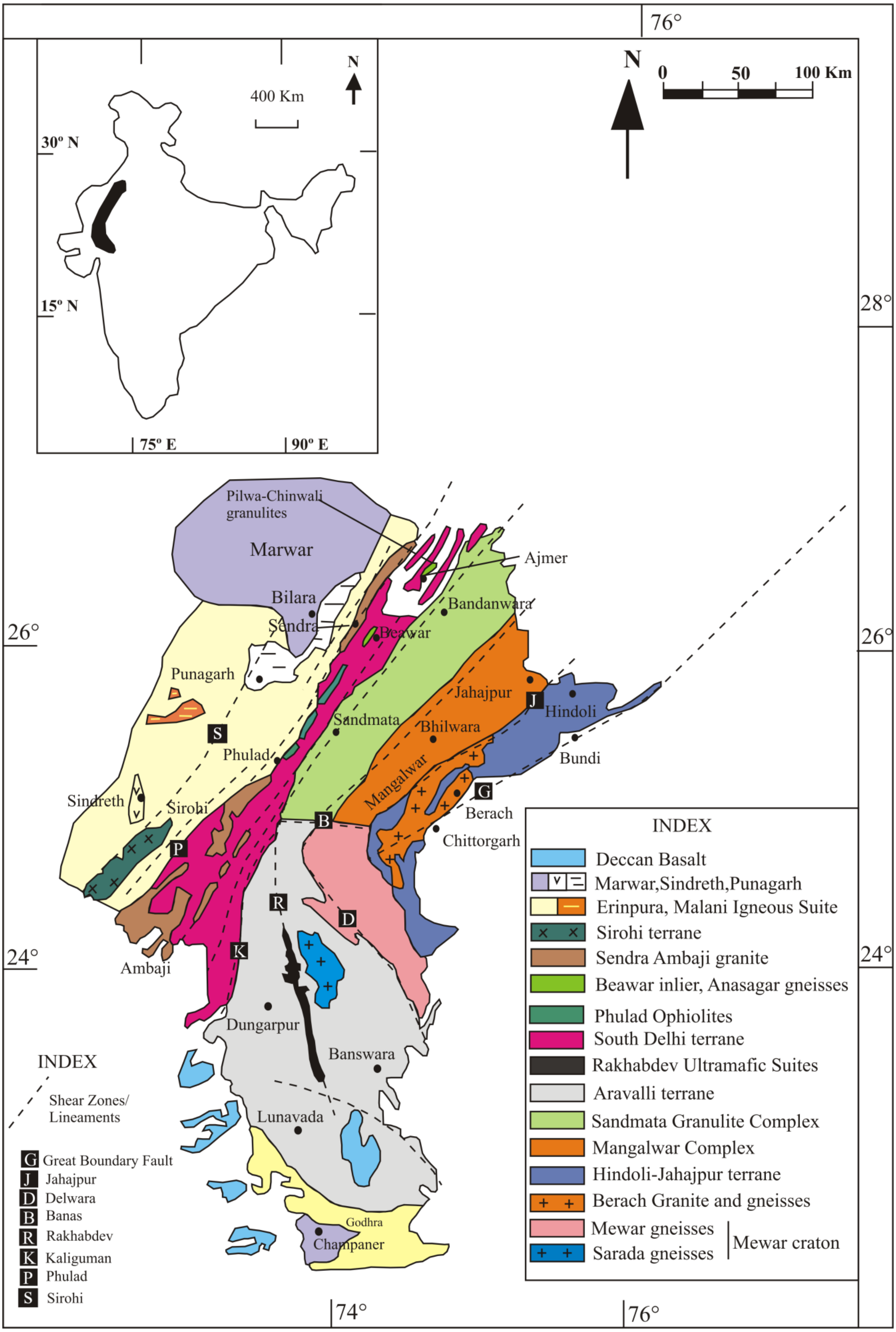


Figure 2.1: Generalised geological map of the Aravalli Mountain belt, (modified after Singh et al.,2010).

A vast amount of geological information with respect to lithostratigraphy, sedimentology and structure had been gathered since nineteenth century. This information is proved to be quite useful to author to get acquainted with this area and to carry out further studies of the area under investigation on that basis. Hence the author found it necessary to present a brief historical perspective of previous studies carried out in the Aravalli region, mainly, around southern Rajasthan and north-eastern Gujarat.

Blanford (1869), one of the architects of Indian Geology was the first to reveal the geology of the Aravalli region. He divided the rocks of the southern part of the Aravalli mountain range into four series (Blanford, 1869, p.27) as below:

Vindhyan series

Bijawar series

Champaner beds

Metamorphic series

Later on, Hackett (1877) revised the nomenclature of the oldest "Metamorphites" of Blanford's classification as the "Aravalli Series". Some workers of the Geological Survey of India provided succinct account on the geology of southern parts of the Aravalli region, namely, the geology of Baroda state by Bruce Foote (1898); in and around Shivrajpur region by Fermor (1909); a work on Idar granites by Middlemiss (1921); geology of Chotta Udepur region by Hobson (1926) and geology of Baria state by B. Rama Rao (1931).

Heron (1953) revised the status of the said sequence as "Aravalli System" (Table. 2.1). In the year 1966, the Aravalli System was designated as "Aravalli Group" by Mathur. Mathur et al., (1973) uplifted the "Aravalli System" to "Aravalli Supergroup" in lithostratigraphic hierarchy considering various groups within the Aravalli Supergroup.

(Gupta et al.,1980) constructed a lithostratigraphic map of the entire Aravalii region and reviewed the lithostratigraphy of Proterozoic rocks of Rajasthan and Gujarat in 1992. According to Gupta et al., (1980; 1992), the parts of Bundelkhand Gneiss, the entire BGC and some parts of the lower Aravalli System of Heron belong to the Bhilwara Supergroup and this basement is overlain by early Proterozoic Aravalli Supergroup and the middle Proterozoic Delhi Supergroup.

