CHAPTER -IV

CARBONATE PETROGRAPHY

4.1. GENERAL

Since the pioneering work of Henry Clifton Sorby (1851, 1858) the sections of rock ground thin enough to transmit light have been the stable material for sedimentary petrography. The main aim of petrography is to identify the framework components and their interrelationships in the rocks to understand the mode of life (endo- or epibiota), boring organisms, existence of predators, mechanical breakdown of the skeletons in a high energy environment, transportation and isolation of the hard parts and dissolution in the case of carbonate rocks. Carbonate sediments and rocks preserve valuable information regarding the physical, chemical and the biological conditions that have prevailed during the deposition and post-depositional conditions that have passed through it. The texture and composition of limestones in the recent period and their progressive development into characteristic forms are very important and thus the study of carbonate rocks are interesting compared to that of elastic rocks. Carbonate rocks in the present study are characterized by various framework elements such as bioclasts which give the idea about the palaeoecology and palaeoenvironment, together with other elements such as ooids, peloids, intraclasts, etc., whose mineralogical composition give idea about the energy condition prevailed during the marine depositional environment and the conditions of diagenetic realm.

The lower and middle part of the Jhurio Formation (type section) is characterised by bedded limestones, oolitic limestones and calcareous shales and the upper part of the succession is characterised by various rock types such as sandstone, shale, limestone and evaporites. The limestones are hard compact and often nodular in character.
More than 85 thin-sections of carbonate rock samples were studied using petrologic microscope to know the framework elements, texture, depositional facies and nature of diagenetic modifications. All the carbonate samples were stained with 2 % dilute HCl solution of Alizarine red-S to distinguish calcite from dolomite. The staining test has revealed that the presence of calcite in most of the rock samples and dolomite in few samples at some stratigraphic levels. The framework composition has been identified in thin sections under the petrologic microscope with the help of a number of standard reference guides (Carozzi, 1961; Scholle, 1978; Milliman, 1974; Flugel, 1982 and Adams et al., 1984,) to understand the petrographic characteristics.

4.2. CARBONATE PETROGRAPHY

The carbonate rocks of Jhurio Formation in Jhura Dome of Kachchh Mainland have been critically examined under the microscope and are described in detail with respect to their microfacies classification, depositional and diagenetic properties. Since this is the only section where carbonate rocks form the continuous succession, the study has been concentrated in depth on this particular succession. The petrography of carbonate rocks from the other localities (Habo and Jumara Domes) where Middle Jurassic exposures present also has been carried out to know the spatial/lateral variations in the depositional and diagenetic conditions during the Middle Jurassic Period.

Carbonate rocks are basically composed of two elements, which include the allochem and the orthochemical particles. Allochem particles are the main framework elements that are deposited in any marine basin. These elements are bounded together to form carbonate rock by the syndepositional or postdepositional material called cements and matrix which are the orthochemical particles. Both these particle textures are modified...
greatly by diagenesis resulting changes in their composition and texture with varying environmental setup.

4.2.1. Allochem Carbonate particles

In carbonate rocks these grains are produced chemically or biochemically within the basin of accumulation and hence most of them are intrabasinal in origin. Limestones, whether current deposited or formed in situ, are made up of large complex grains. To these grains Folk (1959, 1969) has applied the term allochems. Thus there are four principal types of allochems viz., skeletal grains, oolites, intraclasts and pellets. The Petrographic study of the carbonate rocks of Jhurio Formation has revealed finer details on the mineralogy, types of texture, nature of frame work elements, microfacies types and its constituents and diagenetic characteristics. The temporal variation in allochem particles of Jhurio Formation is shown in Fig. 4.1.

4.2.1.1. Skeletal Particles

Because of their different rates of evolution and various diversities, organisms appearing in the thin-sections of limestones have varying abundance in individual systems (Flugel, 1982). The destruction of organic tissue, types of microstructures and the primary porosity of the skeletons control the fragmentation of hard parts. The basis of microscopic work is the determination of the shape, size and orientation of crystals and crystal groups and the spatial relationships between them - in a nutshell the study of mineralogy and fabric (Bathurst, 1975). Carbonate rocks are of primary deposition: consequently, an understanding of skeletal structure allied to mineralogy is indispensable as a basis for the varied investigations. The skeletal components of limestone relate to distribution of carbonate secreting organisms through space and time. The main skeletal
Fig. 4.1 Temporal variation of Framework elements
elements in the Kachchh Jurassic sequence includes the fragments of calcareous algae, molluscs, echinoids and brachiopods followed by other such as sponges, corals, bryozoa and foraminifers. These are the important carbonate particles displaying varying stages of abrasion and rounding. In the present samples all stages of transformation of shell fragments to peloids is observed which can be attributable to the process of abrasion and increasing micritization by the boring action of algae.

4.2.1.1.1. Molluscs

Molluscan shells are constructed for the most part of organized aggregates of micron sized crystals disposed in layers. These layers differ from one another in structure, orientation of structure and mineralogy. In any one unaltered species the layers are either all aragonite or interlayered aragonite and calcite: both high magnesian and low-magnesian calcite occur (P.D.Blackmon in Cloud, 1962). Bivalves, gastropods, belemnites and ammonites are the important molluscan skeletal structures that have been identified in these carbonate rocks thin-sections. Bivalves are the most commonly and frequently found molluscan grains in the thin-sections of carbonate rocks of Middle Jurassic succession of Kachchh Mainland. They are abundant in the oolitic grainstone of lower and middle parts and in the bioclastic grainstones of middle and upper parts of the Jhurio Formation.

The original aragonitic mineralogy of these bivalves is replaced by the low magnesian calcite as evidenced by the characteristic coarse mosaic texture of calcite (Plate.4.2 – 1 & 2). The replacement has been occurred by the dissolution-reprecipitation process and the incomplete filling of the intragranular porosity by the coarse calcite mosaic is an example of the original aragonite mineralogy (Plate.4.2 – 4). Molluscan shells are
chiefly aragonitic and hence appear as a mosaic of calcite in the older rocks. Some pelecypod shells have an outer layer of calcite. In some genera (notably Ostrea and Pecten) in two layers. The outer and principal layer has a prismatic structure in which the prisms, unlike those of brachiopods, are perpendicular to the shell surface. The inner pearly layer has a fine lamellar structure. Similarly most gastropods have an aragonitic shell, but a few exhibit a two-layer structure consisting of an inner aragonitic layer covered by an outer calcitic layer. The guard of belemnite is calcite, with the calcite fibers set radially about an axis (Plate.4.4 – 5). However, the radiating crystals show the ghosts of original aragonite mineralogy with square tips.

4.2.1.1.2. Brachiopods

Brachiopods and molluscan shell fragments can normally be differentiated on the basis of differences of shell structures in addition to their shell mineralogy and shell layering. The skeletal elements are normally well preserved because of their shell mineralogy. The low-Mg calcite skeleton of brachiopods undergoes relatively little observable structural change during diagenesis, hence are well preserved. Brachiopods skeletal elements in the present samples are chiefly calcitic. Their shells are built up of bundles of prisms, the prisms of each bundle being parallel and having a quadrangular cross-section. The brachiopod valve reveals a two-layered wall of low magnesian calcite in thin-sections. The brachiopods shells are disarticulated and the important varieties seen are endopunctate and impunctate. The most brachiopods are seen associated with oolitic grainstones in the lower and middle and in the bioclastic grainstones and lithoclastic-bioclastic rudstones in the middle and upper part of the Jhurio Formation.
4.2.1.1.3. Echinoderms

Crinoids and echinoids are abundant in the peloidal packstone-grainstones of the lower and middle part of the Jhurio Formation. Spines and other skeletal parts of echinoids are present; crinoidal and echinoidal fragments can be identified by their characteristic structure delineating a regular lattice; the sterom. The hard parts of echinoderms are most singular in that each plate or skeletal element is a single crystal of calcite. Larger ones clearly show the calcite cleavage to the unaided eye, and the limestone composed primarily of such remains accordingly has a marked "crystalline limestone". In most cases the oscicles and plates have been cemented with clear calcite in crystallographic and optical continuity with crinoid fragments. The original fragment is distinguished by a dusty area showing the usual circular or elliptical (in oblique section) outline with internal canals (Plate: 4.1-4; Plate: 4.3-1). The original fragment, however, is traversed by cleavage cracks that pass uninterrupted into a secondary cement. Usually the echinoderms disarticulate rapidly so that one sees only scattered debris whose shapes are highly variable because of original growth or the plane sectioned. Their crystallographic unity is their diagnostic feature (Pettijohn 1962). Crinoids are also seen in the bedded limestones and as nuclei for the ooids in the oolitic grainstones. The crinoidal oscicles and echinoidal spines display syntaxial rim cementation (Plate: 4.1-4; Plate: 4.3-1 & 6).

4.2.1.1.4. Foraminifers & Ostracods

Smaller foraminifers (protoglobigerinids) and larger benthic foraminifers such as miliolids, textularids and fusulinids are abundant. The miliolids and smaller foraminifers (protoglobigerinids) are abundant in the peloidal limestones of the lower and middle part of the Jhurio Formation (Plate: 4.3-5 & 6; Plate: 4.4-2 & 3). The benthic foraminifers are
present in moderate amounts in the middle and upper part of the Jhurio Formation. Ostracod carapaces are seen in the oolitic limestones and in the bioclastic limestones (Plate: 4.5 - 1) and in the bioclastic wackestone (Plate: 4.8 - 2). They present in moderate amounts in the lower, middle and upper part of the formation.

