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Carbonate Fan Fabric Structures (FFS) in time and space: A case study from the Palaeoproterozoic Kajrahat Limestone, Vindhyan Supergroup, India

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This paper describes and discusses the origin of the carbonate Fan Fabric Structures (FFS), a rare and typical feature of the Precambrian Eon, observed in the Kajrahat Limestone near the Kota area, Sonbhadra District, Uttar Pradesh, India. In the Kajrahat Limestone, FFS escaped later recrystallization and subsequent dolomitization which otherwise obliterates the depositional texture as noted in most of the Proterozoic carbonate deposits. Characteristic FFS is noted exclusively in the upper part of the Kajrahat Limestone, Semri Group, Vindhyan Supergroup. The FFS varies from microscopic to mesoscopic in size. The depositional environment of the hosting carbonate units is inferred with the help of FFS morphology and configuration. The absence of actual microfossils, however, is conspicuous suggesting very rapid lithification. The origin of aragonite crystals and the possible role of organisms in the formation of FFS are discussed. The study reveals that these carbonate fans were formed below the sediment-water interface by the interplay of sedimentation and vertically upward nucleation of the crystal. Low diversity of stromatolites is also present in the Kajrahat Limestone and the overlying Salkhan Limestone. The Rohtasgarh Limestone, the top-most unit of the Lower Vindhyan is, however, completely devoid of FFS and stromatolites therefore, it is inferred that the FFS are restricted in time and space.

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INTRODUCTION

Carbonate successions are extensively investigated for understanding depositional sedimentary environment, temperature, chemistry, and geochronological dating (Schidlowski *et al.,* 1975, Xiao *et al.,* 1997; Sarkar and Bose, 1992, Gopalan *et al.,* 2002; Grotzinger and James, 2000; Kumar B. *et al.,* 2003; Ray *et al.,* 2004; Kumar S. 2004; Kumar S. *et al.,* 2005; Kaufman *et al.,* 2006; Banerjee *et al.,* 2006, 2007; Heindel *et al.,* 2015; Sarkar et al., 2020, Ansari *et al.,* 2018, 2020). Constituents of carbonate rocks are good indicators to infer the depositional facies (Singh, 1976; Srivastava and Kumar, 1994; Grotzinger and James, 2000; Sumner and Grotzinger, 2004; Allwood *et al.,* 2009; Bergmann *et al.,* 2013; Thorie *et al.,* 2018; Meinhold *et al.,* 2019; Li *et al.,* 2021; Geymann and Maloof, 2021; Kah and Bartley, 2021). Certain peculiar patterns/structures, exclusively found in the carbonate rocks, are variously defined *viz.,* carbonate precipitates, crystal fan, radiating fan, acicular bladed structure, pseudomorphs, needle fan, etc. The carbonate fan was classified as radial fibrous texture (Bartley *et al.,* 2000), upward radiating crystal fan (Seong-Joo and Golubic, 1999, 2000), microdigitate stromatolite (Grotzinger and Knoll, 1995), laminated tufa microfacies (Kah and Knoll, 1996). The type of occurrence of these structures shows spatial variation, for example, isolated fans, clustered fans, overgrowth fans, and continuous fans in lateral extension (Sumner and Grotzinger, 2000). Fan Fabric Structures (FFS) occur in the carbonate successions of the Precambrian Eon which are recorded from the Archaean to Palaeoproterozoic as a result of Ca-oversaturation and diverse nutrient/sediment supply in the Precambrian ocean (Grotzinger, 1993; Sumner, 2002; Sumner and Grotzinger, 2004; Bergmann *et al.,* 2013). Most of the carbonate fans are restricted to the shallow marine environment (Grotzinger and Read, 1983; Peryt *et al.,* 1990; Kah and Knoll, 1996; Bartley *et al.,* 2000; Pruss *et al.,* 2008; Tang *et al.,* 2013). In certain cases, exceptionally large size FFS, also known as carbonate fan fabric, are noted in field studies (Grotzinger, 1993; Kumar and Sharma, 2012). The occurrence of fan crystal throws light on the geobiological activities taking place at the site of nucleation (Bergmann *et al.,* 2013). In this paper, we document, describe and discuss the occurrence of FFS in the Kajrahat Limestone, Semri Group, Vindhyan Supergroup exposed in the Kota area, Sonbhadra district, Uttar Pradesh, India. The study examines 1) the morphological and petrological attributes of these carbonate fans; 2) attempts to answer the question related to

