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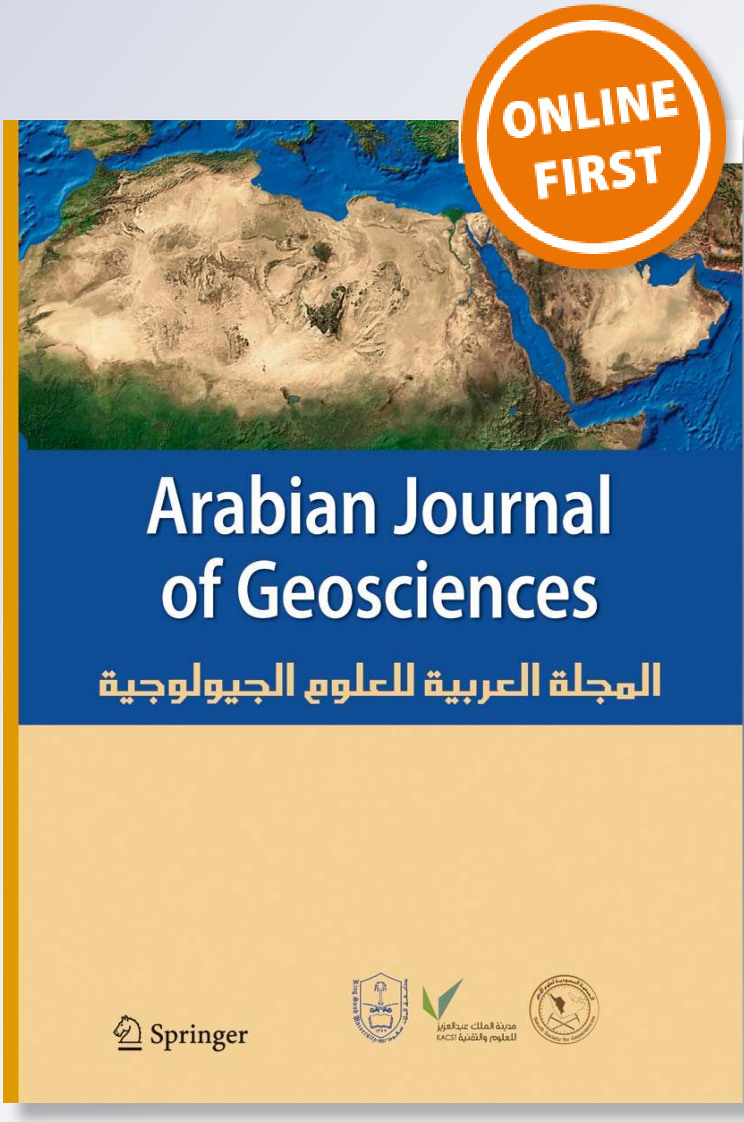

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ORIGINAL PAPER

Lithofacies architecture and depositional environment of Late Cretaceous Lameta Formation, central India

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Abstract Establishment of lithofacies and interpretation of depositional environment of the Lameta Formation have been carried out for a new area having three nearby exposures. Overall, the successions are broadly differentiable into three major units, i.e. arenaceous in the lower part, argillaceous in middle and calcareous at the top, which more or less serve as three lithofacies associations. Each association consists of various lithofacies which are identified and established on the basis of field observations, added with significant petrological details. The arenaceous association includes five lithofacies, viz. massive sandstone lithofacies; green sandstone lithofacies; thinly bedded, yellowish orange and greyish brown sandstone lithofacies; coarse-grained sandstone lithofacies and dark brown bioturbated sandstone lithofacies. The argillaceous lithofacies association consists of yellowish-brownish-greenish clay–siltstone lithofacies and light grey silty–clay with concretions lithofacies, whereas the calcareous lithofacies association is represented by calcrete lithofacies, nodular limestone lithofacies, chertified limestone lithofacies and intraformational breccia lithofacies. The facies analysis reveals that the deposition of Late Cretaceous Lameta sediments took place in fluvial–lacustrine environments in semi arid condition.

Keywords Late Cretaceous · Lameta · Lithofacies · Fluvial–lacustrine environments · Central India

A. K. Srivastava (✉) · R. S. Mankar
P. G. Department of Geology, SGB Amravati University, Amravati 444602, India
e-mail: ashokamt2000@hotmail.com

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Introduction

The Lameta Formation of Late Cretaceous age covers about 5,000 km^2 area in the central and western parts of India, distributed largely at Jabalpur, Madhya Pradesh; Nagpur and Chandrapur districts of Maharashtra and Anjar and Kheda districts of Gujarat. This stratigraphic unit is under investigation from long back for the reconstructions of depositional environment and palaeobiological condition including dinosaurian remains. These two aspects of the type area succession exposed at Jabalpur remain to be a matter of debate from last five decades, i.e. marine or non-marine environment of deposition and their geographical extent, which still continues. The shallow marine environment has been suggested on the basis of petrology, algal structures, glauconitic beds and lithological architecture (Chanda 1963a, b, 1965, 1967; Singh 1981; Singh and Srivastava 1981; Chanda and Bhattacharya 1966), and lithological architecture and extensive crab burrows including *Thalassinoides* (Kumar and Tandon 1977, 1978, 1979). Recently, Shukla and Srivastava (2008) and Saha et al. (2010) suggested coastal complex setting which is mainly based on the occurrences of lizard eggs and trace fossils. The second school of thoughts advocating fluvial environment of deposition is based on fossil biota and lithological characteristics, i.e. non-marine flora and fauna including dinosaurian remains (Pascoe 1964; Mately 1921; Mohabey 1996; D'Emic et al. 2009); green sandstone from Jabalpur area (Tandon et al. 1990); lithological setting showing alluvial plain environment under hot and semi-arid conditions, Jabalpur area (Brookfield and Sahni 1987); fluvial and pedogenically modified semi-arid fan palustrine flat system, Nand-Dongargaon area of Nagpur (Tandon et al. 1990); alluvial limic setting (Joshi and Ganapathi 1990; Mohabey et al. 1993) and lacustrine set-up, Nand-Dongargaon area, Nagpur (Singh and Tandon 2004; Mohabey and Samant 2005). Calcretes from the Jabalpur area are also considered to be formed in sub-aerially exposed area of low gradient alkaline flat alluvial setting (Tandon et al. 1995, 1998; Tandon and Andrews 2001).

Dinosaurian remains from these sediments of various areas are also an aspect of extensive study from long back (Hislop 1859): dinosaur eggs and nests (Mohabey 1983), eggs and skeletal remains (Tandon et al. 1995; Mohabey 2001; D'Emic et al. 2009; Carrano et al. 2010) and coprolites (Ghosh et al. 2003), and still a matter of high interest for palaeobiologists. These skeletal remains have also been interpreted for the reconstructions of palaeoclimatological and palaeoenvironmental conditions which favour semi-arid climate and fluvial–lacustrine environments of deposition (Mohabey 1987, 1990, 1991, 1996, 1998a, b, 2000).

It is now evident that the Lameta Formation has a special significance in Indian stratigraphy that also bears an impact on global level. However, there are certain patches which are still unexplored even for their basic sedimentological details. One such belt lies in the northern part of Maharashtra, falling at the boundary of district Amravati, Maharashtra and Betul, Madhya Pradesh having small, isolated outcrops exposed tectonically in Deccan Trap plateau. Three such comparatively large patches lie at Bairam (lat. 21°22′25″ N, long. 77°37′23″ E), Belkher (lat. 21°21′48″ N, long.77°31′23″ E) and Salbardi (lat. 21°25′15″ N, long.78°00′00″ E) localities have been considered for the present study (Fig. 1). The prime object of the work is to establish the lithofacies architecture in the sediment columns followed by reconstruction of palaeoenvironmental condition during their deposition. The data collected is also significant in palaeogeographic reconstruction during Late Cretaceous as the present locations lie far away from those reported earlier.

Geology and stratigraphy of study area

The Archaean Gneiss, Upper Gondwana, Lameta and Deccan Trap form the regional stratigraphic set-up. The basement consists of quartz–feldspathic gneiss of Archaean age, over which the Gondwana sediments rest with an unconformable boundary. Lameta succession disconformably overlies the Gondwana and overlain the Deccan Trap with unconformable boundary. The basalt of Deccan Trap is vastly exposed, covering most of western India including large sector of Maharashtra and partially Madhya Pradesh and Gujarat. Intertrappeans are the small, isolated sedimentary units that occur at different stratigraphic levels in the basaltic trap. Alluvium and soil make the topmost horizons (Table 1).

Gondwana sediments along with the Lameta are exposed in the country of basalt due to the tectonic activity of Satpura Fault and occur as isolated, small patches in a linear fashion along the same. The previous at Bairam and Belkher localities yield rich and diversified gymnosperm and pteridophytic megafloral remains assigning Upper Jurassic to Early Cretaceous age (Srivastava et al. 1999). The same age has also been assigned to the Gondwana sediments of Salbardi, which is based on their lithological similarities with the previous two localities (Srivastava and Mankar 2008). The overlying Lameta successions, at all the three locations, are mainly represented by arenaceous–argillaceous–calcareous sediments.

Details of the Lameta succession

Locality 1: Bairam area

The succession at this locality is ca. 39 m thick, represented by almost equally thick lithounits of clay–marl, sandstone and limestone (Fig. 2). The lower 12 m column is brownish-greenish-yellowish clayey beds, of which the lower 2 m is reddish brown and massive to faintly laminated. The overlying 4 m succession consists of greyish green clayey unit with thin interbeddings of greenish grey, hard and compact siliceous limestone, which is succeeded by 2-m thick, dark yellowish orange clay. The overlying 4 m succession shows alternations of greyish green and reddish brown clayey beds.

The overlying arenaceous succession contributing middle 13 m column consists of arenaceous beds of different nature along with abundant concretions. The lower 2 m is greyish brown, friable, medium to coarse-grained sandstone bed, which overlain 9 m thick, light grey to greyish black, clayey sediments having discontinuous thin siliceous limestones with irregular concretions. The size of the concretions varies from 2 to 14 cm having infillings of clay, similar to the host rock. The above 2-m unit is dark brown, hard and compact, medium to coarse-grained sandstone with bioturbation.

The upper 14 m is nodular and chertified limestones, of which the lower 8 m is bluish grey nodular limestone with angular clasts of chert ranging in size from 0.5 to 2 cm. The percentage of clasts shows an increasing upward trend. Successive 3 m lithounit is the alternations of bluish grey nodular limestone and chertified limestone. The topmost 3 m rock is light grey to greyish white, hard and compact, highly chertified limestone and occasionally shows faint tendency of flat bedding.

