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# Facies and diagenetic evolution of the Bathonian-Oxfordian mixed siliciclastic-carbonate sediments of the Habo Dome, Kachchh Basin, India

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**Key words:** facies, diagenetic evolution, Habo Dome, Kachchh Basin, India.

**Abstract.** This paper examines the depositional environment and diagenetic aspects of the exposed Patcham and Chari formation within the Habo Dome. The Patcham Formation is represented by the Black Limestone Member. The Chari Formation is represented by two distinct sedimentary successions: (i) shale and carbonates, and (ii) coarse clastics. The paper describes eleven lithofacies from these successions. The depositional framework constituents of these facies have been greatly modified by diagenetic evolution through time. Two main depositional environments, *i.e.* foreshore intertidal and shoreface (subtidal), have dominated during their deposition. The diagenetic signatures observed within these sediments suggest early or syndepositional changes in marine phreatic and burial environments. Two phases of early mechanical compaction have largely governed porosity evolution within the limestone facies. Micritization of the allochems was caused by endolithic algae prevalent within the restricted lagoon environments with stagnant marine phreatic zone conditions. Random dissolution of microcrystalline grains has created vugs with patchy distribution reflecting neomorphism within the meteoric vadose zone. The types of cements within the sandstone facies include silica, calcite, and its replacement by Fe-calcite cement. The sandstones were deposited in a relatively low energy environment below storm wave base. The depositional conditions have controlled the early diagenesis of the sandstones which in turn have influenced their burial diagenesis.

## INTRODUCTION

In western India mixed marine siliciclastic-carbonate sediments of Jurassic age are exposed in the Kachchh Basin. This is a pericratonic rift basin representing the westerly dipping eastern flank of the Indus shelf. This basin is filled up with three sediment packages of Mesozoic, Tertiary and Quaternary ages. The Mesozoic package comprises Late Triassic to Early Jurassic continental and Mid to Late Jurassic marine and Late Jurassic to Early Cretaceous marine to fluvio-deltaic sediments. The Mesozoic Kachchh Basin is bordered by the subsurface Nagarparkar massif in the north, the Radhanpur-Barmer arch in the east and the Kathiawar uplift to the south (Biswas, 1982). Mesozoic sediments ranging in

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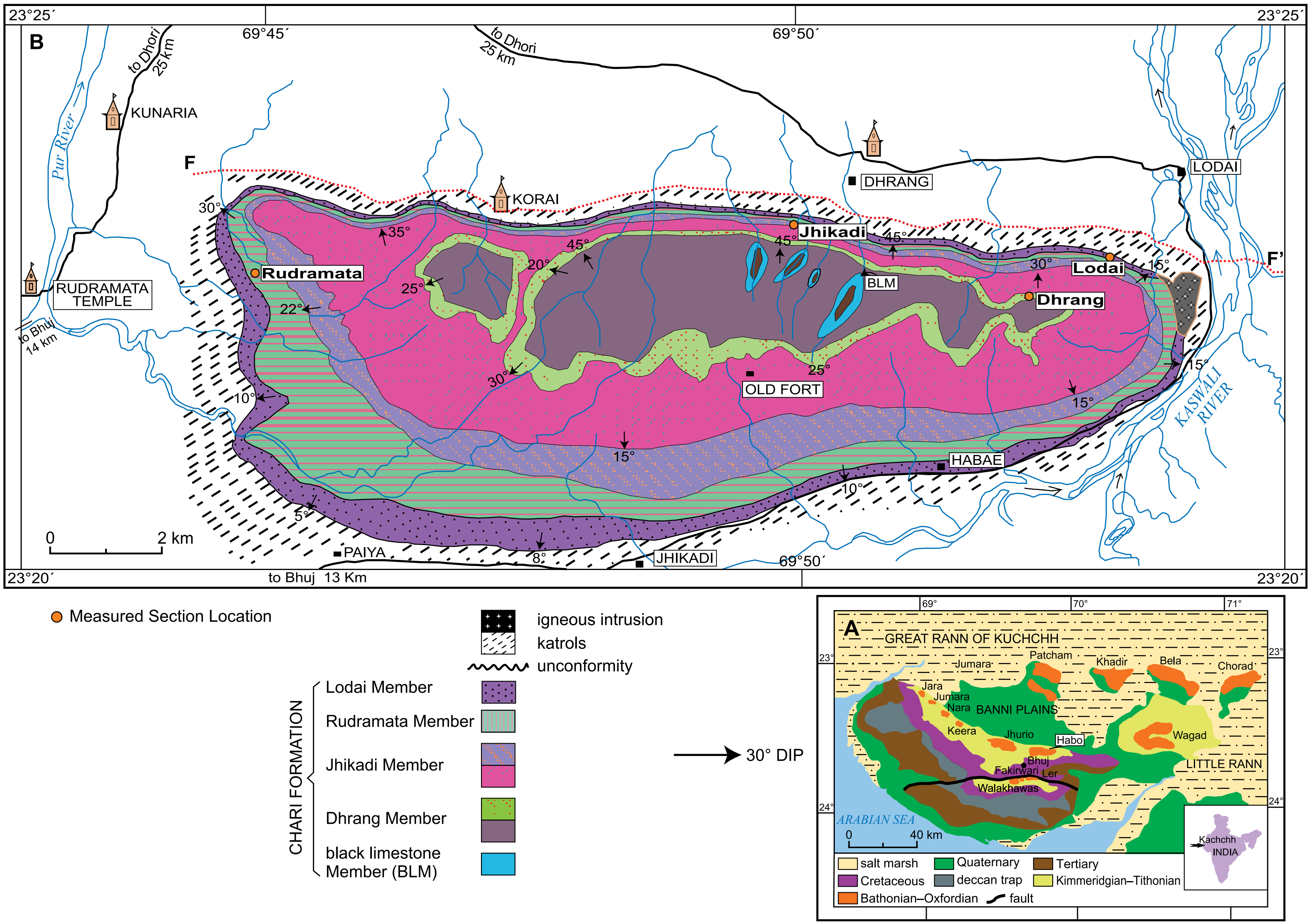


**Fig. 1 A. Geological map of Kachchh Basin (Fürsich *et al.*, 2001). B. Habo Dome (modified after Kanjilal, 1978)**

age from Pliensbachian to Albian lie unconformably on the Precambrian basement (Bardan, Datta, 1987; Rai, Jain, 2013). Marine Jurassic siliciclastic-carbonate sediments exposed in the Kachchh Basin bear signatures of an inundation by the sea during the Bajocian which persisted throughout the Jurassic and Early Cretaceous until the Albian. The Habo Dome is located approximately 40 km NE of Bhuj (Fig. 1). The southern slopes are relatively gentle whereas the northern ones are steep. The available faunal evidence suggests that the Chari Formation is Callovian–Oxfordian in age. The lithostratigraphic classification worked by Kanjilal (1978) and Fürsich *et al.* (2001) based on the lithological variations among the various units is presented in Table 1. The Chari Formation has been studied by many workers in the past. The main focus of these works has been paleontological and biostratigraphical (*e.g.*, Rajnath, 1932; Maithani, 1968; Kanjilal, 1978; Bhalla, Abbas 1978; Bardan, Datta, 1987; Pandey, Dave, 1993; Fürsich *et al.*, 2001; Fürsich, Pandey, 2003). Much work has also been carried out on the depositional environment (Balagopal, Srivastava, 1975; Singh, 1989; Osman, Mahender, 1997; Nandi, Desai, 1997; Ahmad *et al.*, 2008; Patel *et al.*, 2008; Ahmad, Majid, 2010). However, the detailed facies investigation and diagenetic evolution of the formation has not been addressed to date. The present study is focused on these aspects of the Chari Formation exposed in the Habo Dome.