4.2.1.1.5. Bryozoans

Bryozoans along with calcareous algae are abundant in the peloidal limestones (Plate: 4.7 - 4; Plate: 4.8 - 1) and in the lower and middle part of the formation (Plate: 4.5 - 3 & 4).

4.2.1.1.6. Corals

Coral fragments occur in Kachchh Jurassic sediments in minor quantities. Sometimes these are confused with echinoid plates. Exact identification of corals can be made only in oriented sections (transverse and longitudinal sections). Due to their rapid diagenetic alterations and recrystalization, the identification of corals becomes somewhat difficult. In some thin sections, longitudinal and oblique sections often exhibit a net-like porous structure of the septal filaments. The coral elements can be identified by their characteristic patterns in transmitted light.

4.2.1.1.7. Sponges

In a few instances, the limestones of Kachchh Jurassic (mainly wackestones) show the presence of hollow or calcite filled external molds of siliceous sponge spicules. The presence of cherty dolomite in some beds is indicative of the original presence of sponges.

4.2.1.1.7. Calcareous Algae

The calcareous algae are seen abundant in the algal foraminiferal peloidal fenestral laminated wackestone, peloidal packstone-grainstones (in both foraminiferal and crinoida
and in oolitic intraclastic bioclastic grainstones.

4.2.1.2. Non-skeletal grains

Non-skeletal grains are those not obviously derived from the skeletal material of micro-organisms or invertebrates or thalli of calcareous plants (Tucker and Wright, 1990). Four main types are recognized (Folk, 1959): coated grains (oolids mainly), peloids, intraclasts and aggregate grains.

4.2.1.2.1. Ooids:

A remarkable variety of coated grains occurs and many classifications including Peryt's (1983), have distinguished two broad categories of coated grains; chemically formed (especially ooid) and biogenically formed (oncoids). According to them an ooid (or oolith) is a coated grain with a calcareous cortex and a nucleus which is variable in composition. The cortex is smoothly and evenly laminated especially in its outer parts, but individual lamina may be thinner on points of stronger curvature on the nucleus. The shape is typically spherical or ellipsoidal with sphericity increasing outwards. In the Jhurio Formation the main coated gains present are ooids and there are some oncoids present. The ooids rarely grade in to pisoids. Such pisoids are seen with in the oolitic packstone-grainstone towards the top of the bioclastic peloidal wackestone/oolitic packstone-grainstone shallowing upward cycle.

The ooids are tight packed and are abundant in oolitic packstone-grainstone microfacies. Basically there are two types of ooids, one is with peloidal nucleus and concentric layers of calcite and the other type with radiating calcite crystals (Plate: 4.1-1; Plate: 4.3 – 2 & 4). These are the true ooids with many concentric layers. These ooids have perfect spherical to ovoid shape. There are considerable amount of superficial ooids which
have variable shapes. The nucleii of such superficial ooids are bioclasts, including ostracod carapaces, foraminiferal and algal grains and crinoidal and echinoidal spines. The vast amount of superficial ooids indicate that the energy conditions of the depositional medium was very high which led to the coating of almost all the grains available within the area. Both types of ooids are coated with iron oxide matter which in many samples imparting golden yellow to yellowish brown and brownish black colour to the ooids. Thus in all the types of ooids mentioned above the nucleii include micritised bioclasts such as the crinoidal and echinoidal spines, foraminiferal, algal and molluscan shell fragments.

Also seen are the quartz grains as nucleii of the ooids which are in considerable amounts towards the top of the shallowing upward cycle where the ooids generally have the larger size and sometimes grade into pisoids.

The size of the ooids vary from 0.2 mm to 1 mm. The maximum size sometimes reaches to 2 mm. The size is almost homogenous in individual thin-section. The colour varies from golden yellow to yellowish brown and sometimes brownish black when fresh. These characters strongly suggest a dynamic deposition and reject a strictly in situ intrasedimentary genesis of ooids (see Odin, 1988). Ooids with larger nuclei are characterised by thin layers in concentric to random pattern. Whereas those with small one are characterised by the presence of many concentric layers. Some are composite ooids, which show two or more ooids bounded by cement. The percentage of ooids ranges from 25-40% in oolitic packstone-grainstones and in oolitic intraclastic bioclastic grainstones it ranges from 10 - 15%.

Mineralogy of ooids influence not only their subsequent diagenesis but also their microfabric (Tucker and Wright, 1990). Shearman et al., (1970) observed an anomalous
fact that in many ancient ooids, detrital nucleus presumably once aragonite has been replaced by calcite cement, yet the oolitic coat, which has been superimposed a pattern of radial-fibrous calcite crystals. This is true in the case of ooids of Jhurio Formation, where the original aragonitic mineralogy has been evidenced from the XRD-studies of ooids. The XRD-studies (given Chapter-V) indicate that the present mineralogy is low-magnesian calcite. The coating of the ooids are mainly goethite in composition. This goethite coating upon oxidation gives a golden colour to the ooids. Shearman et al., (1970) suggested that, during diagenesis, the original aragonite was dissolved but the organic matter remained as a template on which tiny crystals of calcite cement grew with the typical preferred orientation that accompanies competitive growth.

That could be the reason for the preservation of radial calcitic structures in the most perfect ooids of Jhurio Formation. The re-use of pieces of broken ooids, is also noticed. This indicates that already hard ooids were present and were used again as nuclei for the growth of new ooids. In other words, favourable conditions for growing iron coated ooids are also compatible with an in situ reworking of previously deposited hard ooids of similar composition. Therefore, the genesis can be inferred as to the site of formation of original aragonitic ooids, iron is introduced probably from the submarine source (see Khadkikar, 1996) or from the land. The oolitic structure itself indicates the sea-water movements, and sea-water roughness also indicated by the figure drawn on sediments and underlain by the ooids. Finally the movements must have sometimes been very strong in order to break already indurated ground mass or ooids found today as nuclei in other ooids. Therefore, ooids appear to have formed in a very stirred environment usually regarded as necessarily linked with high oxidising conditions in sea water (see Odin, 1988).
The ooids also show dissolution of the nuclei and the original aragonitic concentric layers in fresh water phreatic conditions and reprecipitation as calcite, where as the outer goethite coating has remained as such. This is an example of oomouldic porosity preservation and cementation (Plate: 4.3 - 1; Plate: 4.6 - 1)

4.2.1.2.2. Peloids

McKee has coined the term peloid to embrace all grains that are constructed of an aggregate of cryptocrystalline carbonate, irrespective of origin (McKee and Gutschick, 1969). A peloid is a sandsized grain with an average size of 100-500 um, composed of microcrystalline carbonate. The peloids are abundant in the lower and middle part of the Jhurio Formation. These grains are observed with the bedded lime mudstones (peloidal packstone-grainstone and bioclastic mudstone-wackestone microfacies types) (Plate: 4.1-4; Plate: 4.2 - 4; Plate: 4.3 - 5 & 6; Plate: 4.4 - 2 & 3; Plate: 4.5 -2). The percentage ranges from 20-45 % in the bedded lime-mudstones. Size increases from lower to middle in the section in a shallowing upward cycle. The shape is usually rounded or subrounded, spherical, ellipsoidal to irregular and are internally structureless. The colour is usually greenish black to brownish black. The peloids are important constituent of shallow water marine carbonate sediments. They indicate a particular facies along with the particular fossil abundance which indicate a quite water depositional conditions.

It is widely felt that, in both recent and ancient carbonate sediments, elongated peloids, ellipsoids of revolution, are faecal pellets. Similarly the experience of Purdy(1963a, 1963b) and Barthust(1966) in the Bahamas suggests that the many of the irregular grains, at least, are skeletal particles that have been replaced by micrite as a result of processes associated with endolithic algae. This is true in the case of peloids present
in the criniodal peloidal packstone-grainstones (MF-23) of Jhurio Formation. Here many peloids are micritised skeletal particles (Plate: 4.3-5 & 6). Some peloids are clubed together to give a grapestone to lump structure (Plate: 4.1 - 4). It could be due to bioturbation. It may also be due to the fact that, it has long been known that in some peloidal grainstones the peloids tend to merge (Beales, 1958). The apparent blurring of the outline of peloidal to form grumeleuse structure, is not much evident from the peloidal packstone-grainstones of the lower and middle part of the section of the Jhurio Formation. Where as this kind of tendency is seen in few rock types especially pure peloidal grainstones where peloids are formed by the micritisation of skeletal fragments.

