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Diagenesis and Porosity Evolution of Pachmarhi Sandstones (Early Triassic), Satpura Gondwana Basin, Central India

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Abstract: This study deals with the diagenetic history of the Pachmarhi Sandstones of Satpura Gondwana Basin, Central India. The sandstones are classified as quartz-arenite and sub-arkose type. Monocrystalline quartz grains dominate the detrital mineralogy followed by polycrystalline quartz grains, feldspars (more alkali-feldspar than plagioclase), rock fragments, detrital mica and heavy minerals. The diagenetic signatures observed in the Pachmarhi Sandstones include mechanical compaction, cementation (Fe-oxide, quartz overgrowths, calcite, matrix and clay minerals), replacement and dissolution of feldspar and calcite cement. The most commonly observed type of secondary porosity is dissolution of feldspars. The porosity loss is mainly due to cementation by pore occlusion and by early stage of mechanical compaction. In addition, several clay minerals occurred as pore-filling and pore-lining cements. The nature of various types of grain- to grain contacts suggests early cementation and consequent minor compaction. Among the various cements, calcite is the earliest followed by iron oxide while silica cementation occurred probably at a late stage. The carbonate cement formed during burial by dissolution and re-precipitation represents redistributed calcite which was buried with the sandstone. The iron cement was perhaps derived from weathering and leaching of ferromagnesian minerals of overlying Deccan traps. Silica cement was derived from the corrosion of quartz and feldspar grains. Types of grain contacts, minus-cement porosity and porosity reduction indicate a shallow depth of burial conditions for these sandstones.

Keywords: Satpura Gondwana basin, Pachmarhi Sandstones, Mechanical compaction, Cementation, Dissolution, Porosity modification.

Introduction

The relationship between diagenesis and reservoir quality is well documented in geological literature and detailed information of diagenesis comes from studies involving sandstone reservoir properties evaluation and quality prediction (Wilson, 1994; Primmer et al., 1997; Jeans, 2000, Ahmed and Bhat, 2006, Ahmed et al., 2006). Assessment of reservoir quality is based on understanding of potential controls of diagenesis, framework grains and provenance composition (De Ros et al., 1994; Bloch, 1994; De Souza et al., 1995; Nentwich and Yole, 1997; Ramm, 2000, Jamwal et al., 2020, this volume)), palaeoclimate (Worden et al., 2000) and depositional environment (Fuchtbauer, 1983; Lowry and Jacobsen, 1993; Bloch and McGowen, 1994; McKay et al., 1995; Hamlin et al., 1996; Bailey et al., 1998; Dos Anjos et al., 2000; Rossi et al., 2001; Hiatt at al., 2003).

The Gondwana deposits of Peninsular India record resumption of sedimentation during the Carboniferous period after a prolonged depositional gap since the Proterozoic. In Peninsular India, the Gondwana sedimentary successions (~1-4 km thick) accumulated in a number of discrete, intracratonic basins which record depositional history up to the Cretaceous period. The Gondwana Basins of the Peninsular India are intracratonic rift basins within Proterozoic terrains. The basins occurring along three distinct linear belts are defined by the present-day ENE-WSW trending Narmada-Son-Damodar valley, NNW-SSE trending Pranhita-Godavari valley and NW-SE trending Mahanadi valley (Fig. 1). It is widely believed that these basins originated under extensional tectonic regime due to failure of attenuated crust along the pre-existing zones of weakness imparted by Precambrian structural grains (Chatterjee and Ghosh, 1970; Naqvi et al., 1974; Mitra, 1994; Biswas, 1999; Acharyya, 2000; Chakraborty and Ghosh, 2005). However, disposition of the basins and their structural architecture indicate that the kinematics of all the basins cannot be extensional (Chakraborty and Ghosh, 2005). The current study focuses on diagenetic signatures in the Pachmarhi Sandstones of Satpura basin vis-à-vis compaction, cementation and porosity evolution in these rocks.