## GEOLOGICAL SETTING

The Kachchh peninsula is occupied by a varied groups of rocks ranging in age from Archean to Recent and it has about 3000m of sediments extensively developed in the Kachchh Mainland, Wagad, the Islands of Patcham, Bela, Khadir and Chorad. The basin formed due to rifting and counter clockwise rotation of the Indian Plate during the Late Triassic/Early Jurassic (Biswas, 1987). Two factors control the accommodation of the basin fill sediments: tilting of fault blocks and the sea level stand during the depositional cycle. The mainland outcrops expose a continuous succession from Bajocian to Albian and form a prominent ridge extending for about 193 km from Jawahar Nagar in the east to Jara in the west. Sedimentation finally ceased in the Upper Cretaceous with the onset of Deccan volcanism, as evidenced from the presence of the huge lava flows which overly the Cretaceous Bhuj sandstone in the mainland, particularly on its western and southern flank (Guha, Gopikrishna, 2005). Carbonate and mixed carbonate siliciclastics in the Kachchh Basin are largely confined to the Bathonian and Early Callovian ages and represent storm-dominated shallow shelf environments (Fürsich *et al.*, 1991). Fürsich *et al.* (1991) interpreted these siliciclastics as being deposited in a wide range of depositional settings including coastal and estuarine environments,

**Table 1**

**Middle-Upper Jurassic stratigraphic succession of the Habo Dome (modified after Kanjilal, 1978; Fürsich *et al.*, 2001)**

| Formation | Member | Lithology | Age |
|---|---|---|---|
| Chari | Lodai (= Dhosa Oolite member) | alternating beds of limestone and shale (limestone yellowish to light brown; shale grayish green to yellowish) | Oxfordian |
| | Rudramata (= Gypsiferous Shale) | yellowish shale overlain by ferruginous sandstone | |
| | Jhikadi (= Athleta Sandstone) | ferruginous and calcareous sandstone with beds of shale and discontinuous conglomerate and coral bed on top sandstone exhibits cross-bedding and ripple marks | |
| | Dhrang (= Ridge Sandstone) | yellowish to grayish yellow limestone and yellowish shale | Callovian |
| Patcham | Black limestone (=s ponge limestone member) | black to greenish grey limestone | Bathonian |
| | | base not exposed | |

subtidal bar, storm influenced shallow shelf and mid shelf environments below storm wave base, and sediment starved offshore settings.

## METHODOLOGY

The study is based on the measurement of stratigraphic sections, facies variation and the collection of samples. We measured five stratigraphic sections at Dhrang, Jhikadi, Rudramata and Lodai area (Fig. 2). Special attention was paid to the study of facies variation, nature of sedimentary structures like cross-bedding, laminations, ripple marks, bed contacts, color, lateral and vertical facies variations, *etc*. Oriented standard thin sections were prepared of 70 samples for petrographic and diagenetic investigations.

## FIELD OBSERVATIONS

Bed by bed measurements and field observation of the measured sections reveal rapid vertical lithological variation. The individual beds are generally bounded by sharp, mostly erosion surfaces representing depositional phases, punctuated by frequent episodes of non-deposition. These depositional events are cyclic in nature and are related to the creation of accommodation space during transgressive episodes, whilst the omission events are related to pulses of regression. We recorded the following lithofacies in this study:

### Black Micritic Limestone Facies

The black micritic limestone facies (Pl. 1: 1) is 20 m thick and well exposed in the scarp section facing the Kalajar Nala, south of Dhrang village. This facies is the youngest member of the Patcham Formation exposed only in the Dhrang area. The lithology consists mainly of black to grayish black, compact limestone with thin layers of shale, thick-bedded / massive in the lower part and thin bedded in the upper part. Although the base of the limestone member is not exposed in many places, we observed it directly overlying a basic igneous dyke. This facies is prominently laminated and is in part highly bioturbated. Megafossils are rare and include *Lopha*, *Modiolus* and *Bositra*; microfossils are represented by foraminifera (Tewari, 1957; Bhalla, Abbas, 1978). Trace fossils reported include *Chondrites*, *Thalassinoides*, *Lockeia*, *Sabularia*, *etc.* (Patel *et al.*, 2008). The allochemical constituents of the limestone facies include mainly pellets and a few superficial ooids set in a microsparitic matrix.

### Matrix Supported Conglomerate Facies

A number of narrow, laterally discontinuous conglomerate beds are encountered in the Dhrang, Jhikadi and Rudramata sections of the Chari Formation. The conglomerate beds are lenticular in shape and composed of rounded to sub-rounded, moderately sorted to moderately well-sorted pebbles and cobbles (Pl. 1: 2). The Jhikadi Member contains a few scattered belemnites, corals and bivalve fragments. The Rudramata Member consists of conglomerate that contains well-preserved bivalves, cephalopods and echinoids. The conglomerate beds are 0.5 m thick in the Dhrang Member, which coarsens upwards. The clasts are polymictic, consisting of vein quartz, pink, black and white quartzites and red jasper. The granules and pebbles range in size from 5 to 9 mm and occasionally reach 13 to 18 mm. Pebbles and cobbles are scattered within the conglomerate facies. The tabular-cross bedded conglomerates show erosional contacts with the intervening sandstone beds.

### Interbedded Limestone and Shale Facies

This facies displays alternating limestone and shale units in the Dhrang and Lodai members. The shales are grey and green, often splintery, brittle and micaceous in nature. The thickness of each shale unit varies from 1.2 to 3.0 m. Thin, red, nodular mudstone beds are common in the shales. The shale facies is thick and thin-bedded and contains bivalves and ammonoids (Pl. 1: 3). The limestone unit thickness varies from 0.8 to 1.5 m and is yellowish brown, compact and laminated. The thickness of each calcareous unit increases gradually towards the top of the facies. Both the limestones and shales are highly fossiliferous. The fauna present in the Lodai and Dhrang members include ammonoids (Mayaitidae, *Peltoceratoides*, *Perisphinctes* including *Alligaticeras*) and bivalves (*Pinna*, *Oxytoma*, *Eopecten*, *Neocrassina*, *Pleuromya*) (Kanjilal, 1978). Texturally the allochems are mud-supported and grain-supported. The allochems observed within this facies include peloids, intraclasts, ooids and bioclasts (brachiopods, algae, echinoderms, foraminifers and gastropods).

### Tabular Cross-bedded Sandstone Facies

This facies is well developed in the Dhrang and Jhikadi members at one stratigraphic level. This facies is composed of coarse medium-grained pebbly sandstones, consisting of moderately- to well-sorted quartzarenite and subarkose. These sandstones are reddish brown to whitish brown, thick-