The peloids are polygenetic group of grains and identifying their exact origin is often impossible in limestones. The peloids present in the sediments of Jhurio Formation are mainly micritized skeletal grains and some are faecal pellets. Faecal pellets are soft and significant compaction can occur during even very shallow burial (Ginsburg, 1957; Shinn and Robin, 1983). Many ancient, finely mottled lime mudstones, wackestones and packstones probably owe their origin to the compaction of soft faecal pellets (Tucker and Wright, 1990). Peloids are probably the most abundant ubiquitous of the allochems (McLane, 1995). Most faecal pellets are initially quite soft and under overburden pressures are readily mashed into what commonly comes to be labeled as matrix (Shinn and Robin, 1983; McLane, 1995). Some of the peloids are very minute as seen in foraminiferal peloidal packstone-grainstones (Plate: 4.3 – 1; Plate: 4.5 – 2). Marshal (1983a) suggested that such small spherical peloids formed by chemical precipitation. Criteria for their recognition in limestones have been discussed by Flugel (1982) and concentrations of well-sorted peloids especially in burrow structures are often used as evidence of a
faecal origin (Tucker and Wright, 1990). The preservation of recognizable pellets in limestones is clear evidence of early lithification. The peloids of foraminiferal as well as crinoidal peloidal packstone-grainstones mostly represent micritised grains such as abraded shell fragments or ooids (Plate: 4.1-4; Plate: 4.3-5). The original grain has been completely micritized by endolithic microorganisms (Barthust, 1975).

4.2.1.2.3. Intraclasts

The fourth category of non-skeletal grains are limestone clasts (Tucker and Wright, 1990) or intraclasts (Folk, 1959). They are reworked sediments of at least partly consolidated carbonate sediments. Intraclasts are fragments of typically weakly consolidated sediment reworked from within the area of deposition. Intraclasts present in moderate amounts in the oolitic packstone-grainstones, oolitic intraclastic bioclastic grainstones and in peloidal grainstones (as mud intraclasts). Minor amounts of intraclasts are seen in the lithoclastic bioclastic rudstones and in peloidal grainstones. In oolitic packstone-grainstones the presence of mud intraclasts are noticed. The percentage of intraclasts in oolitic intraclastic bioclastic grainstones ranges from 15 - 20 %. In lithoclastic bioclastic rudstones also the percentage is approximately same.

4.2.1.2.4. Aggregate grains

Grain aggregates are found when several carbonate particles become bound and cemented together (Tucker and Wright, 1990). Such aggregate grains are seen in lithoclastic bioclastic rudstones, oolitic intraclastic-bioclastic grainstones and in bioclastic wackestonet-grainstones (Plate: 4.1-3; Plate: 4.3-6). The size usually range from 0.5 mm to 3mm and have irregular shapes. In some peloidal grainstones especially in crinoidal peloidal packstone-grainstones the peloidal gains are cemented together to form a grapestone to
lump structure (Plate: 4.1-4). These aggregates are an important environmental indicator of its depositional energy conditions. The percentage of aggregate grains is 10-15% in the peloidal grainstone-packstones and in the oolitic intraclastic bioclastic grainstone and 5-10% in the bioclastic wackestone-gainstones.

4.2.2. Orthochemical Constituents

The orthochemical particles are matrix or cement precipitated from the sea water and the interstitial solutions. These orthochemical particles are generally aragonite or high Mg-calcite in the carbonate sediments and then these particles are modified into different morphologies and have characteristic textural patterns. Accordingly early diagenetic and late diagenetic cements have different textures and mineralogy. Usually orthochemical particles show low Mg-calcite mineralogy in the ancient carbonate sediments since both aragonite and high Mg-calcite are metastable. The characteristic orthochemical particles and their textural types are micrite and sparite and their different morphological varieties such as microsparite, columnar fringe cement, coarse blocky sparite and syntaxial rim cement. These cement textures are described in the discussion on diagenesis.

4.2.3. Visual Porosity

The visual porosity types are identified as different pore spaces under low porosity magnification in carbonate and in mixed carbonate-siliciclastic-evaporite microfacies types. Different types of porosities are observed under the microscope in the rock sections of Jhurio Formation. These are the following types:

4.2.3.1. Intergranular porosity

The pore spaces available between the framework elements are usually considered as intergranular porosity. It is usually abundant in recent carbonate types and which are
buried at shallow depths. Whereas during the post depositional changes including the deep burial, much of the primary porosities are lost. Thus in ancient limestones the primary porosities are rarely preserved. This occurs due to the cementation by carbonate cement. Thus intergranular porosity dependent on particle shape, sorting and alteration during diagenesis. The intergranular porosities in Jhurio Formation is present in bioclastic grainstones, oolitic grainstones and in calcareous sandstones (Plate: 4.1-1; Plate: 4.2-3; Plate: 4.4-4; Plate: 4.7-3 & 4; Plate: 4.8-2). The peloidal mudstones which form more than fifty percent of the Jhurio Formation are almost devoid of intergranular porosities.

4.2.3.2. Intragranular porosity

This is the most abundant types of porosities available in ancient carbonate rocks. It is basically formed simultaneous with the deposition, but mostly during the post depositional changes. The porosity is developed due to the dissolution within the bioclasts and pore-spaces are usually partially or completely left unfilled by the secondary calcite cement. Such intragranular porosities are observed in considerable percentage in bioclastic grainstones, oolitic grainstones, oolitic intraclastic bioclastic grainstones and in peloidal group of microfacies (Plate: 4.2-4; Plate: 4.3-3 & 4; Plate: 4.7-1 & 3; Plate: 4.8-1).

4.2.3.3. Secondary void porosity

The secondary void porosity is exhibited by the various allochem particles such as oolites, intraclasts, etc. Oomoldic porosity is well exhibited by oolitic grainstones (Plate: 4.1-2; Plate: 4.6-1). The voids are produced by undersaturated fresh water reaction with the calcareous ooids. The nucleus which are usually of peloidal bioclasts are dissolved and thus leaves voids which are latter produced by the reprecipitation processes. Some of the intraclasts also exhibit the same type of secondary void porosity especially in the oolitic
intraclastic bioclastic grainstones.

4.2.3.4. Disrupted porosity

Different types of porosity are formed with irregular shapes during the postdepositional changes in carbonate rocks. The bioclastic grainstones exhibit peculiar types of disrupted porosities which are associated with the stylolites and are similar to the stylolites but are very short and small (Plate: 4.2-3; Plate: 4.4-4). The main causes of formation of disrupted porosities are activity of burrowing organisms, slumping and pressure dissolution under burial diagenesis.

4.3 CARBONATE DIAGENESIS

Because diagenetic structures related to lithification can be confused with primary depositional structures and textures, knowing the possible diagenetic processes is extremely important for the interpretation of microfacies characteristics (Flügel, 1982). The diagenesis of carbonate sediments and rocks encompasses all the processes that affect the sediments due to physical, chemical and biochemical changes immediately after the deposition until realms of incipient metamorphism at elevated temperatures and pressures. Diagenetic changes can begin on the sea floor, as the grains are still being washed around or as a reef is still growing, or it may hold off until burial when overburden pressure has increased or pore-fluid chemistry has changed so that reactions are induced within the sediments (Bathurst, 1975).

A variety of factors influence the diagenesis of carbonates, which according to Chilingar et al., (1967) include: i) Geographic factors, ii) Geotectonism, iii) Geomorphic position, iv) Geochemical factors in regional sense, v) Rate of sediment accumulation, vi) Initial compaction of the sediments, vii) Purity of sediments, viii) Grain size, ix)
Accessibility of limestone framework to surface, i) Interstitial fluids, xi) Physiographic conditions and xii) Previous diagenetic history of the sediment materials. The processes of diagenesis includes six major processes: cementation, microbial micritization, neomorphism, dissolution, compaction (including pressure dissolution) and dolomitization. Thus in summary the major controls on the diagenesis are the composition and flow rates, geological history of the sediment in terms of burial/uplift/sea-level changes, influx of different pore-fluids and prevailing climate (Tucker and Wright, 1990).

4.3.1. Diagenesis of Jhurio Formation (Jhura Dome), Kachchh Mainland

Cementation, Micritisation, dissolution-reprecipitation, neomorphism, compaction, dolomitisation are the important processes of diagenesis with small scale processes of silicification and stylolitisation.

4.3.1.1. Cement Textures

The petrographic study of carbonate rocks of Jhurio Formation has revealed the three different types of cements such as the carbonate, iron oxide and smectite that have developed during the successive stages of diagenetic environments. Also there are seven types of cement textures which are the products of diagenesis developed during the four diagenetic environments. The four diagenetic environments are in the order as marine phreatic, fresh water phreatic, burial and fresh water vadose diagenetic.

