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Mahakut Chert Breccia in Kaladgi basin, India: Unsolved Issues

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Widespread deposition of cratonic sediments within the Purana basins dates back from Late Palaeoproterozoic to Neoproterozoic time. These sediments were deposited over the Archaean basement of the Indian Peninsular shield but separated by a pronounced unconformity. The Proterozoic sediment package of the Kaladgi Supergroup occupies the intracratonic Kaladgi-Badami basin that extends over an area of about 8000 km^2 in the northern part of the Dharwar Craton. The Mahakut Chert breccia horizon, geographically the most widely distributed chert breccia horizon, within the Kaladgi Basin occurs as disjointed patches throughout the outcrop of the Bagalkot Group and contains intrabasinal clast fragments that have undergone pervasive silicification. Preliminary field observations suggest that the upper and the basal contact of the massive chert breccia horizon with the argillaceous units are masked. The silicified organo-sedimentary structures identified from the chert breccia horizon are tell-tale evidence of the biogenic activity within the basin suggesting a shallow shelf environment, within the photic zone. This is also supported by the presence of a tepee structure, another indicator of a shallow water environment with intermittent exposure. The presence of silicified ooids suggests a tropical climate conducive to evaporation and is suggestive of a highly agitated shallow marine intertidal environment. Basin-scale detailed studies are needed to understand the depositional environment before silicification; the rate and timing of the silicification of the host rock, the source and volume of the silica saturated fluid needed; and the brecciation mechanism of the chert horizon. Based on the preliminary field studies the authors proposed that the Mahakut chert horizon was original of a carbonate lithotype but now silicified and brecciated. There were probably two inferred silicification phases – one pre-brecciation and at the early diagenetic stage and the other post-brecciation and at the late diagenetic stage. Seismic shocks are inferred to be responsible for the brecciation of the silicified host rocks formed during the early diagenetic silicification while the host soft sediments become silicified during the late diagenesis period. Future research may be directed towards these aspects which will have wide implications for understanding the formation of the largest and laterally most persistent (approximately kilometers of exposed length, continuous along the southern basin margin) replacive chert breccia horizon in India.

ARTICLE HISTORY

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INTRODUCTION

Pervasive silicification of carbonates, calcareous sandstone, volcanogenic rocks, and evaporites are a common feature in the Precambrian (Hanor and Duchac, 1990; Maliva *et al.*, 2005). The Precambrian cherts are of great importance because they preserve early life forms (Perry and Lefticariu, 2014) and record the geochemical signatures of the early ocean and paleo-climatic conditions. In India, the occurrence of brecciated chert horizons from the Precambrian platform sequences (from the Bijawar, Kaimur, and Semri Groups, Vindhyan basin; from the Bagalkot Group, Kaladgi basin, and from the Ajabgarh Group, Delhi basin) has long been reported by several workers (Blanford, 1869; Foote, 1876; Pascoe, 1959). These chert breccia horizons are usually associated with shallow shelf deposits, interbedded within the sediments of near-shore, tidal and subtidal environments (Radhakrishna, 1987; Singh, 1985, Kale and Phansalkar, 1991). Despite having been aware of these chert breccia horizons for a long time (e.g., Blanford, 1869; Foote, 1876), these horizons are yet to get the required scientific attention they deserve. The mode of origin, nature and source of the silicification fluid, diagnostic signatures, and brecciation mechanisms of these chert breccia horizons are still not well understood. Of these Precambrian chert breccia horizons, the Medhikhera chert breccia horizon is the thickest while the Mahakut chert breccia from the Kaladgi basin is geographically most widely distributed. The present study aims to examine Mahakut chert breccia to better understand the disposition of sediment-hosted chert breccia and the processes associated with its origin.

GEOLOGY OF THE STUDY AREA

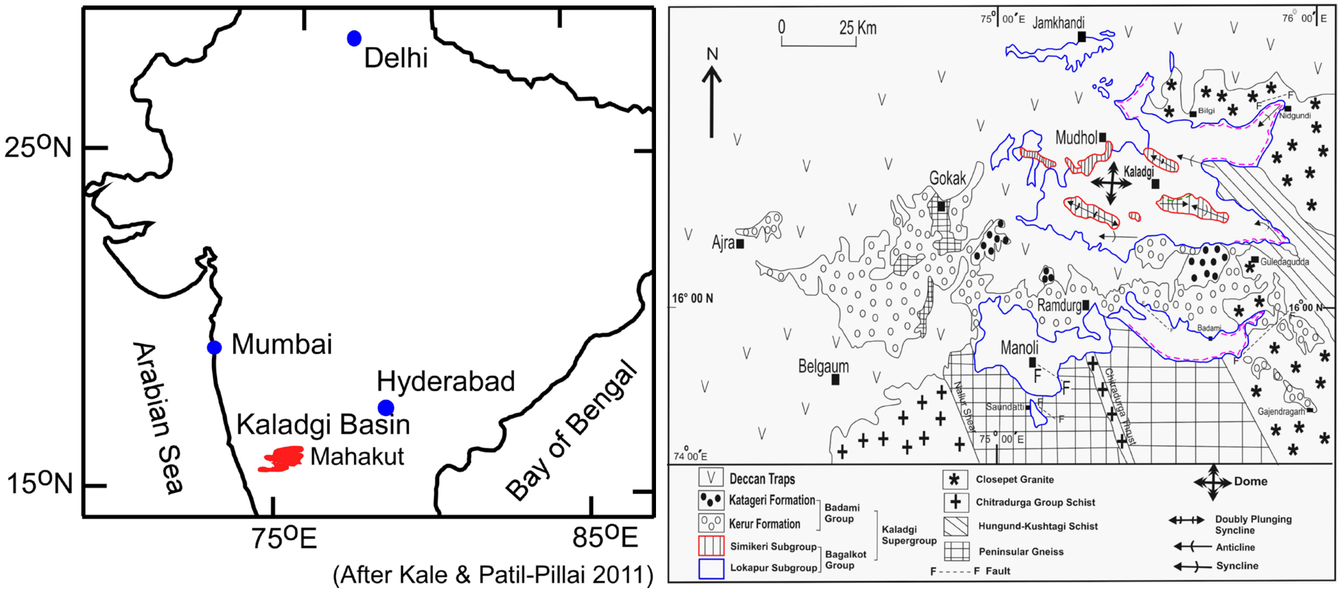
The Kaladgi basin, outcropped in the northern fringes of the Dharwar craton, covers an area of about 8,000 km^2

and has an irregular elliptical outline with a strike extent of ~200 km and maximum exposed width of ~100 km. A substantial part of the basin is concealed beneath the basaltic lava flows of the Deccan Traps in the north and the west (Fig. 1). Overlying the Archaean basement rocks, the sedimentary succession deposited in the basin has a maximum thickness of approximately 3,900 m (Dey, 2015). The sediments were deposited in an intertidal shallow marine depositional environment (Viswanathiah *et al.*, 1975; Chandrasekhara Gowda *et al.*, 1978). The sediment accumulation space of the basin was created by the tectonic subsidence and subsequent sea-level rise (Patil Pillai and Kale, 2018). The 3900 m thick sediment cover of the Kaladgi basin is divided into two groups: the older Mesoproterozoic deformed sedimentary succession of the Bagalkot Group and the overlying generally flat-lying Neoproterozoic Badami Group of sediments. The older Bagalkot Group and the younger Badami Group is separated by a distinct angular unconformity (Jayaprakash *et al.*, 1987; Joy *et al.*, 2019).