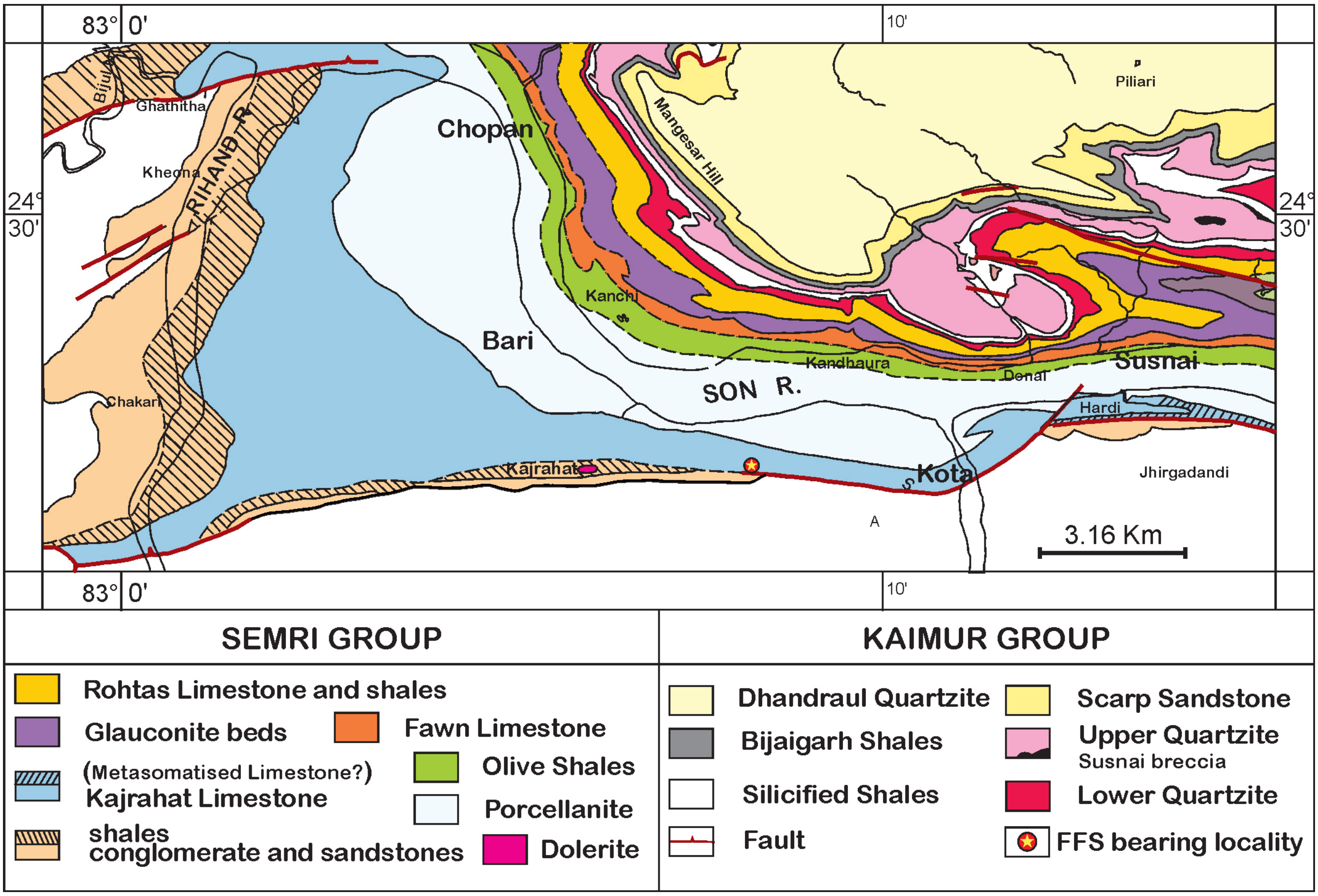


Fig. 1. Part of the geological map of the Vindhyan basin showing the extent of the Kajrahat Limestone in Kota, Kajrahat and Bari areas in Sonbhadra district, U.P. FFS bearing spot is marked with a star (redrawn after Auden 1933).

Table 1. Stratigraphic subdivisions of the Semri Group, Vindhyan Supergroup (after Auden, 1933; Soni *et al.,* 1987).

By Auden (1933)			Used in the present work	
		Limestone and shales	Rohtas Subgroup	Bhagwar Shale
		Nodular limestone and shales		
	Rohtas Stage	Banded shales		
		Limestone		Rohtasgarh Limestone
		Nodular limestone and shale		
		Glauconite beds	Kheinjua Subgroup	Rampur Formation
SEMRI GROUP	Kheinjua Stage	Fawn Limestone		Salkhan Limestone
		Olive Shales		Koldaha Shale
	Porcellanite Stage	Porcellanites etc.		Deonar Formation
		Kajrahat Limestone		
	Basal Stage		Mirzapur Subgroup	Kajrahat Limestone
		Basal Conglomerate		Arangi Formation
				Deoland Formation

the origin of these structures, and 3) correlating them with other occurrences all around the globe at the same time.

GENERAL GEOLOGY AND AGE

The Vindhyan basin is the largest intracratonic, sickle-shaped basin of India comprising 5000m thick succession of sandstone, shale, porcellanite, and limestone (Auden, 1933; Krishnan and Swaminath, 1959; Prasad, 1984; Soni *et al.,* 1987; Bose *et al*., 2001, 2015; Kumar and Sharma, 2012). The entire litho-succession is sub-divided into four groups namely, the Semri, the Kaimur, the Rewa, and the Bhander Groups exposed around Bundelkhand Granitic Complex (BGC) in central India. Sections exposed to the east of BGC are drained by Son River and are termed as the Son Valley

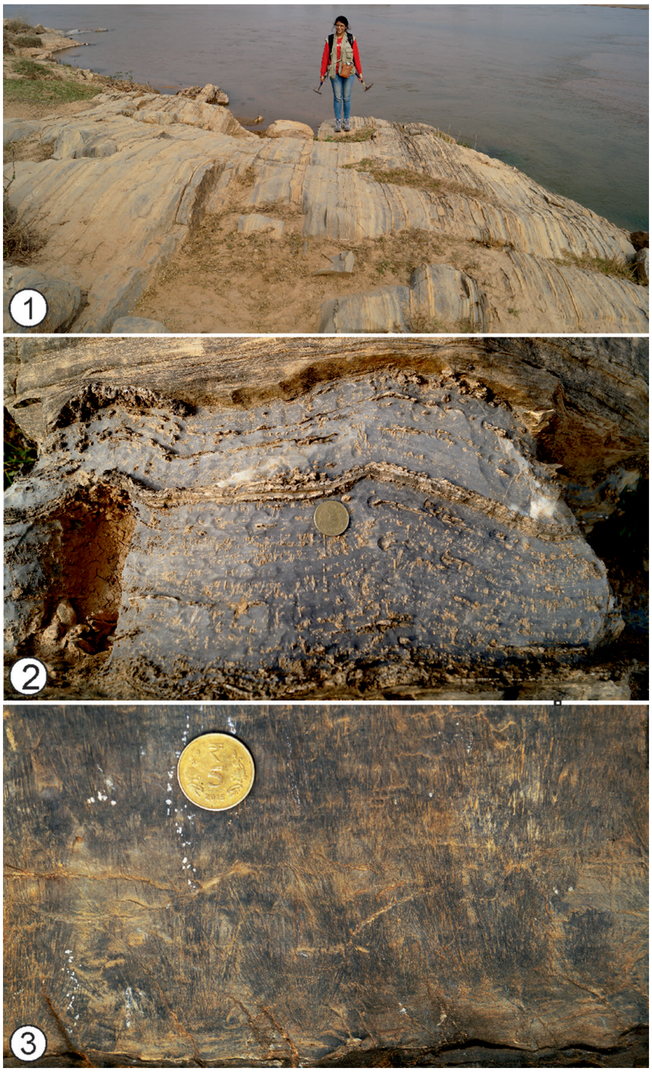


Fig. 2. Outcrops at Kota village showing nature and distinct patterns of Fan Fabric Structure (FFS) of the Kajrahat Limestone, Sonbhadra district, U. P. Fig. 2.1. Overview of the inclined Kajrahat Limestone beds dipping at 80-85 degrees NNE direction; Fig. 2.2. Sporadic occurrence of FFS; Fig. 2.3. Continuous occurrence of FFS. Divya Singh (162 cm) in Fig. 2.1. is for scale. The coin for scale for Figure 2.2 and 2.3=2.5 cm in diameter.

succession whereas, the sections exposed to the west of BGC are drained by Chambal River and are known as the Chambal Valley section of the Vindhyan Supergroup. Except for the Kaimur Group succession, lithostratigraphy on either side of BGC cannot be correlated with confidence (Kumar and Sharma, 2012). In the Son Valley, Auden (1933) divided the Vindhyan succession into Lower Vindhyan (Semri Group) and Upper Vindhyan (Kaimur, Rewa, and Bhander Groups) respectively. The Vindhyan sedimentary sequences are tectonically least disturbed, virtually unmetamorphosed, and rich in stromatolites and microfossil assemblages. General lithostratigraphic succession is given in Table-1. The Semi Group is the oldest succession of the Vindhyan Supergroup, which unconformably overlies the BGC in the central Son Valley section or Mahakoshal Phyllite in the eastern Son Valley Section. In stratigraphic order, the Semri Group is divided into the Deoland Formation, Arangi Shale, Kajrahat Limestone, Deonar Formation, Koldaha Shale, Salkhan Limestone, Rampur Formation, Rohtasgarh Limestone, and Bhagwar Shale (Auden, 1933; Sastry and Moitra, 1984, Mandal *et al.*, 2019). The Kajrahat Limestone is the lowermost biochemically precipitated succession of the Semri Group which is underlain by the Arangi Formation and overlain by the Deonar Formation (Auden, 1933). This unit is dominantly constituted of limestone, dolostone, and shales; based on the observable change in the lithology Prakash and Dalela (1982) subdivided the succession into 12 members. All these members are noted over a vast tract in lateral extent from Sonbhadra to Satna (Maihar) districts. Banerjee (2007) subdivided the upper part of the Kajrahat Limestone, seen near the Kuteshwar-Dhanwahi area, into 7 litho-units. Intermittent occurrence of black shale horizons of considerable thickness is of interest to several researchers (Fox, 1929; Prakash and Dalela, 1982). The four major bio-chemically precipitated units of the Semri Group in the Son Valley are the Kajrahat Limestone, Porcellanites (Koldaha Shale), the Salkhan (Fawn) Limestone, and the Rohtasgarh Limestone (Fig. 1). Microfossils and stromatolites are recorded from the Kajrahat Limestone and the Salkhan Limestone (Kumar, 1978; Kumar and Srivasatva, 1995; Srivastava, 2005; Sharma, 2006; Shukla and Sharma, 2016). Microfossil assemblages also indicate the late Palaeoproterozoic and early Mesoproterozoic age for the Semri Group. The Rohtasgarh Limestone is an unaltered primary limestone unit of the Precambrian Eon which is devoid of stromatolite and other microfossil.