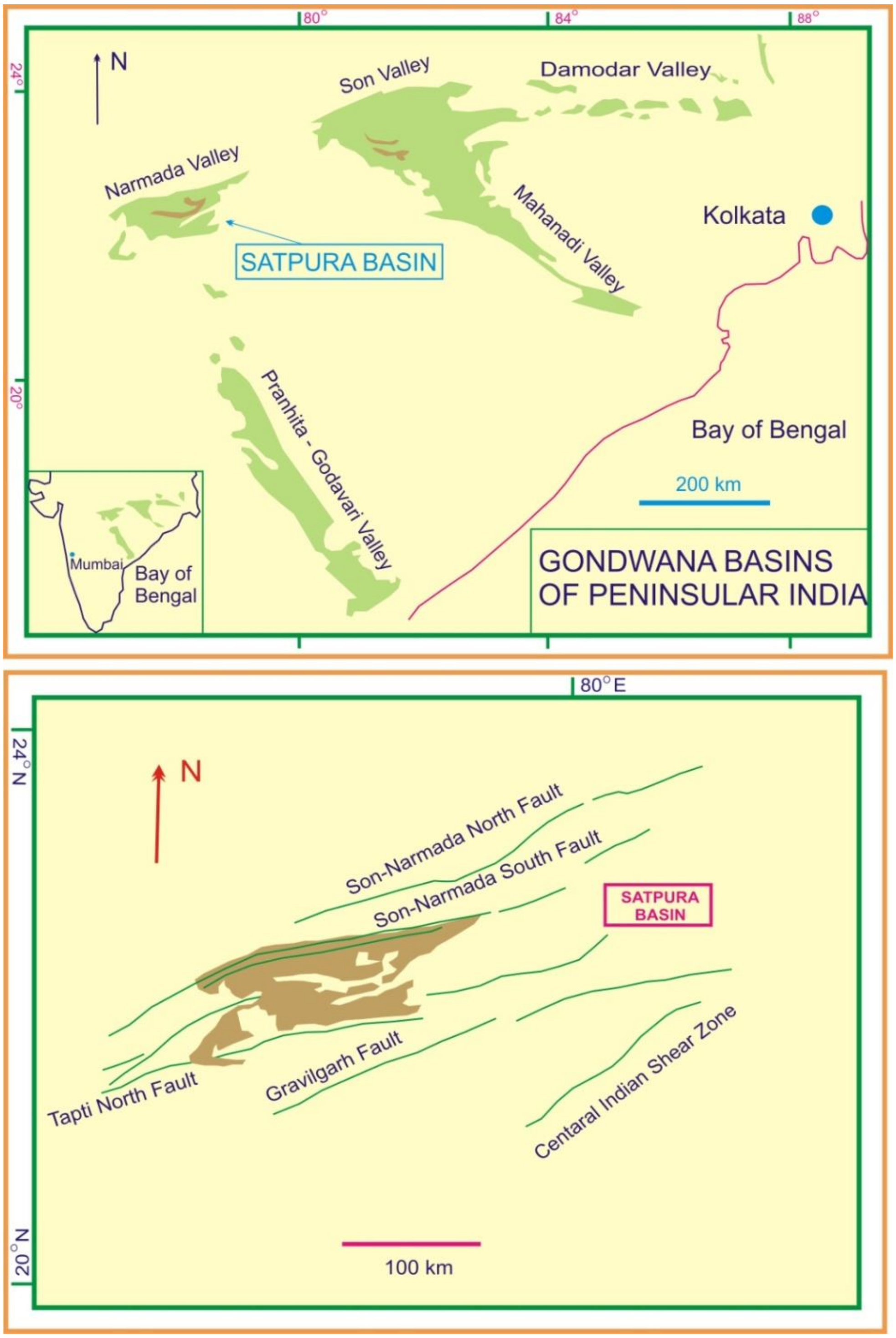

Fig. 1. (a) Outcrops of the Gondwana basins in the Peninsular India. Note that the Satpura basin is the westernmost Gondwana basin cropping out along the present-day ENE– WSW trending Narmada–Son–Damodar valley. (b) Major boundary faults of the Satpura Gondwana basin (based on Narula et al., 2000). Shaded area represents the outcrop of the Satpura basin.

Geological Setting

The Satpura Basin of Central India is the westernmost of the series of discrete Indian Gondwana Basin occurring along the ENE-WSW trending Narmada-Son- Damodar valley and preserves stratigraphic record of Permian to Cretaceous (Robinson, 1967; Crookshank, 1936). This basin is located between latitude 22° 06′ N and 22° 28′ N and longitude 77° 48′ E and 78° 53′ E. The basin (~200 km long, ~60 km wide) is rhomb-shaped, elongate along the ENE-WSW direction and is filled with approximately 5-km-thick pile of siliciclastic sediments which unconformably lies over the Precambrian basement. The regional strike of the basin-fill strata is NE–SW, and the regional dip (~5°) is northerly. Based on the shape of the basin, its disposition, and structural architecture, Chakraborty and Ghosh (2005) considered it to be of pull-apart origin. The Gondwana succession of Satpura Basin has been classified into seven major lithostratigraphic units which include the Talchir, Barakar, Motur, Bijori, Pachmarhi, Denwa and Bagra formations, from old bottom to top in chronological order (Fig. 2).