The Bagalkot Group is further subdivided into the Lokapur Subgroup and the Simikeri Subgroup (Table 1). The sediment package of the Lokapur Subgroup is dominated by arenite, shale, and carbonate rocks with subordinate conglomerates and a chert breccia horizon named Mahakut chert breccia. The Mahakut chert breccia horizon is continuous and well exposed along the southern margin of the Bagalkot Group and has a maximum exposed thickness of 150-200 m along the eastern fringe of the basin around the towns of Bagalkot and Badami. Kale and Patil Pillai (2011) reported that the fragments of the Mahakut chert breccia consist of one or more intrabasinal rocks that have undergone silicification. They interpreted that the chert horizons are transported debris, deposits of syntectonic material released during the episodic activity of the growth faults of the Kaladgi Basins that was later diagenetically silicified. Gravity gliding-induced deformation of the Mesoproterozoic cover sediments of the Kaladgi basin due to possible crustal flexure and subsequent tectonic uplift of the basement in the north (Mukherjee *et al.*, 2016) could be another possible cause of brecciation of the Mahakut Chert.

FIELD OBSERVATIONS AND PETROGRAPHY

Reconnaissance traverses were made and chert breccia samples were collected for thin section studies from several locations [for example GPS locations for some of the locations visited are (N15°55'52.5"; E75°43'14.8"); (N15°56'11.8"; E75°43'19.4"); (N15°56'14.3" E75°43'08.9"); (N15°52'28.9" E75°43'18.5"); (N16°14'48.8" E75°48'34.7"); (N16°14'55.6" E75°48'48.7"); (N16°04'00.2"; E75°55'27.0")]. The stratigraphic contact between the chert breccia horizon and the overlying and underlying argillaceous units is masked due to the massive poorly stratified and rubbly nature of the chert breccia horizon (Fig. 2.1). Preliminary field observations and hand specimen studies of the collected chert breccia samples in this study suggest that most of the collected silicified clasts were derived from carbonate protoliths (both stromatolitic and non – stromatolitic variety) that are completely replaced by silica, but in most examples preserve the morphological and textural details of the protolith (Fig. 2.2). This chert breccia bed is massive and in the absence of visible stratification, it becomes difficult to correctly identify the original orientation of this horizon, in the absence of bounding surfaces. The Mahakut chert breccia can be described as matrix-supported breccia with variable matrix to clast concentration and the angular to subangular framework clasts ranging between coarse sand to cobble size (size range 0.5 to 80 mm). But very large boulders (256 to 300 mm) are also locally present as outsized clasts. Field observation indicates that the Mahakut chert breccia horizon at places preserves the jigsaw fit of the clasts. Mostly, the clast, matrix, and cement are composed of



(After Kale & Patil-Pillai 2011)

Fig. 1. The Kaladgi basin, outcropped in the northern fringes of the Dharwar craton, covers an area of about 8,000 km^2. The Mahakut chert breccia horizon is represented by dashed pink line (after, Dey, S., 2015).