Table 2.1: Pre-Cambrian stratigraphic framework of the Aravalli Mountain Belt (after Heron, 1953).

| | | | |
|---|---|---|---|
| | Malani Series | Rhyolite tuff | Granite, ultrabasic rocks |
| | | | Erinpura Granite, pegmatite, aplite, epidiorites and hornblende-schists |
| **Delhi System** | Ajabgarh Series | Upper Phyllites<br>Limestones<br>Biotic Limestones and calc-gneisses<br>Calc–Schists and composite gneisses | |
| | Alwar Series | Quartzites<br>Arkose, grits and conglomerates | |
| | Raialo Series | Garnetiferous biotite-schists<br>Limestone (marble)<br>Local basal grit | |
| | | | Aplogranite, epidiorites and hornblende-schists ultrabasics. |
| **Aravalli System** | | Impure limestones, quartzites, phyllites, biotite schists, composite gneiss.<br>Quartzites, grits, and local soda syenites conglomerates<br>Local amygdaloids and tuffs | |
| Banded Gneissic Complex | | Schists, gneisses and composite gneiss<br>Quartzites | Pegmatites,granites, aplites and basic rocks |

Since the study area falls within Gujarat, the author found it relevant to present the stratigraphy of the Proterozoic rocks of Gujarat given by Gupta et al.,(1980; 1992) and Merh (1995). Table 2.2 displays the lithostratigraphy of the Proterozoic rocks of Rajasthan and Gujarat described by Gupta et al., (1980; 1992). Table 2.3 gives the succession of the Proterozoic rocks in Gujarat (Merh, 1995).

Table 2.2: Classification of the Aravalli Supergroup (after Gupta et al., 1980; 1992)

| | | | | |
|---|---|---|---|---|
| CHAMPANER GROUP | Rajgarh Formation | | | |
| | Shivrajpur Formation | | | |
| | Jaban Formation | | | |
| | Narukot Formation | | | |
| | Khandia Formation | | | |
| | Lambia Formation | | | |
| LUNAVADA GROUP | Kadana Formation | | | |
| | Bhukia Formation | | | |
| | Chandanwara Formation | | | |
| | Bhawanpura Formation | | | |
| | Wagidora Formation | | | |
| | Kalinjara Formation | | | |
| SYNOROGENIC GRANITE AND GNEISS | | | | |
| RAKHABDEV ULTRAMAFIC SUITE | | | | |
| JHAROL GROUP | DOVDA GROUP | | NATHDWARA GROUP | |
| Samlaji Formation | Devthari Formation | | | Rama Formation |
| Goran Formation | Dapti Formation | | | Haldighati Formation |
| | | | | Kodmal Formation |
| BARI LAKE GROUP | Khamnor Formation | | KANKROLI GROUP | Sangat Formation |
| | Varla Formation | | | Puthol Formation |
| | Sajjangarh Formation | | | |
| UDAIPUR GROUP | Udaipur Sector | | Sarada Sector | Rajnagar Formation |
| | Nimachmata Formation | | Zawar Formation | Morchana Formation |
| | Banswara Formation | | Baroimagra Formation | Madra Formation |
| | Balicha Formation | | Mandh Formation | |
| | Eklinggarh Formation | | | |
| | Sabina Formation | | | |
| DEBARI GROUP | Debari Sector | Jaisamand Sector | Sarada sector | Ghatol Sector |
| | Jamarkotra Formation | Babarmal Formation | Kathalia Formation | Jagpura Formation |
| | Berwas Formation | Dakankotra Formation | Sisamagra Formation | Mukandpura Formn. |
| | Jaisamand Formation | Jaisamand Formation | Nathariya-ki-por Formn. | Jaisamand Formation |
| | Delwara Formation | Delwara Formation | | Delwara Formation |
| | Gulari Formation | | Basal Formation | Gurah Formation |

Table 2.3: Proterozoic Succession of Gujarat (Merh, 1995)

| | |
|---|---|
| Delhi Supergroup | Post-Erinpura Granite Mafic rocks, Erinpura Granite (= Malani),Godhra Granite<br><br>Pre-Erinpura Granite Mafic rocks<br>Sirohi Group<br>Ambaji Granite<br>Kumbhalgarh Group<br>Gogunda Group |
| Aravalli Supergroup | Champaner Group<br>Lunavada Group<br>Rakhabdev Ultramafic Suite<br>Jharol Group |

## 2.2 Aravalli Supergroup exposed within Gujarat

Out of nine groups of the Aravalli Supergroup (Gupta et al., 1992), only three groups namely, the Jharol Group, the Lunavada Group and the Champaner Group are exposed within Gujarat (Merh, 1995). These groups are described below:

### *2.2.1 Jharol Group*

The shaly, flysch-like as well as non-calcareous clastics which represent the orogenic phase of the 'Aravalli Geological Cycle' have been termed as the Jharol Group. This group encompasses oldest Proterozoic rocks of Gujarat and is exposed in the Sabarkantha district, north of Modasa, extending northward through Shamlaji into Rajasthan. The strike length of this group is about 190 km with a width of 40 km. The Jharol Group thins out towards the northern direction, where its width reduces to 2-5 km. The constituent rocks are phyllites, chlorite schist, gametiferous mica schist with intercalations of quartzite which are thicker in the upper part of the group, along with minor lenses and bands of calc-schist and crystalline limestone.

Towards east, the rocks of the Jharol Group lie unconformably over the the Bari-lake Group, whereas the basal rocks of the Delhi Supergroup are found to be resting over it towards west with structural incongruence. The rocks have undergone polyphase deformation and show a progressive increase in metamorphism from lower greenschist facies in the east to lower amphibolite facies in the west.

### *2.2.2 Rakhabdev Ultramafic Suite*

These rocks occur in the Antaliya-Rakhabdev-Kherwara-Dehlana area and consist predominantly of serpentinite which due to extensive metamorphism has altered to talc rocks. In Gujarat they are present as discrete outcrops around Idar and Lunavada areas. Irregular lensoidal bodies of these rocks are distributed in three different belts, each having nearly 5 km in length. The first belt extends from Dad in Dungarpur district in the south-east to Sero-ki-Pal in the north over a distance of 77 km, the second from Kanthria to Kaliguman over a distance of 115 km and the third from Kaunthal to Titri over a distance of 15 km. Occurrence of the Rakhabdev Ultramafic Suite along the Rakhabdev and Kaliguman lineament indicates deep roots within the mantle.

From their structural setting it is revealed that they were emplaced during an early stage of Aravalli orogeny (Mathur, 1966; Basu and Arora, 1968; Rakshit, 1969; Arora, 1971; Chattopadhyay, 1975) and hence this suite has a concordant relationship with the folding of Aravalli supracrustals (Gupta et al., 1997). The ultramafic belt of North Gujarat and South Rajasthan forms a large regional antiform whose limbs fall within Gujarat (Patel and Merh, 1967). The western limb occurs in Idar and Shamlaji area while the eastern limb extends from Dungarpur in Rajasthan to Ditwas near Lunavada area in Gujarat. According to Merh (1995) it represents the closing period of Aravalli sedimentation and an on-set of deformation due to which these intrusives occur as bands and lenses parallel with the schistosity of Aravalli meta-sediments.