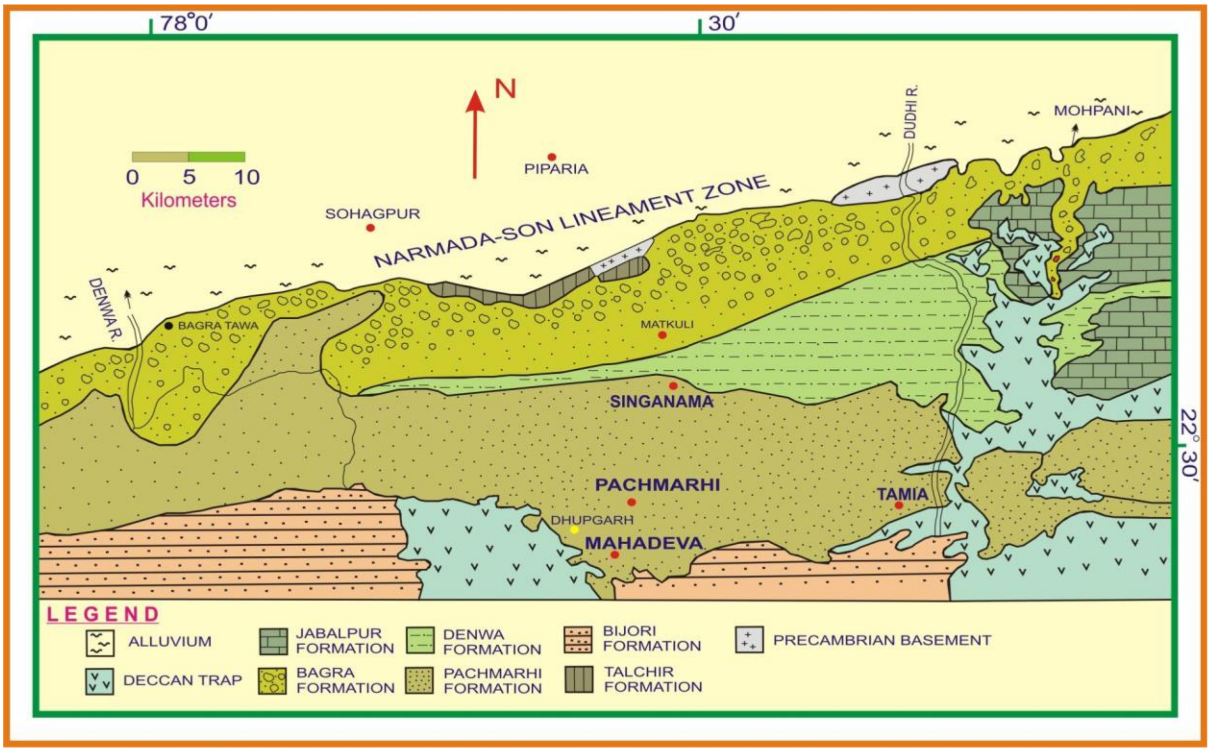

Fig. 2. Geological map of the Satpura Gondwana succession, Central India (modified after Raja Rao, 1983).

Methodology

The present study is based on 50 representative sandstone samples which were cut into standard petrographic thin sections. Some thin sections were etched and stained for identification of carbonate cement and potassium feldspars. The sampling of sandstone units was carried out at regular intervals of the measured section keeping in view the physical variation between different units (Fig. 3). About 300 to 350 grains were counted per thin section. The traditional method (Ingersoll et al., 1984) was used for classification and tabulation of grain types. Standard petrological techniques using a polarizing microscope were employed to describe the thin sections. Authigenic components (cement and matrix) were counted separately and the amount of matrix, cement and porosity were measured by a single operator. In order to reconstruct the original detrital composition of the sandstones, the effect of diagenesis was taken into consideration as far as possible during the counting. Taylor's (1950) method was applied for the study of the nature of detrital grain contacts where as computation of contact index was made as per Pettijohn et al. (1987). Scanning electron microscopy (SEM) was applied to study clay minerals, and diagenetic features. The samples were coated with a gold palladium alloy and were examined under a (JSM-6510LV model; Jeol, Japan) scanning electron microscopy (SEM).

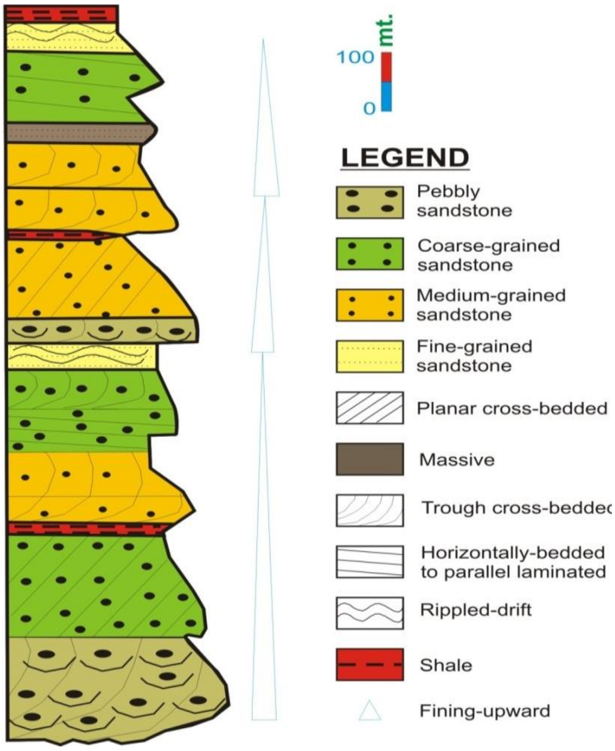

Fig. 3. A generalized litholog of the Pachmarhi Formation, Satpura Gondawana Basin.

Detrital Mineralogy

The Pachmarhi sandstones are composed of various types of quartz, feldspars, rock fragments, detrital mica and heavies which are medium- to coarse-grained, moderately to moderately well sorted, and with generally loose packing. These sandstones are in general texturally sub-mature to mature. The overall average composition of these sandstones is $Q_{95.55}$ $F_{2.70}$ $R_{1.75}$. As per Folk's scheme (Table 1, Fig. 4; Folk, 1980) these sandstones are mostly quartz-arenite and minor amounts of sub-arkose.

Table 1. Grain size, sorting and detrital mode of the Pachmarhi Sandstone

Sample No.	Texture		Framework		
	Mean size (Mz Φ)	Sorting (σ1 Φ)	Quartz (Q)	Feldspars (F)	Rock fragments (R)
Range	0.26-3.5	0.66-0.93	91-98	1-5	0-4
Avg.	1.86	0.78	95.55	2.70	1.75

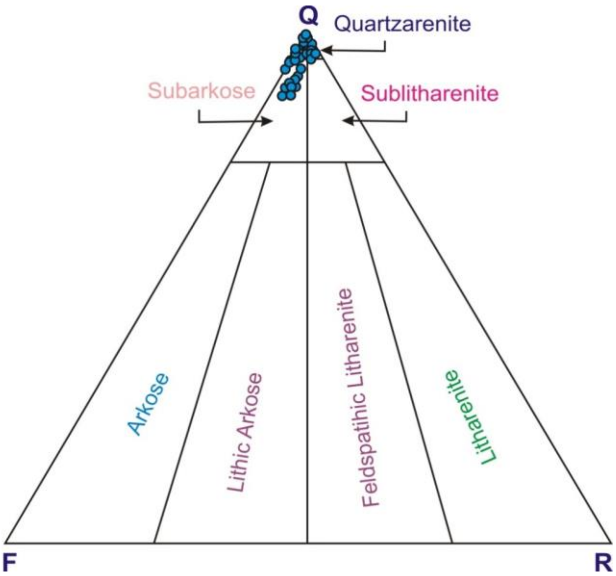

Fig. 4. Detrital composition of Pachmarhi Sandstones samples plotted on Folk (1980) classification diagrams.