Many of these litho-units of the Semri Group are geochronologically well-dated (> 1600 Ma) using different methods for the deposition of this group (Crawford and Compston, 1970; Rassmussen *et al.,* 2002; Gopalan *et al.,* 2002; Sarangi *et al.,* 2004; Ray *et al.,* 2006; McKenzie *et al.,* 2011; Bengston *et al.,* 2017; Bickford *et al.,* 2017, Mishra *et al.,* 2018). The Pb-Pb isochron ages were calibrated on the basal part of the Kajrahat Limestone (1721 ± 110 Ma) and the uppermost part of the Rohtas Limestone (1599 ± 48 Ma) (Sarangi *et al.,* 2004). Therefore, collectively these analyses indicate the late Palaeoproterozoic time period for the deposition of the Semri Group.

MATERIALS AND METHODS

The Kajrahat Limestone samples for the present study were collected from the left bank of the Kanhar River in the Kota village (N 24˚26'44.5", E 83˚08'12.2") in Sonbhadra district, Uttar Pradesh. A few additional samples have also been obtained from the Kuteshwar section (N 23˚58'77", E 80˚50'74") in Katni district, Madhya Pradesh. In Kota village, the outcrop is in faulted contact with the Mahakoshal Group of Rocks. Beds are dipping 80-85 degrees NNE direction (Fig. 2.1). Millimeter to centimeter size FFS is distinctly visible on the outcrops across the bedding plane. Lithologs of the outcrop sections showing FFS and stromatolites were prepared (Figs. 3-4). Hand specimens of the FFS were collected on the measured section (vertical as well as lateral). For petrological studies, standard-oriented thin section slides were prepared in the lab and studied under the petrological microscope (Nikon Eclipse LV100N POL). Large size slides

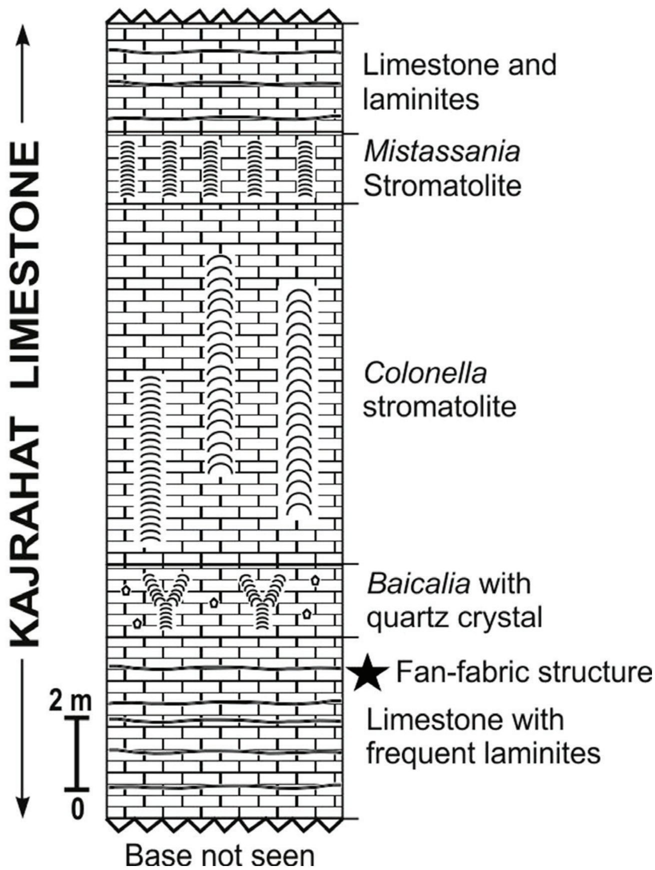


Fig. 3. Litholog of the exposed section of the Kajrahat Limestone at Bari section, Sonbhadra district. Note the level of stromatolites.

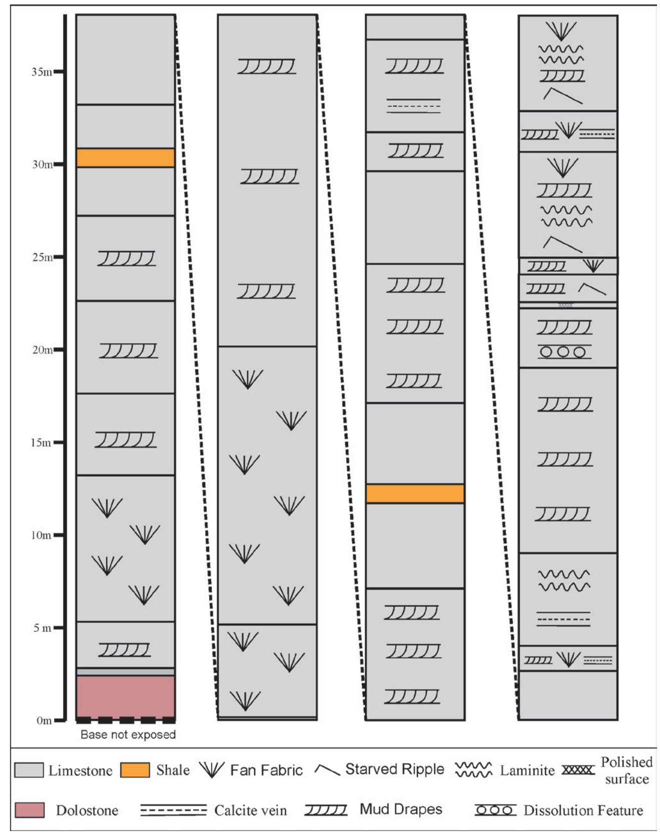


Fig. 4. Measured section of the Kajrahat Limestone exposed near Kota village on the left banks of the Kanhar River, Sonbhadra, district. Note the cyclicity of Fan Fabric structures and laminites.

(Size 50 x 75 mm) were also prepared and examined under a reflected low-power microscope (Olympus SZ 61 with SC 50 photo attachment) to study the FFS. Photo-documentation of the FFS has been done both on the low power as well as petrological microscopes attached with digital photography units. All the studied hand specimens, slides, and additional materials are deposited with BSIP Museum and can be retrieved vide statement numbers (BSIP 1544 and 1567).