4.3.1.1.1. Micrite

Micrite cement is abundant in the peloidal packstones and bioclastic wackestone-grainstone microfacies types(MF-20, 21, 22 23 & 40). The microfacies numbers (MF- 21, 40,etc.) are explained in the classification of microfacies. The micritisation must have occurred in a stagnant marine phreatic environment where by abundant micritic mud has
been produced by disintegration of skeletal material by endolithic bacteria. The micritic matrix latter neomorphosed to form microspar at places in bioclastic wackestone (MF-40) which grade in to grainstone at places (Plate: 4.5-1) The micritisation is the main diagenetic process that have predominant in this microfacies. The peloidal packstone-grainstones (MF-20, 21, 22 & 23) in the lower and middle part of the Jhurio Formation is also predominantly originally micritic cement which latter neomorphosed in to microspar to pseudospar (Plate: 4.1-4; Plate: 4.3-1, 5 & 6). In bioclastic peloidal mudstone-wackestone microfacies(MF-21) micritic mud is predominant nearly about 50% which later neomorphosed in to microspars and pseudospars. Thus neomorphism is the dominant process that occured in the peloidal group of microfacies. Where as in the case of peloidal packstones the micritic cement binding the peloids comes about 20 - 35 %. This variation can be inferred from the percentage of peloids. The bioclastic mudstone-wackestones are cyclically deposited with the oolitic packstone-grainstone. In peloidal packstones and bioclastic mudstone-wackestones the micrite shows the tendency to form clots. In oolitic intraclastic bioclastic packstones and bioclastic grainstones the micritisation is evidenced by presence of micrite envelopes(Plate: 4.2-1 & 2). Micritisation is also evidenced in the SEM-analysis as observed in the Plate: 4.7- 3, 4 & Plate: 4.8 - 6. These micrographs shows the micritised algal, foraminiferal, bryozoan and ostracodal skeletons. In Plate: 4.2 – 1 & 2, the micrite envelope is composed of micritic calcite. As is noticed by Bathurst(1975), the outer surface of the coat has gentle smooth contours and the inner surface is irregular. The envelope apparently formed centripetally in carbonate grains by precipitation of micrite in vacated algal bores is initially composed of micritic aragonite or high magnesian calcite, with some impurity depending on the amount of
residual primary carbonate. Where as in ancient limestones it is low magnesian calcite micrite and if it should have formed around an aragonite grain while on the sea-floor, then that aragonite core has normally been replaced by calcite spar (Plate: 4.2-1 & 2). So the micritic envelope has a great role in repeating diagenetic history of a carbonate sediment. Thus micritisation and micrite cement are the product of stagnant phreatic marine environment. Subsequent burial at shallow depth brings the microsparite patches in some microfacies types (e.g. bioclastic wackestone-grainstone).

4.3.1.1.2. Equant calcite cement

The equant calcite cement of first generation marine phreatic diagenetic environment is noticed over the ooids and bioclasts in the oolitic intraclastic bioclastic grainstones (MF-11) and oolitic packstone-grainstone (MF-10) microfacies types. Here the earlier marine phreatic equant cement is partly covered by late diagenetic micrite matrix at places (Plate: 4.1-1 & 2). In Plate: 4.1-1, the central portion shows the early cemented oolites. In the microfacies, oolitic packstone-grainstone, the early equant cement over the oolite grains is an evidence of the active marine phreatic environment where true calcareous oolites have been formed which later replaced by low magnesian calcite. During the formation of this first generation cement the water depth was very shallow and active waves and shallow agitating water was strong enough to form oolites with almost all the material available in the area.

4.3.1.1.3. Columnar fringe sparite

The columnar fringe sparite with scalenohedral habit which is of earlier generation is seen over the bioclasts in oolitic intraclastic bioclastic grainstone microfacies (MF-11). This sparite cement has grown over the molluscan bioclasts (Plate: 4.2-1 & 2).
The length and width varies from 0.05 to 0.5 m. and 0.02 to 0.06 mm. respectively. The scalenohedral fringe cement is not bright and clear compared to the rhombohedral sparite cement formed after the fringe cement. The cementation of this fringe type must have formed in a marine phreatic environment. Because it resembles columnar fibrous cement and is seen as isopachous fringes over the grains (over molluscan bioclasts in Plate: 4.2-1 & 2). Finally it is followed by rhombohedral sparry cement (Tucker and Wright, 1990).

4.3.1.1.4. Blocky mosaic calcite

The blocky mosaic calcite sparite is very coarse clear and bright compared to that of first generation marine phreatic cements. This cement occupies both intragranular and intergranular porosities (Plate: 4.1-1 & 3; Plate: 4.2-1 & 2; Plate: 4.3-3). The approximate diameter of the crystals vary from 0.1 to 0.5 mm. This cement type is observed in oolitic intraclastic bioclastic grainstones(MF-11), oolitic packstone-grainstone (MF-10) and bioclastic packstone-grainstone(MF-41). It has been originated usually by the dissolution of original aragonitic or high magnesian calcite mineralogy and reprecipitation into low magnesian calcite by inversion or recrystallisation in a fresh water phreatic diagenetic environment. The Plate-4.7-1 & 4 and Plate: 4.8-1 show the coarse sparite cement formation from the algal grains due to the dissolution reprecipitation process. During the precipitation process some of the porosities are still left unfilled as micropores.

4.3.1.1.5. Syntaxial replacement rim

Syntaxial replacement rim cements are seen in peloidal packstone-grainstones (MF-23 and in bioclastic mudstone-wackestones (MF-21). The host is usually crinoid ossicles and echinoid spines. The Plate: 4.3-1 shows the rim cement over the crinoid ossicles at the center and in the central lower portion. The syntaxial overgrowth is seen
over the foraminiferal and other few bioclasts. In the Plate-4.1, Photomicrograph-4, the rim cement embay the surface of pellets. The nuclei that underwent syntaxial enlarge usually seen floating in the spar. In both the microfacies the main primary cement is micrite cement. This is an indication of stagnant marine phreatic cement. The quite water conditions of the depositional medium were evidenced by the peloids mainly the faecal pellets. The syntaxial replacement rim cement is formed due to the shallow burial diagenesis. Plate-4.7, SEM-micrograph-4 shows the syntaxial rim cementation in peloidal grainstone, showing the cementation over the micritised crinoidal and algal grains.

4.3.1.1.6. Ferrugenous micritic cement

The ferruginous micritic mud is observed as main binding material in the lithoclastic bioclastic rudstone microfacies (Microfacies 30). This carbonate mud is red to reddish black in colour and is iron oxide in composition. The micritic mud is filled both the intergranular and intragranular primary porosities and gives a compact form for the microfacies. The micritic mud is dark colour under the microscope. The mud has been filled within the borings of many bioclasts (Plate-4.4-6). The bioclasts which are bored on the subaerial exposure in the intertidal area and were reworked during the flooding due to transgression of the sea and the bioclasts were carried to the place of red micritic mud. The ferruginous micritic mud has been lithified during the early diagenetic processes.

4.3.1.1.7. Smectite rim cement

The algal foraminiferal peloidal fenestral laminated wackestone microfacies (MF-22) is characterised by the thin smectite rim cement lining the fenestral laminations (Plate-4.5 - 3 & 4). This microfacies is very thin bedded (5-15cms. thick) and is cyclically deposited with crinoidal peloidal packstone-grainstone. The smectite abundance
in insoluble residues of the above microfacies is evidenced by the XRD-studies. The glycolation studies of insoluble residue revealed the dominance of smectite over quartz in this microfacies. The laminations of fenestral cement are parallel to the bedding and at intervals. The smectite must be of authigenic in character.

4.3.1.2. Compaction

Compaction refers to any processes that reduces the bulk volume of the rocks. This includes mechanical processes that decrease the bulk volume of single grains (grain deformation) or that cause closer packing of grains (re-orientation) and pressure solution which decrease the volume of grains and cementing materials. Important evidences of compaction observed in Kachchh Jurassic rocks are (i) some oolites show pressure solution effects in which some grains have been pressed into others, and (ii) fecal pellets, presumably soft at the time of deposition, commonly show effects of squeezing and bending due to compaction (Plate: 4.1-4). Over packing of pelecypod shells in bioclastic grainstones (Plate: 4.2-3; Plate: 4.4 -4) is also indicative of compaction.

4.3.1.3. Dissolution

Dissolution produces pore space by dissolving pre-existing minerals. This process is particularly important in carbonate rocks because it often creates additional porosity that might serve as a hydrocarbon trap. Dissolution can leave a variety of distinctive and interesting textures in the limestone rocks. Selective dissolution of aragonitic or high-Mg calcitic fossils and ooids are seen selectively dissolved producing voids (Plate: 4.3-2). Such dissolution produces secondary porosity (Plate: 4.2-4).
4.3.1.4. Neomorphism

The term neomorphism was introduced by Folk (1965) to cover processes of replacement and recrystallization where there may have been change of mineralogy. Recrystallization, strictly, refers to changes in crystal size without any change of mineralogy. Since many carbonate sediments originally consist of mixtures of calcite and aragonite, the term recrystallization cannot properly be applied to replacement textures and neomorphism is used instead. Neomorphic processes takes place in the presence of water through dissolution-reprecipitation; that is, they are wet processes. Most neomorphism in limestones is of the aggrading type, that is leading to general increase in crystal size, and this occurs chiefly in fine grained limestones, resulting in microsparitic patches, lenses, laminae and beds. The opposite, degrading neomorphism, is not most common. Calcitisation is another process of neomorphism, wherein aragonitic skeletal grains and cements are replaced by calcite. Dolomite and evaporitic minerals can also be replaced by calcite. The calcitization process involves gradual dissolution of the original mineral and precipitation of calcite, so that usually some minute relics of the original shell or cements are retained in the neomorphic calcite (Plate: 4.4-5). In the present samples it can be clearly observed in some carbonate particles especially bioclasts wherein the original metastable minerals probably aragonite and high-Mg calcite have been selectively replaced by the neomorphic calcite (Plate: 4.2-1 & 2; Plate: 4.4-5). However, under the light microscope there is no change is observed in the original shell structure.
4.3.1.5. Micritisation

Micritisation is a process whereby bioclasts are altered while on the sea floor or just below by endolithic algae, fungi and bacteria. The skeletal grains are bored around the margins and the holes filled with fine grained sediment or cement. Micrite envelopes are produced in this way and if the activity of the endolithic microbes is intense, completely micritized grains are formed. The Middle Jurassic Limestones of Kachchh Mainland exhibit in many samples, the process of micritisation wherein some bioclasts are in the process of the micritisation and other are completely micritised with the continuous and boring activity of algae. Evidences of micritisation is left as micrite envelopes on some bioclasts (Plate: 4.2-1 & 2).