Diagenesis

The Pachmarhi Sandstones in the Satpura Gondwana Basin has undergone through compaction, cementation, replacement, and dissolution of feldspars and carbonate cements resulting in the secondary porosity development.

Compaction and Porosity

The process of compaction results in the expulsion of pore fluids and reduction of pore volume due to the load of overburden (Fuchtbauer, 1967; Rittenhouse, 1971; Chilingar, 1983, Ahmed and Bhat, 2006). Compaction occurs in response to four types of processes grain rearrangements, plastic deformation, dissolution and brittle deformation (Wilson and Stanton, 1994, Ahmed and Bhat, 2006). In sandstones, compaction is in fact controlled by various factors, which includes inherent grain properties, mass properties, fluid and basinal dynamics, tectonics, rate of sedimentation and burial time. Mechanical compaction and cementation of sediments plays a vital role in reducing porosity (Fisher et al., 1999, Ahmed and Bhat, 2006). A grain to grain contact of sediments gives an idea about pore space reduction and compaction history of the sediments. Both, the nature of contacts and contact index are helpful in understanding the aggregate packing of the rocks. Grain contacts of the Pachmarhi Sandstones were studied in thin sections with a view to interpret their compaction history. In the present study the closely packed sandstones exhibit four types of grain contacts (after Taylor, 1950; Ahmed and Bhat, 2006), which include point, long (line contact), concavo-convex and sutured contacts (Plate 1A).

The observed number of various types of grain contacts in different samples is given in Table 2 and bar diagram constructed on the basis of grain contact data is shown in Fig. 5. In loosely packed sandstones some grains may not make any contact with other grains, such grains are referred to as floating grains (F). The average percentage of different types of contacts in the studied sandstones is 1) floating grains (8.85%), 2) point contact (13%), 3) long contact (57.7%), 4) concavo-convex contact (10.9 %), and 5) sutured contact (9.65 %) (Table 2). The dominance of point and long contacts, together averaging at 70.70% in the Pachmarhi Sandstones, indicates that the detrital grains did not suffer much pressure solution, as a result of either shallow burial or early cementation. Long contacts might have developed in the early stages of compaction as a result of rotation and adjustment of grains to the adjacent grain boundaries. The pressure effects are absent or at minimum in sandstones which have undergone early cementation (Taylor, 1950).