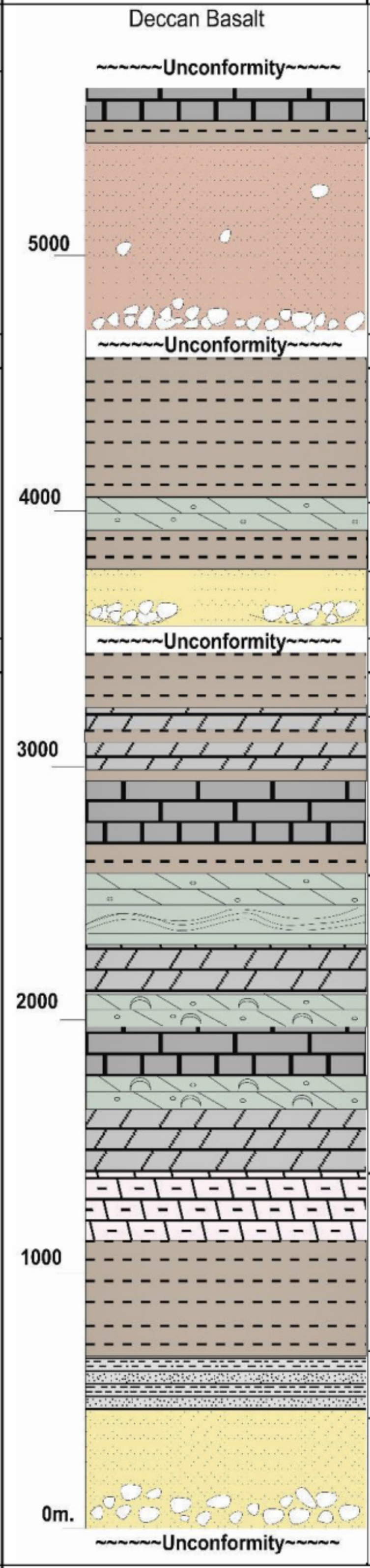
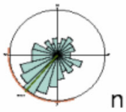
			Formation	**lithology**	**Depositional environment**
			~~~~~Unconformity~~~~~~		
Badami Group			Katageri Fm. (95m)	Quartz arenite, shale, limestone	Tidal shelf
			Kerur Fm. (695m) 	Conglomerate, red-brown sandstone, shale	Fluvial to tidal
			~~Unconformity~~~~~~		
Kaladgi Group	Simikeri Subgroup		Hoskatti Fm. (700m)	Slate, local dolerite dyke#	Pelagic shale
			Arlikatti Fm. (248m)	Slate, chert, dolomite	Tidal flat to minor fluvial
			Kundargi Fm. (197m)	Conglomerate, quartz arenite	Alluvial fan to tidal shelf
			~~Unconformity~~~~~~		
	Lokapur Subgroup		Yadhalli Fm (58m)	Shale/slate	Offshore muddy shelf
			Muddapur Fm. (566m)	Shale/slate, limestone, dolomite	Muddy tidal flat
			Yendigere Fm. (1142m)	Shale/slate, dolomite & dolomitic limestone	Muddy tidal flat
			Yargatti Fm. (720m)	Shale/slate, dolomite	Muddy tidal flat
			Malaprabha Fm. (194m)	shale, chert, chert breccia	Nearshore, tidal, sub-tidal shelf
			Ramdurg Fm (414m) 	Basal conglomerate, feldspathic- to quartz arenite	Fan-delta to shallow shelf
		Dharwar schist, Hungund schist , Closepet granite			

Table 1. Litholog, stratigraphy, depositional environment and palaeocurrent patterns of the Kaladgi Basin (from Joy *et al.,* 2018).

Fig. 2.1. The massive, poorly stratified and rubbly outcrop photograph of Mahakut chert breccia horizon (N16°14'35.3" E75°48'28.4"; near kadlimatti railway station).

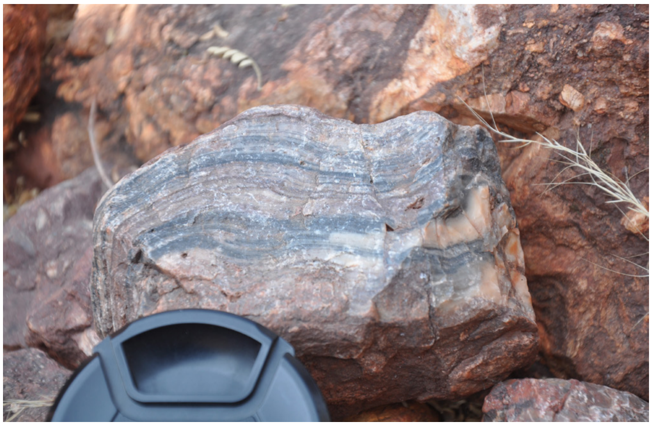


Fig. 2.2. Completely silicified stromatolitic rock fragment.

Fig. 2.3. Matrix-supported, variable matrix to clast concentration and angular to subangular framework clasts.

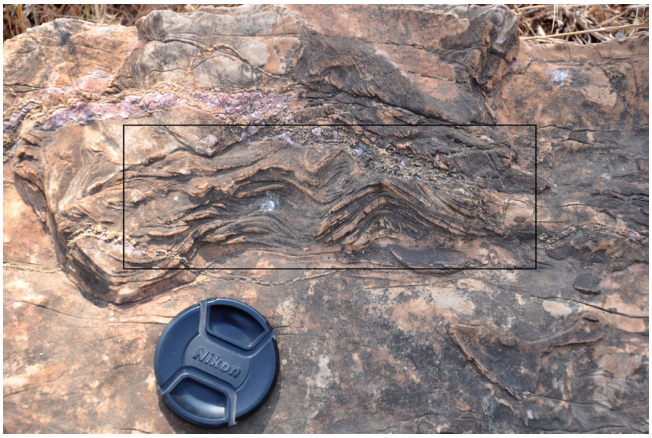


Fig. 2.4. Tepee structure in the Mahakut chert breccia horizon.