4.3.1.6. Replacement

Simultaneous dissolution of original material and precipitation of a new mineral while preserving the original form is known as replacement. In the present samples many evidences of replacement have been observed. Many carbonate particles such as fossils or ooids, have been replaced with all the fine details still intact suggesting slow, step-by-step dissolution and immediate cementation (Plate: 4.2-4). In some samples the dolomite is seen replacing the original calcite grains indicating a replacement origin of dolomite (Plate: 4.2-3; Plate: 4.4-4). At some levels some samples show replacement of calcite by chert.

4.3.2. Diagenetic environments

The three kinds of cements and seven types of cement textures are basically formed during the four different types of diagenetic environments, such as marine phreatic, meteoric phreatic burial and fresh water vadose diagenetic in the order. By identifying the different cement textures from the petrographic evidences and integrating the
environments of diagenesis, it is understood that the carbonate microfacies together with the mixed carbonate-siliciclastic-evaporite facies belonging to Jhurio Formation have undergone alternative episodes of marine and freshwater influence during early diagenetic processes and subsequently been subjected to burial diagenesis and after the upliftment it has again undergone the fresh water vadose diagenetic condition. During this mesogenetic regime mineralogical and textural changes preserved the magnitude of diagenesis in these ancient carbonates. Marine diagenesis of carbonates of Jhurio Formation is characterized by the presence of kinds of cements such as calcitic micrite and isopachous smectite rim cement. The cement textures such as micrite, equant calcite cement and columnar fringe cement are also a development of marine diagenesis (Plate-4.1-1; Plate-4.2 - 1 & 2). The main change in porosity during marine diagenesis is one of porosity loss through cementation (Tucker in Wright, 1993). The cements are mostly precipitated directly from sea water and many thousands of volumes of water must pass through a pore to occlude the porosity. The marine phreatic diagenetic environment is characterised by a stagnant and active condition prevailed during marine diagenetic processes. During the formation of oolites and their early diagenesis, active marine phreatic environment prevailed which caused the formation of equant calcite cementation over the oolites. While during the stagnant marine conditions the early diagenesis took place in the bedded limestone and calcareous mudstone which have undergone diagenetic bedding.

Fresh water phreatic diagenetic environment is then followed the marine diagenetic conditions. During the meteoric phreatic environment the blocky sparite and bladed calcite sparite are formed. Since the fresh water is having low ionic concentrations cements were precipitated slowly and thus exhibits coarse, clear and bright calcite crystals.
under the microscope. In the near surface fresh water diagenetic environment, porosity can be gained or lost. Porosity reduction mostly occurs through cementation (plus internal sedimentation) and this may take place in vadose and/or phreatic zone. During meteoric diagenesis porosity is created in these carbonate sediments through leaching of grains by carbonate undersaturated waters. The main controls on meteoric diagenesis are climate, amplitude and duration of sea-level fluctuations causing subaerial exposure and original sediment mineralogy. Climate is the fundamental control on meteoric diagenesis, since the quantity and frequency of meteoric water passing through the sediments control the degree of leaching and cementation. The magnitude of relative sea-level fall is important in controlling the depth to which the meteoric processes operate. The original sediment mineralogy is important in terms of the degree of leaching and cementation that can take place, that is, the sediment diagenetic potential. Modern shallow water carbonate sediments are composed of a mixture of aragonite, high-Mg calcite and low-Mg calcite grains. Aragonite is the least stable in meteoric waters and is readily dissolved. The evidences of fresh water phreatic diagenesis is recorded in the oolitic grainstones, bioclastic grainstones, and peloidal mudstone-packstone-grainstone exhibiting micrite through microsparite to pseudosparite cement textures and drying and dewatering through the cracks. The oomoldic porosity preserved in the oolitic grainstones are due to the activity of freshwater due to which dissolution or leaching of original aragonite occurred in the shallow burial conditions. Since the mineralogy of the sediments and as well as limestone forming organisms of Jurassic/Cretaceous Period was dominantly calcitic, the amount of meteoric leaching is less in the sediments of Middle Jurassic of Kachchh. During the transition period between the marine diagenesis and the fresh water diagenesis the carbonate
sediments and rocks are buried at shallow depth in mixed marine-fresh water diagenetic conditions for short period if the regression is soon followed by the next transgression. During this condition the rocks undergoes dolomitisation. The evidences of such dolomitisation and partial dolomitisation processes are seen in some of the microfacies types (Plate: 4.2-4; Plate: 4.2-3; Plate: 4.3-5; Plate4.4-4; Plate: 4.6-4).

Burial diagenetic processes lead to almost complete destruction of the porosity. Cementation in burial environment is by calcite spar, and in many limestones this has completely occluded the porosity. In many carbonate reservoirs, it appears that oil entry took place early, before burial spar cementation in adjacent rocks. The intensity of burial is also an important factor in the development of typical cement textures and complete occlusion of porosity. The burial diagenetic features are characterized by shallow burial and deep burial cement textures. In the case of bedded limestones of Jhurio Formation, the syntaxial rim cement over the crinoids and echinoids are characteristic of shallow burial diagenetic processes. The burial diagenetic condition has also brought changes in the cement textures of oolites. The oolitic textures are also seen with neomorphosed textures. The compaction of sediments, especially both the shallow marine deposits of oolitic grainstones and deep shelf deposits of bedded limestone/calcareous mudstone exhibit evidences of burial diagenesis. The fragmentation of bioclasts in oolitic grainstones and oolitic intraclastic grainstones and neomorphosed microspars of bedded limestone and the presence of syntaxial rim cement over peloids are the result of diagenetic processes that has taken place under the burial diagenetic conditions. The dolomitisation processes are also initiated during the burial diagenesis in some of the microfacies. The stylolitisation is the another important process that have occurred to microfacies types such are bioclastic
grainstones and peloidal group of microfacies types (Plate-4.2-3; Plate-4.4-4; Plate-4.8-2). The stylolites are produced due to the chemical diagenesis and pressure dissipation during the compaction due to deep burial pressure conditions. In the final the carbonate rocks of Jhurio Formation in its type section have undergone fresh water vadose diagenetic condition. During this period the oolites have developed oomoldic porosity and cemented later (Plate: 4.3-2; Plate: 4.6-1). The other important properties are the geopetal structures in some of the microfacies types (Plate: 4.5-1) and the fenestral cements in the algal foraminiferal peloidal fenestral laminated microfacies (Plate: 4.5-3 & 4). These cement textural types developed during the fresh water vadose diagenetic environment.

4.4. CLASSIFICATION

The classificatory schemes of both Dunham (1962) and Folk (1959, 1962) distinguishes allochems, matrix or micrite, and sparry calcite cement, and both emphasize texture. In the Folk's classification, sparry allochemical limestones (sparites) and micritic allochemical limestones (micrites) are subdivided on the basis of the kind and proportion of allochems and given composite names. Micritic limestone contains less than 10% allochems; specific varieties are named based on the predominant allochem. The recrystallized, bioturbated micrite is called dismicrite. Biolithites are limestones that were crystallized directly from the activity of reef-building corals or algae. Folk (1962) introduced the concept of limestone textural maturity, which is determined by measuring the grain-to-matrix ratio (GMR). Textural maturity adds precision to limestone description and allows energy conditions at the depositional site to be implied. Stronger or more frequent currents (contingent in most instances on shallower depth) abrade away micrite; allochems become better sorted and, with continued abrasion, better rounded. One major aspect of limestones not reflected in Folk's classification is whether the sparry calcite is primary
cement or a secondary recrystallization of micrite. In other words, any limestone with a spar...micrite. Since this determination is often hard to make, Folk's classification is much more descriptive and objective.

The Dunham's (1962) classification emphasizes limestone texture, especially grain ( allochem) packing and the ratio of grains to matrix. Allochem type is ignored. In his scheme five types of limestones are identified: mudstone, wackestone, packstone, grainstone, and boundstone. All except boundstone accumulate as clastic carbonates; individual components are not bound together during deposition. Mudstone, wackestone, and packstone contain mud (any silt- or clay-size grains, regardless of composition). Mudstone and wackestone are mud-supported in which allochems are scattered through the micritic rock. Packstone contains less mud and is grain-supported. Grain-supported limestones typically have their allochems in tangential contact. Grainstone contains no mud, and allochem grains support one another. Limestones in which the components have been bound together from origin (such as reef rocks) are called boundstones (equivalent to Folk's biolithites). A sixth category, crystalline carbonate, refers to any limestone in which the original depositional texture is unrecognisable. Embry and Klovan (1972) further modified the original Dunham classification to provide niches for limestones that contain allochems coarser than 2 mm. Those with a matrix-supported texture are called floatstone. Those with a grain-supported texture coarser than 2 mm are called rudstone. Boundstones are further subdivided into framestone, bindstone, and rafflestone.