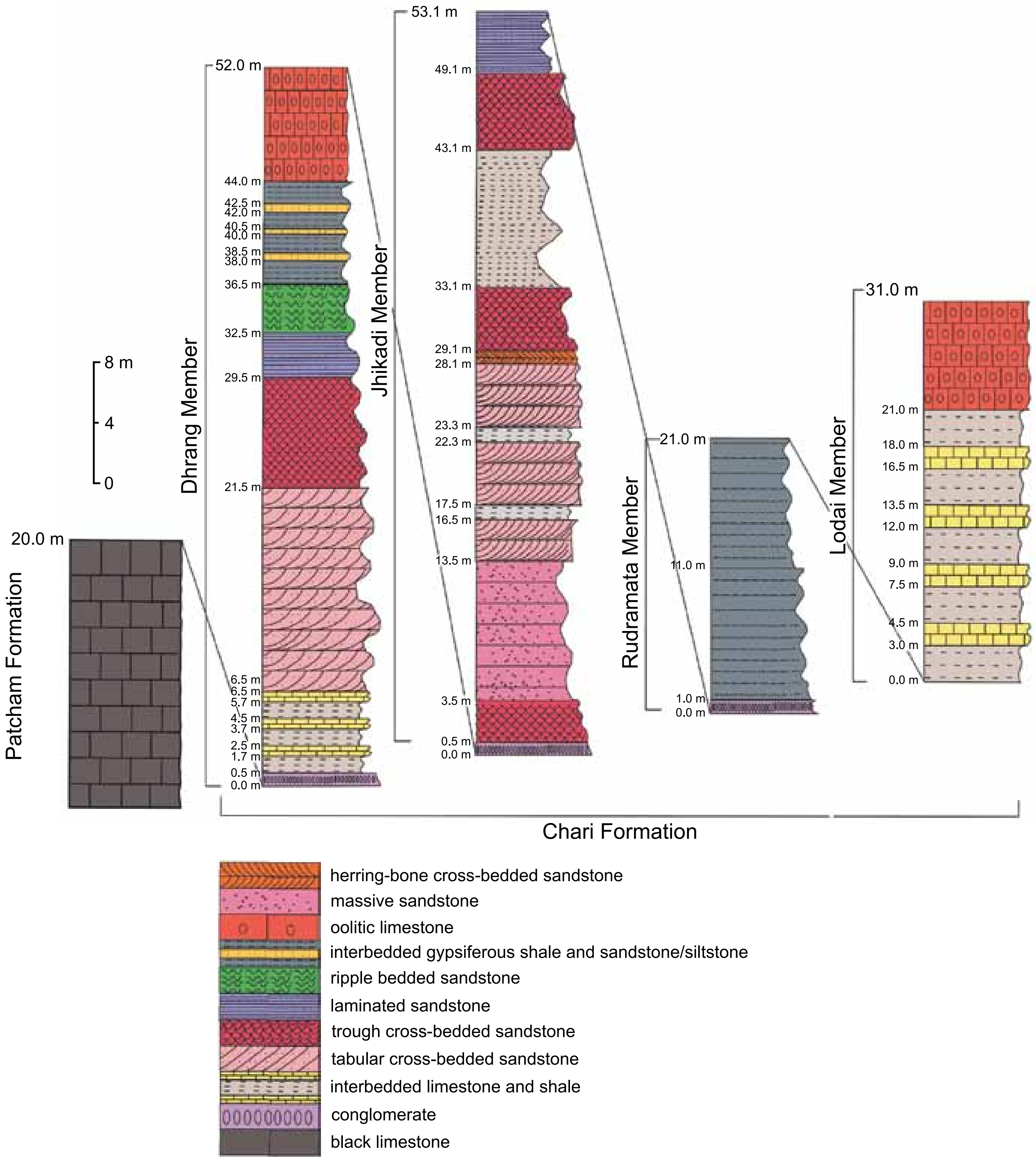


**Fig. 2. Measured sections from Habo Dome**

and thin-bedded. Tabular cross-beds laterally grade into parallel laminated beds. Cross-beds occur both in cosets and in single sets (Pl. 1: 4). The cross-bedded sandstone units vary in thickness from 3 to 15 m. Small scale, low angle, tabular cross-bedded sandstones are also observed associated with this facies at one stratigraphic level in the Dhrang section. The bounding surfaces of the cross-beds are undulating. The foresets show bimodal paleocurrent pattern. The main mode is directed towards the SW whilst others show NE, SE and NW directions. Some tabular cross-stratified sandstone beds, superimposed on the trough cross-beds, were formed by subordinate syndepositional currents. Trace fossils are abundant and are mainly represented by *Ophiomorpha* and *Gyrochorte* (Patel *et al.*, 2008). Large scale planar cross-bedding indicates high energy combined-flow conditions in a storm-influenced lower shoreface environment (*e.g.* Duke *et al.*, 1991). The sandstone facies is highly bioturbated and a variety of burrows is present including *Laevicyclus*, *Lockeia*, *Skolithos*, *Paleophycus*, *Planolites*, *Anchorichnus*, *Fucopsis*, *Chondrites*, *Cladichnus*, *Spongeliomorpha*, *Ophiomorpha*, *Thalassirodes*, *Parahaentschelinia*, *Rhizocorallium*, *Gyrochorte*, *Sabularia*, *Halymenidium*, *etc.* (Patel *et al.*, 2008).

## Trough Cross-bedded Sandstone Facies

Both large- and small-scale trough cross-bedding is observed in this facies (Pl. 1: 5). This sandstone unit is composed of 3 to 8 m thick erosive based, medium to coarse grained beds with pebble layers. Trace fossils reported from these beds include *Ophiomorpha* and *Gyrochorte* (Patel *et al.*, 2008). The framework grains are subangular to subrounded. This facies occurs in the Dhrang and Jhikadi sections at one and two stratigraphic levels respectively. The foresets show a bimodal paleocurrent pattern. The main mode is directed towards the SW and others are NE, SE and NW directed. This facies also cotains highly bioturbated ferruginous sandstone layers in places. These can be recognized from a distance due to their spotted and mottled nature. The spots consist of dark brown bioturbated spots within the light brown background. In places the framework grains are coated with ferruginous and micritic material.

## Laminated Sandstone Facies

This facies is characterized by planar stratified, moderately to moderately well sorted, coarse-, medium- and fine-grained sandstones (Pl. 1: 6). The upper and lower bounding surfaces within the beds of the facies are sharp. The framework grains are subangular to subrounded. Some of the beds show a combination of planar lamination and low angle cross-bedding with sharp contacts. The bed-sets with planar-bedding are massive, planar-bedded to planar- laminated. Fragments of bivalves and ammonoids are found within this facies. These sandstones are texturally and compositionally mature. This facies occurs at one stratigraphic level the Dhrang and Jhikadi members. The thickness of the sandstone unit ranges from 3 to 4 m.

## Ripple-Bedded Sandstone Facies

Ripple-bedded sandstone facies occurs at one stratigraphic level in the Dhrang Member. This facies consist of reddish-brown to whitish-brown, medium- to coarse-grained, moderately sorted to moderately well-sorted and thinly-laminated sandstones. The beds are mostly evenly laminated. The bed contacts are sharp. Both symmetrical and asymmetrical ripples are observed. The crests of the ripples are straight to sinuous, sometimes rounded and flat. The sandstone unit is 4 m thick, comprising of planar-laminated beds and cross-beds. Long rounded-crested asymmetrical ripples and long-crested wave generated symmetrical ripples are present. The tops of rippled surfaces contain abundant bivalve shells (*Trigonia*, *Astarte*). The facies is highly bioturbated and contains of abundant unidentified trace fossils.

## Interbedded Gypsiferous Shale and Sandstone/Siltstone Facies

The gypsiferous shale beds which are green, yellow, red and brown in color and contain abundant diagenetic gypsum crystals of varying shapes. The thickness of this shale unit varies from 1.5 to 10.0 m and represents the basal member of the Katrol Formation. The gypsiferous shale beds gradually pass into laminated siltstone and fine sandstone beds upsection. Fine sand to silt with small-scale wave ripples and bioturbation structures are present (Pl. 1: 7) within this facies. The shale beds exhibit an alternation of thin, red, concretionary hematite beds. Arenaceous material is abundant in the upper part of the facies. This unit contains ammonoids, molluscs and brachiopods. This facies occur both in the Dhrang and Rudramata sections.

## Oolitic Limestone Facies

The oolitic limestone facies is characterized by greenish-grey and brown, coarse- to medium-grained, thick to thin-bedded, soft and friable to compact fossiliferous beds with straight to irregular bounding surfaces. This facies occurs at one stratigraphic level in the Lodai and Dhrang members.

In the Dhrang section, it is represented by numerous beds. The lower beds are sandy, while the upper beds are oolitic (Pl. 1: 8). These limestones are 8 to 10 m thick and are intercalated with shales. Other subfacies reported within this facies include a bioclastic facies, an ooid bearing calcareous sandstone facies and micritic or sparitic limestone facies. Texturally the rocks are sub-mature to immature, containing rounded to subrounded silt to medium sand-size quartz grains. The framework grains are coated with either ferruginous or calcareous material. The cement is mostly sparite but in some cases ferruginous patches have also been observed. The ooids enclose mainly ostracods and spores covered by micritic and ferruginous material. Belemnites are abundant whereas trace fossils are limited in the upper parts of the facies. The interbedded shale is buff and greenish, soft and weathered.

### Massive Sandstone Facies

This facies is observed in the Jhikadi Member at one stratigraphic level and the thickness of the facies is 1 m. The sandstone is medium- to fine-grained, moderately sorted to moderately well-sorted and is mainly composed of quartzarenite. Internally the facies is composed of thick and thin sandstone beds which are occasionally laminated. Herringbone cross-beds are associated with an occasional tabular cross-bedding facies.

### Herringbone Cross-bedded Sandstone Facies

This facies occurs in the Jhikadi Member at one stratigraphic level. The sandstone is generally coarse, medium- to fine-grained, moderately sorted to moderately well-sorted. The framework grains are subangular to subrounded. The facies shows sharp contacts with the underlying and overlying facies. The lack of primary sedimentary structures can be ascribed generally to the reworking of sediments by biogenic disruption and to physical deformation such as rapid deposition. The facies contains a few scattered belemnites, brachiopods and bivalve shell fragments. The thickness of sandstone unit is 10 m. This facies is bioturbated and contains abundant trace fossils comprising *Laevicyclus*, *Fucopsis*, *Spongeliomorpha*, *Ophiomorpha*, *Rhizocorallium*, *Halymenidium*.

## FACIES ASSOCIATIONS

In the sections studied we observed three distinct facies associations whose salient features are briefly described here:

### Facies Association – I (Tidally Influenced Fluvial Facies)

This lithofacies association comprises matrix-supported conglomerate, tabular and trough cross-bedded sandstones, and herring–bone cross-bedded sandstones. The average size of the clasts of the conglomerate facies is 1 to 2 cm. The clasts are poorly sorted, unstratified, disoriented and are stacked in thick and thin beds. The facies assemblage is dominated by medium- to fine-grained, compact, tabular and trough cross-bedded sandstones laterally continuous and upward-fining with erosional basal surfaces.