similar protolith material which leads us to rethink the origin of the clasts to be autoclastic in nature with minimal transport also supported by the retention of the angularity of the clasts (Fig. 2.3). The field study also suggests the presence of tepee structures, completely silicified but beautifully preserving the primary sedimentary structure (Fig. 2.4). Under crossed polarized light, the chert displays a composition of very fine-grained, microcrystalline quartz of replacement origin. Both, the matrix and the intergranular spaces are observed to be entirely constituted of the same material, i.e. silica. This very fine-grained, microcrystalline quartz replaced the carbonate, both clasts, and matrix, leaving no traces of the precursor rock composition. However, they also preserve several kinds of microbial mat structures with low synoptic relief, and ooids, giving clue to their origin (Figs. 2.2; 3.1, 3.2, 3.3, 3.4). The development of quartz occupying the interstitial voids is not part of the replacement process but is formed later by void filling (Fig. 3.6). The quartz grains show patchy to undulate extinction, equigranular texture, with relatively straight grain boundaries forming triple junctions (~120°) (Fig. 3.2). The shape of quartz grain aggregates varies between inequigranular polygonal to inequigranular interlobate with no preferred orientation of grain shapes. Silicification of the carbonate host rock preserved the stromatolitic laminations and the oolitic structure of the parent clasts (Figs. 3.1, 3.3). The oolites are replaced by microcrystalline quartz completely obliterating the internal radial and radial–concentric fabrics but still preserving the spheroidal shape and volume of the ooids, and in rare cases one or two outer concentric shells (Figs. 3.3, 3.4). Microscopic observations do not show any radial fractures or compression of the spheroidal shape (Fig. 3.4). Banerjee *et al.* (2021) showed that silicification of limestone is favorable than that of dolostone. Hence, the silicified stromatolitic and oolitic parent carbonate rocks probably have limestone protolith. The sparry carbonate matrix surrounding the oolites is also silicified, through replacement by relatively coarse-grained quartz (Fig. 3.5). Frequently opaque oxides (mainly reddish-brown limonite type) are encountered along with the intergranular spaces and in the framework clasts, which probably represent a late precipitate phase during diagenesis. These opaque oxides are at places found along the relict bedding planes. Pseudomorphs of quartz for the rhombic carbonates, another reliable criterion of replacement, are also identified in petrographic studies. The field and petrographic evidence suggest that the silicification of the parent rocks of the Mahakut chert breccia is a volume retentive replacement phenomenon that pervasively replaced the host rock but kept the original textures and grain pseudomorphs with clear boundaries.

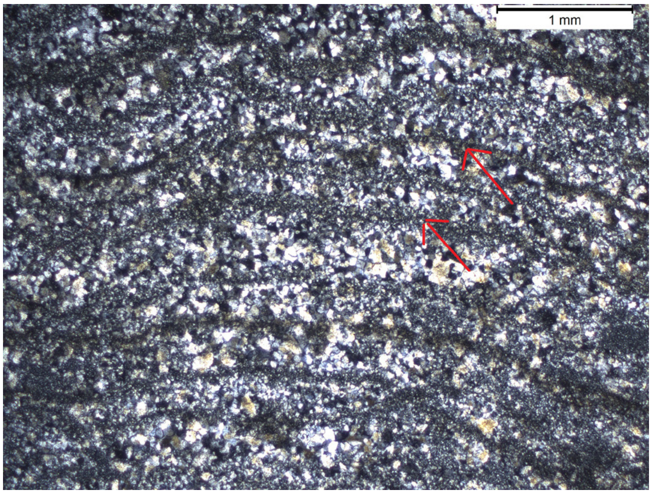


Fig. 3.1. Photomicrograph of the silicified and completely replaced stromatolitic protolith. The red arrows in Figure 3.1 marks the individual microbial lamina still preserved.

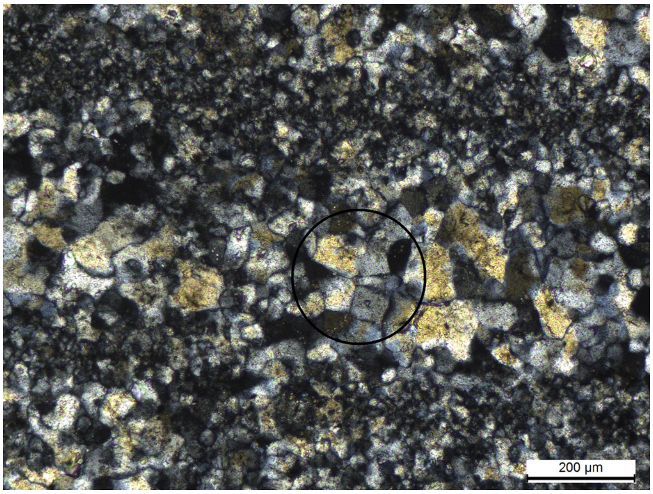


Fig. 3.2. Photomicrograph shows the rhombic ghost of carbonate crystals now completely replaced by silica (inside the circle). Equigranular quartz grains with straight grain boundaries forming triple junctions (~120^{o}) and show undulose extinction are common.

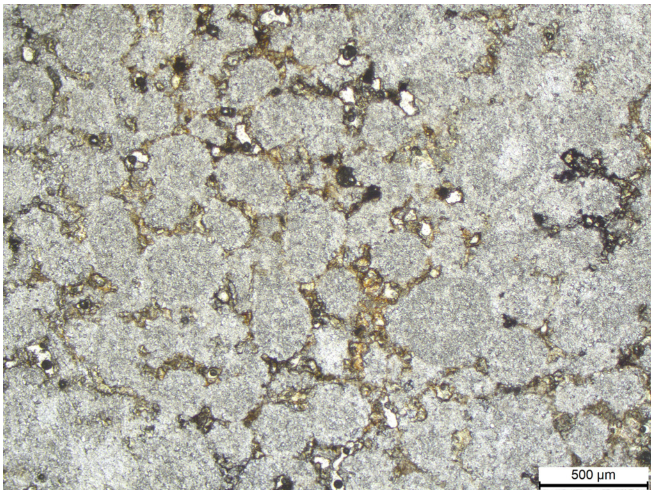


Fig. 3.3. Silicified oolite still preserving the spherical shape but oobliterating the internal radial and radial–concentric fabrics.