For the present work, the classification of carbonate rocks proposed by Dunham (1962) has been largely followed. Dunham's (op.cit.,) classification is considered useful for its simplicity and direct utility in interpreting the depositional environment. Though
Dunham’s original terminology has been retained a few prefixes have been added to the types present in the area with an aim to distinguish the petrographic sub-types which are important for environmental reconstruction. The wackestone and packstone with variable amount of allochems are dominant types followed by grainstones and mudstones. The petrographic types identified in the present study have close resemblance to the standard microfacies assemblages (SMF-9, 11, 14, 15 and 16 etc.,) characteristic of facies belts 6, 7, 8 & 9 of Wilson (1986). The various petrographic types of Kachchh Jurassic carbonates are described as follows.

4.4.1. Carbonate Microfacies Types

Carbonate facies are the product of complex, interwoven processes. The microfacies classification of carbonate rocks of Jhurio Formation is carried out based on the petrographic properties and the criteria used are the types of dominant biota, non-skeletal grains, texture of the microfacies, proportion of sparite to micrite, etc. The quantitative microfacies classification is based on the modal analysis of different elements in the section. The concept of depositional interpretation of microfacies may be credited to French micropalaeontologist J.Cuvillier (1952) of the Sorbonne in Paris. An early review of the importance of the concept was given by Fairbridge (1954). Many of the basic types have been categorized by Flugel (1972) who added sedimentological criteria to the basic palaeontological approach used by Horowitz and Potter (1971). Using the general category of Folk (1962), Dunham (1965) and Flugel (1972), Wilson (1975) proposed a classification of Standard Microfacies Types (SMF) which has been utilized in the present study. The microfacies are named as 10, 20, 30, 40, 50 and 60 representing different textural groups. The use of numerical series is standard practise in microfacies studies, it associates
genetically related microfacies, provides an opportunity to accommodate new data (Dawson and Carozzi, 1986; Feiznia & Carozzi, 1987), since the present study included only on the microfacies of Middle Jurassic of Kachchh Mainland. Further microfacies studies on the Upper Jurassic rocks in future can be added to the genetically related microfacies types of the present study. From the studies of different vertical stratigraphic sections of Jhurio Formation about 9 microfacies types which belongs to four microfacies groups have been identified and described, which occupy almost the lower and middle part and also at the topmost portion of the upper part of the Jhurio Formation. The four microfacies groups fall in to two facies belts such subtidal facies and peritidal facies. Subtidal facies includes the peloidal group. Where as the peritidal facies includes oolitic, bioclastic and lithoclastic groups. Fig.4.2 shows the temporal distribution of microfacies types of Jhurio Formation.

4.4.1.1. Oolite Group

4.4.1.1.1. Microfacies 10: Oolitic grainstone (Plate: 4.3-2; Plate: 4.6-1).

The oolitic grainstone microfacies is constituted by the ooids, superficial ooids and few bioclasts, especially of brachiopods and molluscan shells and ostracod carapaces. The nuclei of ooids are both peloids and fine quartz grains. The ooids cemented by first generation marine phreatic cement and followed by the second generation coarse blocky sparite of the meteoritic phreatic diagenetic environment (Plate-4.3-2; Plate-4.6-1). The intragranular porosities filled with the reprecipitated sparry cacite and the original aragonitic concentric layerings of the ooids are neomorphosed into low magnesian calcite. The grainstones grade into well sorted packstone. The ooids constitute approximately 30-40% of the rock volume. The size of the ooids in the microfacies increases towards the
Fig. 4.2 Temporal distribution of Carbonate Microfacies of Jhurio Formation.
top with in the bed and the average grain size of the ooids increases in the top of the ooid grainstone cycle. The microfacies is further characterised by the coating of goethite over the calcareous ooids and gives a yellowish to brownish golden colour to the ooids. Most of the ooids are seen with only one or few concentric layerings. Such are superficial ooids. Most of the larger bioclasts and other grains can be thus included under superficial ooids. This indicates high energy conditions in a shallow marine shoaling environment. Thus the microfacies is mineralogically and compositionally matured. The oomoldic porosity shown by the ooids of oolitic grainstone microfacies (Plate: 4.3-2; Plate-4.6-1) is indication of fresh water phreatic diagenesis.

4.4.1.1.2. Microfacies 11: Oolitic intraclastic bioclastic grainstone (Plate: 4.1-1; Plate: 4.2-1 & 2).

The oolitic intraclastic bioclastic grainstone comprises oolitic patches and bands and bioclasts of bivalves and brachiopods, echinoids, crinoids and ostracods. The microfacies differs in colour from dark grey to greenish brown. The ooid grains shows first generation of cement (Plate: 4.1-1). The bioclasts show the neomorphic changes mainly inversion through dissolution of original aragonitic mineralogy of molluscan bioclasts to coarse granular mosaic calcite (Plate: 4.2-1 & 2). The ooids comprises 10-15%. Intraclasts also constitute the approximate volume. The bioclasts comprises 30-35% of the volume.

4.4.1.2. Peloidal Group

4.4.1.2.1. Microfacies 20: Algal foraminiferal peloidal packstone-grainstone (Plate: 4.2-3 & 4).

The foraminifers are mainly smaller ones (protoglobigerinids) and larger ones
(benthic) such as miliolids, and fusulinids forms the main biota along with algal grains and few crinoid and echinoid spines. The peloids are small and the size increases upward in a shallowing upward cycle. The peloids include both faecal pellets and small micritised bioclasts. The sparite cement is the microspar produced by the porphyroid neomorphism. Syneresis cracks filled with coarse blocky sparite reveals the tectonic upliftment form the basin and consequent dessication and dewatering of fresh water.

4.4.1.2.2. Microfacies 21 : Bioclastic peloidal mudstone-wackestone (Plate: 4.3-1).

The bioclasts are thin-walled bivalves, spicules and few smaller foraminifera. The micrite mud is the main cement which is sparitised at places due to porphyroid neomorphism. The microfacies has a yellowish brown colour. The peloids are mainly faecal pellets and some are fine micritised bioclasts probably of smaller foraminiferal tests. The peloids are seen with blurred boundaries in some.

4.4.1.2.3. Microfacies 22 : Algal foraminiferal peloidal fenestral laminated mudstone-wackestone (Plate: 4.5-3 & 4).

The foraminifers are smaller and the encrusting fine algal mats are cemented with micritic cement. The microfacies is characterised by the fine laminations of fenestral sparite cement. This fenestral laminations are lined with smectite. Thus thin bedded microfacies (5-15 cms. thick.) is characterised by the dominance of smectite over quartz. The microfacies is seen cyclically deposited with the crinoidal peloidal packstone microfacies. The microfacies is mineralogically and compositionally poorly matured. The environment of deposition might have been quite water conditions in a deep shelf slope to basinal environment.
4.4.1.2.4. Microfacies 23: Foraminiferal echinoidal crinoidal peloidal packstone-grainstone. (Plate: 4.2-4; Plate: 4.3-1 & 6).

The echinoidal spines and crinoidal oscicles are abundant along with minor amounts of benthic foraminifera such as miliolids and fusulinids and smaller foraminifers. The crinoid oscicles and the echinoid spines are centred with syntaxial replacement rim cement. The peloids are larger and in some they club together which appears to form grapestone to lump structure. This indicates a quite water depositional conditions. Partial dolomitisation is observed which is due to the fresh phreatic, burial diagenetic conditions and the final fresh water vadose diagenetic processes during the upliftment of the basin deposits.

4.4.1.3. Lithoclastic Group

4.4.1.3.1. Microfacies 30: Lithoclastic bioclastic rudstone (Plate: 4.3-4; Plate: 4.4-6)

The bioclasts include large bivalves, brachiopods and oysters. The bioclasts are extensively bored and embedded in ferruginous micritic mud along with large pebblictic lithoclasts. In some rudstone types the place of ferruginous mud is occupied by the micritic mud in which reworked ooids and aggregate grains are seen along with large bioclasts. Both types can be considered under the same microfacies headings since both appear as a lag deposit with its thin bedded form at the base of a shallowing upward cycle.

4.4.1.4. Bioclastic Group

4.4.1.4.1. Microfacies 40: Bioclastic wackestone-grainstone (Plate: 4.5-1).

The bioclasts include brachiopods, bivalves, belemnites, algal and coral grains. The microfacies contains abundant matrix and is neomorphosed in to microsparite cement. The microfacies grade in to packstone. The characteristic feature of this microfacies is the
abundant belemnites compared to the other microfacies types. The belemnite rostrum shows the evidence of original aragonitic mineralogy seen concentric and is later inverted to sparry calcite. The tabular pointed crystals of sparry calcite is the clear evidence of original aragonitic mineralogy. The umbrella effects and geopetal structures are seen in the microfacies types. This microfacies type is seen at the top of the Jhurio Formation in the central northern portion of the Jhura Dome. Where as in the north-eastern part, the microfacies is seen deposited cyclically with the Microfacies-61, indicating a deep lagoonal environment.