Locality 2: Belkher area

The succession is comparatively well developed attaining a thickness of about 47 m, however, similar to the previous locality (Fig. 3). The lower 21-m column consists dominantly of various coloured clays intercalated with minor sandstone beds. The basement consists of yellowish orange, parallel bedded, medium- to coarse-grained sandstone of 1 m thickness which overlain equally thick, yellowish orange clay.

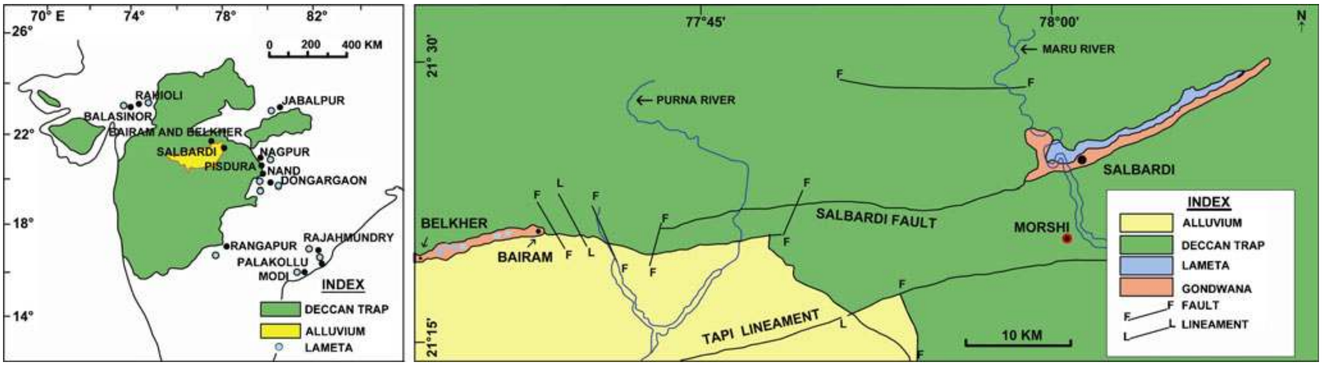

Fig. 1 Geological map of the area showing locations and extents of Lameta sediments exposed at Bairam, Belkher and Salbardi areas; *inset* shows the distribution of Lameta sediments in the vast Deccan Trap country in India

Vertically up 9 m succession is again alternations of thinly bedded, yellowish orange and greyish brown sandstones, followed by 2-m thick column of reddish brown clay having faint laminations. It is overlain by 2-m thick, thinly bedded, yellowish orange, medium- to fine-grained, hard and compact, parallel-bedded and cross-bedded sandstone. The same lithology with reduced thickness of >1 m alternating with equally thick beds of reddish brown clay constitutes the upper 6 m succession.

The calc–marl succession forming the middle 12-m column contains abundant concretions, of which the lower 5 m is reddish brown clay with discontinuous beds of hard, greyish green, compact siliceous limestone. Overlying is a lithocolumn of 4 m thickness, light grey and friable clay which is easily distinguishable because of having greyish to greenish black, subangular to subrounded, hard and compact concretions ranging from 2 to 10 cm in diameters; intercalations of thin siliceous limestones are noticed in the upper part. Dark brown, hard and compact, medium- to fine-grained sandstone bed having vertical and inclined burrows of *Thalassinoides* constitutes the overlying 3-m column.

The upper 14-m succession is calcareous in nature, of which the lower 9 m is bluish grey, fine-grained, nodular limestone having abundant clasts of chert. Locally, 5 to 10 cm thick patches of reddish brown, hard and compact, medium- to fine-grained sandstones are recorded showing high bioturbation. The nodular limestone extending vertically about 2 m may show alternations of thin discontinued beds of chertified limestone. The topmost 3 m is greyish white, hard and compact, faintly laminated, sheet-like bodies of highly chertified limestone. The boundaries of the three lithounits are gradational.

Table 1 Regional stratigraphic set-up of the area

Age	Stratigraphic units	Rock types
Quaternary		Soil and alluvium
Unconformity		
L. Cretaceous to Eocene	Deccan Trap	Greyish black, hard and compact, non porphyritic and porphyritic basalts
Unconformity		
L. Cretaceous	Lameta	Sandstone, claystone, mudstone and limestone
Disconformities		
E. Cretaceous	Upper Gondwana (Jabalpur Formation)	Sandstone, siltstone, conglomerate, clay and mudstone
Unconformity		
Archaean		Quartz–feldspathic gneiss with dolerite intrusions

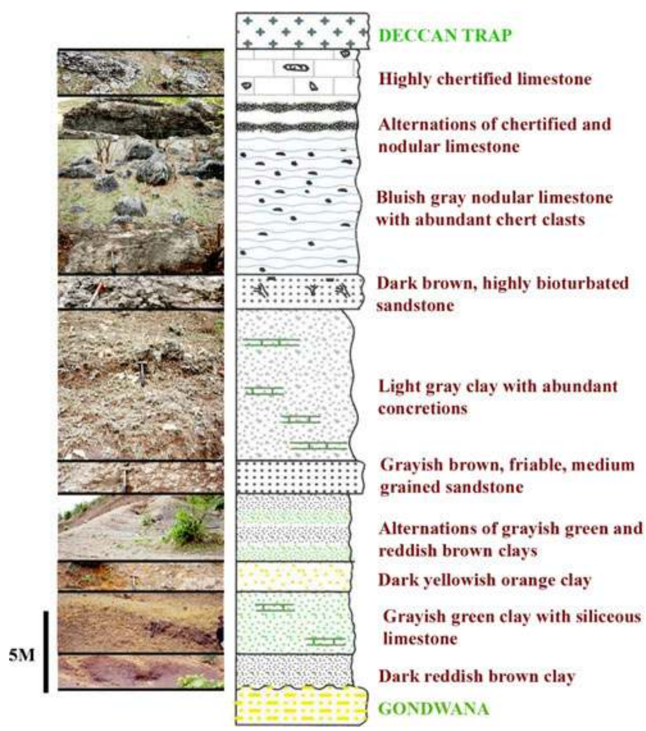

Fig. 2 Detailed sedimentary log of the Lameta successions at Bairam area

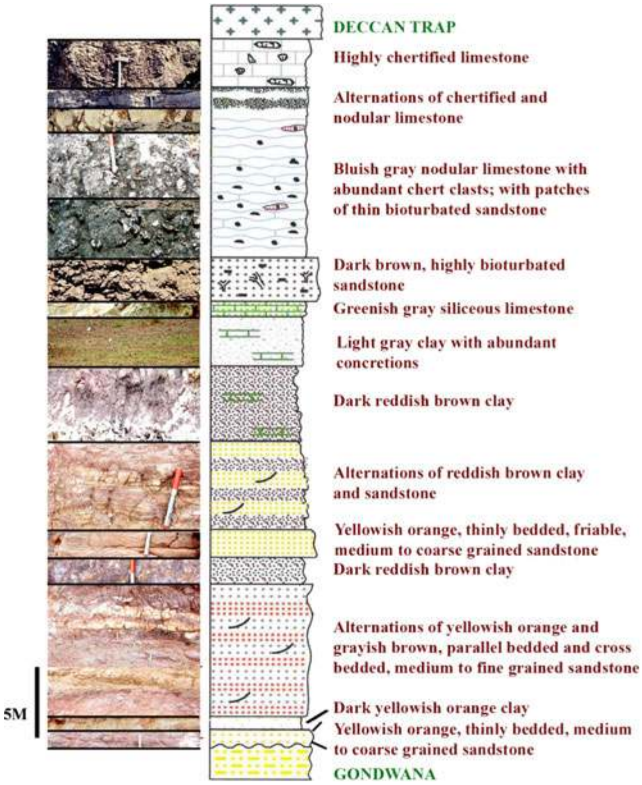

Fig. 3 Detailed sedimentary log of the Lameta successions at Belkher area

Locality 3: Salbardi area

The succession is almost similar to the previous two localities having a thickness of about 35 m; however, some additional beds are identified (Fig. 4). The lower 9 m is dominantly arenaceous, of which the basal 2 m is dark brown, thinly bedded, coarse- to medium-grained, hard and compact, parallel-bedded and cross-bedded sandstones followed by equally thick reddish brown clay, locally, showing thin films of gypsum. Greyish green clay of 1 m thickness overlies this horizon, followed by 4 m thick, medium green, parallel-bedded and cross-bedded calcareous sandstone.

The middle 10 m succession is represented by calcretes, sandstones and interbedded clayey horizons. Two calcrete horizons are identified, of which the lower is 2 m thick, light grey in colour having cylindrical pipes, whereas the upper is 3 m, light brown, massive and contains abundant clasts of greenish sandstone, nodular limestone and basalt. These two calcretes are separated by 1 m thick, light green, parallel-bedded, calcareous sandstone bed. The overlying 3 m column is represented by the alternations of greenish grey and dark reddish brown clayey beds. The top 1 m is medium green-coloured, medium-grained sandstone bed.

The upper 16 m succession is calcareous in nature, of which the lower 6 m is represented by alternations of thin beds of brownish to greenish grey clays with bluish grey, hard and compact nodular limestone having ferruginous concretions, whereas the remaining 3 m is continuation of the previous lithology; however, concretions are very less. The next 3 m is thick, bluish grey, hard and compact, highly chertified limestone which is followed by 4 m thick intraformational brecciated limestone which is dark reddish brown in colour and embodies angular to subrounded clasts of nodular and chertified limestone, basalt and greenish sandstone ranging from 5 to 20 cm in diameters in the host rock of bluish grey micritic limestone.

An attempt has been made for lithological correlation of the successions exposed at all the three localities with the type area of Jabalpur (Mately 1921) and two other significant exposures laying at Nand-Dongargaon area, Nagpur district (Mohabey 1996), and Rahioli and Balasinor area, Kheda district, Gujarat (Khosla and Sahni 2003). The exact lithological correlation is very difficult as the lithofacies architecture of all the areas vary considerably. The lower parts of successions under study have certain similarities with those of Nand-Dongargaon (Mohabey 1996) and Rahioli and Balasinor (Khosla and Sahni 2003) successions represented by clay–marl–sandy beds. The upper calcareous part, i.e. chertified limestone and nodular limestone, has correlatibility with the lower limestone of the type area (Mately 1921). Mohabey (1996) also concluded that an exact correlation of the lithounit of the Lameta Formation exposed at different areas in central and western India is difficult because of their restricted deposition in separate inland basins, viz. (1) Balasionor-Jhabua basin, (2) Jabalpur basin, (3) Sagar basin, (4) Amarkantak-Ambikapur basin and (5) Nand-Dongargaon basin having different settings.