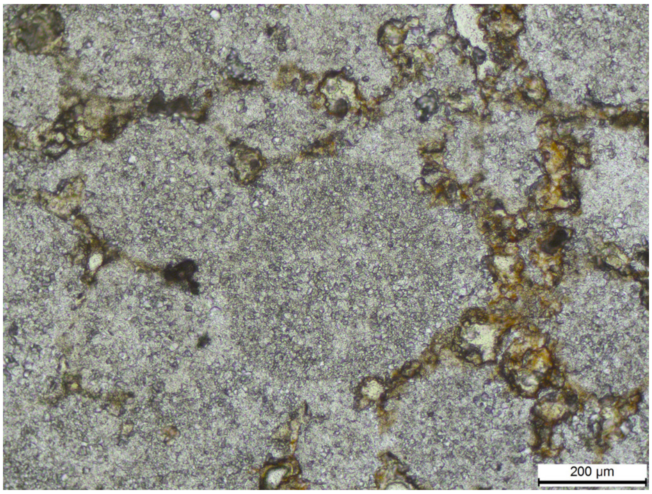


Fig. 3.4. Absence of radial fractures within or the compression of the spheroidal shape of the silicified oolite is noted.

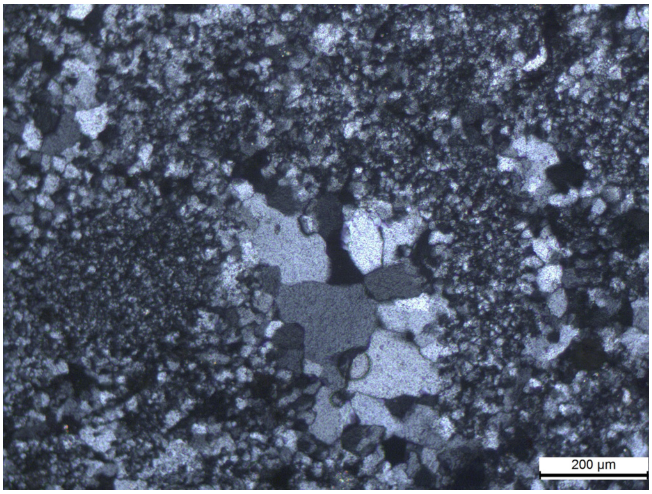


Fig. 3.5. Silicified sparry carbonate matrix surrounding the oolites and replaced by relatively coarse-grained quartz.

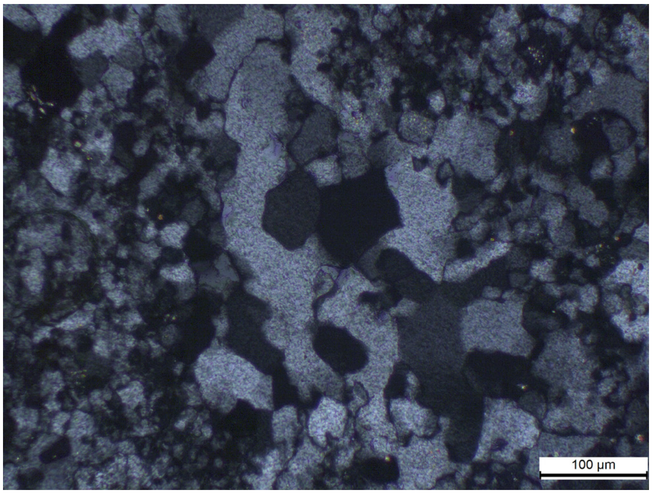


Fig. 3.6. Development of quartz occupying the interstitial voids and not part of the replacement.

DEPOSITIONAL ENVIRONMENT

The conglomerate and quartzite members of the lowermost Formation of the Lokapur Subgroup suggest mass flow deposit and channel aggradation capped by wave-influenced sandstone (upper part of the Saundatti Quartzite) and represented near-shore and shoreline (beach, offshore sand bar, and prograding delta) depositional environment. The fining-upward sequence consisting of shale and carbonate rocks (of the Malaprabha and Yargatti Formations) is considered to be deposited in a transgressive systems tract that changes from fluvial to marine/lacustrine depositional environment (Bose *et al.*, 2008). The presence of silicified stromatolite fragments in the Mahakut chert horizon suggests a shallow shelf deposit, within the photic zone. The stromatolites are mostly laminites indicating that the water depth was minimal. Rarely small humps are noted in a single clast (Fig. 2.2), which represents part of cumulate type biostoromes. The synoptic relief is very low which further indicates shallow water depth. The stromatolites of the inner ramp unit thrived in shallow-water settings as evidenced by the growth of laminites. Tepee structures also indicate shallow water depth, with intermittent exposure. The proliferation of shallow-water wave-resistant stromatolites also provides favorable conditions for ooid formation. Ooids form in the very specific depositional environment i.e., shallow sea with high salinity and tropical climate conducive to evaporation, and are also suggestive of highly agitated marine water that is commonly associated with zones of high tidal activity in a subtidal or lower intertidal environment. The underlying Manoli argillites and the silicified and brecciated carbonates of the Malaprabha Formation indicate tidal flat depositional environment (reefs, mudflats and carbonate ramps). Kale *et al.* (1996) proposed that the water depth was less than 10 meters during the time of sediment deposition. Joy *et al.* (2019) proposed the maximum depositional age of the basal conglomerate of the Ramdurg Formation as 2,287 Ma and obtained the age of 1861±4 Ma from the dolerite dykes that intruded the Yendigere Formation. These two reported ages (2287 Ma and 1861 Ma) bracketed the time of the brecciation and silicification.