4.4.1.4.2. Microfacies 41: Bioclastic grainstone (Plate: 4.2-3; Plate-4.4 - 4)

Mainly bivalves and subordinate brachiopods, and very few algal remains, foraminifers and peloids. The bivalves are packed and pressure welded due to pressure solution by the over packing due to shallow burial. Thus the chemical diagenesis during the burial conditions has produced abundant irregular stylolites. The bivalves are aligned parallel to the bedding plane. The original aragonitic mineralogy has been inverted to coarse blocky sparite due to fresh water dissolution and reprecipitation. The micritic matrix is very little, about 5-8%. The dolomitisation of the bioclasts is initiated in the microfacies.

4.4.1.5. Mixed Siliciclastic-carbonate-evaporite Microfacies Types

The mixed siliciclastic-carbonate-evaporite microfacies belt is seen at the upper part of the Jhurio Formation (Member G) comprised of terrigenous materials which ranges from 35-70%. The siliciclastic microfacies belt is thus very important in the prediction of sea-level change during the deposition of the formation. The absence of any siliciclastic belt in the lower and middle portion of the Jhurio Formation and its presence in the upper part
is the indication of nearshore proxy and the migration of microfacies towards land from
the shallow marine environment.

4.4.1.4.1. Microfacies 50: Sandy bioclastic grainstone (Plate: 4.4-1; Plate: 4.6-3)

The main bioclasts are bivalves, brachiopods, foraminifers, algal grains
(Dascycladaceae ?) and ostracods. The fibrous calcite cement forms the major cement.
The terrigenous grains including quartz (mainly) and feldspars are about 30-35%. Few
mica flakes are seen. Ferrigenous bands are characterised by the abundant bioclasts.
Microfossils are coated and their intragranular porosities are thus filled with ferrigenous
matter. Thus ferruginous matter replaced the carbonate skeletons in many bioclasts. The
presence of characteristic algal grains (Dascycladaceae ?) in the similar microfacies
types forms the microfacies of that type (Sandy dascycladacean grainstone?).

4.4.1.4.2. Microfacies 51: Calcareous sandstone (Plate: 4.5-5 & 6; Plate: 4.6-2 & 4)

The dominant mineral is quartz about 50% and few feldspars and mica flakes. The
calcareous cement is fibrous and meniscus at places indicating a beach environment. The
quartz grains are replaced marginally by the calcareous cement. The microfacies is
characterised by the few bioclasts such as molluscan shell fragments and few algal
grains. Dolomitisation is well documented in this microfacies due to the burial in the mixed
marine-fresh water phreatic environment (Plate-4.6-4).

4.4.1.4.3. Microfacies 52: Sandy mudstone

The thin beds of sandy mudstone microfacies is seen with in the gypseous
mudstone beds. The thick ness of this microfacies increases towards up with in the shale
bed. The sand content of the microfacies also increases towards up. The gypseous
laminations separate the sandy mudstone microfacies from the gypseous mudstone beds
and also between the individual microfacies of the sandy mudstone. The sandy mudstone microfacies thin out laterally.

4.4.1.4.4. Microfacies 60: Gypseous mudstone

The microfacies is observed at the upper part of the Jhurio Formation. The mudstone is greenish, yellowish brownish and reddish in colour with gypsum crystals and gypsum laminations. The evidence of precipitation of gypsum crystals from the mudstone is observed. This probably due to the evaporation and dessication of shale beds which were under the shallow lagoonal environment.

4.4.1.4.5. Microfacies 61: Calcareous mudstone

This microfacies is observed in the lower and middle part and thick bedded in the upper part of the Jhurio Formation. The top portion of the formation is characterised by the limestone nodules in this microfacies. The microfacies is nodular to lenticular. Fossils include brachiopods (Rhynconella and Terebratula mainly), foraminifera (planktonic and benthic), algal remains and ostracods. This microfacies is deposited cyclically with the Microfacies - 40, in the north-eastern part of the Jhura Dome indicating a deep lagoonal depositional conditions on that part behind the barrier ridges situated near the present Badi section.

4.5. SPATIAL DISTRIBUTION OF CARBONATE PETROGRAPHIC TYPES

The carbonate sedimentology and diagenesis of Jhurio Formation is well explained so far. The Jhurio Formation exposed at Jhura Dome is the only continuous section and it provides a complete variety of carbonate microfacies developed during the early transgression of the Tethys sea across the Kachchh Basin. The carbonate rocks of Jhurio Formation exposed at Jumara are very thin bedded and are not continuous and are
mainly interbedded with thick shale beds. While at Habo, being situated towards the shore, only very thin-bedded section of Jhurio Formation is exposed. Thus an attempt is made to understand the carbonate sedimentology of Middle Jurassic of Kachchh Mainland. In order to understand the sedimentology of carbonate rocks deposited during the Middle Jurassic, the sections exposed at these three domes Jumara(near the depocentre), Jhura (middle) and Habo (near the shore) are studied. The Middle Jurassic sections in these areas comprises two formations the lower Jhurio and the upper Jumara which are deposited during a major transgressive-regressive phase. The carbonate rocks of these sections studied under the microscope and depositional and diagenetic properties are being described.

4.5.1. Jumara Dome Section

The temporal distribution of framework elements in the carbonate rocks of Jumara Dome section is given in the Fig. 4.3a. The intraclasts ranges from 12-51%. The Jhurio Formation is characterised by the presence of less intraclasts compared the Jumara Formation carbonates. The oolites ranges from 6-42%. The amount of oolitisation was more during the deposition of Jumara Formation especially during the deposition of Dhosa Oolite Member on the top of Jumara Formation. The Dhosa Oolite Member is a marker horizon and is continuous throughout the Kachchh Mainland. The peloids are less abundant compared to both the intraclasts and oolites in the carbonates of Jumara Dome section. Fossils makes up 27-57%. The main bioclasts include brachiopods, molluscs, algae, foraminifers, bryozoans, corals and ostracods. The important microfacies types grainstones grading to packstones (bioclastic packstone-grainstones, algal grainstones, oolitic grainstones, and coralline bioclastic grainstone), wackestones (bioclastic
Fig. 4.3a. Vertical variation of framework components of limestones, Jumara Hi

Fig. 4.3b. Vertical variation of framework components of limestones, Jhura Hi

Fig. 4.3c. Vertical variation of framework components of limestones, Habo
wackestones, algal wackestones, etc.), few rudstones (lithoclastic bioclastic floatstones grading in to rudstones) and few mudstones.

The depositional environment of carbonate rocks of Jhurio Formation is characterised by the deep marine environment during the deposition of coralline bioclastic grainstone microfacies to shallow marine shelf environment with the deposition of algal grainstone microfacies. The environment became very shallow and shoaling increased in the bottom causing the deposition of oolitic grainstones. The diagenesis of carbonate rocks of Jumara Dome section is characterised by the four diagenetic environments such as marine phreatic, fresh water phreatic, burial and fresh water vadose. These environments followed in the same manner from one to other. Thus each diagenetic environment has produced its peculiar textural types. The main type of cements are micrite, coarse blocky sparite, syntaxial rim cement, and ferruginous cement.

4.5.2. Jhura Dome Section

The Jhura Dome section is characterised by the lower Jhurio Formation (278m. thick) and upper Jumara Formation (272m.). The carbonate rocks of Jhurio Formation is already explained. The temporal distribution of various framework elements in the temporal scale of Jhurio Formation (Fig.4.1) indicates the abundance and diversity of bioclats in the upper part of the formation, that is in the Member-G. The distribution of non-skeletal materials show relative abundance which are evidently environmentally controlled. For example, in the case of ooids the percentage abundance is characterized in the Member-C and E and also in the Member-A. The Member-C and E are characterized minor regressive phases of transgressing sea across the basin, during which the high energy prevailed has lead to the formation of calcareous oolites. Where as the peloids
which are characteristic of quite water environments are seen very minor percent in the oolitic limestones or sometimes absent. Instead peloids make the dominant constituent in the bedded limestones (Member-B, D and F) deposited during the transgressive phases of the Tethys sea. The intraclasts also makes significant presence in the lower and middle part of the formation indicating a submarine erosion and deposition during the deposition of sediments in the active carbonate realm.

Compared to the carbonates of Jhurio Formation, the frame work elements of carbonates of Jumara Formation (Fig. 4.3b) shows characteristic abundance of intraclasts and oolites while peloids are very small in percentage. Oolites are abundant in the middle and upper part of the Jumara Formation in the Jhura Dome. The main microfacies types present in the carbonate rocks of Jumara Formation are grainstones (oolitic packstone-grainstone, molluscan bioclastic grainstone and foraminiferal algal grainstone), wackestone-mudstone (bioclastic wackestone-mudstone) and few rudstones (lithoclastic bioclastic rudstones) which sometimes appear as floatstones. The depositional environment of carbonate rocks of Jumara Formation is characterised by deep to shallow shelf marine to shoaling environment towards the top. The diagenetic textures include the micrite, microspar, coarse blocky sparite, syntaxial rim and ferruginous cement. The diagenetic environment are marine phreatic, fresh water phreatic, burial and fresh water vadose. Dolomitisation and silicification is evidenced from the microfacies types. While stylololites are not so evident as seen in the carbonates of Jhurio Formation.