Serpentinites form from complete serpentinization of ultramafic rocks,they have shades of green, compact or dense nature, breaks with a conchoidal fracture and show a greasy appearance. Along minor slickensides and slip planes within these rocks, the development of asbestos can be noted. Petrography shows a network of prismatic laths or flakes of antigorite along with chrysotile, chlorite,carbonate minerals as well as magnetite, chromite, altered olivine and pyroxene in some thin sections.

### *2.2.3 Lunavada Group*

The rocks of the Lunavada Group roughly occupy a polygonal area, extending from Mahur in the north to Sejwada in the southeast and between Dharsua in the west to Kushalgarh in the east. It forms the uppermost part of the Aravalli Supergroup and possesses thick metasediments with few bands of chemogenic as well as biogenic rocks. There are total six formations within the Lunavada Group namely, Kalinjara, Wagidora, Bhawanpura, Chandanwara, Bhukia and Kadana on the basis of strike persistence and local relationship of superposition (Gupta et al., 1980; 1992).According to Iqbaluddin (1989), only parts of the Kadana formation fall within Gujarat while rest of the formations occupy areas of southern Rajasthan.

Towards southwest, this sequence is terminated by the Godhra Granite. The southeastern boundary is covered by Deccan traps and Cretaceous infratrappeans. The constituent rocks represent a sequence of phyllite, mica schists, quartz chlorite schists, meta-subgreywacke, meta-siltstone, meta-semipelite, meta-protoquartzite with minor layers and thin sheets of dolomitic limestone, petromict metaconglomerate, manganiferous phyllite and phosphatic algal dolomite (Gupta et al.,1980; 1992).

According to Merh (1995), the lithological characteristics of this group represent a shallow marine environment, perhaps in the intertidal beach and shelf zones. At a few places, the rocks are reported to have preserved sedimentary structures like laminated bedding, cross-bedding and ripple marks. The quartzites stand as high ridges while low-lying areas are characterized by softer rocks such as chlorite schists (Gupta and Mukherjee, 1938; Narayana, 1974).

According to Mamtani (1998);Mamtani et al.,(2000); Mamtani et al.,(2001),the Lunavada region has experienced three phases of deformation. $D_1$ and $D_2$ deformations are coaxial having NE-SW trending folds. The $D_3$ phase of deformation has developed broad open warps and kinks on kilometre-long limbs of $D_1$ and $D_2$ folds. The superposition of these three deformational events resulted in the complex zig-zag patterns of quartzites with dome and basin structures. A combination of $D_1$ and $D_2$ folds has generated “Type III” or “Hook shaped” geometry whereas the last phase of deformation has developed “Type I” i.e. “Dome and Basin” geometry.

The $D_3$ deformation is associated with the syn to post thermal event also i.e. Godhra granite. The grade of metamorphism in the Lunavada region increases from chlorite-schists in the north to garnet-mica schists in the south, respectively. The overall regional metamorphism has reached up to upper greenschist to lower amphibolite facies condition.

### *2.2.4. Champaner Group*

The Champaner Group is one of the well-developed Pre-Cambrian sequences of Gujarat which extends from Jambughoda in the east to Champaner in the west and Malao in the northwest to Rustampura in the south. The group forms an‘inlier’ as it is surrounded by younger rocks i.e. Godhra granites, which lie to its east, north and south direction whereas Deccan traps are exposed to its western direction which are younger than the rocks of the group.The Champaner Group consists of a sequence of meta-subgreywacke, sandy phyllite, mica-schists, protoquartzite, petromict meta-conglomerate, dolomitic limestone and manganiferous phyllite.

The entire sequence is folded to form an anticlinorium with westerly plunging antiforms and synforms (Merh, 1995). The Champaner rocks were deposited on older gneisses unconformably as indicated by the presence of conglomerate at their contact. On the basis of lithological homogeneity and mapability, this group is divided into five formations, viz.the Lambia, the Khandia, the Narukot, the Shivrajpur and the Rajgad Formations.

Abundant manganese mineralization within the rocks of this group was the main attraction for earlier workers. This group has undergone simple deformation leading to the formation of open to tight isoclinal folds with axial traces having WNW-ESE to E-W trend and axial plane schistosity, oblique to the original bedding planes (Roy, 1985,1988; Merh, 1995).

The grade of regional metamorphism has reached upto greenschist facies. The development of calc-silicate skarns due to Godhra granite intrusion can be clearly seen at Jothwad village near Jambughoda (Merh,1995).According to (Gupta et al.,1997), the Champaner sequence represents an original accumulation of clastic sediments with carbonate rocks, representing molassic association deposited in a basin separated from the Lunavada Group. Merh (1995) has suggested that the Lunavada and the Champaner basins were perhaps separated by a basement high.

### *2.2.5 Godhra granite*

Godhra granite and gneiss occupy the areas including Chhota Udepur, Godhra, Balasinor and Sodiamba. Due its maximum coverage in the Godhra area, it has been named as ‘Godhra granite’ (Gupta et al., 1997). Gupta and Mukherjee (1938) determined their age as post –Delhi which is supported by the radiometric age of 950 Ma given by Crawford (1969) and the recent Rb-Sr isochron age at 955 ± 20 by Gopalan et al., (1979). According to (Gupta et al., 1997), the Godhra granite is intrusive to the Champaner and the Lunavada Group. This granite is coarse to medium grained, mostly porphyritic and generally has a greyish-white or pinkish colour. General mineralogical composition of this granite is quartz, potash/ plagioclase feldspar, biotite/muscovite, tourmaline and occasionally garnet as observed in the field. It shows gneissic texture near the contact with metapelites. On the basis of mineralogy and textures three types of granites have been identified, viz. a) Soda granite, composed predominantly of plagioclase feldspar, b) Potash granite, consisting predominantly of potash feldspar and c) Porphyritic potash granite with phenocrysts mostly of potash feldspar and accessories of muscovite and tourmaline.

## 2.3. Background information on the study area

### *2.3.1. Gupta and Mukherjee (1938)*

Gupta and Mukherjee studied the geology of the southern Rajasthan and northern Gujarat in terms of lithostratigraphy in 1938 for the first time which included the Dungarpur, Banswara and Kushalgarh areas of southern Rajasthan and parts of Sabarkantha and Panchmahal (erstwhile Rewakantha states) around Lunavada, Santrampur, Sanjeli, Kadana and Balasinor.