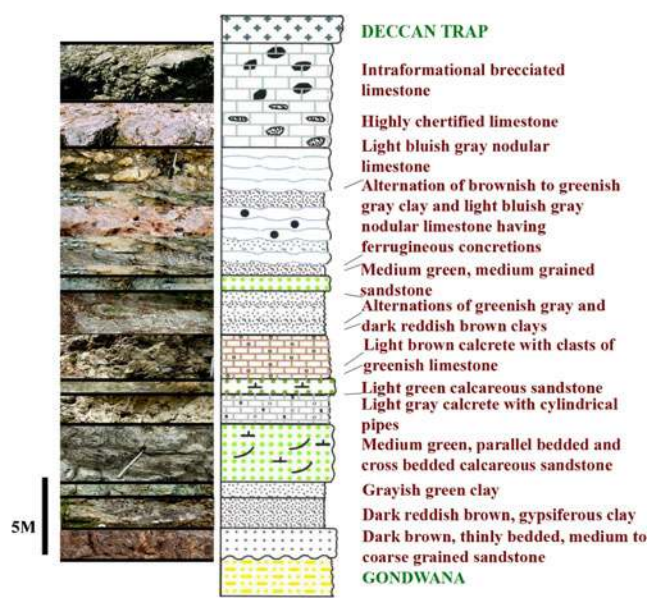

Fig. 4 Detailed sedimentary log of the Lameta successions at Salbardi area

Lithofacies analysis

The lithologs belonging to all the three areas show remarkable similarity as having almost identical architectural set-up of arenaceous, argillaceous and calcareous sediments. Accordingly, the columns have been subdivided into three lithofacies associations (Fig. 5):

1. Arenaceous lithofacies association
2. Argillaceous lithofacies association
3. Calcareous lithofacies association

1. Arenaceous lithofacies association

   This association is marked by various types of sandstone beds constituting lower part of the successions particularly at Belkher and Salbardi localities. Occasionally, clayey or calc–marl horizons are recorded as interbeddings. Five lithofacies have been identified in the association (Fig. 5):

   (a) Massive sandstone lithofacies
   (b) Green sandstone lithofacies
   (c) Thinly bedded, yellow orange and greyish brown sandstone lithofacies
   (d) Coarse-grained sandstone lithofacies
   (e) Dark brown bioturbated sandstone lithofacies

   (a) Massive sandstone lithofacies

   The lithofacies is 2-m thick, dark brown, medium-grained, hard and compact sandstone having ferruginous cementing material. It is well exposed at Salbardi locality where it forms the lower part of the lithocolumn and rests on the Gondwana succession with a sharp boundary (Fig. 6a). Its distinction from the underlying Gondwana sediments is very clear as the later is represented by loosely packed, poorly cemented, conglomerate-pebbly bed. Bedding characteristics and mechanically formed sedimentary structures are difficult to record in the lithofacies as the entire unit is massive in nature. Rounded to subrounded pebbles of quartz and feldspar, ranging up to 2 cm in diameter, make frequent occurrences.

   (b) Green sandstone lithofacies

   This lithofacies is about 4 m thick, represented by alternations of medium green, hard and compact, medium-grained, large-scale cross-bedded sandstone beds and equally thick, thinly bedded sandstones however, restricted to the Salbardi area (Fig. 6b). Individual beds are 10 to 15 cm thick with clear demarcations as bounded by erosional surfaces showing break in sedimentation. Occasionally, elongated, sometime ferrugenized burrows of *Planolites* are recorded. Both lower and upper boundaries of the lithofacies are distinct as the previous underlain clay bed, whereas the later overlain calcrete bed.

   (c) Thinly bedded, yellowish orange and greyish brown sandstone lithofacies

   This lithofacies consists of yellowish orange and greyish brown, medium- to coarse-grained sandstone beds (Fig. 6c). The bed rocks of both are texturally similar and occur in alternations of 1- to 2-meter thicknesses consisting of thin beds of 10 to 20 cm. The cementation is poor resulting to friable nature of rocks. The entire unit shows nodular tendency because of differential weathering along minor vertical cracks having abundant occurrence in the beds. Rounded to subrounded pebbles of quartz and feldspar up to 1 cm diameter have also been recorded. Occasionally, the thick beds show large-scale cross beddings.

   (d) Coarse-grained sandstone lithofacies

   The lithofacies is 1 to 2 m thick, reddish brown to greyish white, friable, poorly sorted, coarse-grained sandstone beds having poor cementation that occurs at Bairam and Belkher locations (Fig. 7a). The bed rock consists dominantly of subangular to angular grains of quartz and feldspar; however, abundance of granule size, subangular to angular quartz, feldspar and dark-coloured minerals distinguishes it from the rest of the lithocolumn. The dark coloured minerals ranging up to 2 mm, or occasionally more, are noticed to have their concentration in small pockets, which are unevenly distributed in the bed rock. The lower and upper contacts of the lithofacies are sharp with clayey beds.

   (e) Dark brown bioturbated sandstone lithofacies

   This lithofacies is 2-m thick, compact, medium to dark brown, medium-grained, highly cemented sandstone showing nodular tendency (Fig. 7b). It is highly bioturbated having vertical to inclined, cylindrical burrows of *Thalassinoides* (Srivastava and Mankar 2012). Due to intense biogenic activity, mechanically formed sedimentary structures are difficult to record; however, occasionally, the traces of parallel and cross laminations are visible. Both lower and upper surfaces are sharp having distinct contacts with overlying and underlying clayey beds. It is well developed in Belkher locality with a thickness of 2 m and also traceable in Bairam locality having reduced thickness of about 1 m.

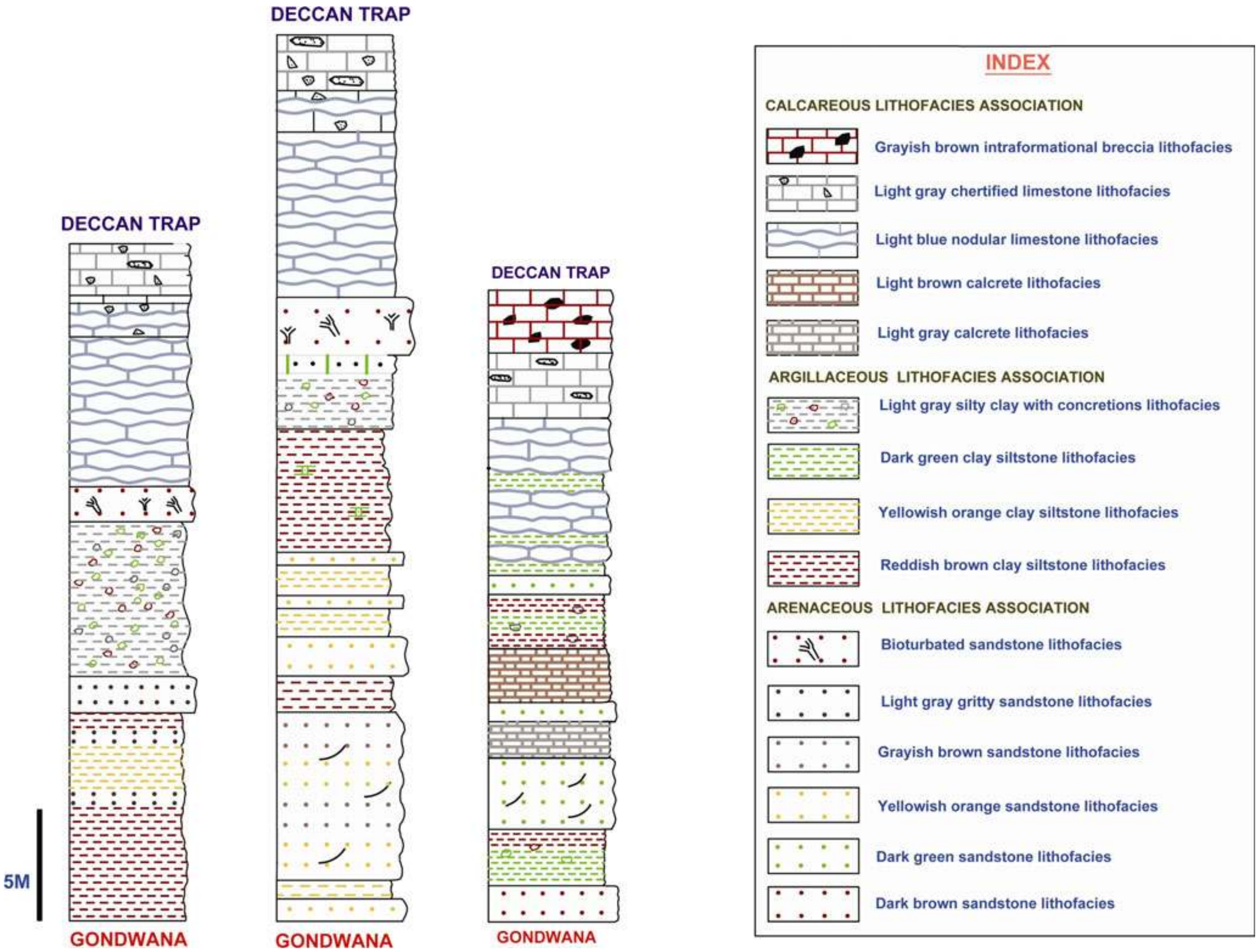

Fig. 5 Diagram showing lateral variations of the lithofacies in vertical columns at Bairam (*left*), Belkher (*center*) and Salbardi (*right*) areas

Petrography and diagenesis

The massive sandstone, a greywacke, is dominantly constituted by detrital, subangular to subrounded, medium- to fine-grained, poorly sorted monocrystalline quartz showing undulose extinction which indicates a plutonic source (Blatt 1967) (Fig. 8a). Minor quantity of polycrystalline quartz having sutured contacts (Fig. 8b), orthoclase and plagioclase are also identified. Inclusions of zircon, tourmaline and opaques may represent both plutonic or metamorphic source (Blatt et al. 1980). Cracks and vacuoles have frequent occurrences in the quartz grains, of which the latter rarely show a straight line orientation (Fig. 8c) indicating their low-temperature origin, e.g. hydrothermal vein (Adams et al. 1984). Fragments of yellowish brown clay having fine-grained texture have also been recorded. The matrix is argillaceous, in which the grains seem to be floating; however, concavo-convex and straight contacts are locally visible (Fig. 8). Floating nature of the grains indicates lack of compression, whereas fractured nature depicts mechanical compaction, or over burden, but, as such, there is no other evidence of this process is observed. Therefore, it is interpreted that the grains were fractured prior to their present deposition, may be at the nearby provenance. The cement is dark brown ferruginous material that also occurs as crack fill. Quartz and orthoclase grains may show corroded boundaries and dark rim of iron oxides. The ferruginous nature of the cementing material indicates that the solution was acidic in nature and might have been formed at low depth in hot and dry climate (Sengupta 1996).