DESCRIPTION OF FAN FABRIC STRUCTURES

Characteristic FFS are found towards the top of the Kajrahat Limestone outcrops and also show the presence of stromatolites, microbial mat, and distinct sedimentary structures. Because of their upward growing fan-shaped trend, these are termed Fan Fabrics. Outcrop logging suggests that they occur rhythmically and continue for a considerable extent over the vertical and lateral extents (Fig. 4). FFS occurs sporadically or continuously; propagate invariably in a vertically upward direction. In sporadic occurrence, a bunch of an aggregation of tapering acicular crystals constitutes a single fan (Fig. 2.2). In some segments of the outcrop, the second type of FFS is constituted of lateral continuous occurrence of crystal fans. They are represented by the regular, adpressed acicular to bladed crystal fans found adjacent to each other (Fig. 2.3).

Five representative Kajrahat Limestone hand specimens (Plate-I, Figs. 1-5) were selected for the detailed study of FFS. Size of FFS varies from centimeters in length to less than millimeters in width; length/width ratio is less than 1. A similar ratio is also observed when studied at a microscopic level. All the samples are light grey and react with weak HCl establishing the broad mineral composition of the rocks (calcium carbonate). Laminae between two FFS layers are comparatively dark in color. In a few cases, equant crystals are noted on the basal side above which radiating fan fabric structures develop (Plate-I, Fig. 1). In most of the cases, on the basal side, fans initiate over a lamina from a point and radiate outwards (Plate-I, Figs. 2-5).

Microscopic observations - Thin sections of the FFS were studied under reflected light on a low-power microscope. Based on crystal arrangements and radiation patterns FFS are divided into 4 groups. 1) Fan structure: In this group, acicular crystals originate from the base and develop in a vertically upward direction. Crystals are wider at the base and taper at the other end. Their arrangements show a typical fan fabric feature (Plate-II, Figs. 1-3). Based on the size of the crystals these structures have been further divided into two subgroups. 1A) Equal length crystals arrangement: FFS are formed of equidimensional crystals, where the lengths of the FFS are approximately equal in length (mean length=

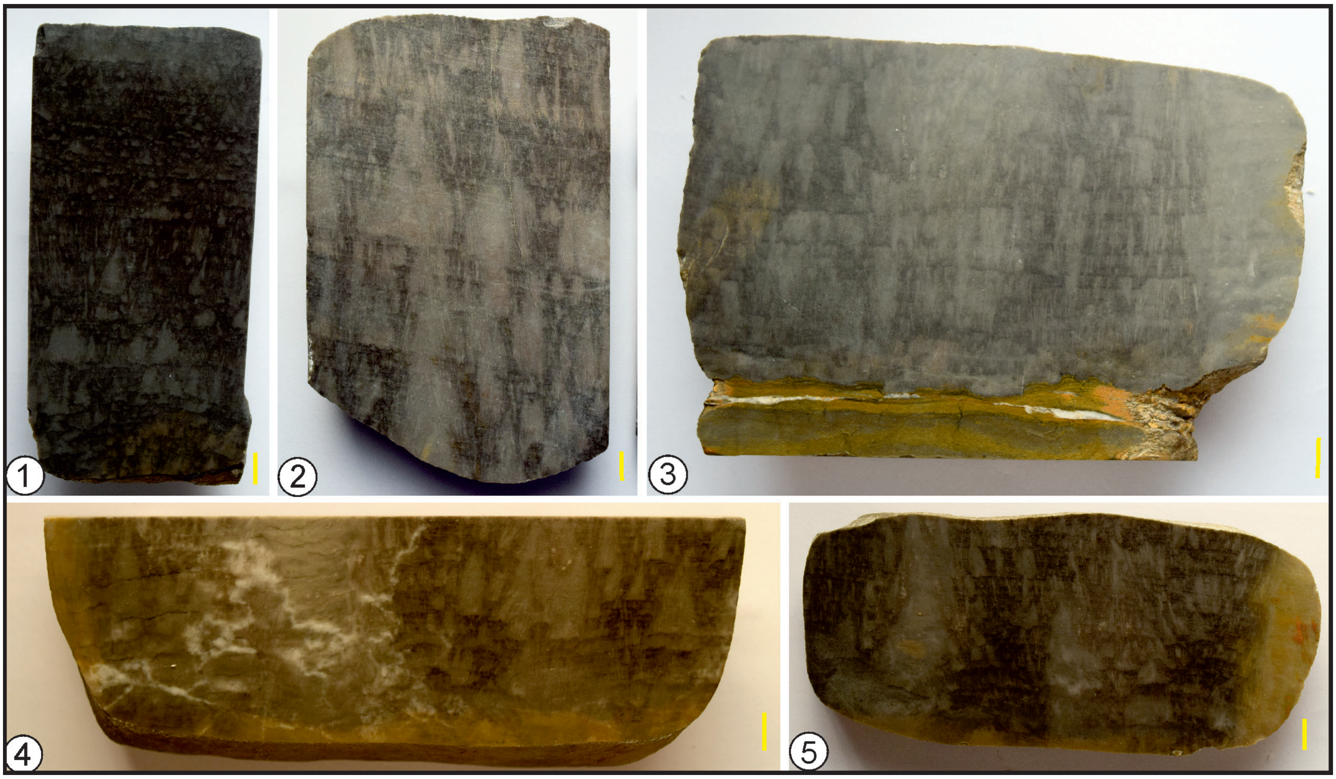


Plate-I. Representative hand specimens showing different patterns of FFS were collected from the left bank of the Kanhar River, Kota area. Fig. 1. Note distribution pattern of equant crystals on the basal side above which radiating fan fabric structures were developed (1-BSIP Museum Specimen no. 41997); Figs. 2-5. In these specimens FFS initiates over a lamina from a point and radiates outwards (2-BSIP Museum Specimen no. 41998), (3-BSIP Museum Specimen no. 41999), (4-BSIP Museum Specimen no. 42000), (5-BSIP Museum Specimen no. 42001). Scale bar=1cm (Figs. 1-5).

3.598 mm, mean width= 0.292 mm, N= 10) (Plate- II, Figs. 4-5); 1B) Sun-rays crystal arrangement: FFS are constituted of alternation of long and short crystals arrangement (mean length=3.75 mm , mean width= 0.378 mm, N= 10) (Plate-II, Figs. 6-7). 2) Overarching Fan: Lateral continuous FFS under the microscope show tightly pressed crystals sometimes overlapping each other giving an impression of a thicket. This arrangement of crystals can be further divided into two subgroups. 2A) Overarching crystals: FFS classified under this subgroup are made up of simply adpressed vertical crystals (Plate-II, Fig. 8). The individual crystals are acicular in shape and grow in a V-shaped overarching arrangement (mean length= 3.198 mm, mean width= 0.151 mm, N=5). These structures are easily identified in the field being larger which is further resolved under the microscope. 2B) Criss-cross Fan: The growth of the crystal shows a criss-cross relationship. In some cases, two different fans originate from the same point giving the impression of a branching fan (Plate-II, Figs. 9-11) (mean length= 9.610 mm, mean width= 1.078 mm, N=15). In some cases at the termination of the first crystal fan, the new crystal fan appears like a bud (Plate-III, Fig. 1) (mean length= 8.913mm mean width= 0.5708 mm, N= 5). Crystals show the interlocking pattern and their orientation is haphazard and random instead of vertical as in the case of all other groups. 3) Oriented equant crystal fan: Small oblong loosely packed crystals are oriented in such a scheme that the aggregation and arrangement resemble the shape of a Fan (Plate-III, Figs. 2, 3) (mean length= 1.785mm, mean width=0.497mm, N=10). 4) Fan along with equant crystals: In this arrangement, acicular crystal fan and equant crystals both are observed in close vicinity or overlap each other (Plate-III, Fig. 4).