According to them the regions of Dungarpur, Banswara, Sant and Kadana were investigated earlier by N.D.Daru under the supervision of C.S.Middlemiss between 1907-1914 while the parts of Pratapgarh, Jhabua and Kushalgarh were studied by Walker and Heron in 1907-1908. The areas to the south of the above regions were investigated by Gupta and Mukherjee between1931-1935. All of the above work was compiled then and published by Gupta and Mukherjee (1938). They have stated that the area studied has undulatory topography with highly resistant quartzites occurring as ridges while the planer areas were occupied by comparatively softer rocks like chlorite schists. Table 2.4 presents the details of the geological formations given by Gupta and Mukherjee.

According to these workers, a highly involute gneissic complex,i.e pre-Aravalli gneissic complex or BGC represents the oldest formation of the area which shows continuity with the BGC of central Mewar. These rocks are reported from Pratapgarh, Dungarpur and Banswara and are characterized by a heterogeneous assemblage of various igneous rock types. The rocks of the Aravalli Supergroup overlie these gneisses and the contact is being marked by an erosional unconformity shown by bands of the conglomerate.

According to them, the Aravallis are the most widespread geological unit in southern Rajputana and north and central Gujarat and are represented by (1) a basal quartzitic or conglomeratic formation (2) an impure calcareous facies and (3) an argillaceous series along with arenaceous intercalations.

Gupta and Mukherjee (1938, p.179) have stated ***"It is not possible to map the various types of the argillaceous metamorphics separately. The intermittently soil covered condition of the country and the infinite gradation obtaining between the different types have rendered any attempt at the separate mapping of these on the one inch to the mile scale maps impracticable"***

They reported the presence of streaky and highly foliated biotitic gneisses at the southern part of the Aravalli schists. Again the Aravallis appear at the south of these gneisses extending towards the Panchmahal and Vadodara districts. These were the Champaner Series earlier described by Blanford (1869) and considered as the southern extension of the Aravallis. The Aravallis are intruded by granite along with aplite and pegmatite dykes. Mapping of these granites has been carried around Godhra where they are abundantly present.

To the north, the granite lies along the southern boundary of Lunavada state whereas in the east it occurs extensively at the southwestern part of Baria. In the west the granites cross the Mahi extending up to Balasinor and across Kalol taluka of Panchmahal towards southward direction.

These granites show no dynamic effects and their mode of occurrence and association with the Aravallis indicate that they had no role in the tectonic movements that resulted in the folding of the ancient sediments. Alwar quartzites, the basal part of the Delhi System occupy the northwestern corner of the area mapped by Gupta and Mukherjee and are having continuity with the Alwar quartzites of Mewar and northeastern Rajputana.

The Palaeozoic rocks are totally absent in the area. The formations belonging to the Mesozoic era (the infratrappeans, viz. Ahmednagar Sandstone, Bagh and Lameta beds) which overlie the Pre-Cambrian rocks have sporadic occurrence thus marking an unconformity.

Gupta and Mukherjee described the outcrops of the infratrappeans, especially Lameta bed from Kushalgarh-Banswara region, Jhalod and Dohad talukas and parts of Baria, Balasinor, Lunavada and Gabat. Bagh beds occur as a lensoidal and discontinuous outcrop along the margin of the Deccan Traps in Jhabua, Alirajpur States of Central India Agency (Madhya Pradesh) and Vajir, Agar, Naswadi, Boriad and Chhota Udepur states of the Rewakantha agency (Gujarat).

The Deccan Traps overlie the infratrappean in various parts of NE Gujarat like Dohad and Jhabua area and within the Lunavada and Balasinor states.

Table 2.4: Formations present in Gujarat (after Gupta and Mukherjee, 1938)

| | | | |
|---|---|---|---|
| Recent and PostTertiary | Recent and sub-recent soil<br>Kankar, calcareous conglomerate, laterite etc. | | |
| | | | Erosion unconformity |
| Eocene | Deccan Trap | | |
| | | | Eruptive unconformity |
| Createaceous | Infratrappeans | Bagh beds, Lameta beds<br>Nimar sandstone<br>Ahmednagar sandstone | |
| | | | Eruptive unconformity |
| Algokian | Delhi System | Alwar quartzites | |
| | | | Erosion unconformity |
| Archean | Aravalli System | Composite gneisses, phyllites, slates and schists with quartzite intercalations<br>Limestone<br>Basal quartzite and conglo-merate | Intrusive quartz veins, pegmatites, Granites, Epidiorites (amphibolites) |
| | | | Erosion unconformity |
| | Pre-Aravallis | Banded Gneissic Complex | |

***2.3.2. Narayana (1969, 1970/71, 1974)***

Narayana (1969, 1970/71,1974) studied the Proterozoic rocks around Godhra and Devgadh Bariya in detail. On the basis of megascopic and microscopic characteristics, Narayana (1969) classified the Godhra Granite into three types viz. fine grained granite, coarse-grained granite and porphyritic Granite. He concluded that the Godhra Granite is an igneous plutonic rock and is intruding Aravalli rocks. Quartzites possessing sillimanite are also reported by Narayana near Vejalpur near granitic bodies which according to him are on account of contact metasomatism due to granite. Narayana (1970/71) reported mylonitic rocks from Devgadh Baria along granitic intrusion.

According to him, mylonitization indicates dislocation metamorphism caused due to the emplacement of the post-Aravalli granites and the nature of the original rock controls the formation of various types of mylonites. If the original rock was quartzite, it will undergo extreme granulation followed by recrystallization, thus resulting in crushed rocks like hartschiefer and if the original rock was granite, it was not affected by high degree of crushing and recrystallization as the quartzites and in such conditions, kakirites are developed from granites. Narayana (1970/71) concluded that the occurrence of the mylonites is indicating thrust fault may be due to the gliding of Aravalli formations over granites. Narayana (1974) reported amphibolites to the south and southeast of Devgadh Baria in the form of discontinuous bands lying parallel within the rocks of the BGC and also as caught-up patches in granites. Based on the field studies and petrogenesis, he classified the amphibolites into two types, viz. ortho and para-amphibolites.

### *2.3.3. Patel and Merh (1967)*

The talc-serpentinite ultramafic rocks occurring around south Rajasthan and north Gujarat were studied by Patel and Merh (1967). According to them, these rocks occur as a linear stretch with NNW-SSE trend extending from Kherwara, Rakhabdev and Dungarpur areas of Rajasthan right up to the borders of Panchmahal in Gujarat and also occur around Idar, Shamlaji, Modasa and Bhiloda areas of north Gujarat. Based on the mode of occurrence, structural aspects and the tectonic setting,these ultramafic exposures were classified into three groups:

1. Exposures at the west within Idar area of Sabarkantha occurring in the fold cores.
2. Exposures at the north occurring around Kherwara-Rakhabdev in the form of prominent outcrops at the crests of the hills or as bands in chlorite schists.
3. Exposures at the east extending from Dungarpur for more than 50 km and running parallel to the foliation of the country rocks in the form of continuous and narrow bodies.