The bulk mineralogy of green sandstone is similar to the previous, however, differs because of having more argillaceous content and calcareous cementing material (Fig. 8d). Clasts of greyish green micrite are frequently recorded, whereas yellowish to brownish green, irregular pellets and lenses of clay have rare presence. Matrix is yellowish to brownish green argillaceous material. Non-ferroan spar forms isopachous rim around the grains (Fig. 8e) and also developed as drusy calcite having straight crystal boundaries. Such development occurs during early phase of diagenesis in sub-arid, reduced rainfall

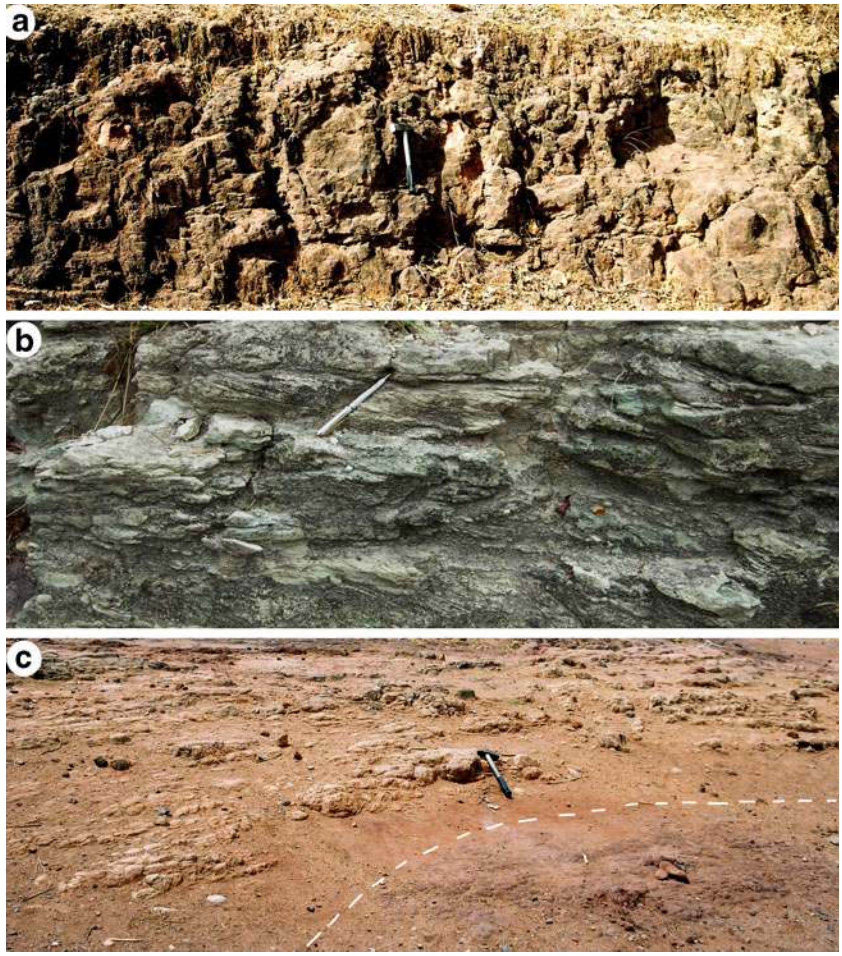

Fig. 6 Photographs showing **a** dark brown, hard and compact massive sandstone; **b** thinly bedded, medium green, hard and compact, cross-bedded and parallel-bedded sandstone; **c** yellowish orange, hard and compact, medium- to coarse-grained, cross-bedded and parallel-bedded sandstone; greyish brown, fine-grained, cross-bedded and parallel-bedded, thinly bedded sandstone

and hot environments allowing little chemical weathering; the interstitial water, in such condition, contains more calcium and magnesium making it alkaline in nature (Burley and Worden 2003). The yellowish orange sandstone is also greywacke having angular to subangular, medium- to coarse-grained quartz. The polycrystalline grains are comparatively more and show sutured contacts; however, a few grains of sheared quartz are also noticed having sutured crystal boundaries and orientation of the crystals in one direction indicating metamorphic provenance (Adams et al. 1984) (Fig. 8f). Jafarzadeh and Barzi (2008) suggested that polycrystalline grains from plutonic source normally have five or more crystals with straight to slightly curved boundaries, whereas metamorphic source are characterized by irregular to crenulated intercrystal boundaries (Folk 1974; Blatt et al. 1980; Asiedu et al. 2000). Colourless, cloudy, subhedral grains of orthoclase and microcline show perthitic intergrowth of local occurrence (Fig. 8g). Rock fragments of medium-grained sandstone are frequent (Fig. 8h). Concavo-convex contacts of grains (Fig. 8i), brakeage and bending of mica flakes show mechanical compaction (Fig. 8j), whereas sutured contacts, dark rim of ferruginous material around the grains revealing chemical process together depicts the phase of mesogenesis (Dapples 1972; Chilingarian 1983; Pettijohn et al. 1987; Burley and Worden 2003). Greyish brown sandstone is almost similar to the yellowish orange sandstone; however, feldspar content is comparatively higher (Fig. 6h).

Medium to fine, subangular to subrounded, poorly sorted, monocrystalline quartz is the main constituent of the bioturbated sandstone, whereas polycrystalline quartz, orthoclase and plagioclase feldspars constitute minor quantity (Fig. 8k). Rock fragment of volcanic origin having phenocrysts of quartz and feldspar are common beside minor clasts of subangular to subrounded chert. Matrix is fine-grained, argillaceous and feldspathic, whereas cement is both ferruginous and siliceous in nature; previous occurs as coating on grains and rock fragments, whereas the later precipitated as chalcedony filling intergranular spaces showing prevalence of reducing environment (Dabard 1990). Poorly cemented, loosely packed, coarse-grained sandstone contains fine-grained quartz–feldspathic matrix and minor cement. Straight and concavo-convex contacts of the grains, occasionally with corrosion and coating of iron oxides are visible (Fig. 8l).

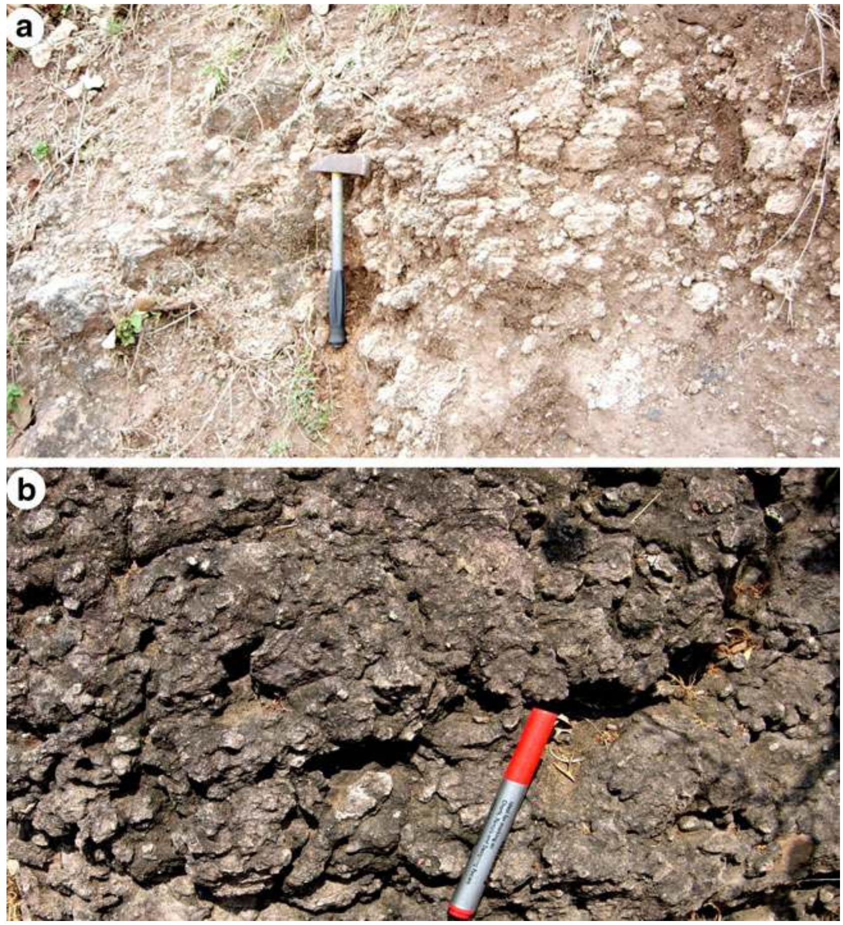

Fig. 7 Photographs showing **a** reddish brown to greyish white, coarse-grained sandstone; **b** dark brown, hard and compact, medium- to fine-grained sandstone showing vertical and inclined burrows of *Thalassinoides*

Interpretation

The arenaceous lithofacies association shows a changing pattern of the depositional environment as the lithofacies are highly variable in their overall architecture. The brown-coloured massive sandstone lithofacies, forming the base, is a deposit of low energy environment as interpreted by its fine-grained nature and lack of wave or current-generated structures. It disconformably underlain conglomerate-pebbly bed of Gondwana which is considered to be a channel floor deposit (Srivastava and Mankar 2010). Similar pebbles, as of Gondwana succession, also make appearance in this lower most lithofacies of the Lameta succession, however, less in number. It indicates that the source of pebbles during the sedimentation of both Gondwana and Lameta successions was the same.