Petrographic thin sections of the Kajrahat Limestone were also studied (Plate-IV, Figs. 1-8). Here, aragonite is the ‘precursor mineral’ at the time of precipitation. The original morphology of aragonite as short to long acicular prismatic crystal is preserved as ‘pseudomorph’. Diagenetic replacement of aragonite with calcitic in-filling constitutes the pseudomorph. Infilling of the pseudomorphs is composed of coarse to fine-grained calcite. Some secondary veins of coarse-grained calcite crystal are also observed in thin sections. These secondary veins grow in un-oriented directions and a few veins cross-cut each other representing the post-depositional in filling of calcite. The micritic cement is formed as a result of the rapid precipitation of calcium carbonate. The gradation in grain size represents variation at the time of crystallization. The host rock/cement shows a gradation of calcite equant crystal from coarse-grained to micrite. The grains inside the pseudomorph and the host rock show a characteristic interlocking mosaic pattern of calcite crystals. Some of the pseudomorphs of crystal fan are bordered by dark brown colored lining which is syn-depositional. These dark-colored linings could be rich in organic matter or precipitates of iron-rich sediment. Overall, post-depositional calcification is observed throughout the thin sections.

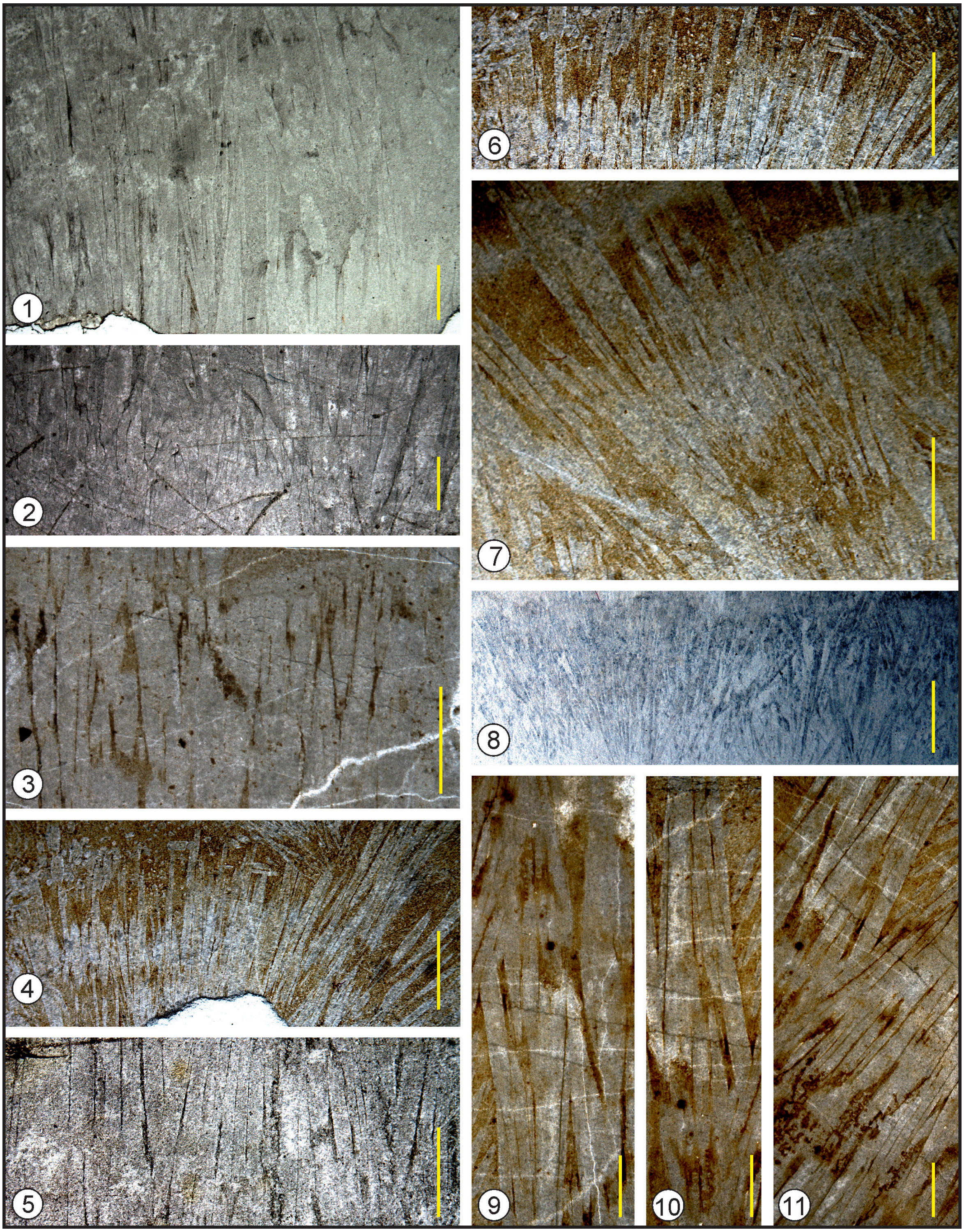
DISCUSSION

Textures and depositional environment of the Son Valley Kajrahat Limestone

The Kajrahat Limestone, is well exposed in fresh mines of the Chopan area of the Sonbhadra district. Excavations by the Cement industry (Mukti Nath and Mehta, 1951; Prakash and Dalela, 1982) allow newer sections for the study. In the last two decades emphasis was laid on understanding the depositional environment of the Kajrahat Limestone (Banerjee *et al.,* 2006; Jeevankumar and Banerjee, 2008; Sarkar and Banerjee, 2020; Singh *et al.,* 2020). FFS were, however, not recorded in these studies in the Kajrahat Limestone. Banerjee *et al.* (2006) studied the equivalent correlatable Kajrahat Limestone unit exposed 320 km south-west of Chopan near Mahanadi over-bridge connecting Dhanwahi-Kuteshwar and divided the 255 m thick succession into 3 major divisions (lower, middle and upper). These three divisions are also identifiable in the Kajrahat Limestone section exposed in the Chopan area, Son valley. There is no unanimity as to the thickness estimates of the Kajrahat Limestone; Auden (1933) mentioned its thickness about 600 meters in the Billi area whereas, Prakash and Dalela (1982) estimated its thickness to be 1199 meters based on observations on drill cores in Kajrahat area. Palaeobiological shreds of evidence are, however, poorly documented from the Kajrahat Limestone. Studies recorded the occurrence of stromatolites in the Chopan area (Kumar, S., 1976, 1978; Gupta, 2004). Jeevankumar and Banerjee (2008) described the mat structures found in the 12m thick succession of black shales in the lower part of the Kajrahat Limestone exposed in the Chopan area. Following Schieber's (1999) classification scheme, they had documented microbial mat-growth, microbial mat-destruction, microbial mat-diagenetic features, and pyritic laminae in the shale unit. Singh *et al.* (2020) also studied the same section and documented the soft-sediment deformation features i.e., convolute bedding, contorted cross-bedding, autoclastic breccias, and small-scale folds in the middle part of the Kajrahat Limestone. However, in the Dhanwahi section, Banerjee *et al.* (2006) established Facies A-G in the upper division of the Kajrahat Limestone. Their study revealed the highly dolomitized nature of the lower division, with cross-stratified lenses of dolomite deposited in the intertidal regime. In this section, the middle division of the Kajrahat Limestone was recorded as non-descript thin dolostone bands deposited in shallow lagoons with intermittent evaporitic deposits. The upper division was studied in detail and stromatolites were recorded by these authors. A distinct cyclicity was observed in this division with diverse stromatolites are found in the Facies E, F, and G with larger, smaller stromatolites and biolaminites types respectively. The upper-division is considered to have deposited in intertidal to the supratidal regime. Carbonate samples of larger stromatolites and microbial laminites were also analyzed by them (Banerjee *et al.,* 2006) for their isotopic values; $\delta^{18}O$ (-7.9 to -13.4‰) and $\delta^{13}C$ values (1.1 to -2.5‰) of stromatolites indicate their least altered primary nature, whereas the isotopic values of microbial laminites are depleted and help conclude to be constituted of isotopically lighter fluid which could be derived by organically charged meteoric water. These values can be correlated with similar values obtained on the Palaeoproterozoic carbonates of other studies (Hotinski *et al*., 2004; Kumar *et al.,* 2003). In the Chopan area, carbonate FFS are noted in the lower as well as upper parts of the Kajrahat Limestone (Fig. 4). Small domal and branching stromatolites are found in the upper part of the Kajrahat Limestone (Fig. 3). Stromatolite-bearing carbonate is considered to have deposited in the inter-tidal to the sub-tidal region of the tidal flat depositional environment (Kumar, 1976).