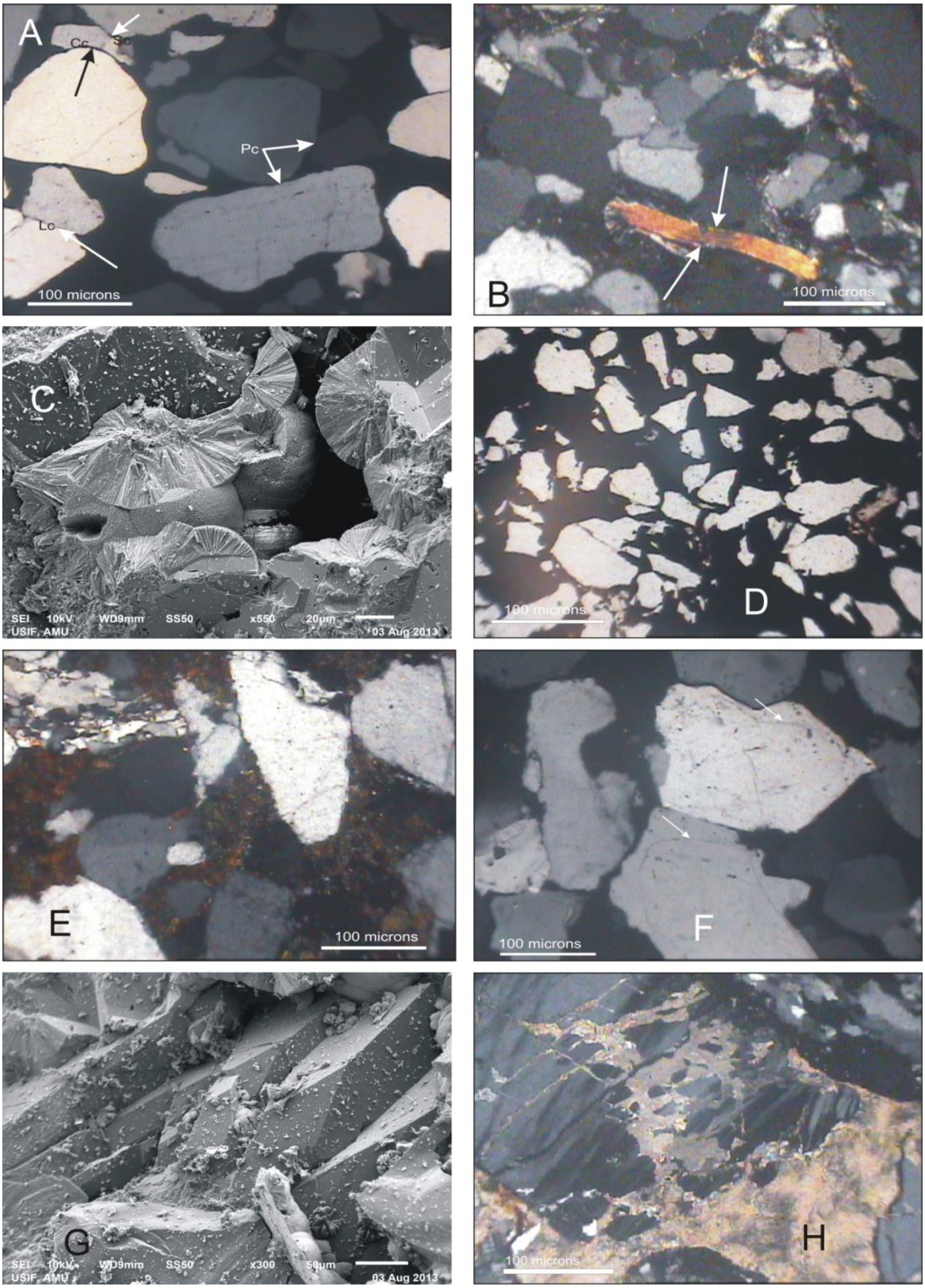

Plate 1. (A) Photomicrograph showing different types of grain contacts (Pc = point contact, Lc = long contact, Cc = concavo-convex and Sc = suture contacts), (B) Muscovite flake in contact with quartz grains showing effect of compaction, (C) SEM Photograph showing pore occluding iron-oxide cement, (D) Pervasive iron oxide cement extensively corroding and digesting framework grains, (E) Pervasive pore filling iron oxide cement replacing calcite cement, (F) Quartz overgrowth partially fill the intergranular spaces. The grain contacts are generally long; (G) SEM Photograph showing quartz overgrowth, (H) Photomicrograph of calcite replaced the framework grains.

Table 2. Percentage of various types of grain to grain contacts for the Pachmarhi Sandstones, Satpura Gondwana basin, central India.

	Types of grain contacts					No. of contacts per grains						Contact index (CI)
	Floating	Point	Long	Concavo-Convex	Sutured	0	1	2	3	4	>4	
Range	4-25	3-23	38-78	1-29	3-21	1-27	15-59	20-53	3-32	1-9	1-2	1.55-2.72
Avg.	8.85	13.0	57.7	10.9	9.65	9.25	32.4	38.35	16.9	2.95	0.15	2.20

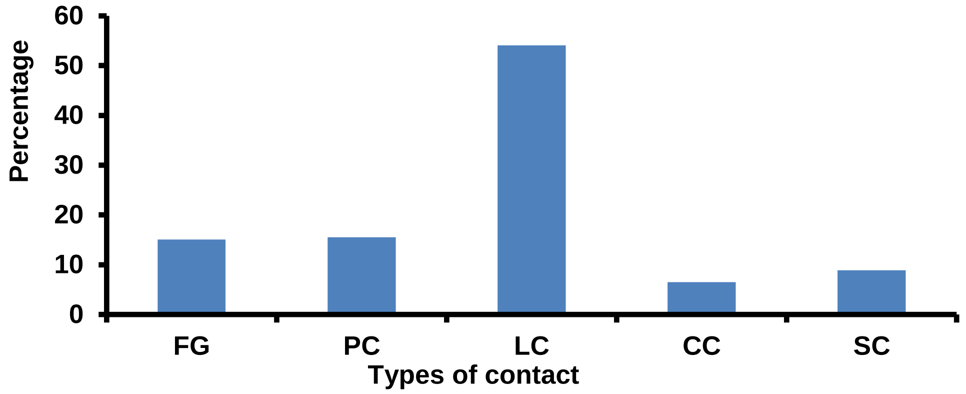

Fig. 5. Bar diagram showing types of grain contacts for sandstones of the Pachmarhi Formation, Satpura Gondwana Basin. (FG = Floating grains, PC = Point contact, LC = Long contact, CC = Concavo-convex contact, SC =Sutured contact).

It is well known that the original porosity of sandstones generally vary between 30 and 50%, which can reduce by 10-17% by mechanical compaction (Pryor, 1973, Beard and Weyl, 1973). The intergranular quartzose cement (minus-cement porosity) averages 32% porosity, which may be due to less mechanical compaction during the early stages of diagenesis. Less mechanical compaction and high content of intergranular cement may be related to high grain strength, good sorting and early cementation. Mechanical compaction and physical readjustment to the overburden load in the sandstones are evidenced by deformed mica grains (Plate 1B). The compaction effect is also evidenced by straight, concavo-convex and sutured contacts of neighbouring framework grains. During compaction framework grains are sliding past each other and packed into a tighter configuration. The presence of sutured boundaries of quartz overgrowth indicates the post cement compaction. Therefore, it may be concluded that some compaction of the Pachmarhi Sandstones took place in the early stages, when grains rotated and adjusted themselves to the boundaries of adjacent grains, and later compaction took place after cementation.

The contact index (C.I.), is the average number of grain contacts a grain has with its neighbouring grains (Pettijohn et al., 1987), infers the degree of compaction of the sediments. The grains are in contact with two grains followed by three grains. The overall average contact index value of the Pachmarhi Sandstones is 2.20 (Table 2). This is due to the dominance of long and point contacts and also attributed to mechanical compaction, which increases the value of contact index and packing density. Presence of significant numbers of sutured as well as concavo-convex contacts indicates that chemical compaction also played a role, which resulted in pressure dissolution in point and long contacts which converted them to concavo-convex and sutured contacts.

Cements

The cementation is normally considered to reduce the porosity but dissolution improves porosity and permeability of the reservoir. Most of the secondary porosity resulted from the partial or complete dissolution of feldspar and calcite cement. Three types of cementing materials occur in the sandstones of the Pachmarhi Formation 1) iron oxide, 2) calcite and 3) silica overgrowths while clay occurs as matrix.