The energy condition was comparatively high during the deposition of green sandstone lithofacies as it is well marked by cross beddings and parallel beddings. Fluctuation in the energy condition of the depositing medium is evident as the beds show truncation of the structures due to erosional activities. In the type area of Jabalpur, this lithofacies happens to be a matter of debate for its depositional environments. The evidences in support of shallow marine environment include the presence of glauconite minerals (Chanda 1963a, b; Chanda and Bhattacharya 1966); *Thalassinoides*-type burrows and lateral as well as vertical facies associations of green sandstone with bioturbated carbonates and marl indicate it as a deposit of estuarine channel having tidal influence (Singh 1981; Singh et al. 1983; Ahmad et al. 2010). The fluvial environment, precisely the point bar, is suggested on the basis of parallel beddings, small-scale unimodal cross beddings, small ripple beddings with mud drapes and bar beddings (Kumar and Tandon 1979). Brookfield and Sahni (1987) discarded the marine influence and suggested semi-arid piedmont deposits, whereas Tandon et al. (1995) interpreted that the green sandstone is a product of shallow braided channel which show evidences of stage fluctuations. Our study also supports the point bar environment of deposition having fluctuation in energy condition. In the present study, the green colouration of the rock is not attributed to glauconite as this mineral has not been identified in the thin section; however, patches of dirty yellowish to moderate greenish yellow, fine-grained clayey material have been recorded which is considered to be the principal constituent for green colouration. The same has also been confirmed by thin section study of light

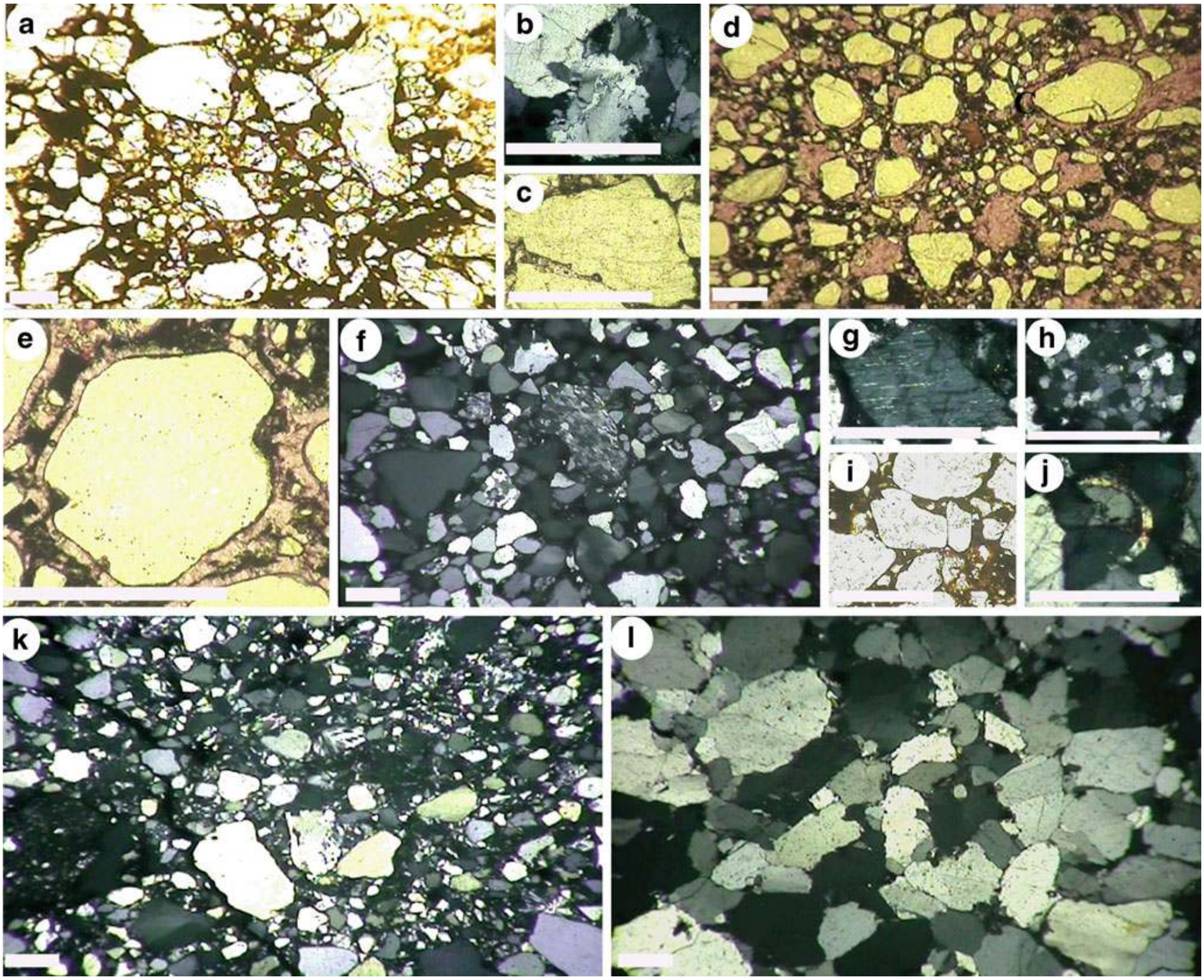

Fig. 8 Photomicrographs showing **a** subangular to subrounded, medium- to coarse-grained, poorly sorted detrital grains floating in argillaceous matrix; **b** a polycrystalline quartz grains showing sutured contact; **c** quartz grain showing presence of vacuoles in straight line orientation; **d** coarse to fine, poorly sorted grains having well-developed isopachous rim of spar; **e** close up view of the quartz grain having isopachous rim of spar; **f** angular to subangular, medium- to coarse-grained, moderately sorted rock; polycrystalline quartz with sutured contacts in center; **g** grain showing perthitic growth of orthoclase; **h** rounded clast of medium-grained sandstone; **i** grains showing concavo-convex and straight contacts; **j** bending of mica flake; **k** medium- to fine-grained, subangular to subrounded grains cemented by ferruginous siliceous material; **l** angular to subangular, coarse- to medium-grained, moderately sorted sandstone having well-developed sutured contacts

green coloured, clay–marl concretions occurring in greenish-brownish-yellowish clayey beds that also show the abundance of light green to yellowish green amorphous clayey material.

Thinly bedded, yellowish orange and greyish brown sandstone lithofacies is medium- to coarse-grained with occasional presence of large-scale cross beddings. It indicates medium to high energy conditions of the deposition and is interpreted as a product of point bar environment. The alternations of yellowish orange and greyish brown sandstones revel fluctuations of the depositional site. The yellowish orange colouration may be due to subaerial exposure, whereas, the greyish brown is because of ferruginous cement which developed in well-oxygenated condition. The source of sediments for both the lithotypes were same as the reworked pebbles of similar nature are equally distributed in entire lithofacies.

The coarse-grained sandstone lithofacies having poorly sorted, medium to coarse, subangular to angular grains show the influx of the sediments formed in nearby areas. The dark brown bioturbated sandstone lithofacies exhibits well-oxidized environment, in which extensive development of crustacean community animals has taken place. The medium grain size of the rock and traces of poorly preserved small-scale parallel beddings and cross beddings indicate low energy environment of deposition.

2. Argillaceous lithofacies association

The argillaceous lithofacies association consists dominantly of clay–siltstone beds which occur mostly in the lower part of the successions at all the three localities. These beds are dominantly weathered, loosely packed in nature and either covered with vegetation or lie as down slope sediment debris, therefore, pose a difficulty for their detailed study. A few of the accessible outcrops are highly distorted because of the agricultural activities over the same. Limiting to these restrictions, only two lithofacies could be identified (Fig. 5).

(a) Yellowish-brownish-greenish clay–siltstone lithofacies
(b) Light grey silty clay with concretions lithofacies

(a) Yellowish-brownish-greenish clay–siltstone lithofacies

This lithofacies is 3 to 5 m thick, represented by greenish-brownish-yellowish coloured argillaceous sediments and mostly massive in nature; however, traces of horizontal laminations can be seen (Fig. 9a). Silt-size sediments in variable proportions can be noticed and with increasing amount of the same, the clay grades to siltstone. Occasionally, faint laminations in silt-dominated beds are traceable. Some of the horizons are marked by abundant clac–marl concretions ranging from 10 to 30 cm in diameters which are of the same colours as of the host rocks, i.e. shades of greenish, brownish or yellowish colours (Fig. 9b). Locally, the lithofacies shows interbeddings of thin, continuous, coarse-grained sandstone and discontinuous, silicified limestone. Occasionally, the upper surface of the bed shows the presence of gypsum as thin white film or irregular, subrounded to elliptical patches in the clayey host rock (Fig. 9c). The lithofacies is well represented in the lower part of the successions at Bairam and Belkher localities; however, their traceability is difficult as the exposures are less, as well as, highly weathered.

(b) Light grey silty–clay with concretions lithofacies

It is characterized by massive and highly weathered, light grey silty clay having abundant greyish brown to black, smooth to rough, calc–marl concretions of 2 to 10 cm diameters (Fig. 9d). On breaking, it may show septarian structures or filled with angular to subangular quartzs, feldspars and rock fragments ranging up to the size of 0.5 cm, which are welded together by clay–marl matrix that often shows silicification and calcification. In a few concretions, radial inside growth of calcite can also be seen. In the field, this lithofacies can be easily identified by the presence of abundant pieces of concretions on the surface; however, at a few places, these may form discontinuous beds having the thickness of 10–15 cm.

Interpretation

The yellowish-brownish-greenish clay–siltstone lithofacies depicts its deposition in a quite water environment mainly through the suspension mode. This condition is a typical of restricted pond or lake in a fluvial regime; however, fluctuation in the energy condition during the deposition is quite evident as the clay horizons are interbedded with coarse-grained sandstone beds, prominently at Belkher locality. It indicates that the lakes were periodically recharged by the river water carrying larger clastic sediments from the nearby areas. At Salbardi, this lithofacies underlain calcrete and overlain nodular limestone that also reflect fluctuating conditions in the deposition, where the energy condition was very low as well as pedogenic activities were also taking place.

The light grey silty–clay lithofacies with concretions is also interpreted as a product of restricted lake of low energy condition as the beds are massive and devoid of laminations; however, the sediment admixture contains sand-size angular clasts which reveal their influx from the nearby area. The concretions, forming discontinuous beds, may represent short phases of subaerial exposure of the sediments that caused leaching of the iron oxides and formation of dark brown to greyish brown concretions. The exact process of formation of these concretions is unclear, however, definitely represents a change in environmental and climatic conditions.