SILICIFICATION MECHANISM

Silicification is explained by the bulk dissolution of host carbonate and precipitation of silica in the resulting transient void space, the two events separated by an infinitesimally brief time interval (Knauth, 1979; Schmitt and Boyd, 1981; Hesse, 1989). The major flaw of the proposed mechanism is that the two reactions i.e., carbonate dissolution and silica precipitation – separated by an infinitesimally brief time interval – are neither physically nor chemically coupled and hence are unable to impose the necessary condition for replacement i.e., the convergence of the two rates of reactions in space and time (Bastin *et al.*, 1931; Maliva and Siever, 1988, 1989; Nahon and Merino, 1997). Sathyanarayan and Muller (1980) suggested that a growing quartz crystal has a higher thermodynamic "force of crystallization" than limestone or dolomite, leading to quartz replacement of carbonate. Maliva and Siever (1989) proposed that the two reaction rates – i.e., carbonate dissolution and silica precipitation – are coupled by the crystallization stress exerted by silica growth (Maliva and Siever, 1989; Bustillo, 2010) automatically equalizes the rate of guest mineral growth and host mineral dissolution and also enforce that the rate of two reactions must go hand – in – hand at the same time and the same place.

Conventionally balanced chemical reactions cannot provide a valid description of constant-volume replacement (Lindgren, 1912; 1918). Since replacement reactions preserve solid volume, chemical reactions should be balanced on volume (Merino and Dewers, 1998) and volume-adjusted mass balance calculations for silicification of carbonates (limestone and dolostone) are stated below

$$CaCO_{3(c)} + 1.45\ H_4SiO_{4(aq)} = 1.45\ SiO_2\downarrow + Ca^{2+} + 2.9\ H_2O + CO_3^{2-}, \qquad (1)$$

and

$$CaMg(CO_3)_2 + 2.83\ H_4SiO_{4(aq)} = 2.83\ SiO_2\downarrow + Mg^{2+} + Ca^{2+} + 5.66\ H_2O + CO_3^{2-}. \qquad (2)$$

The multiplying factor 1.45 (i.e., the molar volume of calcite is 1.45 times greater than that of silica) and 2.83 (i.e., the molar volume of dolomite is 2.83 times greater than that of silica) in equations (1) and (2) respectively ensures conservation of solid volume during silicification.

Fletcher and Merino (2001), proposed that for guest mineral *G* (here silica) replacing the host *H* (here carbonate minerals) the rate of replacement (R_r) and the crystallization stress σ (in MPa) can be expressed as

$$R_r = k_G RT \left[\frac{k_H V_0^H}{k_H V_0^H + k_G V_0^G} \right] \ln \Omega_G \text{, and} \qquad (3)$$

$$\sigma = \frac{k_G RT \ln \Omega_G}{k_G V_0^G + k_H V_0^H} \qquad (4)$$

Where R_r in cm/s, k_G and k_H are the rate constants of guest formation and host dissolution respectively in s/cm, Ω_G is the saturation state of guest, V_0^G and V_0^H are the specific volumes (cm^3/gm) of guest and host minerals. R is the universal gas constant and T is the absolute temperature. This constant volume replacive silicification process can be mathematically described by a set of continuity equations that are scaled and solved numerically.

FACTORS INFLUENCING SILICIFICATION

The limiting factor for silicification is the availability of silica and silica saturation. It is also generally accepted that the fluctuations in pH are a major controlling factor of silica precipitation (Walker, 1960; Siever, 1962; Bustillo, 2010). While the increase in pH (>9) favors SiO_2 solubility and precipitation of carbonate, a decrease in solution pH favors the dissolution of carbonates and precipitation of silica. Interstitial waters saturated with carbonate and silica at a particular pH would tend to precipitate carbonate minerals and dissolve more silica upon encountering the geochemical environment of higher pH (> 9). On the other hand, if saturated interstitial waters migrate into the geochemical environment of lower pH (elevated P_{CO2}), the replacement relationships would be reversed, and silica replacement of carbonates would occur. Other parameters that can influence silicification process are temperature, host rock porosity and permeability, the surface area of the reactant grains, and diffusivity of silica through porous media. Banerjee *et al.* (2021) proposed an abiotic silicification model for carbonate rocks and predicts that the driving forces for silicification were the composition of the host rock, degree of silica supersaturation, temperature, the grain size of the host rock, porosity, and permeability. Though salinity and its effect on inorganic silicification have yet to be reported it has been studied that fluid salinity neither affects the growth nor interferes with the biosilicification of organisms like diatoms (Vrieling *et al.*, 2007).

UNSOLVED ISSUES

The volume of silica saturated fluid needed

Thiry *et al.* (1988) calculated that to form a quartzite lens of volume 60000 m^3 it would need approximately 6 10^9 m^3 of groundwater which converts to 10^5 m^3 of fluid required per m^3 of rock. Hanor and Duchac (1990) also suggested that 10^5 m^3 of fluid is needed for every m^3 of rock for silicification of Early Archean komatiites. Pervasive silicification of the brecciated rocks of the basin must have required the introduction of large volumes of silica saturated fluid over extended periods. Assuming that the Kaladgi basin resembles the geometry of an ellipse and its long axis is 200 km and the short axis is 100 km then the periphery of the basin will be

$$P = 2\pi\sqrt{\frac{1}{2}\left(a^2 + b^2\right)} \qquad (5)$$

Putting a = 100 km and b = 50 km, P comes out as 544.3 km. Assuming the Mahakut chert breccia is continuous along the periphery of the basin with a constant thickness of 100 meters and width of 500 meters the volume of the silica needed to form the chert breccia horizon will be 544358.8 m · 100 m · 500 m = 2.72 · 10^{10} m^3. This estimate will vary if we consider the pre lithification thickness. Following Thiry *et al.* (1988) to silicify a volume of 2.72.10^{10} m^3 approximately 2.72.10^{15} m^3 volume of groundwater will be needed. We can compare the required volume of water for silicification with that of the total water present on our planet. According to USGS estimate, the largest sphere represents all of Earth's water has a diameter of about 860 miles, and has a volume of about 332,500,000 cubic miles (mi^3) or 1.39.10^9 km^3 or 1.39·10^{18} m^3. This sphere includes all of the water in the oceans, ice caps, lakes, rivers, groundwater, atmospheric water, and even the water present in the living world (https://www.usgs.gov/media/images/all-earths-water-a-single-sphere). In the absence of any extensive igneous activity in the basin, the source of voluminous fluid required for this basin-wide extensive replacement process remains enigmatic.