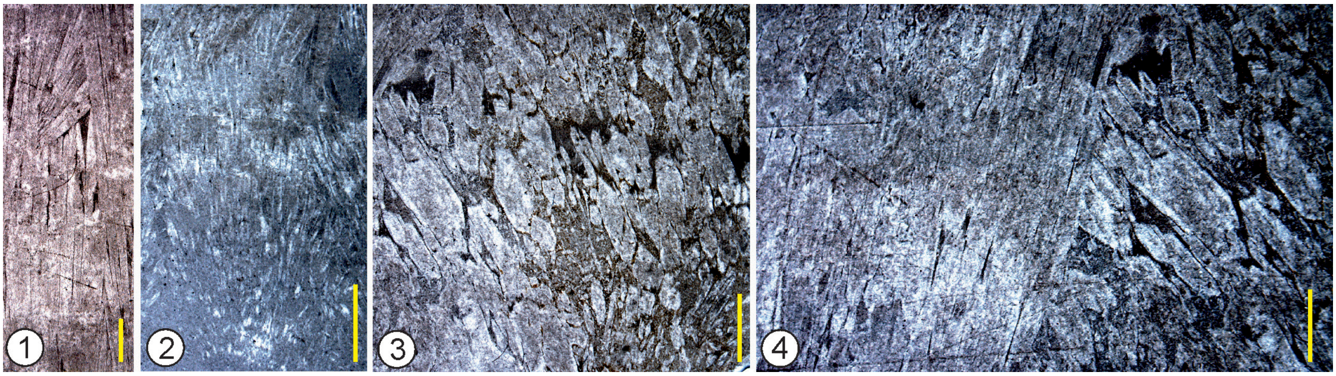
Formation of FFS

Precipitation of extensive micrite in the depositional environment and the presence of a lesser amount of fabric disturbing microbes are the reasons for massive carbonate depositions in the Precambrian oceans (Grotzinger, 1993). The carbonate fans are one of the characteristic sedimentary features which help decipher the depositional environment of the unit in which they are found. Originally composed of aragonite, the carbonate fan fabric is metastable and rarely preserved. Pruss *et al.* (2008) suggested that carbonate fans are formed close to the sediment-water interface by the interplay of sedimentation and vertically upward nucleation of the crystals. Various studies on the Proterozoic carbonate platform deposits suggest that the carbonate fans generally originate from the organic-rich layer and radiate perpendicular to the bedding plane as acicular and bladed crystal from the base (Sumner and Grotzinger, 2000, 2004; Bartely *et al.,* 2000; Winefield, 2000). The basic/elementary/limiting condition for nucleation of fan includes- Ca- oversaturation, high alkalinity, and sediment-water interface. The Ca-oversaturation condition retarded due to the occurrence of various inhibitors (Grotzinger and Knoll, 1995) such as Fe^{2+} and Mn^{2+} in the depositional milieu that slow down the nucleation of micritic cement and fostered the nucleation of fan crystals (Winefield, 2000). Records in the given Table-1 emphasize that these structures are not just a localized sedimentary feature rather it can be inferred that these structures precipitate in response to a characteristic Physico-chemical and microbial condition of the Precambrian ocean, at the sediment-water interface. The nucleation centers of these crystal fans are organic-rich, black in color, but devoid of any microfossil. A dilemma related to these structures is whether the organic-rich layer truncated the growth of the crystal fan as it draped over the crystal fan or vertically upward radiating crystal fan overgrew over the organic-rich layer. Presence of organic matter, which stimulates the nucleation of calcite/aragonite may be a possible reason for the precipitation of carbonate fans (Sumner, 2002). In certain cases, the occurrence of fan crystal in the Neoproterozoic successions are associated with cap carbonate rocks such as Marinoan deglaciation event (Grotzinger and Knoll, 1995). The other factors that play a major role in their precipitation are the temperature and pCO2 of the ocean water. The extent of evaporation limits the type of precipitation: 1) if the evaporation is less than 20%



EXPLANATION OF PLATE II

Types of crystal arrangements and radiation patterns of FFS observed in polished thin section photographs of fan-fabric structures noted in the Kajrahat Limestone exposed in Kuteshwar area, Satna district, M.P. (Slide nos. BSIP-16653, 16654) and near Kota area in Sonbhadra district, U.P. (Slide nos. BSIP-16966-16972). Figs. 1-3. Equal length crystals arrangement where the lengths of FFS are approximate of equal in length, (1-BSIP Museum Slide no. 16966), (2-BSIP Museum Slide no. 16967), (3-BSIP Museum Slide no. 16654). Figs. 4-5. Sun-rays type crystal arrangement where FFS show alteration of long and short crystals arranged in length, (4-BSIP Museum Slide no. 16653), (5-BSIP Museum Slide no. 16968). Figs. 6-7. Overarching Fan showing tightly pressed crystals sometimes overlapping each other giving impression of a thicket (6-BSIP Museum Slide no. 16653), (7-BSIP Museum Slide no. 16653). Fig. 8. FFS constituted of overarching crystals adpressed vertical crystals (8-BSIP Museum Slide no. 16654). Figs. 9-11 Criss-cross FFS showing the criss-cross relationship between the crystals (9-11-BSIP Museum Slide no. 16654). Scale bar 2mm (Fig 1-11).



EXPLANATION OF PLATE III

Types of crystal arrangements and patterns of FFS. Fig. 1. Note the budding structure of crystal fan at the termination of other FFS (1-BSIP Museum Slide no. 16969). Fig. 2-3 Small oblong loosely packed crystals oriented in the shape of a Fan (2-BSIP Museum Slide no. 16654), (3-BSIP Museum Slide no. 16654). Fig. 4. Acicular and equant crystals were noted nearby and in some cases overlapped each other (4-BSIP Museum Slide no. 16654). Scale bar 2mm (Figs. 1-4).