3. Calcareous lithofacies association

Calcareous lithofacies association is represented by various types of carbonate rocks, forming almost upper half of the lithocolumns. Based on the nature of the rocks, four lithofacies have been identified (Fig. 5):

(a) Calcrete lithofacies
(b) Nodular limestone lithofacies
(c) Chertified limestone lithofacies
(d) Intraformational breccia lithofacies

(a) Calcrete lithofacies

This lithofacies is restricted to two stratigraphic levels in Salbardi area and can be subdivided into two sublithofacies, viz. (1) nodular rhizomorphic calcrete sublithofacies and (2) Nodular calcrete sublithofacies. The previous is about 2 m thick, very hard and compact, greyish white to light grey calcretes with abundant cylindrical pipes up to the

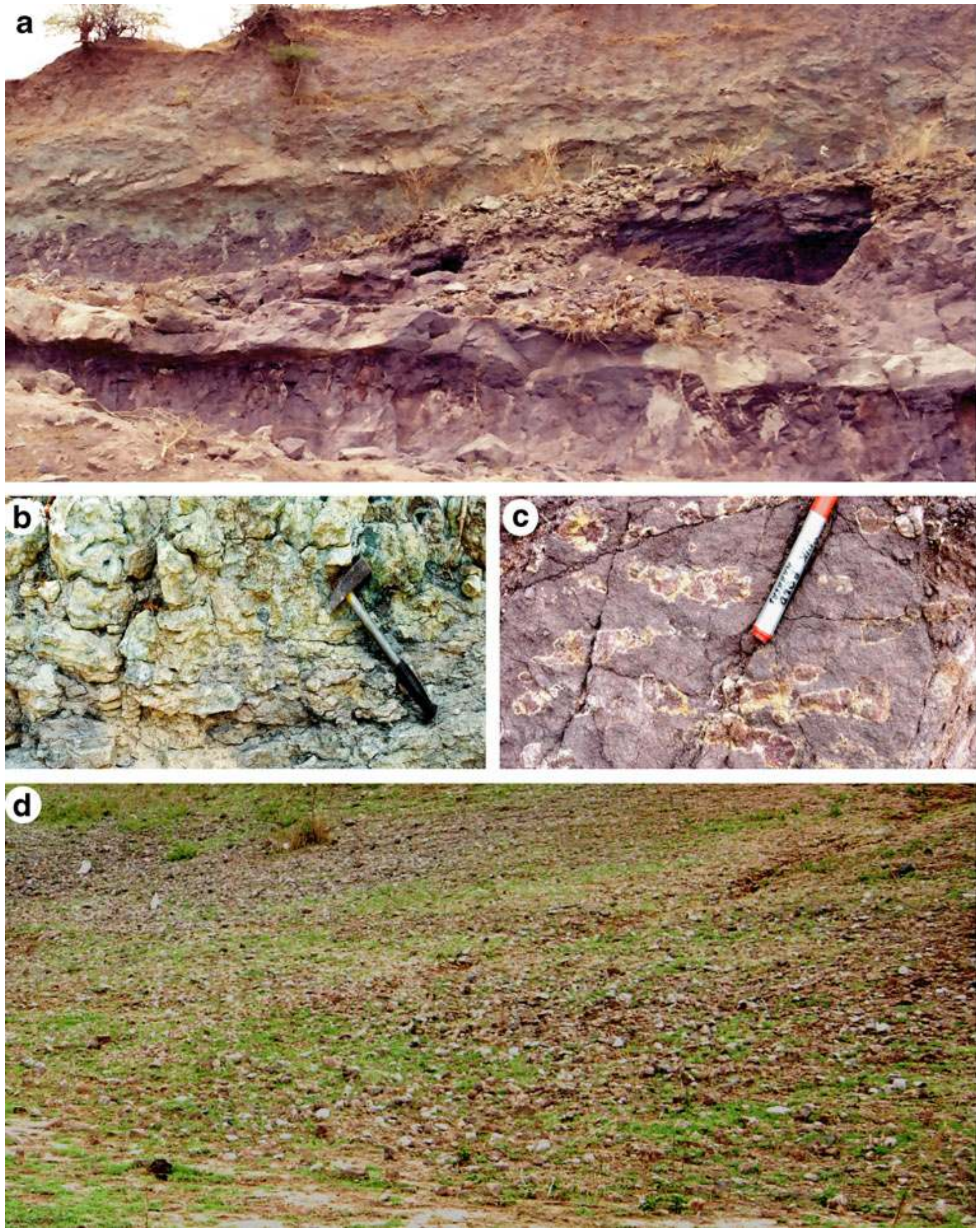

Fig. 9 Photographs showing **a** reddish-greenish-yellowish clayey unit with greyish white, medium- to coarse-grained friable sandstone bed; **b** greyish green clay with large nodules of irregular (Salbardi area); **c** light brown clay showing the pockets of gypsiferous clays (Belkher area) and **d** light grey silty clay with abundant greyish brown to black concretions

length of 15 cm and diameters in the range of 0.5 to 1 cm (Fig. 10a). The entire unit is highly calcareous having very less percentage of detrital material including clay and silt. It rests over the green sandstone lithofacies with a sharp boundary. The upper boundary is also distinct and overlain the clay bed. The second sublithofacies, viz. nodular calcrete, is also equally thick and represented by light brown, compact and detritus-rich carbonates having abundant carbonate nodules (Fig. 10b); however, cylindrical tubes of 1 to 2 cm diameter are rarely noticeable. The bed rock contains abundant angular clasts of green sandstone, limestone, basalt, chert and jasper ranging from 2 to 10 cm.

(b) Nodular limestone lithofacies

This lithofacies is represented by light grey to greyish blue, hard and compact, nodular limestone and well developed at all the three localities with the thickness of 4 to 5 m (Fig. 11a). Excluding nodular feature of the rock, any other sedimentary structure is difficult to identify. Individual beds are 15 to 20 cm thick and contain angular clasts of chert ranging up to 3 cm, which show both increasing and decreasing trends in vertical columns. At a few places, chertification occurs in the form of discontinuous bands. The upper boundary is difficult to delineate from the overlying chertified limestone as the same is represented by alternations of thin beds of nodular

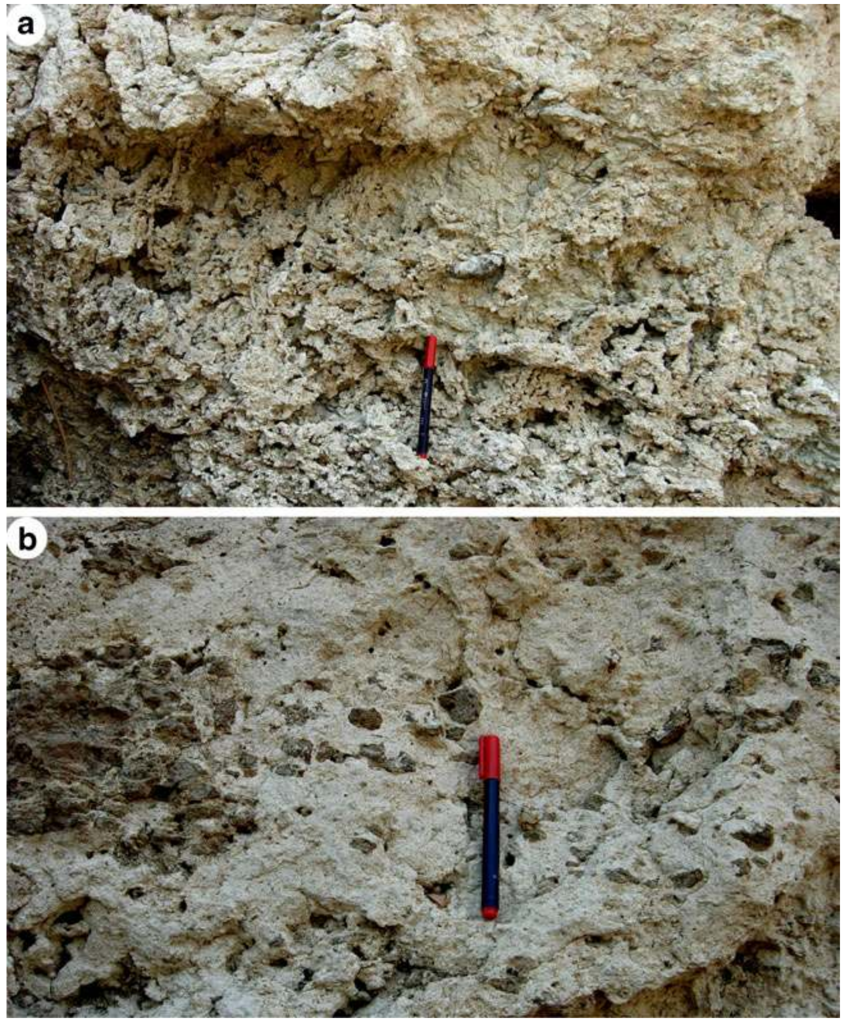

Fig. 10 Photographs showing **a** light grey calcrete with abundant vertical to inclined cylindrical pipes; **b** light brown nodular calcrete having clasts of greenish sandstone, nodular limestone and basalt

limestone and chertified limestone (Fig. 11b). Ferruginous clayey–silty concretions having diameters up to 3 cm are also recorded. At Salbardi area, the nodular limestone is interbedded with clay beds.

(c) Chertified limestone lithofacies

This lithofacies is also very distinct and occupy the top of the lithocolumns except at Salbardi locality, where it overlain the intraformational breccia. It is light grey to greyish brown, very hard and compact micritic limestone, however, shows intense chertification (Fig. 11c). The thicknesses of beds range between 2 and 3 m. Chertification occurs in lateral continuity in the form of bedding, as well as in pockets; besides, the clasts of the same along with jasper and quartz are also present. Sedimentary structures are mostly diffused; however, a tendency of horizontal bedding can be noticed because of the differential weathering of chertified and non-chertified limestones.

(d) Intraformational breccia lithofacies

Intraformational breccia lithofacies is exposed only at Salbardi, represented by hard and compact, greyish brown, calc–marl unit with abundant large size clasts (Fig. 11d). The clasts are mostly angular to subangular fragments of nodular and chertified limestone and basalts. The dominant size range of the clast is 5 to 10 cm; however, larger fragments are also common and may be up to 30 cm. The calc–marl matrix appears to be structureless on both vertical and horizontal surfaces of the bed.