The matrix-supported beds of the conglomerate facies have been interpreted as debris flow deposits (*e.g.* Khalifa *et al.*, 2006). They occur in the Dhrang, Jhikadi and Rudramata members. The companion trough cross-beds are a product of mega-ripple migration in the active channels during prolonged high-water stand whilst the tabular cross-beds are formed by lateral accretion of transverse bars. The associated herring-bone cross-bedded sandstone facies clearly indicates tidal influence within the channel environment.

This evidence suggests that facies association I can be attributed to a tidally influenced fluvial channel environment. The fining and thinning upward facies successions are bounded by sharp, often erosional bases attesting to their deposition during decreasing flow energy, typical of channel fills (*e.g.* Bose *et al.*, 2001; Chakraborty, Bhattacharya, 1996). The matrix-supported conglomerates record episodes of the highest energy, while the trough cross-bedding facies was formed by migration of small to medium-scale bedforms within channels. Moderate to poor sorting coupled with very coarse sand to gravel size sediments are the features which suggest tidal influence in the fluvial channel deposition. Bipolar cross-beds coupled with reactivation surfaces are suggestive of tidal reworking. Erosive bases and fining / thinning upwards trends indicate deposition within channels. A possible interpretation is that the fluvial system was flooded during the transgression to form an estuarine-setting. The presence of herring-bone cross-beds reflects bed load deposition by reversing, tidal currents of equal bed shear intensity and bottom-current velocities. Flow direction reversals are generally bipolar. The occurrence of herring-bone cross-beds in the measured sections probably records relatively weak tides (*e.g.* Chakraborty, Bhattacharya, 1996).

### Facies Association – II (Foreshore-Offshore Facies)

This facies association contains the ripple-bedded sandstone facies, the tabular and trough cross-bedded sandstone facies, the massive sandstone facies, the laminated sandstone facies and the oolitic limestone facies. Asymmetrical ripples are either the manifestation of moderately deep offshore water or of much shallower water within the range of the backshore-shoreface environment. Symmetrical ripple marks with rounded crests reflects planning-off during tidal reversal. Reineck and Singh (1986) reported symmetrical wave ripples on 4 m deep water of the offshore region, and asymmetrical wave ripples from 0 to 2 m deep water of backshore-shoreface Zone of Gulf of Gaeta, Italy. The tabular cross-bedded sandstones indicate high energy combined–flow conditions in a lower shoreface environment (*e.g.* Arnott, 1993). Small scale tabular cross-bedding represents deposition in tidal sand- sheet bars in the upper shore surface. High-angle trough cross-bedded sandstones oriented in the current direction flowing alongshore are the product of upper shoreface deposition by long-shore currents. The massive-bedded sandstone facies reflects deposition within the middle shoreface environment (Galloway, Hobday, 1983). The parallel-laminated sandstone represents offshore transport of sand during storms on the shoreface (Brenchley *et al.*, 1993; Allen, Leather, 2006). Evenly laminated sandstones are produced by heavy storms, which erode sand from upper part of the beach and transfer it into the turbulent water.

Sedimentary structures like cross-bedding, wavy bedding (Araby, Motilib, 1999) and herringbone cross-bedding suggest that the associated ooids and/or bioclasts formed on tidally dominated high energy bars and were locally washed into quiet water lagoons (*e.g.* Tewari, 1994). Ooids form the major component of the bar- to bank-system and with corresponding maxima of their frequency and clasticity in the higher energy seaward area subject to high tidal currents. Sparry calcite cement dominated the oolitic bars and banks. The concentration of brachiopods and ooids in the oolitic bar- to bank-system indicates their deposition under high energy conditions, which were partially dispersed and pushed seaward by currents and tides.

The oolitic limestone facies comprises grain-supported and pressure-welded ooid-bearing calcarenite with a sparry calcite cement and micrite. The framework constituents include ooids, bioclasts, intraclasts and peloids. Siliciclastic admixture is present in most of the cases. The ooids commonly range from 0.3 to 0.6 mm in diameter and contain angular to subangular quartz grains as nuclei. Some ooids are pressure-welded with spalled outer cortical layers. Some ooids show evidence of reworking such as breakage, abrasion and truncation. The common size of fossil fragments ranges from 0.5 to 1.8 mm and these include mostly brachiopod, bivalve, echinoid and algae fragments. These fossils are coated with a non-ferruginous coating.

### Facies Association – III (Tidal Flat Lagoonal Facies)

This facies association contains the black micritic limestone facies, the interbedded gypsiferous shale and sandstone/siltstone facies, the interbedded limestone and shale facies and thin lenses of fine grained sandstone characterised by plane- to wavy-lamination with ripple marks. The black limestone consists predominantly of carbonate mudstone (burrowed) with rare to common interbeds of peloidal, bioclastic wackestone-packstone facies. The framework constituents of the limestone facies consist of peloids, and superficial ooids set in fine-grained calcite cement. This facies association characterizes a relatively low energy condition of the depositional environment below wave base. Thin lenses of fine-grained sandstone, interlayered with siltstone show wavy lamination, and symmetrical and asymmetrical ripples indicating both tidal traction currents and wave processes. This interlaminated siltstone and sandstone may represent a response to tidal processes, possibly related to seasonally controlled fluctuations of sediment supply. Color banding in shale-siltstone may also indicate seasonal change in chemistry at the sediment/water interface. Gypsiferous shale indicates that these sediments were deposited in a quiet water, protected, lagoonal environment, with low wave and current energy (*e.g.* Patel *et al.*, 2008). Presence of wave ripples is characteristic of deposition in shoreface conditions under the more or less continuous influence of waves. Lack of other sedimentary structures and the fine-grained nature of the sediments indicates that the facies represent a low energy, offshore environment below storm wave base (Fürsich, Pandey, 2003). The present study suggests that the sediments were deposited by suspension activity in shallow, quiet water with the periodic influx of the tidal currents and waves, similar to the facies assemblage of the shallow lagoon and tidal flats (*e.g.* Elliot, 1978; Reineck, Singh, 1986; Hobday, Horne, 1997). The fine clastic assemblage is overall characteristic of an active shore parallel lagoon and related depositional systems. These related systems are mixed tidal flats, tidal creeks and washover fans that are located behind protective barrier islands (*e.g.* Elliot, 1978).

## DEPOSITIONAL MODEL

The Early Mesozoic transgression and the Late Mesozoic regression are believed to have generated two megacycles which register two major tectonic phases in the Mesozoic Kachchh Basin; one is an early rift phase and another is the termination of the early phase by failing of the rifting processes (Biswas, 1982). The Jurassic sedimentation in the Kachchh Basin corresponds to this early rifting and represents a transgressive succession punctuated by small cycles of transgression and regression (Osman, Mahender, 1997). The carbonates and mixed carbonate-siliciclastic sediments of the Chari Formation are interpreted as representing storm-dominated shallow shelf deposits. These shallow shelf deposits pass upwards into fine grained siliciclastic rocks of the mid-shelf characterized by several transgressive –regressive events.

Two main depositional environments, *i.e.* tidal flat and wave- and storm-dominated shoreface are suggested for the basal part of the Chari Formation. The evidence suggests tidal estuary and tidal flat sub-environments (Fig. 3) for facies association-1. The matrix-supported conglomerate and medium- to coarse-grained, thick- to thin-bedded/laminated, soft and friable to compact, cross-bedded sandstone facies with trace fossils is interpreted as low energy marine deposition during a stand-still period with low sediment supply within the transgressive phase. This interpretation is supported by the presence of fine-grained ferruginous oolitic beds and a well preserved marine fauna (ammonites) together with bioturbation of the sediments. Deposition of the oolitic facies probably took place in relatively agitated offshore settings, below fair weather wave base. The thick sequence of cross-bedded sandstone facies represents a subtidal bar environment. The forset cross-bedding and various reactivation surfaces are suggestive of deposition by tidal currents and may also result from migration of subtidal bars under the influence of tidal currents. The occurrence of massive sandstones above sharp to erosional surfaces suggests deposition during transgressive episodes. Gypsiferous grey shale with well developed gypsum crystals suggests that the sediments were deposited in a quiet water, protected, lagoonal