According to these workers emplacement of these ultramafics occurred during the waning phase of the Aravalli sedimentation and the beginning of the deformation. They stated that the ultramafic bodies in north Gujarat and south Rajasthan are probably on account of the superimposition of the Delhi folding on the Aravalli rocks due to which the entire ultramafic belt folded into a large antiform plunging due north. Thus, Patel and Merh (1967) opined that the ultramafics in southern Rajasthan and north Gujarat belong to a single ultramafic belt in the Aravallis subsequently folded into a large antiform wherein exposures at Idar show prominent axial plane cleavage, indicating an effect of Delhi folding whereas eastern exposures along the Dungarpur are devoid of minor folds indicating no effect of Delhi folding while the northern exposures at Kherwara form the crest of the northerly plunging antiform.

***2.3.4. Iqbaluddin et al., (1976), Iqbaluddin (1989)***

Iqbaluddin et al.,(1976) have carried out the photogeological mapping in parts of the Kadana Reservoir area of the Panchmahal district, with selective checks. The stratigraphy, sedimentology along with the aspects like structural or deformational as well as the metamorphic history of the Proterozoic sequence of Kadana reservoir and adjacent areas (area included in Survey of India toposheet No. 46 E/15 and 46 I/3) have been worked out by Iqbaluddin (1989).

He mapped the parts of Banswara and Dungarpur districts of Rajasthan and the Panchmahal district of Gujarat having an area near-about 500 sq. km falling within latitudes N23° 45’ to N23° 30’ and longitudes E73° 45’ to E74° 15’.

Iqbaluddin recognized that the oldest formation in an area around Kadana reservoir is the Vareth Formation which belongs to the Udaipur Group for the first time and stated that this formation comprises schists and phyllites.

The Lunavada Group which hosts the rocks like chlorite schists, metasiltstones, meta-protogreywacke, garnetiferous-mica schist, quartzite and metaconglomerate is younger than the Udaipur Group and according to him There is a structural variance between the Udaipur and the Lunavada Groups which is clearly seen at Jardo, Mor and Antari in Banswara district, Rajasthan.

Based on lithology, strike persistence and local relationship of superposition the rocks of the Lunavada Group have been classified into Wardia, Nahali, Bhawanpura, Chandanwara, Bhukia and Kadana formations from oldest to youngest. Out of these only Kadana Formation falls within Gujarat while the rest of the formations fall in Rajasthan.The lithostratigraphy of the Kadana reservoir and adjacent areas in Gujarat and Rajasthan constructed by Iqbaluddin(1989) has been shown in Table 2.5.

According to him, the rocks of the Kadana reservoir area show $AD_2$, $AD_3$ and $AD_4$ deformations of the Aravalli tectonics. The $AD_2$ deformation resulted in the $AF_2$ folds having $AS_2$ foliation.

Table.2.5: Lithostratigraphic sequence of the Kadana reservoir and adjacent area, Rajasthan and Gujarat states, India (after Iqbaluddin, 1989)

| Era/Period | | | Metamorphites of Rajasthan | | Metamorphites of Gujarat | |
|---|---|---|---|---|---|---|
| | | | Rank | Lithology | Rank | Lithology |
| | | | Deccan Traps | Basaltic Lava flow | | |
| ---------- Unconformity ---------- | | | | | | |
| Palaeocee to Upper Cretaceous | | | Post-Aravalli Intrusives | Quartz veins<br>Pegmatite veins | | Quartz veins |
| PROTEROZOIC | Aravalli Supergroup | | | **(top not seen)** | | |
| | | Lunavada Group | Bhukia Formation | Meta-protoquartzite with intercalations of meta-subgraywacke, quartzite(Quartz-arenite),meta-siltstone and quartz-sericite schist | Kadana Formation | Quartz-arenite, meta-subgraywacke, meta-semipelite, and meta-silitstone |
| | | | Chandanwara Formation | Meta-subgraywacke with intercalations of quartz-chlorite-sericite schist , metaprotoquartzite and quartzite(Quartz-arenite) | | |
| | | | Bhawanpura Formation | Quartz-chlorite-sericite schist with intercalations of meta-protoqaurtzite and meta-subgraywacke | | |
| | | | Nahali Formation | Quartzite and quartz-sericite schist with intercalations of conglomerate and pebbly quartzite | | |
| | | | Wardia Formation | Quartz-bioite-sericite schist,garnetiferous quartz-biotite-sericite schist with interalations of para-amphibolite, Amphibole quartzite. | | |
| | | | | **(base not seen)** | | |
| | | ---------- Unconformity ---------- | | | | |
| | | Rakhabdev Ultramafic Suite | | Talc-chlorite schist, serpentinite and carbonate rock | | |
| | | Udaipur Group | Vareth Formation | Quartz-chlorite-sericite schist and chlorite phyllite | | |

The $AS_2$ foliation can be seen prominently in the rocks of the Vareth Formation only. Lunavada Group of the rocks in the Kadana reservoir area have experienced $AD_3$ and $AD_4$ deformation and the structural elements consist of $AF_3$", $AF_3$, $AF_3$' $AF_4$ folds; $AS_3$", $AS_3$, $AS_3$', $AS_4$ foliations and $A\beta_3$", $A\beta_3$, $A\beta_3$' and $A\beta_4$ lineations.

The first, second and third phases of deformation correspond to $AD_3$ while the fourth phase to the $AD_4$ deformative episodes. The first phase led to the development of $AF_3$" folds, $AS_3$" foliation and $A\beta_3$" lineation. The second phase of deformation led to the development of $AF_3$ folds and $AS_3$ foliation and $A\beta_3$ lineation. The $AS_3$ foliation is manifested in the form of schistosity in the Kadana formation having a trend from N-S to NNE-SSW and dipping towards the West.

The third deformation phase led to the development of $AF_3$' folds, $AS_3$' foliation and $A\beta_3$' lineation and as the deformation progressed the $AS_3$' crenulation cleavage formed on account of the shear mechanism. The $AF_3$' folds also developed in the form of puckers. The fourth deformative episode developed $AF_4$ folds and $AS_4$ foliation striking WNW-ESE and dipping towards NNE. The $AF_4$ folds are temporally post-tectonic to $AF_3$ and are kinematically related to the WNW-ESE trending Champaner folds.