Table 2. Broad global distribution of the Fan Fabric Structures (FFS) in Precambrian times.

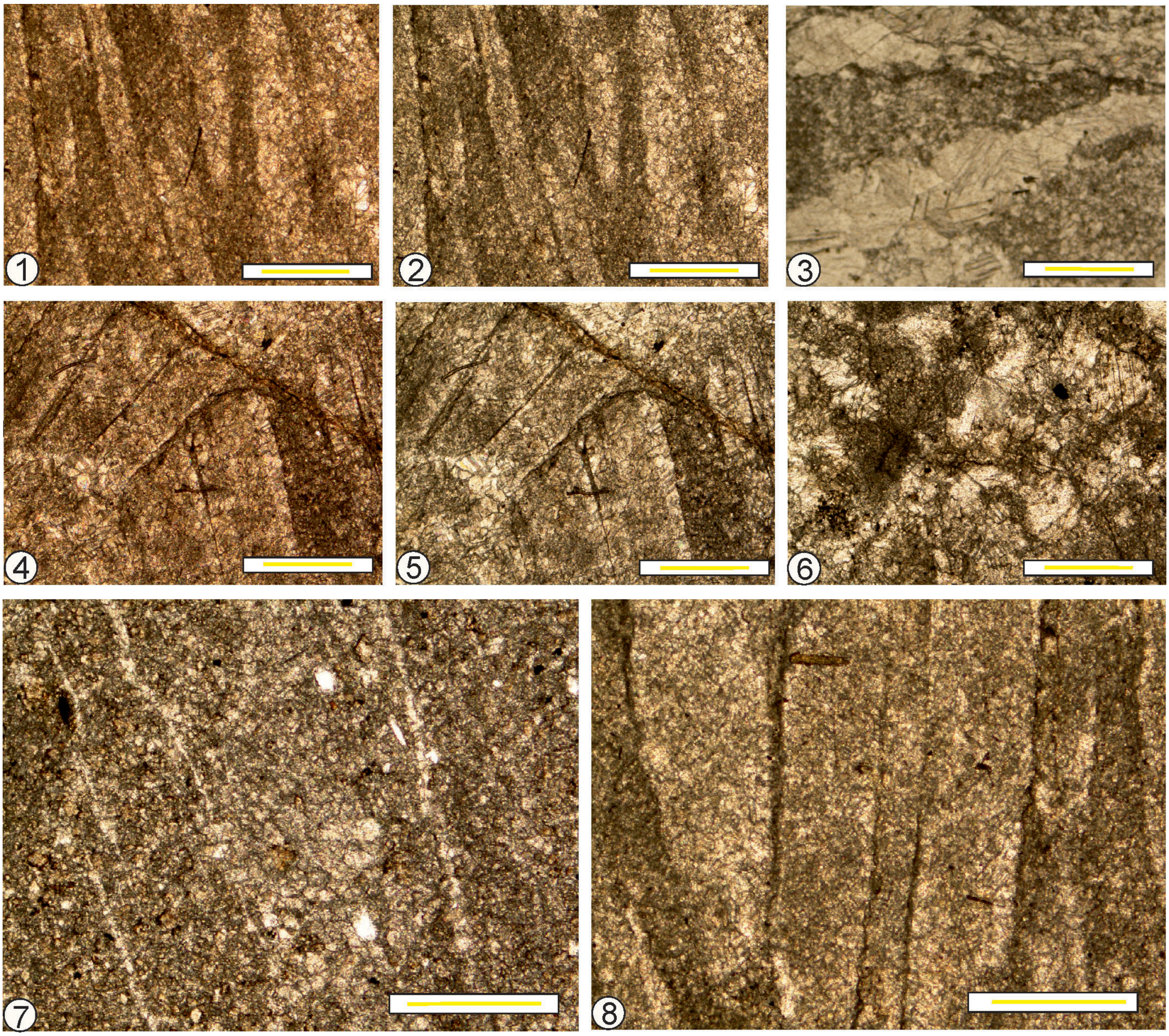
S. No.	Era	Name	Age (Ma)	Location	Context	Depostional Environment	References
1.	Palaeoarchean	Crystal Pseudo-morphs	3450	Strelly Pool Formation, Western Australia	Flat bedded conglomerate association with crystal fan.	Peritidal carbonate platform	Allwood *et al.*(2009); Allwood *et al.*(2006).
2.	Neoarchean	Pseudo-morph Fan	2700	Chesire Formation, Zimbabwe	Crystal fan grew from lag deposits of detrital sediment, associated with microbial laminae	Wave- storm dominated open-marine shelf settings	Sumner and Grotzinger (2000)
3.	Neoarchean	Radiating crystal structure	2500-2800	Belingwe Formation, (Stromatolitic Limestone), Zimbabwe	Blue- grey weathered limestone associated with radiating crystal	Very shallow water origin, most probably Intertidal	Bickle *et al.*(1975); Martin *et al.*(1980)
4.	Neoarchean	Crystal Pseudo-morph	2700	Steep Rock Formation, Canada	Crystal fan originated within fenestrate microbial laminae	Subtidal-shallowing upward sequences	Wilks *et al.*(1988); Sumner and Grotzinger (2000)
5.	Neoarchean	Fanning Pseudo-morphs	2600	Hunstman Formation, Zimbabwe	Crystal fans are interbedded with interpreted microbial laminae and black coatings	Shallow marine sequences	Sumner and Grotzinger (2000)
6.	Neoarchean	Silicified Pseudo-morphs	2600	Carawine Formation, Australia	Crystal fans draped in sediments and sometimes reworked	Shallow marine	Simonson *et al.*(1993); Sumner and Grotzinger (2000)
7	Neoarchean	Fanning Pseudomorph	2540	Campbellrand-Malmani Platform, South Africa	Pseudomorph grew outwards from the sides of stromatolites as botryoids	Open subtidal to evaporitic supratidal environment	Sumner and Grotzinger (2000); Sumner and Grotzinger (2004)
8.	Palaeoproterozoic	Psedomorphs	1950	Beechey Formation, Canada	Crystal fans associated with granular iron formation, sit on transgressive surface	Shallow marine shelf	Grotzinger and Friedman (1989); Grotzinger (1993)
9.	Palaeoproterozoic	Pseudomorph	1900	Odjick-Rocknest Boundary, Canada	Thin authigenic hematite coatings on crystal fans, sit on transgressive surface	Restricted peritidal to subtidal	Grotzinger and Reed (1983)
10.	Palaeoproterozoic	Stromatolitic Fibrous Fan	1880	Pethei Group, Canada	Stromatolite contains some Stromatolitic fibrous cement as vertical masses	Peritidal to subtidal	Sami and James (1996)