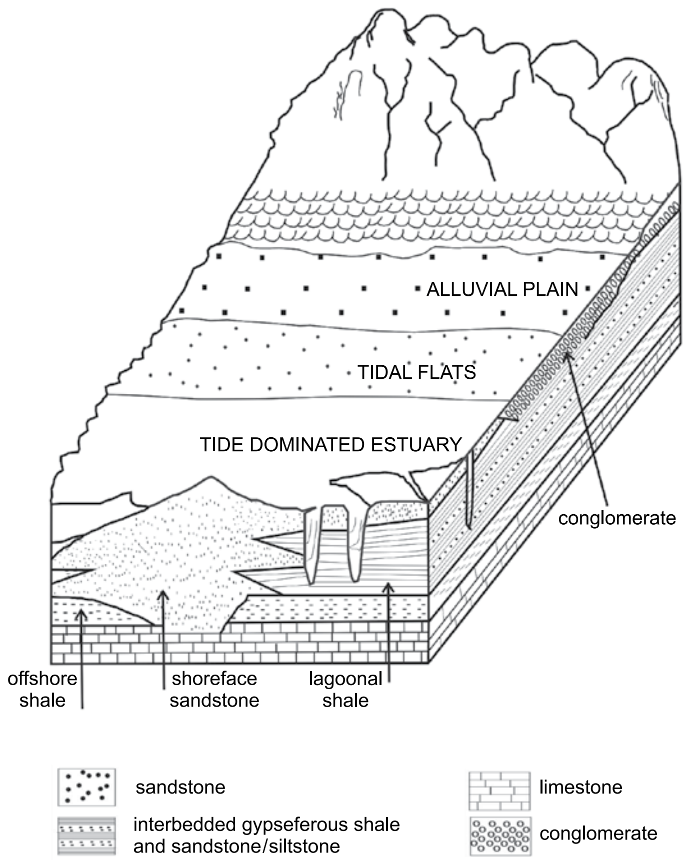


**Fig. 3. Depositional model of Chari Formation**

environment with low wave and current energy (*e.g.* Patel *et al.*, 2008). The fine clastic assemblage was deposited in tidal flats. Oolites form a considerable component of this bioclastic bar system with corresponding maxima of their frequency and clasticity in the high energy frontal area with currents rising up the lower ramp. Erosional and aggregate intraclasts formed in the upper and lower shoreface. In the present case, the occurrence of relatively thick bioclast- dominated and coarse-grained grainstones are interpreted as being deposited by waning currents associated with storm sedimentation. The homogenous, fine grained interbeds are interpreted as the result of intervening fair-weather sedimentation.

During the Early to Middle Jurassic transgression the following facies of the Dhrang Member were deposited: black limestone and conglomerate facies, planar and trough cross-bedded facies, laminated sandstone facies, ripple bedded facies, interbedded gypsiferous shale and sandstone/siltstone facies, interbedded limestone-shale facies. The overlying sandstones of the Jhikadi Member represent shoreline regressive sands (conglomerate facies, planar, trough and herringbone cross-bedded sandstone facies, massive sandstone facies and laminated sandstone facies). The subsequent transgression in the Late Callovian-Oxfordian resulted in the deposition of the top Rudramata and Lodai members (oolitic limestone facies, conglomerate facies and interbedded gypsiferous shale and sandstone/siltstone facies).

In general the sediments of the Chari Formation were transported by mass flows, unchannelized flows, channelized flows, and settling from suspension. Mass flow is demonstrated by the presence of matrix-supported conglomerate (debris flow) deposits with the frequent presence of large size clasts, and fining upward sediments. Unchannelized flows are responsible for deposition of a more or less rhythmic/alternate succession of high and low energy facies such as alternate beds of coarse-grained/medium- to fine-grained sandstones, thick-bedded/thin-bedded sandstones, interbedded sequences of shale-sandstone, *etc*. Channelized flows result in large scale bidirectional, large scale cross-beds, parallel laminations, ripple marks, *etc*. Settling from suspension represents deposition of shale.

## DIAGENESIS OF LIMESTONE

The limestones of the Chari Formation are exposed only in the Dhrang and Lodai members in the Habo Dome. These limestones have undergone through diagenetic changes including compaction, cementation, secondary porosity, micritization and neomorphism. Carbonate diagenesis is primarily driven by the sediment-water interaction most commonly within the marine, meteoric or deep burial environments. Other factors that control diagenetic changes include the depositional fabric of the rocks and the pressure conditions, which increase with deep burial.

We observed compaction driven deformation and breakage of bioclasts in thin sections (Pl. 2: 1). Evidence of mechanical compaction is observed in the form of spalling of the ooid cortices. Inter ooids cavities are filled with peloids and micrite. The absence of a submarine rim cement within the deformed framework constituents suggests early compaction episode within the marine environment. Evidence of post-cementation compaction is seen in the form of breakage of the fabric of both the allochems and the cement. This second phase of early compaction has lead to partial dissolution (Pl. 2: 2) at the mutual contacts of ooids and bioclasts. These two early compaction phases are related to the marine phreatic environment.

We also observed three distinct types of early diagenetic cements within the limestones of the Chari Formation. These include blocky cement, ferroan rim cement and fibrous cement. These types of cement have been interpreted as early marine cements formed during deposition or shortly thereafter (Steinhauff, 1989, 1993). Blocky cements are believed to form in a fresh water diagenetic environment and also are analogous to the meteoric cements in many Holocene ooid sequences (Oldershaw, 1971; Folk, 1974; Bathurst, 1975; Wong, Oldershaw, 1981). The allochems are coated with a ferroan calcite rim. The probable source of Fe-calcite is the presence of a hardground within the sequence. The ferroan coating around the allochems has obliterated syntaxial and fibrous cement growth on them. The fibrous-bladed cement occurs in bundles of calcite crystals embedded in micrite (Pl. 2: 3). The fibrous calcite cement has been interpreted as replacement of a fibrous aragonite cement (*e.g.* Bathrust, 1975). This interpretation is also supported by the evidence of the formation of modern day marine cements as isopachous crests of acicular crystals of aragonite or Mg-calcite (*e.g.* Longman, 1980; James, Choquette, 1983). Also all the recent submarine and beach rock cements are of a bladed to fibrous nature (Bricker, 1971). We interpret the early marine cements as representing high energy environments mainly restricted to the outer ramp and bioclastic bar-bank system where early marine cementation is favored at the sediment-water interface.

Micritization of grains is common in the carbonates of the Chari Formation. Some of the bioclasts are completely micritized leaving only bioclastic lumps with occasional concentric lamination (Pl. 2: 4). Micritization is generally an early marine diagenetic process. However, micritization is also the result of syndepositional recrystallization of the skeletal carbonate (*e.g.* Reid *et al.*, 1992; Macintyre and Reid, 1995, 1998). In most of the cases micrite converts into neomorphic sparry calcite (Pl. 2: 5). The evidence suggests that micrite mostly forms by inorganic precipitation in warm, saline, shallow water, low energy conditions and in some cases by disintegration of green algae (Folk, 1959). The evidence of little sediment movement, ubiquitous microbial micritization of allochems and limited cementation reflects stagnant marine phreatic environments (Tucker, Wright, 1990).

We also observed finely crystalline carbonate replaced by a coarser calcite mosaic (Pl. 2: 6). Such a feature is indicative of aggradational neomorphism (Folk, 1965). Patchy distribution of a neomorphic fabric along with the fabric-selective calcite mosaic are consistent with neomorphism in the meteoric vadose zone (Sherman *et al.*, 1999). Also peloids are internally replaced by coarse calcite grains with a less ordered crystal mosaic representing aggrading neomorphism (Bathurst, 1975). This diagenetic process is attributed to the freshwater phreatic environment which is analogous with the Dorag-type dolomitization (Carozzi, 1989). Secondary porosity has evolved through the biological break down of the carbonate sediments. During dissolution, the unstable aragonite or high magnesium calcite framework grains such as bioclastic shells dissolve and generate secondary porosity. This type of diagenesis is prevalent within the fresh water phreatic environment.

## DETRITAL MINERALOGY OF SANDSTONE

The detrital framework constituents in the sandstones of the Chari Formation mainly comprise quartz, feldspar, mica, rock fragments and heavy minerals. The average detrital mineralogy in the studied sandstones include monocrystalline quartz (84%), polycrystalline quartz (5%), feldspar (8%), mica (2%), and rock fragments (1%). The quartz varieties recorded include common quartz, recrystallized metamorphic quartz and stretched metamorphic quartz. Two varieties of feldspar are recognized which include microcline and plagioclase in order of abundance. The majority of feldspars are altered but some fresh feldspar is also present. Both muscovite and biotite occur as tiny and large elongated flakes with frayed ends. Rock fragments include chert, siltstone, phyllite and schist. Heavy minerals include opaques, tourmaline, zircon, garnet, rutile, staurolite, and hornblende. According to Folk's (1980) classification, all the samples of the studied sandstones are plotted in the quartzarenite and subarkose fields.