Petrography and diagenesis

The light grey nodular rhizomorphic calcrete is represented by recrystallized, non-ferroan calcite with abundant subangular to subrounded, medium to coarse grains of quartz and feldspar (Fig. 12a). A few fractured grains of quartz show infillings of non-ferroan calcite, whereas some may show development of isopachous rim of the same representing simple crystal growth from the calcareous solution (Wright and Peeters 1989). Late crystallization of non-ferroan calcareous solution is also evident by well-developed crystals in voids and veins, beside

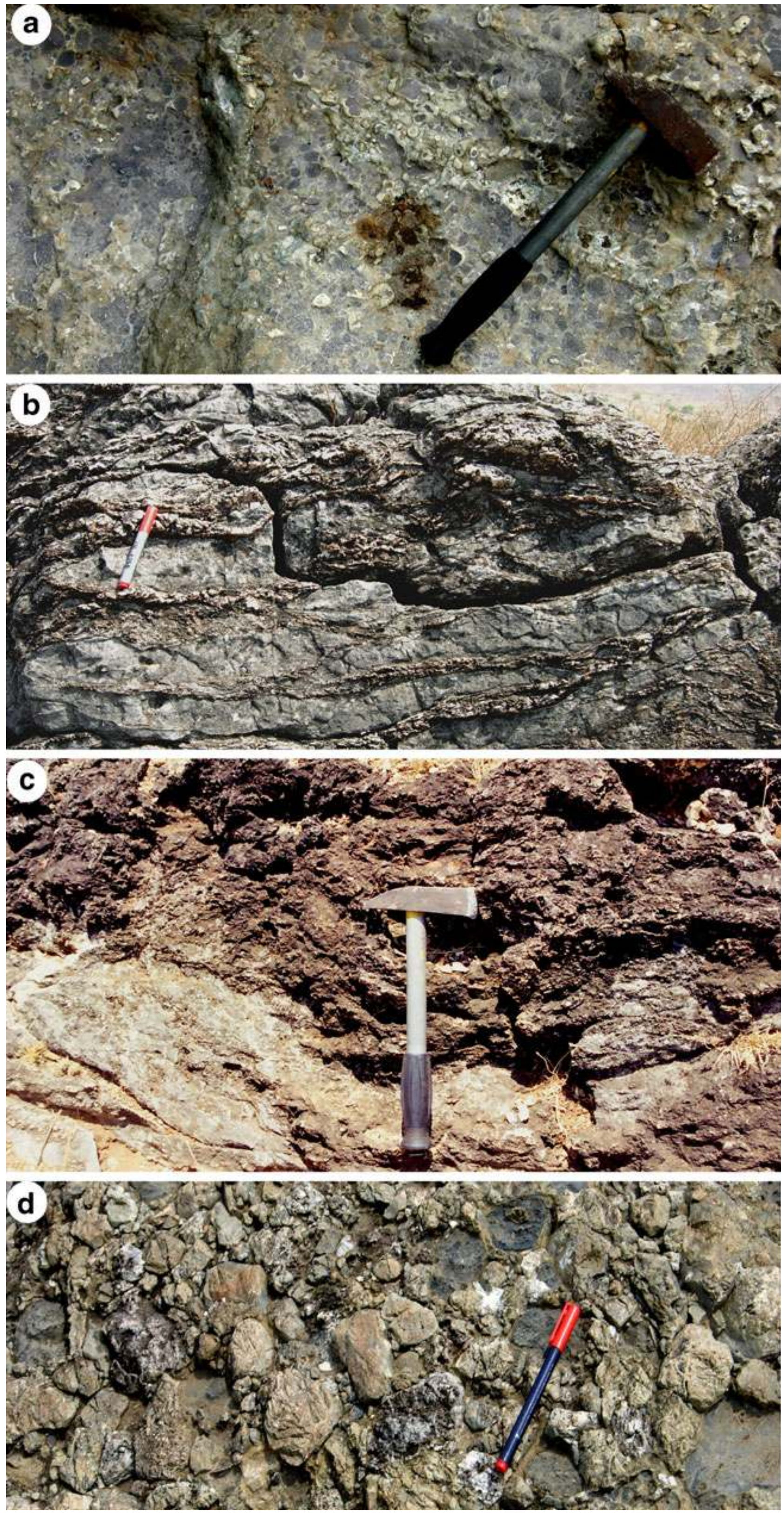

Fig. 11 Photographs showing **a** bluish grey, hard and compact nodular limestone; **b** alternations of greyish blue, compact nodular limestone and light grey chertified limestone; **c** light grey to greyish brown, hard and compact, highly chertified limestone and **d** intraformational brecciated limestone with angular to subangular clasts of sandstone, nodular and chertified limestones

sparite patches in the groundmass. Yellowish brown patches of clay and rarely, volcanic fragments are also noticed; dolomitization of the groundmass is observed in the form of irregular patches. The nodular calcrete is micritic in nature, however, contains abundant angular to subangular grains of quartz which are mostly monocrystalline, fractured with anhedral to subhedral boundaries (Fig. 12b). The groundmass is greyish brown, fine grained and micritic in nature which shows recrystallization and development of sparite patches as of previous. Recrystallized neomorphic crystals have cloudy appearance and contain micritic relicts. Nash and McLaren (2003) suggested that the dominance of micritic cement indicates relatively rapid precipitation of carbonate. Irregular pockets of angular to subangular quartz grains, cemented by ferroan calcite, are noticed having random distribution in the groundmass as of Upper Miocene calcretes of Duero basin, Spain (Huerta and Armenteros 2005).

The nodular limestone is dominantly micritic, however, locally shows pockets of recrystallization in groundmass. Abundant, detrital grains of quartz are noticed which are medium to coarse in size and subangular and subrounded in shape indicating only a short distance transport (Fig. 12c). Development of calcite and coatings of dark-coloured argillaceous material around the large detrital grains and infillings of their cracks and fractures by non-ferroan calcite have frequent occurrences (Fig. 12d). Chalcedony as chert clast and cementing material has been noticed. Recrystallization of micrite and formation of neomorphic spar around the grains indicate meteoric phreatic environment of diagenesis (Heckel 1983; Horbury and Adams 1989; Moore 2001).

Chertified limestone exhibits intense silicification of microcrystalline calcite and development of chalcedony (Fig. 12e). Detrital, subrounded grains of quartz, orthoclase, angular clasts of chert and subrounded to rounded clasts of micrite make frequent occurrence in the ground mass (Fig. 12f). It shows that during the initial phase, precipitation of micrite took place followed by intense chertification that also operated in the form of void filling process resulting in good development of crystals (Fig. 12g). Chalcedony in the form of irregular, sub circular to circular growth of radial fibrous quartz is secondary. It is also represented by microcrystalline to macrocrystalline bands of quartz-forming layered structures. Occasionally, zoning pattern showing successive growth of the crystals is also noticed. The siliceous solution also precipitated in pores and voids forming a pattern of increasing crystal size from periphery to center (Fig. 12h). It is interpreted that this much of silica in solution is possible only by preexisting large quantity siliceous material which can get dissolve and produce the same. It is obvious that the diagenetic environment during this phase of cementation was acidic in nature. However, further changes in the Eh-pH conditions are evident by the development of drusy non-ferroan sprite patches, as well as veins intruding all the existing structures.

Interpretation

The calcrete lithofacies is locally developed in Salbardi area and indicates subaerially exposed, low gradient, alkaline flat environment. The lower unit preserves well-developed rhizocretions which may be a result of root calcritization, whereas, the upper unit is marked by brecciation and input of abundant large clasts of green sandstone, basalt, chert and jasper from the surrounding area. Changes in the depositional environment condition and fluctuation of the depositional site during the formation of both the calcrete horizons are also marked by 1-m thick, interbedded clay horizon indicating a period of low energy environment in between two phases of subaerial pedogenic activities. The calcrete profile of the Lameta succession at the type area of Jabalpur is well elaborated and discussed by Brookfield and Sahni (1987) and Tandon et al. (1995, 1998), and interpreted as a deposit of semi-arid flood plain environment and pedogencially modified sheet wash deposits of semi-arid alluvial plain, respectively.

The nodular limestone lithofacies is micritic and lacks internal bedding structure representing an alkaline environment with almost no supply of even fine-grained terrigenous clasts. Considering these aspects, the lithofacies may be considered as a deposit of semi-arid flood plain environment. The chertified limestone lithofacies is also micritic in nature and almost devoid of mechanically formed structures; therefore, it is interpreted that the environment responsible for the deposition of preceding nodular limestone lithofacies continued for the chertified limestone also, i.e. alkaline flat setting of fluvial regime.

Intraformational breccia lithofacies is a clast-supported unit having micritic matrix. The carbonate matrix indicates prevalence of alkaline environment however, restricted in lateral extent as compared to widespread geographic area for the depositions of nodular limestone and chertified limestone in earlier period. The occurrence of randomly scattered angular fragments of preexisting rocks, like green sandstone, chertified limestone, nodular limestone and basalt, indicate their little transport from the nearby areas. Lack of orientation in the clasts, lamination or other bedding tendency qualifies this lithofacies for its deposition by sediment gravity flow.

Depositional environment

Table 2 is a compilation of bedding geometry, energy conditions of the medium and environments of deposition of the lithofacies. A comparative study of the lithofacies architecture in the lithocolums of various localities show remarkable similarity and depicts fluvial–lacustrine environments of deposition having visible changes in the environmental settings, climatic conditions and nature of depositing mediums. Figure 13 is a schematic depositional model of the Lameta sediments.

The lower most part of succession represented by massive sandstone lithofacies overlies the pebbly conglomerate beds