According to Iqbaluddin (1989), the deformation of the Lunavada Group of rocks in the Kadana reservoir area was followed by metamorphism which is reached up to greenschist facies. A total of five metamorphic phases viz., $M_1$, $M_2$, $M_3$, $M_4$ and $M_5$ have been counted within the Kadana reservoir area. The $M_1$, $M_2$, $M_3$ and $M_4$ phases are on account of $AF_1$, $AF_2$, $AF_3$ and $AF_4$ folding events respectively while the $M_5$ phase is a static event of granitic intrusion.

During the $M_1$ phase elongation of quartz and rotation of sericite flakes parallel to the $AS_3$" foliation took place and the $M_2$ phase led to the recrystallization of quartz and sericitization syntectonically with $AS_3$ foliation. Chlorite-1, muscovite and actinolite crystallized from earlier minerals. During the $AF_3$' folding, crenulation cleavage developed in the Wardia and Nahali formations of the Lunavada Group which was followed by the $M_3$ phase of metamorphism during which garnet developed at the expense of chlorite-1 and quartz. Retrogression of biotite to chlorite-2 perhaps occurred during the receding $M_3$ phase.

$M_4$ phase is reflected by flattening, elongation and micro fracturing of quartz and rotation of sericite along $AS_4$ foliation. $M_5$ phase, a last metamorphic event which is a static event also, is related to the increase in temperature in the area post-tectonic to Aravalli deformation, around 955 Ma on account of intrusion of the Godhra Granite pluton. This event led to the static recrystallization of garnet and chlorite-3.

### *2.3.5. Mamtani et al.,1996, Mamtani (1998, 1999, 2000, 2001, 2005, 2012, 2014, 2015)*

Structural aspects of the Pre-Cambrian rocks of the Lunavada area were studied by Mamtani in great detail. Mamtani et al.,(1996) observed that the micas of crenulated schist of Lunavada Group show microstructures similar to schistosite-cissilament fabric and extensional crenulation cleavage, the characteristics of ductile shear zones. They suggested that during successive stages of formation of crenulation cleavage, solution transfer is dominant during the earlier stages whereas shearing during the later stages. Proper understanding of the structures and deformational mechanisms of the Southern Aravalli Mountain Belt (SAMB) was facilitated by Mamtani (1998).

According to him, this region experienced three deformational phases viz. $D_1$, $D_2$ and $D_3$ with the first two episodes resulted in NE-SW trending tight coaxial isoclinal folds while the third phase gave rise to open WNW-ESE trending fold. Due to the superposition of the three fold events regional scale interference patterns are generated in different parts of the study area. The superposition of the coaxial $F_1$ and $F_2$ folds gave rise to a regional Type-III interference pattern which can be observed in the southern parts of the study area. Type-I interference developed due to the superposition of WNW-ESE trending $F_3$ folds on NE-SW trending $F_1$-$F_2$ folds mainly in the central and southern parts of the study area. $F_3$ folds developed on limbs of $F_2$-$F_2$ folds.

He stated that the degree of overturning of the $D_1$-$D_2$ folds increases from N to S, similarly, Anisotropy of Magnetic Susceptibility (AMS) data coincides with the field structural data, thus indicating a close relationship between the magnetic ellipsoid and the structure of the area. In a few samples, the magnetic foliation does not fit with the field planar data. In such samples, the AMS provides evidence of deformation events which could not be recorded on the mesoscopic scale. Using this technique, $D_3$ folds could be recognized. Similarly, it has been possible to recognize $D_2$ folds in other parts of the area.

According to him, the regional metamorphism in the study area had been progressed up to lower amphibolite facies with the appearance of garnet in some of the schists. Regional metamorphism associated with the $D_1$ and $D_2$ deformation was progressive up to a major part of the $D_2$ event. Chlorite and biotite formed during $D_1$ and progressive metamorphism led to the formation of garnet and new biotite porphyroblasts during $D_2$ deformation. The progressive regional metamorphic events related to $D_1$ and the major part of $D_2$ deformations have been termed as $M_1$ and $M_{2-1}$ metamorphisms, respectively. Some retrogressive metamorphism ($M_{2-2}$) occurred during the waning phases of $D_2$ deformation during which garnet and biotite retrograded to chlorite at their rims and along fractures.

He observed that the grade of metamorphism of the metapelites increases from N to S pointing towards the deeper crustal levels of the study area towards its south, brought up syntectonically or followed by peak metamorphism. Garnets in the garnet biotite schists show growth zoning and a few of them have undergone diffusion zoning also, at the rims. This can be attributed to retrogressive metamorphism subsequent to the achievement of peak metamorphism. On the basis of thermo-barometry, he concluded that there were P-T conditions during the growth of garnet from core to rim indicating uplift during garnet growth (syn-$D_2$ uplift). According to him, fluid inclusion studies also supported the conclusions drawn from thermobarometry of upliftment of rocks subsequent to peak metamorphism. The thermal event of Godhra Granitic intrusion was experienced by these rocks after regional metamorphism.

Some inferences have been drawn from the 'Crystal Size Distribution'(CSD) studies carried out by Mamtani (1998),i.e. due to the annealing of minerals because of the heat supplied by the nearby granitic intrusion , the quartz grains within schists and quartzites show certain characteristics like coarser grain size,sharp extinction along with straight grain boundaries making a triple junction with 120° angle between them, less number of total crystals within unit area, large mean crystal size and bell-shaped CSD plot while quartz grains within schists and quartzites lying away from granitic intrusion exhibit exactly opposite characteristics along with near linear CSD plot. Godhra Granites carried some fluid along with them which were entrapped as inclusions and as per microthermometry data; some of the aqueous fluid inclusions have salinities of NaCl.

Mamtani et al.,(1999) reported the structures similar to mylonites from cleavage zones of differentiated crenulation cleavage in garnet biotite schist belonging to the Lunavada Group of Proterozoic metasedimentary rocks ,India. According to them, although the schist under investigation does not show any macro or mesoscopic scale evidence of mylonitization, they show fabric resembling S-C and C' shear bands within these zones indicating shearing within them during $D_2$ deformation.They put forward a model incorporating shearing along the cleavage zones to explain the genesis of shear structures within them. Accordingly, it is invoked that solution transfer and grain rotation are important deformation mechanisms during the early stages of crenulation.