## DIAGENESIS OF SANDSTONE

The main diagenetic features observed within the sandstones of the Chari Formation in the Habo Dome include mechanical compaction, cementation and porosity reduction. The effect of compaction in the studied sandstones is displayed in the deformation and squeezing of mica (Pl. 3: 1). The deformed siltstone fragments are transformed into a discontinuous paste through partial to complete attenuation of their boundaries against the surrounding competent framework constituents. In the studied sandstones four types of grain contacts are identified: floating, point, long and concavo-convex. The contact index (CI), the average number of grain contacts a grain has with its surrounding grains, was calculated for the sandstone facies. Floating grains are the dominant type accounting for 38% in this study, suggesting very limited mechanical compaction. Point contacts, long contacts and the concavo-convex contacts average at 36%, 23% and 3% respectively, and suggest that the framework grains did not suffer much pressure solution. The contact index values for these sandstones are very low (average of 0.8%). The high percentage of floating grains and point contacts with low contact index values are mainly in sandstones with the pervasive development of calcite and Fe-calcite cement, which are probably precipitated at a very early stage during sedimentation. The early stage of cementation restricted large scale mechanical and chemical compaction, which normally takes place after deposition and is concomitant with burial under the burden of the overlying sediments. The intergranular cement (minus cement porosity) in the present case is about 30% which is attributed to less mechanical compaction during early diagenesis. Syndepositional calcite cementation, high grain strength and good sorting appear to have inhibited mechanical compaction.

## DIAGENETIC PHASES

The most important diagenetic phase in the sandstones of the Chari Formation studied is late diagenetic cementation. Various types of cements observed within the thin sections include calcite (sparry calcite and microcrystalline calcite), ferroan calcite, quartz and blocky cements. kaolinite and illite/smectite. Calcite has been replaced by silica (Pl. 3: 2) by the dissolution process which varies from surface etching to the calcite pseudomorph leaving an insoluble residue within the carbonate cement. The complexities involved in quartz-carbonate replacement as outlined by Pettijohn *et al.* (1972). Pettijohn *et al.* (1972) note that dissolution of the replaced and precipitation of the replacing mineral take place in exceedingly thin film between the bounding surfaces. They showed that the $SiO_4$ tetrahedra dissolve first from the quartz surfaces and hydrate to become $H_4SiO_4$, whose concentration is higher in the film than in the pore fluid and the $H_4SiO_4$ diffuses out into the pores. The concentration of $Ca^{2+}$ and $HCO_3^-$ being higher in pore fluid than the film, the two kinds of ions diffuse in the film. Silica replacement by car-

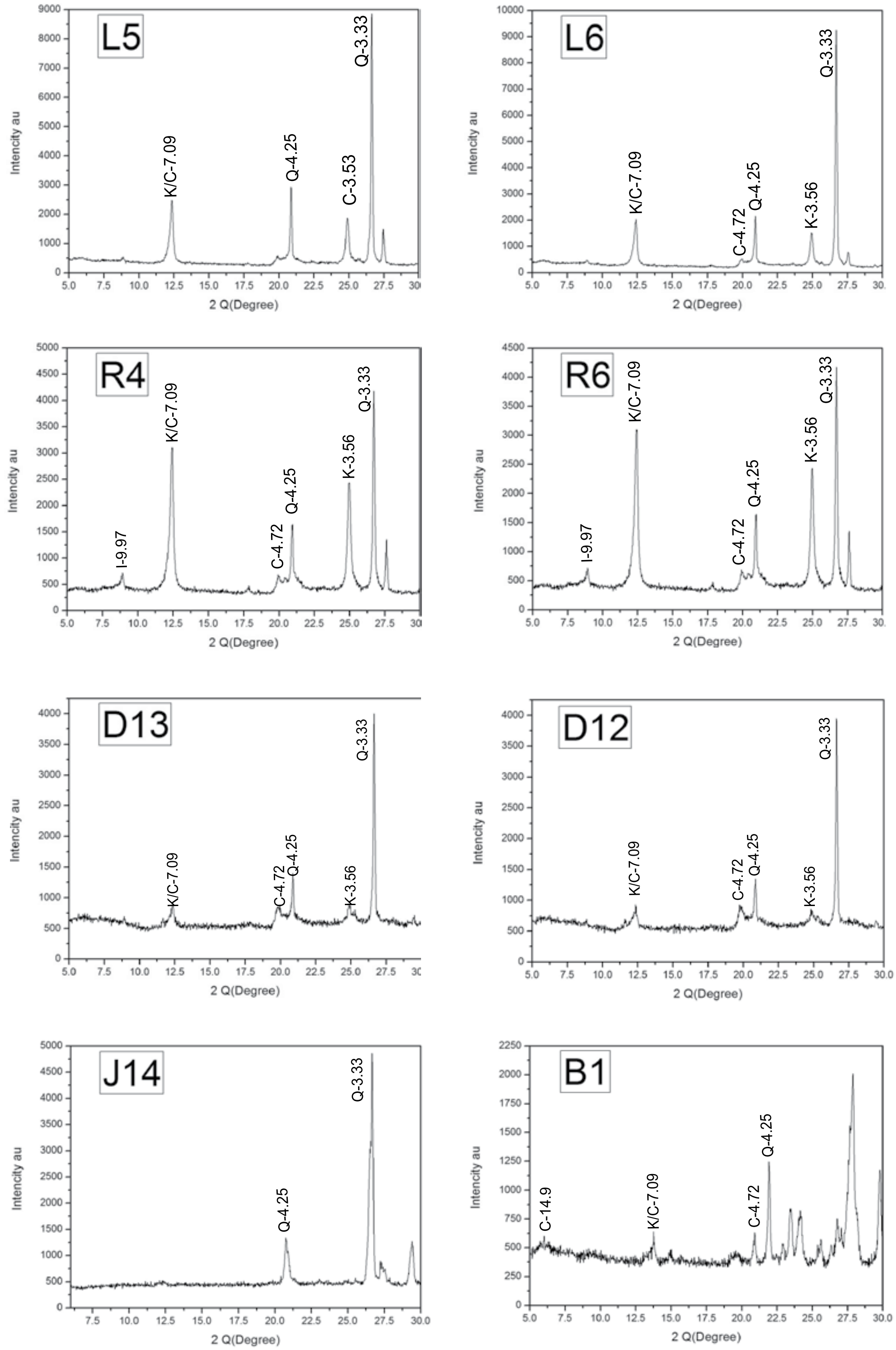


**Fig. 4. Characteristic X-ray diffraction diagram of clay minerals from shale lamina of the Habo Dome, Kachchh, Gujarat**

I – illite, K/C – kaolinite/chlorite, Q – quartz, K – kaolinite; L5, L6, R4, R6, D13, D12, J14, B1 – numbers of samples bonate as observed is considered prevalent in deep burial alkaline environment (Bjorlykke and Egeberg, 1993). Precipitation of the microcrystalline calcite cement took place at a shallow depth above the water table. Later during burial, micrite was replaced by sparry calcite in the meteoric water regime along the interface zone of accretion and saturation.

A silica cement occurs in small amounts as overgrowths around detrital grain boundaries (Pl. 3: 3). In addition a chalcedony quartz cement comprises radiating micro-grains and quartz-forming fan shaped aggregates (Pl. 3: 4). The two most probable sources of silica forming the quartz overgrowths are pressure solutions, and the transformation of smectite to illite within shales (*e.g.* Boles, Franks, 1979). The possible source of chalcedony quartz cement are sponge spicules and intercalations of tuff and volcanic rock fragments, which are characteristic of marine sedimentation in rift basins.

The late Fe-calcite cement infilled residual pore spaces that remained after compaction had produced a much closer packing arrangement. The relatively late formation of this Fe-calcite indicates an alkaline, reducing and relatively Fe rich environment. The dissolved carbonate components within the sandstones may have been the source of this late Fe-calcite cement (*e.g.* Curtis, 1983).

Authigenic clays forms patches within the calcite cement representing replacement of detrital feldspar. Pseudo-hexagonal kaolinite (Pl. 3: 5), smectite (Pl. 3: 6) and mixed layers of illite and smectite are present within studied sandstones. The clays are often stained with patches of reddish brown limonite. The presence of kaolinite, chlorite and illite has been confirmed by X-ray diffraction studies (Fig. 4). Secondary or enhanced porosity is commonly recognized by the dissolution features of primary or diagenetic phases (Schmidt, McDonald, 1979). Most of the studied samples are tightly cemented and have no visible porosity remaining. However, a few thin sections show evidence of dissolution and porosity enhancement.