Sources of silica

Sources of the silica needed for silicification are debatable and have a wide range from the Proterozoic seawater (Holland, 1984) at one end to the interaction between pore fluids and charged marine/groundwaters (Knoll, 1985; Pollack, 1987; McBride, 1988) at the other end. Bustillo (2010) reported that the silica required for the silicification process might have variable sources that include (a) siliceous components within the host rocks, (b) phreatic or hydrothermal fluid, (c) dissolution of the siliceous microfossils during diagenesis, or (d) silica released during opal A → opal CT → quartz diagenetic transition. In the absence of any significant silica secreting biota (Perry and Lefticariu, 2014) the source of silica in the Proterozoic (>700Ma) is thought to be abiotic (Maliva *et al.*, 2005; Hanor and Duchac, 1990; Maliva *et al.*, 2005; Perry and Lefticariu, 2014).

The close association of the chert breccia and dolomite (Mahakut chert and Chitrabhanukot dolomite and Niralkeri chert and Lakshanhatti dolomite) leads to the hypothesis that dolomitization and silicification are probably contemporary and that the fluid responsible for dolomitization of parent limestone probably is also the same fluid responsible for the silicification of the brecciated rock fragments (Chilingar, *et al.*, 1979; Wanless, 1979; Tucker, 1988). But Sathyanarayan *et al.* (1987) based on low Sr and Na content and pronounced $\delta^{18}O$ deficiency, proposed diagenetic reconstitution of the precursor limestone to dolomite with a large-scale involvement of meteoric waters of low ionic strength. The $\delta^{18}O$ and $\delta^{13}C$ isotope studies of the carbonates from various horizons of the Bagalkot Group are consistent with an interpretation of the sequence as a 'normal' marine carbonate facies as previously inferred from geological and sedimentological evidence (Sathyanarayan *et al.*, 1987). As put by Srinivasan *et al.* (1997) the relation of rare earth elements systematic in ancient cherts with their depositional environment in India is still not adequately studied. To understand the plumbing mechanism(s) and fluid source for the chert and dolomite horizons and the redox conditions of the Paleoproterozoic to Mesoproterozoic shallow-water Kaladgi basin of India synthesis of the data generated by sedimentological and geochemical studies is warranted. The chert breccia is known to be overlain by the dolomite units (e.g., Chitrabhanukot dolomite over Mahakut chert and, and Lakshanhatti dolomite over Niralkeri chert). Elsewhere, paired occurrences of the chert breccia and dolomite units have been explained by the hypothesis that the dolomitization and silicification of parent limestone are linked processes mediated by the same fluid source (Chilingar *et al.*, 1979; Wanless, 1979; Tucker, 1988, p. 148-145, Kale and Patil Pillai, 2011). To test this hypothesis geochemical fingerprinting of the rocks is needed to be carried out, and the silicification and dolomitization processes should be arranged in order of precedence which is lacking and may constitute material for further studies.

As put by Srinivasan *et al.* (1997) the relation of rare earth elements systematic in ancient cherts with their depositional environment in India is still not adequately studied. To understand the plumbing mechanism(s) and fluid source for the chert and dolomite horizons and the redox conditions of the Paleoproterozoic to Mesoproterozoic shallow-water Kaladgi basin of India synthesis of the data generated by

sedimentological and geochemical studies is warranted.

Migration of the dissolved silica through porous and permeable sediments from its source and the silicification process depends upon variable factors such as the nature of the carbonate rock, pH, temperature, saturation index of the fluid concerning dissolved silica, porosity, advective flow, and surface area. There is no limit to the maximum distance that silica can migrate, but much of the silica does not migrate far before it is precipitated (Walker, 1960). Some silica may be reprecipitated within a microscopic distance from its source, as suggested by the common occurrence of authigenic silica, and replaced with silicate grains in the same thin section.

Rate and timing of silicification

The estimates of Thiry and Ribet (1999) for the silicification rate of limestone yield the range from 5cm/Ma to 0.05 cm/Ma. It is worth mentioning here that McBride (1988) also suggested a few million years for silicification of the carbonate pebbles by groundwater. The model results of the replacement rate of silica for calcitic limestone as estimated by Banerjee *et al.* (2021) ranges from 72.2 cm/Ma to 0.11 cm/Ma.

Kale and Patil Pillai (2011) proposed that silicification is a superimposed character, post-dating the accumulation of the debris but predating the deformation of the Bagalkot Group. They argue that brecciation happened before silicification in response to an early large-scale slumping event. Brecciation not only increases the secondary porosity allowing fluid percolation but also increases the reactive surface area by fragmenting the protolith. Some of the breccia fragments could be sufficiently large to contain the biotic/fossils, that get silicified later. It can also be argued that regional-scale silicification of the host rock can occur soon after its deposition and before brecciation. Silicification is aided by the primary porosity and permeability of the host before its lithification and brecciation at an early stage. Pre-compactional silicification mostly occurs close to the sediment-water interface and in the early diagenetic setting. Silicification on a regional scale during mesogenesis is less common than in surface environments, and data for continental carbonates in this setting are practically non-existent (Bustillo, 2010). Replacement can also occur after lithification of the host rocks but happens mostly along the secondary flow paths such as fractures and solution openings enhancing the permeability and cannot be all-encompassing as is evident from the regional scale silicification of the Mahakut chert breccia horizon. The Mahakut chert breccia is also not silcretes or siliceous duricrusts (Summerfield, 1983) and hence their formation by meteoric diagenesis at or near the surface is ruled out.