It is proposed that the fabric resembling S-C embryonic C' type shear bands and well-developed C' develop with increasing strain and shearing within cleavage zones. At still higher strains the shear bands may rotate into parallelism with the domain boundary between cleavage zones and the microlithons. The composition of muscovite constituting cleavage zones and microlithons is discussed and it is inferred that the deformation mechanisms that operated during later stages of crenulation especially under upper greenschist to lower amphibolite conditions are similar to those during mylonitization.

According to Mamtani et al., (2000), northern parts of SAMB underwent brittle-ductile deformation whereas the southern portion underwent more ductile deformation. They attempted to visualize the possible causes that led to the deformation of SAMB, the structural geology, established by the authors and to constraint the timing of these events based on already available geochronological data. A‘working hypothesis’ is proposed,which suggests that the deformation of the SAMB is the result of the accretion of these three proto-continents viz. Aravalli, Dharwar and Singhbhum during Mesoproterozoic.

Mamtani et al., (2001) have discussed the relationship between metamorphic and deformation events. According to them from north to south in the Lunavada Group, there is a marked horizon from chlorite to garnet-biotite schists. $M_{2-1}$ metamorphism was associated with the major part of $D_2$ and $M_{2-2}$ was contemporary with the waning phase of $D_2$ deformation. Early $D_3$ deformation was retrogressive. Porphyroblast-matrix relationships within schists have been useful for establishing these facts. The metamorphic rocks studied were intruded by Godhra granite during later $D_3$/post $D_3$ event.

Mamtani et al., (2005) presented the field, microstructural and anisotropy of magnetic susceptibility (AMS) data from the Godhra Granite (Ca.1 Ga) pluton at the southern margin of the Aravalli Mountain Belt (Western India). Microstructural studies revealed the evidences of the deformation of granite with high temperature solid-state deformation fabrics, similar to the presence of preferentially oriented feldspars. Both the stretching lineations and magnetic lineations at the granite margin high strain zones are parallel with the axes of $D_3$ reclined folds in the gneiss. From this fact they inferred that the emplacement of Godhra granite have taken place syntectonically, while the gneiss was undergoing the $D_3$ phase of deformation, the magnetic fabric data of granite and the available geochronological data from rocks of the southern Aravalli region are summarized, based on this information it is suggested that the emplacement of Godhra granite, deformation of southern parts of Aravalli mountain belt and tectonothermal events along the CITZ and Rodinia supercontinent assembly were related events.

Mamtani (2012) evaluated the grain size (d) and shape of 225 magnetic grains that crystallized at T> 600° C in a syntectonic granite,i.e. (Godhra Granite) on the basis of which the deformation mechanism of magnetite had been deciphered . Fractal dimension (D) analysis of magnetite grains was performed. SEM-EBSD studies revealed that the shape of magnetite grains was not controlled by dislocation creep. Finally, it is concluded that the higher serration, increased fractal dimension and finer magnetite grains imply the importance of dislocation creep as an important mechanism of high T for magnetite in polymineralic rock.

Mamtani (2014) presented a concept to quantify vorticity using magnetics fabrics data determined from anisotropy of magnetic susceptibility (AMS) analysis in syntectonic granite whose emplacement is contemporary with the deformation of shear zones. The latter defines the direction of extensional flow apophysis (Ae). It is suggested that the magnetic foliation traces the direction of the max instantaneous stretching axis during the final stage of ductile deformation. Hence the angle between the mean orientation of magnetic foliation and Ae gives the kinetic vorticity number (Wn). This analysis explains the kinematic of fabric development within granites and also the evolution of structural elements in the surrounding rocks.

Mamtani et al., (2015) carried out electron backscatter diffraction data of quartz grains within quartzite samples lying closer as well as of those lying away from Godhra granite. He concluded that the heat supplied by Godhra granite resulted in coarsening of grain size, strong crystallographic preferred orientation (CPO) and dislocation creep in the sample lying in the proximity of to the granite whereas, weak CPO occurred in the sample located away from granite due to which fine grain size is seen.

### *2.3.6 Joshi A, Limaye M A and Deota B S (2013, 2016, 2018)*

Joshi A, Limaye M A and Deota B S (2013) studied the area around Ankalwa, Lunavada Group and prepared a model depicting the successive deformational events of the Ankalwa synform on the basis of structural analyses. They concluded that the study area has undergone two stages of deformation with an inverted type I interference pattern and in this area, tight folding, gentle plunging and steep inclination of this synform can be observed which are the characteristics of the overturned fold.

Joshi A, Limaye M A and Deota B S (2016) studied the microstructural evidences of post deformational brittle-ductile shear zones in the metasedimentary rocks of the Lunavada region. They stated that the petrography of mylonitized biotite schist reveals group 3 mica fish and pull apart microstructures, rarely seen in biotite mica. Also, quartzite along shear zones is cataclasite. According to them, the trend of the shear zones coincides with the axial planes of $F_3$ folds in the Lunavada region and the axial plane of $D_3$ deformation acted as the weak plane for shearing thus giving rise to micro-scaled post deformational extensional features.

Joshi A U, Limaye M A and Deota B S (2018) encountered the intrafolial fold having a fish-hook shape within a quartzite and metapelite band from the Lunavada region, NE Gujarat, near Chandsar along the banks of the Panam river. These folds consist of six antiforms and five antiforms. According to them, the NE-SW principal shortening direction resulted during $D_3$ deformation which produced ductile shear having (top- to- SW) shear sense. The marked and uniform variation in limb thickness implies that the thinned portions within the folded sequence experienced intense localized deformation successive to the asymmetric folding developed on account of top to SW ductile shear. The folds underwent further shear-induced thinning of the limbs to produce the individual fish-hook shaped antiforms and synforms within the folded sequence.

#### *2.3.7 Fareeduddin and Banerjee (2020)*

They reviewed the work carried out during the last century in unravelling the major Archean and Proterozoic events that are responsible for shaping the Aravalli craton and its mobile belt.

#### *2.3.8 Mondal et al., (2020)*

They overviewed the Precambrian geology of the Aravalli craton and the fold belt, north-western India along with the recent development on the status of its Pre-Cambrian geology. According to them, the constituent litho units of the Aravalli craton can be studied in the future to understand the evolution of continents through time, particularly during the Pre-Cambrian. Moreover, the geochemical studies, isotope as well as geochronological studies of most of the lithologies need to be carried out to understand their genesis, geodynamic evolution, delineation of various litho units, timings of their emplacement and metamorphism, thereby ascertaining the probability of participation of Aravalli craton in various supercontinent cycle.