11.	Palaeoproterozoic	Coxco Needle Fan	1640	Teena Formation	Crystal fans interbedded with pink carbonates and sit at the transgressive surface	Peritidal to basinal or deep ramp	Winefield (2000)
12.	Mesoproterozoic	Upward expanding botryoidal	1400	Gaoyuzhuang Formation, China	Crystal fans associated with sediment rich layers	Peritidal to intertid; evaporitic condition and subaerial exposure	Seong-Joo and Golubic (2000)
13.	Mesoproterozoic	Radial fibrous carbon-ate fabrics	Early Meso protero-zoic	Kotuikan Formation, Siberia	Crystals generally originates from organic rich horizons	Peritidal	Bartley *et al.*(2000)
14.	Mesoproterozoic	Crystal Fan	1200	Ruyang Group, China	Crystal fans draped by darker, micritic laminae, blades highlighted by organic matter or hematite	Peritidal	Xiao *et al.*(1997)
15.	Mesoproterozoic	Cement Fans	1100	Society Cliffs Formation, Canada	Crystal fans associated with evaporates	Peritidal	Kah and Knoll (1996)
16.	Neoproterozoic	Fibrous Aragonite	740	Bambui Group, Brazil	High Sr concentrations, Crystal fans are associated with red lime mudstones	Subtidal	Peryt *et al.*(1990)
17.	Neoproterozoic	Aragonitic Seafloor Fans	667	Pocatello Formation, United States	Crystal fans are associated with pink limestones	Shallow Marine	Lorentz *et al.*(2004); Corsetti *et al.*(2004)
18.	Neoproterozoic	Crystal Fans	630	Maieberg Formation, Namibia	Crystal Fans of pseudo-morphosed aragonite form localized masses of seafloor cement	Shallow marine	Hoffman *et al.*(1998); Hoffman *et al.*(2007)
19	Neoproterozoic	Aragonite Fan	580	Johnnie Formation, United States	Crystal fans occurs both in cluster and evenly spaced on bedding plane	Shallow subtidal setting	Corsetti *et al.*(2004) Pruss *et al.*(2008)
20	Neoproterozoic	Barite Fans		Mt. Doreen Formation, Australia	Barite fan within the stromatolite	Deeper water, sediment starved environment	Kennedy (1996)
21	Neoproterozoic			Hayhook Formation		Intertidal	James *et al.*(2001)
22	Neoproterozoic	Crystal Fan	548	Buschmannsklippe Formation, Witvlei Group, Southern Namibia	Fans are in situ and precipitated directly on seafloor	Subtidal	Saylor *et al.*(1998)
23	Neoproterozoic	Aragonite Crystal Fan		Katakuruk Formation, Alaska	The fans are upward shallowing sequence including elongate stromatolites and culminates in exposure surface	Shallow –marine condition	Macdonald *et al.*(2009b)

then the calcite forms micritic cement; 2) if evaporation is more than 20% then aragonite nucleation occurs which forms crystal structure. And high Mg/Ca is generally favored by deposition of aragonite whereas a low Mg/Ca ratio favors calcite deposition (Vieira *et al.,* 2015). Besides, the Kajrahat Limestone, fan fabric structures are also recorded in other geological units of India: FFS are noted in the Vempalle Formation, Cuddapah Supergroup (Sharma and Shukla, 1998) and the Salkhan Limestone (the Jaradag Fawn Limestone), Semri Group, Vindhyan Supergroup (Sharma and Sergeev, 2004). In both these occurrences, FFS are associated with microbial mats as well as microfossils. But in the case of the Kajrahat Limestone except for stromatolites no distinct well-preserved microfossils are found in the vicinity of FFS. The presence of stromatolites, therefore, suggests the possible role of microbes in the precipitation of Kajrahat FFS.

Carbonate Fan Fabric in Time and Space

Widespread occurrence of the fan fabrics in the Precambrian Eon and their distribution in different sedimentary basins in time and space are presented (see Table-2 for global distribution and references). The size of these carbonate fans varies from macroscopic to microscopic. Their genesis is restricted to some extent in time and space and controlled by the depositional environment and type of nutrient/sediment supply through various oceanic processes (Grotzinger and Kasting, 1993; Kah and Knoll, 1996). In Neoarchaean, pure carbonate beds were formed by the rapid precipitation which suggests Ca-oversaturation in the Precambrian ocean (Sumner and Grotzinger, 2004). Profound well-precipitated carbonate fans are observed from the Neoarchean to Terminal Neoproterozoic (Table-1).



EXPLANATION OF PLATE IV

Petrographic thin section photographs showing distinct acicular crystal pseudomorphs of aragonite and secondary veins. Fig. 1. Shows aragonite 'pseudomorph' and micritic calcite infilling under Cross Nicol (1-BSIP Museum Slide no. 16967); Fig. 2. Same spot under plane polarised light; Fig. 3. Shows secondary veins of coarse-grained calcite crystal under plane-polarized light (3-BSIP Museum Slide no. 16970); Fig. 4. Shows aragonite 'pseudomorphs' overlapping each other and micritic calcite infilling under cross nicol light (4-BSIP Museum Slide no. 16968); Fig. 5. Same spot under plane-polarized light; Fig. 6. Shows gradation of calcite cement from coarse-grained to micrite (6-BSIP Museum Slide no. 16971); Fig. 7. Shows un-oriented thin calcite vein under plane-polarized light (7-BSIP Museum Slide no. 16972); Fig. 8. Showing aragonite 'pseudomorph' bordered by dark color matter and micritic calcite infilling under plane polarised light. (8-BSIP Museum Slide no. 16968). Scale bar=500 µm (Figs. 1-8).

Their occurrence is rare in the Mesoarchean successions. These are also encountered in the Phanerozoic but in low magnitude (Bertrand-Sarfati and Walter, 1981; Pruss *et al.,* 2008; Kah and Bartley, 2021). Thus, the occurrence of these structures is marked globally in the Precambrian Eon, precisely from the Neoarchaean to early Palaeoproterozoic and again in the Neoproterozoic. The FFS are an important feature of the Archaean and Palaeoproterozoic platform in the range of shallow marine settings and are restricted to peritidal Mesoproterozoic settings. The Archaean crystal pseudomorphs are commonly larger, vary from centimeter to decimetre in size. Even the downward radiating aragonite crystal fans are also documented from Steep Rock, Ontario, Canada (Kusky *et al.,* 1999). All this information convinces that the nucleation of these carbonate fan fabrics has initiated a unique set of circumstances, associated with precipitation, sedimentation, and microbial activity. These geobiological conditions are not identical, for all the Precambrian succession. Thus, the origin of these structures, whether biogenic or abiogenic is still debatable.

CONCLUSIONS

The documented carbonate FFS are found associated with stromatolites, microbial laminites that indicate shallow (open) marine depositional environment for the Palaeoproterozoic Kajrahat Limestone. Various operating geo-biological processes caused a change in the physicochemical condition of the basin. These changes affect the type of precipitation or precipitation pattern and the type of mineral to be precipitated in carbonates. Petrographic studies indicate that the biochemically precipitating carbonate mineral with fan-shaped structures; their morphology observed under the microscope as well as across the beds on the outcrops represents that the precursor mineral was aragonite. Aragonite, being thermodynamically less stable, is commonly replaced by other minerals. In the case of the Kajrahat Limestone most likely the wet polymorphic transformation of aragonite to calcite had occurred. Since the overall calcification had occurred suggesting that the Precambrian oceans were saturated with $CaCO_3$. As calcite is comparatively more stable that is why it is preserved as aragonitic pseudomorphs. Therefore, the gradation of micrite to the mosaic of coarser crystal is secondary in origin. Litho-unit of the Kajrahat Limestone, from the location where fans are recorded, has organic-rich layers present in between the succession. The association of carbonate fans, with these organic-rich layers, is still not fully explained. As the dilemma regarding the origin of these structures continues, more detailed geochemical investigations such as stable isotope, trace elements, major elements, etc. values of these structures are needed.

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