Iron cement

The iron-oxide cement in the Pachmarhi Sandstones is distinguished into three different forms such as thin coatings around the detrital grain boundary, isolated patches, and pervasive pore fillings (Plate 1C). The iron-oxide cement in the Pachmarhi sandstones ranges from 2% to 40% with an average of 17% (Table 3 and Fig. 6). In some thin sections characterized by Fe-calcite cement, the corroded quartz grains exhibit calcite cement infilling. This evidence suggests the presence of syndepositional calcite cement, which was later replaced by Fe-calcite cement. The oversized pore spaces might have been resulted from destruction and leaching of labile framework grains, possibly feldspars. This cement has corroded the detrital grains extensively (Plate 1D). The clastic grains have lost their grain morphology and are present now in the form of protrusions, embayments and notches. The iron oxide cement also has replaced calcite cement (Plate 1E). Coating of iron cement on detrital grains may be extra-basinal and weathering rinds generated during burial (Walker, 1974). The iron-oxide cement most probably was derived from weathering and leaching of ferromagnesian silicates of overlying Deccan traps by meteoric water which percolated during the upliftment.

Table 3. Percentage of detrital framework grains, cements and porosity of the Pachmarhi Sandstones, Satpra Gondwana basin, central India.

	Detrital grains	Cement					Porosity		Porosity loss	
		Iron	Calcite	Silica	Matrix Clay	Total Cement	Existing Optical Porosity (EOP)	Minus cement porosity (MCP)	Compactional porosity loss (COPL)	Cementational porosity loss (CEPL)
Range	58 - 76	2 - 40	0 - 12	0 - 9	0- 10	17 - 40	1 - 11	24 - 42	5.24 - 27.63	21.97 - 40.01
Avg.	68	17	4	3	4	27	5	32	18.99	29.07

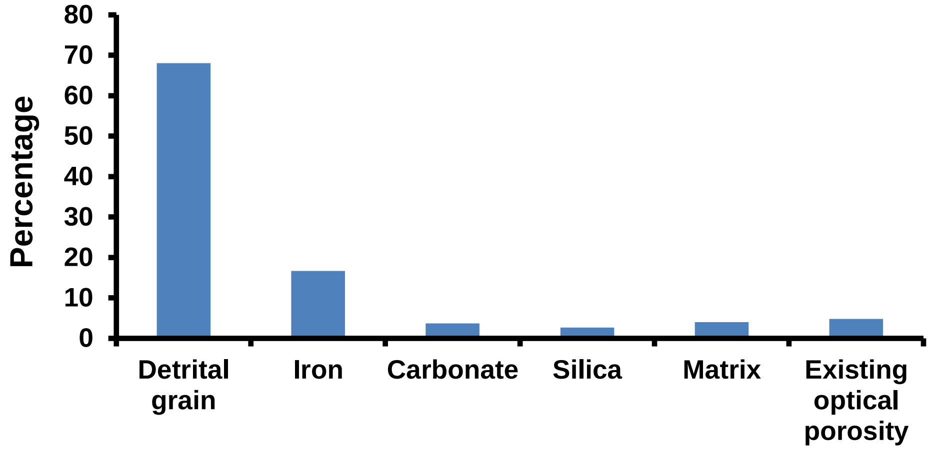

Fig. 6. Bar diagram showing percentage of detrital grains, cement and porosity for sandstones of the Pachmarhi Formation, Satpura Gondwana Basin.

Silica overgrowth

The silica cement occurs in the form of quartz overgrowth (Plate 1F, G) which shows the optical continuity with detrital quartz grains forming secondary enlargement. The amount of silica cement varies from sample to sample depending upon degree of condensation and pressure solution undergone by the rocks. The percentage of silica cement in the sandstones ranges from 0% to 9%, average 3% (Table 3 and Fig. 6). Authegenic quartz overgrowths on detrital grains of quartz are observed to fill up the intergranular spaces partly. In the studied sandstones quartz overgrowths are dominantly developed on monocrystalline quartz compared to polycrystalline quartz grains. The quartz overgrowths partially fill the intergranular space but where well developed, overgrowths from adjacent grains meet along sharp and planar crystal faces. The source of silica cement may be the descending meteoric water saturated with silica or pressure solution of detrital quartz and other silicates at grain contacts (Dutton, 1993; Walderhaug, 1994). The conversion of clay minerals during diagenesis and decomposition or feldspar alteration may release silica solutions (Hower et al., 1976; Bole and Franks, 1979).

Carbonate cement

Calcite cementation plays a key role in the porosity evolution of sandstones (Alaa et al., 2000). Calcite cement shows patchy distribution and forms 0% to 12% and averages at 4% (Table 3 and Fig. 6). Two different kinds of calcite cement are present, 1) poikiliotopic calcite which has large crystal size with well developed cleavage planes and show pin point birefringence, 2) neomorphic xenotopic sparry calcite present in grain supported sandstones. The poikiliotopic calcite cement is in oversized pores and has floating grains than the sparry calcite-cemented sandstone suggesting its early stage precipitation. The calcite-cemented sandstones are high minus-cement porosity and corrosion of detrital grains. Apart from quartz, the feldspars are subjected to corrosion along grain boundary and cleavage planes (Plate 1H). The oversized pore filling poikiliotopic calcite cementation process may have taken place at the sediment-water interface. The xenotopic calcite cemented sandstones show close framework and have corroded to a lesser extent than the poikiliotopic calcite cement. Xenotopic cementation may have taken place after considerable burial under groundwater saturated with calcium carbonate flow through pores (Tandon and Friend, 1989).