Brecciation mechanism

The close association of chert and brecciated structure indicates that the silicified host rocks become sufficiently brittle early in their diagenetic history (Kolodney *et al.*, 2005; Kolodny, 1969; Sander, 1970). Fragmentation of the early diagenetic silicified host rocks can happen due to desiccation/syneresis crack, high pore-fluid pressure (Harper and Tartarotti, 1996), dissolution-collapse (Matton *et al.*, 2005), storm-wave action on the seabed (Bouchette *et al.*, 2001) or seismic activity (Rodríguez-Pascua *et al.*, 2000). Other mechanisms that can trigger fragmentation and re-mobilization are earthquakes and over-steepening of slopes due to tectonic activities (Bouchette *et al.*, 2001). The sedimentary and tectonic process (es) responsible for the brecciation of the parent rocks that form the Mahakut chert breccia horizon is yet to be understood. Brecciation by dissolution – collapse process is not a viable mechanism for the formation of Mahakut chert breccia horizon due to the presence of Manoli Argillite underlying the breccia horizon. Dey (2015) suggested that the Kaladgi basin does not support the foreland basin model and the reactivation of the growth fault and subsequent debris transport cannot explain the Mahakut chert formation (Kale and Patil Pillai, 2011). Mukherjee *et al.* (2016) proposed that the detachment of the Proterozoic sediment cover, its gravity gliding, and subsequent deformation happened between 1.0 to 0.8 Ga during Grenvillian Orogeny. Fairbridge (1978) defined chert breccia as autoclastic breccia such that both the rock fragments and matrix consist of microcrystalline quartz. Autoclastic breccia generally results from in situ deformation or reworking processes, such as dehydration or karstification (Bouchette *et al.*, 2001) or as a result of seismicity and earthquake loading (Ringrose, 1989; Zanchi, 1992). Patil-Pillai and Kale (2011) have reported syn-sedimentary deformation (SSD) structures, produced due to multiple seismic events, from the Saundatti quartzite and Manoli argillite that underlies the Mahakut chert breccia horizon. These authors also reported SSD structures from the Chikkashellikere Limestone member which is stratigraphically younger than the Mahakut chert breccia horizon. The brittle SSD structures in the Kaladgi Basin are often attributed to the hardening of the sediment during early diagenesis by cementation (Patil-Pillai and Kale, 2011). An earthquake magnitude of about 5.5 to 6 is the lower limit at which liquefaction effects become relatively common (Rodríguez-Pascua *et al.*, 2000). Seismic activity is likely responsible for the in-situ fracturing and brecciation of the brittle silicified host rocks formed during the early diagenesis within the surrounding soft sediments. The host soft sediments become silicified during the late diagenesis, providing availability and remobilizing of enough silica. The resulting rock becomes a chert breccia, where both the fragments and cement consist of a siliceous phase (Kolodney *et al.*, 2005). The hypothesis can be represented by a line diagrammatic sequence of events: Mahakut chert initially deposited as carbonate → silicification (first phase during early diagenesis) → Brecciation → Silicification (second phase during late diagenesis).

Initial fracturing probably happens early by sub-aerial exposure and subsequent desiccation and crack formation as supported by the presence of teepee structures and laminites which form in very shallow water (Figure 2b, d), may be of few centimeters of water depth. A few things have to be kept in mind while considering the earthquake-induced in-situ brecciation mechanism. The earthquake loading periods are usually less than 1s and the duration never exceeds a few minutes (Bouchette *et al.*, 2001). Also, high magnitude earthquakes are not frequent, and for brecciation purposes earthquake of magnitude greater than 6 is needed (Obermeier, 1996; Bouchette *et al.*, 2001). On the other hand, the waveinduced in-situ brecciation process restricted within the water depth of less than 200 m (Bouchette *et al.*, 2001) may also have been responsible for the formation of the Mahakut chert breccia horizon.

CONCLUSIONS

Chert breccia — an autoclastic sedimentary breccia in which both the lithic clasts and matrix are composed of microcrystalline quartz — gives us significant information on the geochemical environment, and nature of the fluid source, and the relative timing of the silicification of the host rocks during diagenesis. The Proterozoic basins of India host several chert breccia horizons, of which the Mahakut chert breccia of the Kaladgi Basin is the largest known and laterally most persistent chert breccia horizon in India. This chert breccia horizon does not get the required attention it deserves and despite having been aware of the chert breccia horizon for a long time the brecciation processes, its diagnostic signatures, and mode of origin are still not well understood. Inadequate data exist on the rate and timing of silicification, source and volume of silica saturated fluid needed, and the brecciation mechanism of the chert horizon. A detailed study is needed on the hydrological aspect of the silicification of the Mahakut breccia horizon. Examination of the oxygen isotopes of the cherts may help to clarify the Proterozoic Ocean/sea surface and/or diagenetic temperature of formation. Similarly, other geochemical footprints are also capable of elucidating the source of silica reservoir and interpreting environmental conditions by studying the major and trace elements including immobile REEs, Y, Zr, Hf, Th, Sc and Al or and other isotopic (^{87}Sr/^{86}Sr; δD, δ^{11}B) components during silicification due to the resistance of quartz to weathering and diagenesis. Preliminary field observations and thin section studies suggest that seismic activity probably is responsible for the in-situ fracturing and brecciation of the silicified host rocks. The presence of silicified stromatolite fragments with low synoptic relief in the Mahakut chert horizon, tepee structures, and the presence of ooids suggests shallow shelf deposit, within a photic zone with a tropical climate conducive to evaporation and are also suggestive of highly agitated marine water that is commonly associated with zones of high tidal activity in a subtidal or lower intertidal environment. The brecciation process, its diagnostic signature, and the mode of origin of the Mahakut chert breccia horizon can be compared and contrasted with the chert-bearing horizons from the Proterozoic intracratonic basins of India (Kaladgi, Vindhyan, and Delhi basins) that has long been due.

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