The progressive stages of diagenesis observed in the sandstone thin sections of this study include early and late diagenetic phases. During the early stage of diagenesis little compaction took place; it caused rotation and adjustment of the grains and the formation of point and long contacts. The original porosity of about 40% was reduced to an average of 30%. Compaction was largely influenced by the shape of the detrital grains in the absence of an early major cementation phase that could have stabilized the detrital framework of these sandstones. Initially the pore fluids were alkaline and under these conditions quartz overgrowth and late Fe-calcite cement was precipitated. Later the alkaline pore waters appear to have been replaced by acidic ones. This led to the dissolution of carbonate cements and the detrital feldspars and formation of kaolinite and illite-smectite.

## CONCLUSIONS

1. The sediments studied were deposited in tidally influenced fluvial channel, foreshore-offshore and lagoonal environments. During the Early to Middle Jurassic transgression, the Black Limestone and deposits of Dhrang Member were deposited in low and high energy environments. The overlying sandstones of the Jhikadi Member represent a shoreline regressive facies. The subsequent transgression in the Late Callovian-Oxfordian resulted in the deposition of the top Rudramata and Lodai members.
2. A diagenetic signature observed in the carbonates of the Chari Formation studied suggests that fresh water phreatic and marine phreatic environments dominated, but deep burial phreatic and mixed marine-fresh water phreatic diagenesis also played its role in shaping these rocks through time.
3. The mechanical compaction of the coated grains has led to the spalling of ooid cortices in the limestones. During the second phase of early compaction partial dissolution at the contacts of ooids and bioclasts took place. Three types of cements occur within studied limestones *i.e.*, blocky, rim and fibrous/bladed cements representing marine phreatic, fresh water phreatic and deep burial diagenetic stages. Micritization is represented in the form of micritic envelopes and micritized framework grains leaving bioclastic lumps and vague concentric lamination. The calcitization of aragonite bioclasts resulted in a coarse calcite mosaic and the formation of irregular patches of calcite microspar found within the packstone/wackestone facies, representing neomorphism in these carbonates. Secondary porosity was also generated by the dissolution and leaching of the framework grains and cements.
4. The sandstones studied show different stages of compaction, cementation and porosity evolution. The nature of the various types of grain contact suggests early cementation and consequent minor compaction. The original porosity of about 40% and average minus (? post compaction) cement porosity of 30% also suggest that, in general, little compaction has taken place. Cementation in these sandstones appears to have been initiated with silica followed by calcite and Fe-calcite. Dissolution and leaching of calcite, Fe-calcite cements and feldspar grains produced secondary porosity.

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# PLATE 1

**Field photographs**

Fig. 1. Thick bedded micritic limestone (Black Limestone Member, level I)

Fig. 2. Conglomerate (Dhrang Member, level I)

Fig. 3. Interbedded limestone – shale (Dhrang Member, level I)

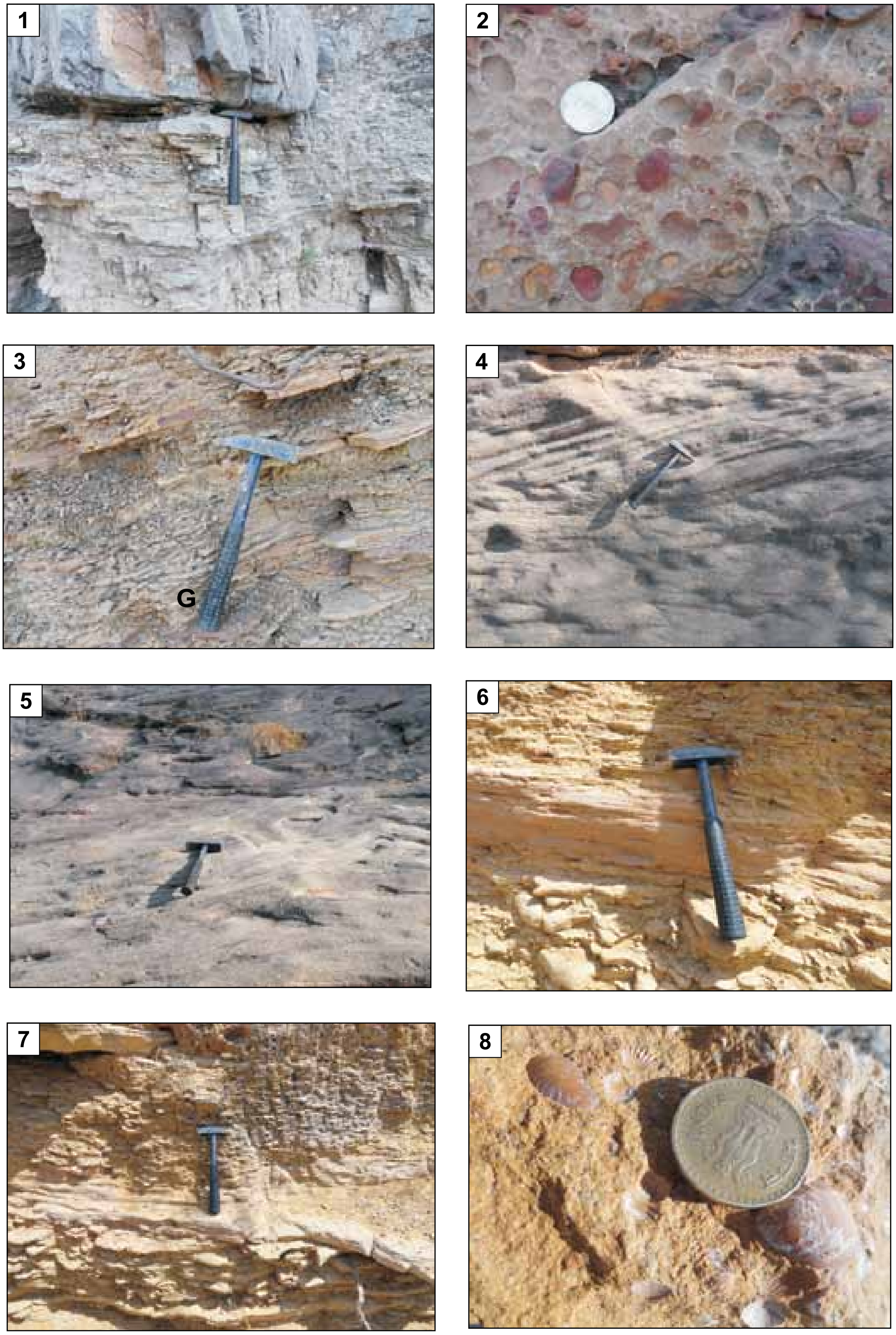
Fig. 4. Planar cross-bedding (Dhrang Member, level I)

Fig. 5. Trough cross-bedding (Dhrang Member, level I)

Fig. 6. Lamination (Dhrang Member, level I)

Fig. 7. Fine grained sandstone – shale (Dhrang Member, level I)

Fig. 8. Oolitic limestone (Dhrang Member, level I)

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## PLATE 2

**Photomicrographs**

Fig. 1. Bending and breaking of the bioclasts due to mechanical compaction. Framework grains are floating in micrite (Dhrang Member, limestone, level I)