4.5.3. Habo Dome section

The Habo Dome section is characterised by the lower Jhurio Formation (50m thick) and upper Jumara Formation (290m thick). The Jhurio formation in Habo dome is
mainly thin-bedded yellow limestones with shale interbeds. The Jumara Formation is characterised by the thin-bedded limestones with interbedded thick shales and thick sandstone beds. The framework elements of carbonates of Habo Dome section (Fig. 4.3b) shows the abundance of intraclasts and oolites in the Jumara Formation than in the Jhurio Formation. Peloids are abundant in the middle part of the Habo section. Fossil content varies from bottom to the top with the abundance in the lower and upper part of the Habo section. The main types of microfacies include grainstone (bioclastic grainstone, oolitic grainstone and algal grainstone) wackestone-packstone (algal packstone-wackestone, peloidal packstone) and mustone (peloidal mudstone) and few rudstones and boundstones. The diagenetic textures include micrite, acicular fringe, coarse blocky sparite, syntaxial rim and minor dolomitic cements. These textural types are developed in marine phreatic, mixed marine-fresh water phreatic, fresh water phreatic, burial and fresh water vadose diagenetic environment.
Plate — 4.1

PHOTOMICROGRAPHS

(Magnification 24X, otherwise stated)

1. Microfacies showing calcareous ooids with equant calcite cement at the centre. Also seen sparitised bioclast with coarse blocky sparite cement.

2. Coarse blocky sparite showing ghosts of original mineralogy is a fresh water diagenetic cement. The algal, foraminiferal and ostracodal bioclasts are the sparitised grains.

3. Large intraclast coated with iron oxide matter and encloses various carbonate grains which seen with first generation marine cement. Calcitic veins formed due to desiccation and dewatering.

4. Microfacies showing peloids (including fecal pellets) showing micritised crinoids, foraminifers and algal grains. The crinoidal peloids show syntaxial rim cement. Peloids showing grapestone to lump structure. Partial dolomitisation and stylolitisation are evidenced due to burial diagenesis.
Photomicrographs
(Magnification: 24X. Otherwise stated)
Plate – 4.2
PHOTOMICROGRAPHS
(Magnification 40X, otherwise stated)

1. Sparitised (Blocky sparite in extinct position) bioclasts (bivalves) in oolitic intraclastic bioclastic grainstone. The original aragonitic mineralogy is evident from the ghosts. Sparitised bioclasts is cemented with first generation columnar fringe cement. This is followed by the second-generation coarse cement (2.5/0.08 – Xn- 10x).

2. Blocky sparite in bright position (same of Photomicrograph-5).

3. Packed bioclastic grains in bioclastic grainstone microfacies. The bioclasts include bivalves and foraminifers (benthic). The microfacies shows sparitisation and partial dolomitisation. Stylolites are abundant which are more or less parallel to the bedding plane.

4. Crinoidal peloidal packstone microfacies showing dissolution-reprecipitation in a bivalve bioclast. The intragranular porosity is preserved due to the incomplete filling by the secondary diagenetic cement.
Plate – 4.2

Photomicrographs
(Magnification: 40X. Otherwise stated)
Plate – 4.3

PHOTOMICROGRAPHS
(Magnification 24X, otherwise stated)

1. Peloidal microfacies characterized by crinoids, foraminifers (planktonic and benthic). Syntaxial rim cement is characteristic of burial diagenetic cement. Micrite to microsparite cement showing evidences of aggrading neomorphism in peloidal microfacies.

2. Normally packed oolitic grainstone microfacies with calcareous ooids coated with iron oxide matter shows first generation cement as micritic rinds. True ooids with spheroidal shape with radiating calcite crystals also seen. Coarse granular mosaic cement formed due to meteoric diagenesis and also evidences of oomoldic porosity indicating the original aragonitic mineralogy.

3. Sandy bioclastic grainstone showing molluscan bioclasts with coarse blocky mosaic calcite. Micritic envelopes are collapsed in the bioclast. Quartz crystals are pressure welded due to compaction under burial diagenesis.

4. Lithoclastic bioclastic rudstone with micrite to sparite cement over the reworked oolites and aggregate lithoclasts. Ooids are with radiating calcite crystals and might be redeposited in the site of deposition.

5. Microfacies showing foraminifers (benthic) and crinoids in the packstone-grainstone microfacies with microsparite to pseudosparite cement. Syntaxial rim cement over foraminifers and crinoids is seen with compromise planes.

6. Packed peloids in foraminiferal crinoidal peloidal packstone-grainstone. Crinoidal oscicles, foraminiferal tests and algal grains are common. Syntaxial rim cement is developed under burial diagenetic environment.
Plate – 4.3

Photomicrographs
(Magnification: 24X. Otherwise stated)
Plate – 4.4

PHOTOMICROGRAPHS
(Magnification 24X, otherwise stated)

1. Calcareous sandstone with ferruginous bands. The bioclasts are abundant in the ferruginous layer, which are coated and corroded iron oxide matrix. Algae, bivalves and brachiopod fragments are the main bioclastic grains.

2. Foraminiferal peloidal packstone-grainstone with abundant smaller (protoglobigerinids) and few benthic foraminifers and algal grains. Syneresis cracks are filled with coarse sparite cement, which are evidence of desiccation upon subaerial exposure. (Plain light).

3. Same as above with Xn position.

4. Packed bioclastic grainstone microfacies. Bivalves and brachiopods are abundant with few benthic foraminifera and ostracods. Partial dolomitisation is seen and stylolites are developed due to compaction and pressure solution under burial diagenesis (40X, Xn).

5. Belemnitic rostrum in bioclastic wackestone microfacies. The original aragonitic mineralogy of the rostrum is neomorphosed in to low Mg-calcite. The evidences of the same are seen as ghosts of original minerals as square tips [40X, Xn]

6. Corroded and bored large bioclasts in lithoclastic rudstone microfacies. The microfacies was formed as a lag deposit forming hardground. The ark cement portion is ferruginous micritic matrix.
Plate – 4.4

Photomicrographs
(Magnification: 24X. Otherwise stated)
Plate – 4.5

PHOTOMICROGRAPHS
(Magnification 24X, otherwise stated)

1. Bioclastic wackestone microfacies with micrite to microsparite cement. Umbrella effects are seen at the centre. Yellow colour of the microfacies is due to the iron content. The main bioclasts include bivalves, brachiopods, belemnites, echinoids, ostracods and algae.

2. Peloidal packstone-grainstone showing abundant faecal pellets, peloids, bioclasts of pelagic bivalves, smaller foraminifera (protoglobigerinids). The microfacies shows a cross laminations.

3. Fenestral laminated wackestone microfacies with abundant algae, foraminifers and faecal pellets and peloids. The bioclasts are seen with smectite rim cement and the fenestral cement lined with smectite cement are seen as parallel bands of laminations.

4. Calcareous sandstone microfacies with medium grained subangular quartz grains seen intensively corroded. Few bioclasts are also seen.

5. Calcareous sandstone microfacies showing abundant angular quartz gains, which are seen, corroded with the carbonate cement.

6. Sandy bioclastic grainstone showing the evidence of sparitisation of the original mineralogy of the molluscan bioclast. The evidences of compaction is also seen with fractured bioclast. The yellow colour is due to the iron content.
Plate – 4.5

Photomicrographs
(Magnification: 24X. Otherwise stated)
Plate – 4.6

PHOTOMICROGRAPHS
(Magnification 40X, otherwise stated)

1. The oolitic grainstone showing the regressive features of the microfacies. The ooids are seen with microsparite to sparite cement and the oomoldic porosity development due to diagenetic stabilization of the allochems with meteoric water during the regressive phase.

2. Corroded grains in a sandy bioclastic grainstone microfacies evidences the regressive phase. The corrosion is intensified with the activity of ferruginous matter. Pseudomorphs of calcite after gypsum (?) are seen.

3. The sandy bioclastic grainstone showing evidences of dolomitisation the dolomitic crystals are formed from the intergranular cement spar and the solution. During mixed marine-fresh water phreatic or burial diagenesis.

4. Photomicrograph displaying dolomitization of calcareous sandstone.
Plate – 4.6

Photomicrographs
(Magnification: 40X. Otherwise stated)
Plate – 4.7

SEM-MICROGRAPHS

1. Dissolution and reprecipitation in an algal grain. The coarse sparite cement is formed with in the algal porosity. Also seen is the disrupted porosity in the algal grain.

2. The replacement of bioclasts, coarse calcite cement and precipitation of granular sparite over the grains. Much intragranular porosity is preserved in the microfacies.

3. The micritised bioclasts of algae, crinoids, etc. in peloidal packstone-grainstone microfacies. The intergranular cement is sparite showing syntaxial rim over the crinoids and algal grains.

4. The formation of secondary coarse sparite in the intergranular spaces of the peloidal packstone-grainstone. The first generation fringe cement is observed over the algal, crinoidal and bryozoan grains.
Plate - 4.7

SEM-micrographs
Plate – 4.8

SEM-MICROGRAPHS

1. Tightly cemented fabric in a bioclastic wackestone microfacies. The dissolution and precipitation of sparite from the algal and bryozoan grains. The zoaria of bryozoans are visible.

2. The ostracod carapace embedded in a micrite to microsparite cement. The porosity is of both intragranular and intergranular types. The stylolites are observed on the top left part of the microfacies.

3. The sparitised oolitic grainstone microfacies with tightly cemented, packed with ooids.

4. Sparitised bioclasts with coarse sparite cement in the oolitic packstone-grainstone microfacies.
Plate – 4.8

SEM-micrographs