The source of carbonate may be biogenic or early marine carbonate precipitated during the period of slow sedimentation. Thus, carbonate cement may have extrabasinal source into the sandstones. Very little carbonate may have precipitate from pore water without the dissolution of other carbonate minerals. The calcite cement formed during deep burial by dissolution and reprecipitation represents redistributed carbonate which was buried with the sandstones. In some thin sections characterized by iron oxide cement, the corroded quartz grains exhibit calcite cement inclusions. This evidence suggests the presence of syndepositional calcite cement, which was later replaced by iron oxide. It is well known that the early precipitation of carbonate cement takes place a few centimetres below the sediment-water interface (Bjorlykke, 1983). This type of cementation occurs by exchange of interstitial marine pore water either by meteoric or pore water expelled from the underlying sediments.

Matrix and clay minerals

In most of the samples, clayey to silty matrix is present in varying amounts (Plate 2A). Matrix constitutes 0 to 10% (average 4%) of the total rock components (Table 3 and Fig. 6). The matrix is represented by silt-size quartz grains, chert and chalcedony mixed with fine grained muscovite and clay. Most of the matrix material is syndepositional, and hence pore-filling. The matrix also influenced diagenetic process by supplying Fe and reducing porosity and permeability by pore occlusion. Very low amount of matrix present in a few sandstone samples is probably decanted from infiltrating muddy pore water.

SEM study also corroborate that Kaolinite is the dominant clay mineral, with illite, smectite and chlorite. Mixed layers of illite smectite also occur in varying amounts and in several forms. Kaolinite is authegenic and includes both cements and replacement of silicate framework grains. Scanning electron micrographs (SEM) of Kaolinite shows good crystals of pseudo-hexagonal plates, commonly with face-to-face stacking (Plate 2B). Pore-filling Kaolinite is a common feature in which pore spaces are usually plugged with authegenic Kaolinite with no apparent preferred orientation (Plate 2C, D). Authegenic smectite clay as pore-filling cement is also present in these sandstones (Plate 2E). However, in some sandstones honeycomb nature of smectite clay indicate the conversion stage to illite, which may act as bridges in the pore spaces and results in decreases of porosity.

The weathering of acidic plutonic rocks was likely responsible for generating the Kaolinite-rich clay in the Pachmarhi Sandstones. This weathering likely involved very intense kaolinization under the influence of a climate characterised by high temperatures and heavy rainfall (Nakagawa et al., 2006; van de Kamp, 2010) and it is therefore suggested that the Kaolinite present in the Pachmarhi Sandstones was derived through the intense chemical weathering of crystalline source rocks containing abundant of feldspar in the presence of meteoric water (Bjørlykke, 1998; Bertier et al., 2008; Islam et al., 2002; van de Kamp, 2010).

Porosity Reduction

Intergranular porosity is primary porosity or has resulted from the dissolution of pore-filling cement (Plate 2F) (Felixa, *et al*., 2005). Essentially all intergranular pores are thought to be primary porosity in the Pachmarhi sandstones. Primary pores were mainly those formed during the connate deposition of rocks and have been preserved till now. The primary pores can be subdivided into the primary intergranular ones remained by compaction, the intergranular ones remained by cementation and the micropores in the matrix. The secondary pores were formed during the burial stage arising from dissolution and other geological factors, such as tectonic movement and syneresis. The dissolved pores (such as intragranular dissolved pores, intergranular pores, mould pores and super pores/ oversized pore) are the main type of secondary pores. Intragranular porosity was generally formed by the dissolution of detrital grains. Mould pores were predominantly generated by the dissolution of detrital feldspar, and sponge spicules. Oversized pores are intergranular pores and intragranular pores large enough to be identified; it is interpreted as the product of complete detrital grain dissolution (Plate 2G). Microporosity generally forms within altered feldspar grains, ductile grains and authegenic clay aggregates (Plate 2H). Microporosity is not only dependent on the amount of rock components but also on the growth habit of the clays. Intergranular void spaces constitute the primary porosity. Estimation, prediction and understanding the evolution of depositional porosity are essential for pre-drill prediction of porosity, permeability and reservoir modelling to enhance hydrocarbon exploitation. The parameters which control the porosity are detrital composition, grain size, sorting; basin temperature and pressure history.

The sandstones, which are mainly coarse to medium grained, moderately to moderately well sorted and have dominance of quartz (average 95.6%) in framework composition, qualify to have an initial depositional porosity (Pi) of 45 % (Atkins and McBride, 1992), which we have used here as an assumed initial porosity and with this value have tried to model the porosity evolution and relative role of cementation and compaction. This has been quantitatively worked out by using the following formula and variation diagram of Lundegard (1992).

Compaction porosity loss (COPL) = Pi – ((100 – Pi) X MCP)/ (100 – MCP)

Cementation porosity loss (CEPL) = Pi – COPL X (Tc/MCP)

Where Pi = the initial porosity (45%), MCP = the minus-cement porosity, and Tc = the total cement.