#### *2.3.9 Roy and Biswas (2020)*

They presented an analysis of imagery from Sentinel-2 earth observation satellite (courtesy: European Space Agency) to identify an array of unique deformational ‘meso’ structures like ‘rootless’ folds, S-C structures and flanking structures from brittle-ductile regime present within the metasedimentary rocks of Lunavada Group which indicate polyphase deformation over a study area of approximately70 $km^2$.

### *2.3.10 Banerjee et al., (2021,2022a, 2022b)*

Banerjee et al., (2021) reviewed the findings in the different segments i.e.the Chhotanagpur Gneiss Complex (CGC), the Satpura Mobile Belt (SMB) and the Aravalli Delhi Fold Belt (ADFB) within the Greater India Proterozoic Fold Belt (GIPFOB) and compared these to evolve possible tectonic scenarios that may explain the Early Neoproterozoic accretion dynamics in the GIPFOB. They introduced lithological-structural aspects in the Godhra- Chhota Udepur sector briefly.

Banerjee et al.,(2022a) suggested that the curved nature of the N/NNE-trending structures at the southern tip of the ADFB is due to the termination of the N/NNE-striking structures against the Early Neoproterozoic E-W-striking $D_2$-$D_3$ accretion-related deformation fabrics in the Godhra-Chhota Udepur sector that forms the westernmost extent of the E-striking southern arm of the GIPFOB, based on the foregoing discussion and findings of their study of analyses of mesoscale and regional structures, U-Pb (zircon) geochronology, and monazite chemical dating. According to them, the GIPFOB is composed of two distinct accretion orogens, e.g., the N/NNE-striking western arm formed due to the convergence between the Marwar Craton (MC) in the west with the North India Block (NIB) and the E-striking southern arm that resulted from the oblique accretion between the NIB and the South India Block (SIB) They suggested that both, the MC-ADFB and NIB-SIB accretions, occurred during the Early Neoproterozoic, but the NIB-SIB accretion in the southern arm postdated the ADFB accretion orogen.

Banerjee et al., (2022b) stated that the Archean lithodemic units of the N/NNE-striking Aravalli-Delhi Fold Belt and the Late Paleoproterozoic high-grade anatectic gneisses of the E-striking Central Indian Tectonic Zone were juxtaposed during oblique crustal accretion between the two terranes, similarly, the N-S crustal accretion involving top-to-the-south thrusting ($D_2$ deformation) and nucleation of transpressional steep-dipping shear zones ($D_3$ deformation) occurred between 1.03 and 0.93 Ga. According to them, $D_3$ contractional deformation was broadly contemporaneous with the emplacement of S-type syn-collisional granites formed by the partial melting of basement rocks and the deformation outlasted the emplacement of the granitoids.

## 2.4. Geochronology

Considerable geochronological studies of rocks of the Aravalli Mountain Belt especially the granites and gneisses have been carried out over the last few decades. Very recently, the Geological Survey of India has also worked out the Rb-Sr geochronological studies of granites from the Pre-Cambrian rocks of the Aravalli region in collaboration with the Physical Research Laboratory.

Significant geochronlogical studies have also been carried out on granites of Gujarat by Crawford (1975), Gopalan et al., (1979), Merh (1978) and Trivedi et al., (1987). Since the study area of the author falls within Gujarat and also because the Godhra Granite occurs at the south-western margin of the Lunavada Group in which the study area is located, the author thought it proper to discuss the geochronological studies of the granites of Gujarat in some details. The granitic pluton is named after the type section occurring at 'Godhra' located at north of the Champaner Group as 'Godhra Granite'.

Gupta and Mukherjee (1938) assigned the post-Delhi status to these granites which was supported by radiometric age of 950 Ma. by Crawford (1969) and the recent Rb-Sr isochron age of 955 ± 20 Ma.by Gopalan et al.,(1979). At the closing period of the Delhi orogeny, two major thermal events of post-intrusive nature occurred viz. 1. Erinpura granite (830 ± 30 Ma.: Choudhary et al., 1981) and 2. Malani Rhyolite (745 ± 10 Ma.: Crawford, 1970). Newania Carbonatite (959 ± 24 Ma.: Deans and Powell, 1968) and the Godhra granite (955 ± 20 Ma.: Gopalan et al., 1979) are considered to be equivalents of the Erinpura granite.

Earlier Crawford (1975) dated the Mount Abu and Idar granite and got an Rb-Sr total rock age of 735 ± 15 and 740 ± 15 Ma respectively; on the basis of this he postulated that all the granites in Gujarat are contemporary of Malani- Mt.Abu suites, the latter of which were dated at 745 Ma by Crawford (1970). Later on, Gopalan et al., (1979) reported Rb-Sr isochron ages of the granites occurring around Godhra and those intruding the Champaner Group rocks and the gneissic rocks around the Champaner. The two granite suites have the same age of 955 ± 20 Ma .within the time span of Delhi orogeny (i.e. 2000-700 Ma. Gupta et al.,1997).

These studies thus contradicted the postulation of Crawford (1975) and revealed that all the granites of Gujarat have a common age of around 745 Ma. The granites in central Gujarat around Godhra are older than the intrusive masses of Idar and Gabbar (Ambaji) in north Gujarat which are almost of the same age as the Mt.Abu and Jalor-Siwana granites of Rajasthan (Merh, 1978).

Dates derived from geochronology suggest that the emplacement of the Godhra granite happened in stages, started around 1168 Ma. and lasted till 938 Ma. These dates include: 1168 ± 30 Ma: Rb/Sr method (Srimal and Das, 1998); 1050 ± 50 Ma: Sm-Nd method (Shivkumar et al., 1993); 965 ± 40 Ma: Rb-Sr method (Goyal et al., 2001); 955 ± 1120 Ma: Rb-Sr method (Gopalan et al., 1979); 950 Ma: Rb-Sr method (Crawford, 1975) and 938.8 ± 20 Ma: Rb-Sr method (Srimal and Das, 1998).

The stratigraphic status of the Erinpura granite and the Godhra granite is debatable. Merh (1995) suggested that the Godhra granites are slightly older than the Erinpura granite. Geographically, the Godhra granite occupies an area of around 5000 sq km and is located in the southern part of the AMB (Mamtani, 2014), having 'C' shape and delineating the Lunavada and the Champaner Group of the Aravalli Supergroup. It covers the areas like Chhota Udepur, Godhra, Balasinor and Sodiamba. According to Gopinath (1972), the Godhra granite has an intrusive relationship with rocks of the Lunavada and the Champaner Groups. Yellur and Gopinath, (1966) coined the term "roof pendants" for Champaner metasediments which are lying over the granite massif and the current structural setting of Champaner Group is on account of granitic emplacement during different stages of deformation.

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