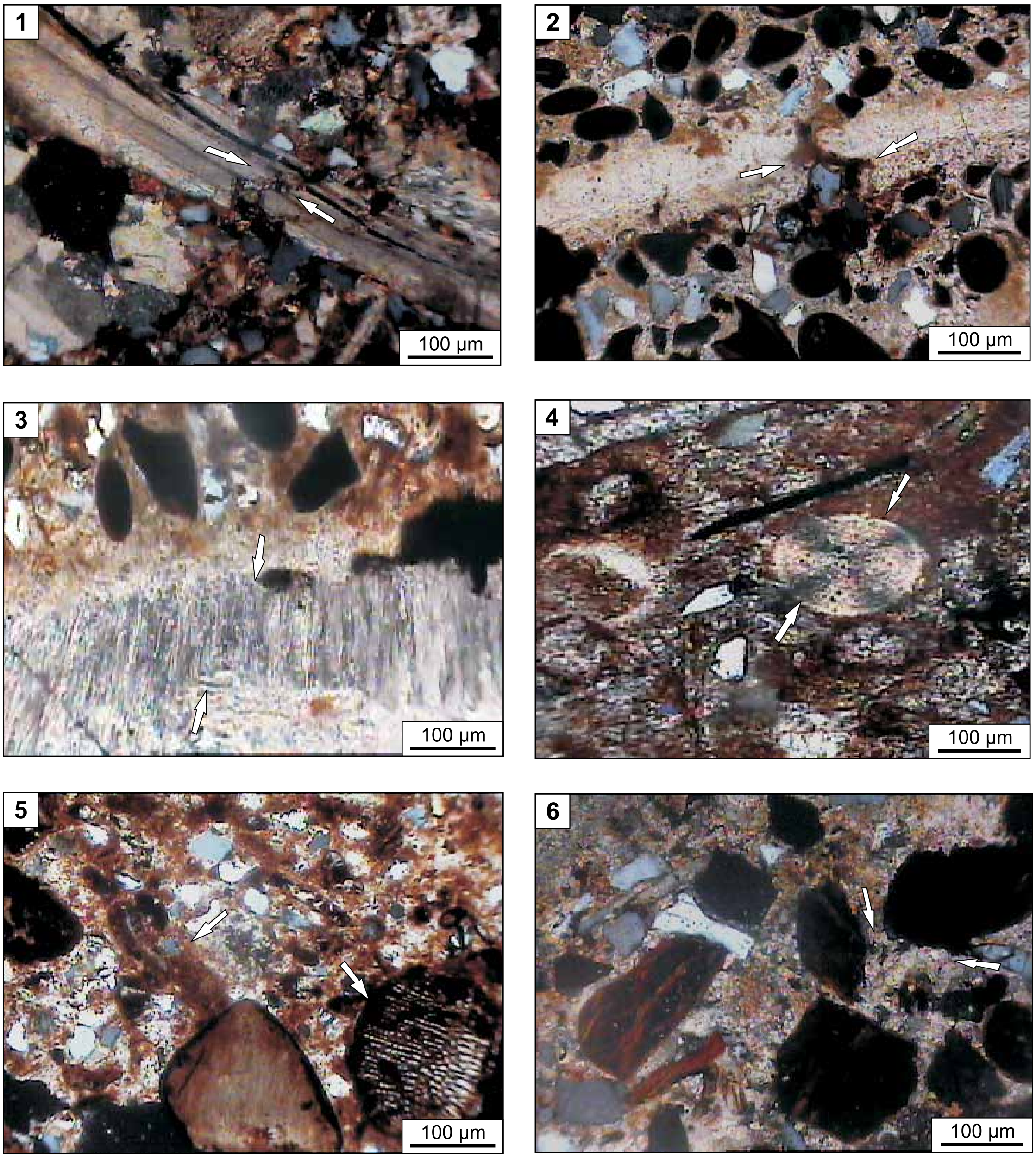
Fig. 2. The framework grains (bioclasts and ooids) are etched and replaced by calcite cement during late diagenetic phase. Ooids are welded by sparry calcite (Dhrang Member, limestone, level III)

Fig. 3. Fibrous cement has completely replaced the fame work grains and has left some ooid relics. Other grains are welded by sparry calcite. (Dhrang Member, limestone, level III)

Fig. 4. Most of the framework grains have been micritized and reduced to micritic lumps. Sparry calcite cement welds the allochemical relics (Dhrang Member, limestone, level II)

Fig. 5. The allochems including bioclasts have been micritized and neomorphic calcite has developed at the expanse of micrite (Dhrang Member, limestone, level II)

Fig. 6. Almost all the allochems have been etched and replaced by coarsely crystalline calcite (Dhrang Member, limestone, level II)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# PLATE 3

**Photomicrographs**

Fig. 1. Angular to sub-rounded framework grains (mostly quartz) floating in matrix. Elongated mica flakes show mechanical bending due to early compaction (Jhikadi Member, massive sandstone, level III)

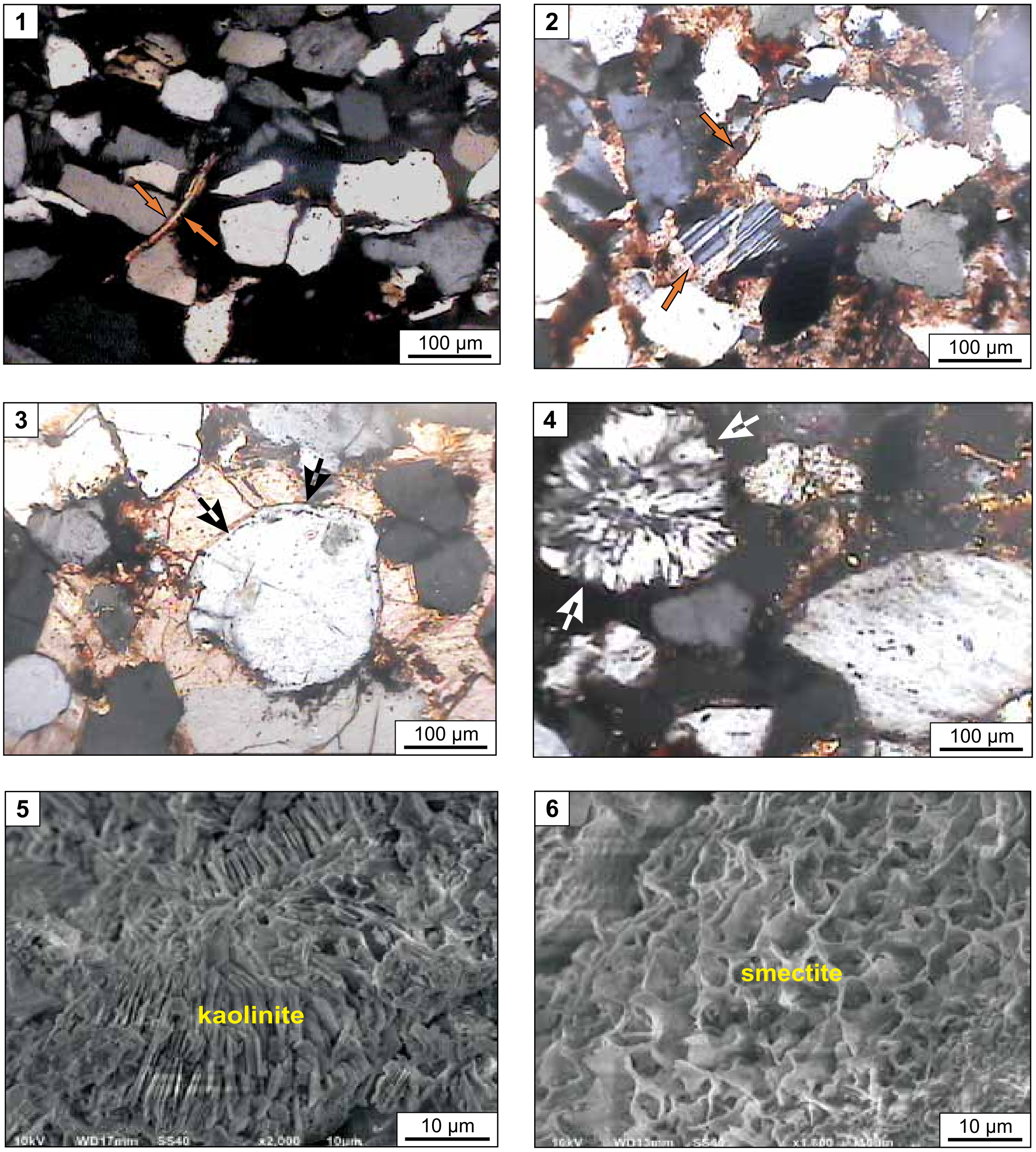
Fig. 2. Intergranular Fe-calcite cement has been replaced by silica cement within the interstices and has converted into silica rims around the quartz grains (Jhikadi Member, planar cross-bedded sandstone, level II)

Fig. 3. Quartz grains are welded by silica cement which has grown as rim cement around the framework grains. In most cases it has welded the grains forming new boundaries among them (Dhrang Member, trough cross-bedded sandstone, level II)

Fig. 4. The framework constituents (mostly quartz) are etched and are floating in matrix. Chalcedony quartz has developed within the matrix (Dhrang Member, ripple-bedded sandstone, level II)

Fig. 5. Scanning electron microphotograph showing kaolinite (Lodai Member, shale, level II)

Fig. 6. Scanning electron microphotograph showing smectite (Dhrang Member, trough cross-bedded sandstone, level II)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