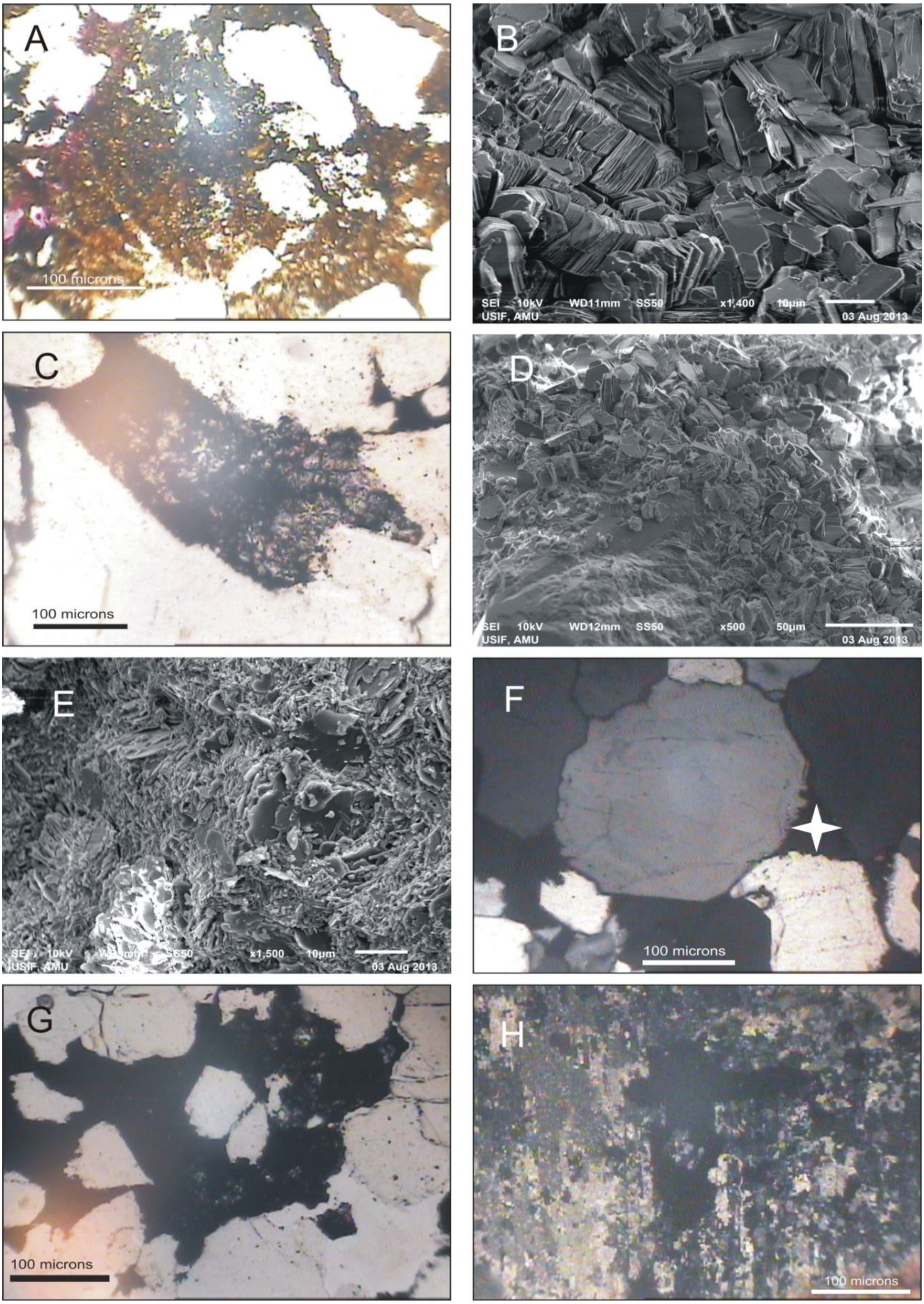

Plate 2. (A) Detrital grains corroded by clayey to silty matrix, (B) SEM Photograph of well crystallized authegenic Kaolinite booklets occurring as grain-replacement cement, (C) Pore-filling clay cement, (D) SEM Photograph of stacks of pseudo-hexagonal plates or books of grain-replacement Kaolinite cement, (E) Pore-filling mechanically infiltrated smectite, (F) Intergranular pores, (G) Oversized pores, (H) Micropores.

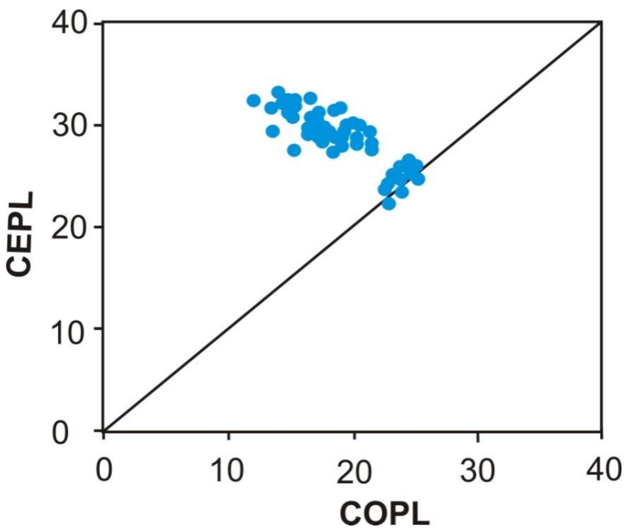

Fig.7. The plot of porosity loss due to compaction (COPL) v/s porosity loss due to cementation (CEPL) reflecting the evolution and relative importance of compaction and cementation in porosity loss.

The plot COPL versus CEPL (Fig. 7) shows a clear, decreasing trend of CEPL with increase in COPL suggesting that cementation was the major cause of the porosity reduction and hence compaction is secondary in porosity reduction. Porosity loss due to compaction averages 18.99% and due to cementation averages 29.07% (Table 3). High minus cement porosity values also suggest low mechanical compaction probably just before cementation, leading to grain dissolution.

Conclusion

Monocrystalline quartz is predominant followed by polycrystalline (recrystallized and stretched metamorphic) quartz. The sandstones are classified as quartz-arenite and sub-arkose. The diagenetic signatures observed in the Pachmarhi Sandstones include compaction, cementation, replacement and dissolution. The porosity loss is mainly due to cementation by pore occlusion and little by mechanical compaction. The nature of various types of grain contacts suggests early cementation and consequent minor compaction. Most of the porosity in the Pachmarhi Sandstones is primary inter-granular and little porosity is secondary inter-granular and intra-granular. The development of secondary porosity is mainly due to dissolution pores in iron oxide and calcite cement and intra-grain dissolution micro-pores in feldspars.

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