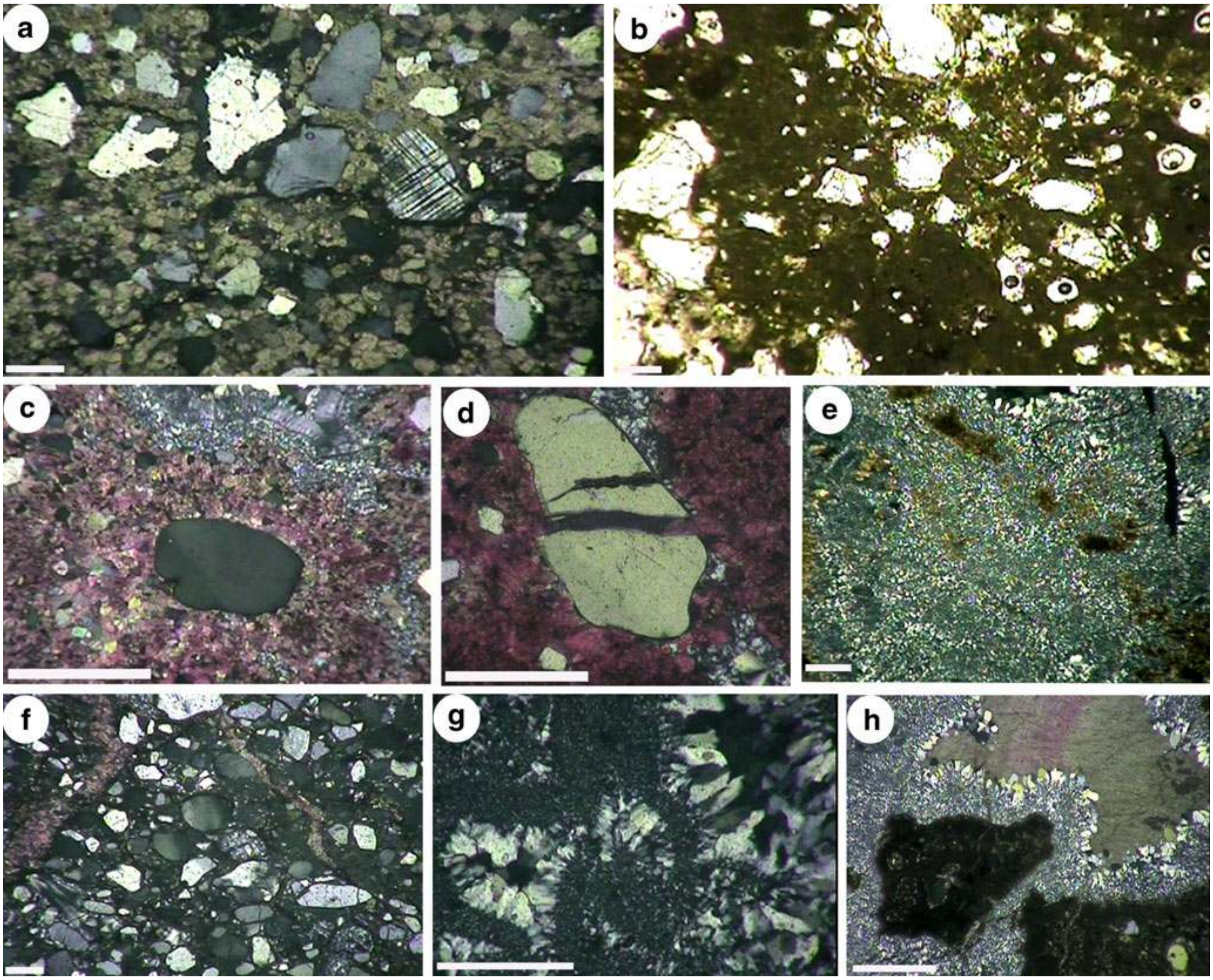

Fig. 12 Photomicrographs showing **a** angular to subangular grains of quartz embedded in fine-grained micritic groundmass; **b** subangular to subrounded, medium to coarse grains of quartz and feldspar embedded in the sparitic groundmass; **c** recrystallized micritic groundmass with angular to subangular grains of quartz; **d** a detrital quartz grain showing development of non-ferroan calcite on the periphery and infillings of the cracks by the same material; **e** microcrystalline calcite showing high silicification; **f** groundmass containing subrounded quartz grains; non-ferroan calcite vein in the left; **g** void fill structure showing gradual increase of the crystals from periphery to center and **j** a large crystal of non-ferroan calcite; zoning pattern of the quartz grain. *Scale bar* 0.5 mm

of Gondwana. The boundary between these lithounits is distinct; however, the colour of rocks and nature of pebbles are same. The bedding characteristics indicate a clear distinction in the energy condition during the depositions of upper most part of the Gondwana and lower most part of the Lameta; however, the source of pebbles and climatological conditions were the same. Fluctuation in the energy condition during the deposition of the lower part of the succession is well evident, the argillaceous and arenaceous lithounits are frequently interbedded. This may happen due to the seasonal variability of energy condition of the river system forming detached lakes and water bodies during low water condition, followed by over flooding and connectivity of the same during the high water condition of the river channels (Fig. 13a–c). The alternations of argillaceous and arenaceous fluvial beds are reported from the Słupiec Formation, SW Poland, and interpreted that the heterolithic nature of the sediments in the formation are because of regular changes in the transport and sedimentation condition, and the sandy fractions represent a deposit under low stagnation period (Kurowski 2004).

Clay–siltstone horizons of this unit are of various colours which reflect a changing pattern of climatic condition as well as chemical nature of the depositing medium. The reddish brown clays may be considered as a product of suspension during well-oxygenated condition, whereas yellow clays may represent the same mode of deposition, but in a lagoonal setting. The changes in energy condition are also marked by green sandstone and thinly bedded yellowish orange and greyish brown sandstone lithofacies which are marked by medium-scale cross beddings and parallel beddings. These sediments are interpreted

Table 2 Characteristics features of various lithofacies and their interpretation

Lithofacies association	Lithofacies	Characteristics features	Depositional environment
Arenaceous association	Massive sandstone lithofacies	Medium-grained, hard and compact lithounit lacking wave- or current-generated structures The lithounit contains pebbles similar as of underlying Gondwana succession, however, less in number. It indicates that the source of sediments for both Gondwana and Lameta formations were the same	Fluvial (channel floor)
	Green sandstone lithofacies	The lithofacies is well marked by cross beddings and parallel beddings indicating high energy condition of deposition Alternations of thin and thick beds of sandstone having large-scale and small-scale cross beddings show fluctuation of energy condition in the depositing medium. This is also evident by the truncation of structures due to erosional activity	Fluvial (point bar)
	Thinly bedded, yellow orange and greyish brown sandstone lithofacies	Alternations of yellowish orange and greyish brown sandstones consisting of medium- to coarse-grained sediments Presence of large-scale cross beddings, rounded to subrounded pebbles indicate medium to high energy conditions of deposition	Fluvial (point bar)
	Coarse-grained sandstone lithofacies	Poorly sorted, coarse- to medium-grained sandstone with abundant granule-size clasts of subangular to angular quartz and feldspar. It indicates a local variation in the energy condition and the influx of sediments from the nearby area	Fluvial
	Dark brown bioturbated sandstone lithofacies	Hard and compact, dark brown, medium-grained sandstone showing nodular tendency. The unit also shows high bioturbation and lack of mechanically formed sedimentary structures The extensive development of crustacean community animals shows well-oxidized environment	Fluvial
Argillaceous association	Yellowish-brownish-greenish clay–siltstone lithofacies	Dominance of argillaceous clayey sediments with faintly laminated, thin silty beds. Occurrence of abundant calc–marl concretions The unit shows quite water environment allowing suspension of fine sediments	Lacustrine
	Light grey silty clay with concretions lithofacies	Silty clay argillaceous facies having abundant calc–marl concretions distributed irregularly in the lithounit It indicates a restricted, comparatively deep water environment having low energy condition. The presence of angular sand size grains revel the influx of coarse sediments from nearby source	Lacustrine
Calcareous association	Calcrete lithofacies	Characterized by both rizomorphic and nodular calcret horizons. The later includes the clasts of chert, basalt and green sandstone The lithofacies is interpreted to be a product of subaerially exposed, low gradient, alkaline flat environment	Pedogenic
	Nodular limestone lithofacies	Hard and compact, micritic limestone having subangular to subrounded, medium to coarse detrital grains of quartz, and, angular to subangular clasts of large size chert up to 3 cm. Beds show the nodular tendency On the basis of micrite as the dominant constituent and lack of internal bedding structures, it is interpreted to be a deposit of alkaline flat environment having low energy condition	Food plain
	Chertified limestone lithofacies	Hard and compact chertified miciritic limestone; sedimentary structures are mostly defused. Beds and lenses of chert are also present It is interpreted to be the continuation of depositional environment as of the previous lithofacies; however, reduced alkalinity may be due to the influx of the siliceous dust produced by the volcanic activity	Flood plain
	Intraformational Breccia limestone lithofacies	Hard and compact, brecciated lithounit having abundant, large size angular to subangular clasts of nodular limestone, chertified limestone and basalt Irregular occurrences of angular clasts of preceeding lithologies in the micritic groundmass show its deposition by sediment gravity flow. It might be a localized phenomena	Gravity flow

to be a deposit of point bar environment. Similar sandstone lithofacies of the Słupiec Formation is also interpreted to be a deposit of braided river channel zone environment (Kurowski 2004). Green claystone and green sandstone are reported from Neogene fluvial and lacustrine deposits of Konya basin, central Antonia, Turkey (Kadir and Karakaş 2002). Cross-stratified

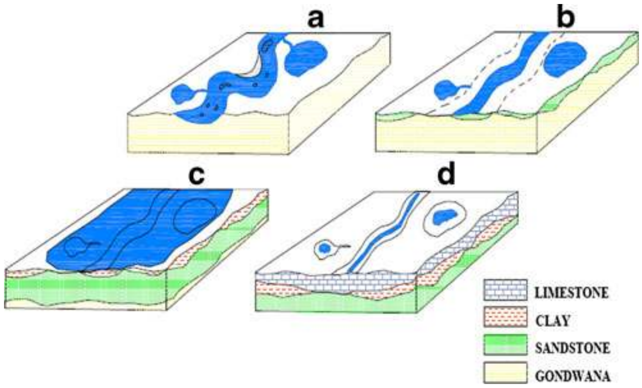

Fig. 13 Schematic model of the depositional environment for Lameta sediments: **a** closures of the Gondwana deposition followed by the initiation of Lameta sedimentation as channel floor, point bar deposits; **b** development of lakes allowing deposition of fine-grained argillaceous sediments and change of river course adding new depositional sites; **c** a high stand of water level overflooding the entire area including lakes during which large sheet-like deposits have taken place and **d** low stand of water due to hot and dry climatic conditions causing reduction of sites for fluvial–lacustrine deposition that ultimately terminated due to volcanic activity. Pedogenic activities might have taken place at any stage but more pronounced during B stage

green sandstone as well as couplets of green sandstone and red sandy mudstone are also reported from the Transylvanian and Hateg basin, in which earlier is considered to be a deposits of point bar environment (Therrien 2005). The colour variations of various lithounits also indicate a change in physicochemical conditions of the environment. Miall (1996) summarized that the drab colour, i.e. grey, green and brown are generated largely by ferrous oxide or carbonates (e.g. siderite) in reducing environment, whereas red, yellow and orange are created by ferric oxide, notably hematite, in oxidizing environment.

Subaerial exposures of the sediments and pedogenic activities are well evident by the occurrence of two different calcrete horizons at Salbardi area. Prevalence of pedogenic features, such as rhizoliths, mottling and carbonate nodules, indicates widespread subaerial exposure, episodic sedimentation and incipient soil formation (Huerta and Armenteros 2005). The calcretes exhibiting cylindrical tubes, mottling and clasts may indicate a boundary between palustrine and pedogenic environments (Alonso-Zarza and Tanner 2003; Hanneman and Wideman 2010). Pedogenic features of dinosaurs bearing fluvial deposits of Transylvanian and Hateg basins are considered to be an indicative of a climate characterized by seasonal precipitation, in which evapotranspiration is more than precipitation (Therrien 2005).

The bioturbated lithofacies shows high growth of the fauna and complete churning of the sediments by the benthonic community. It reveals an almost stagnant, low energy condition of the environment and may occur in ponds, abundant channels, in which laminations may occur due to rhythmic suspension or very low energy condition under flows; however, such stratification is commonly destroyed by the activities of organisms which leads to bioturbation, ultimately churn and mottle texture develops, in which stratification may be rare or absent all together (Reading 1986; Miall 1996). The growth and development of concretions also indicate stagnant or, very low energy condition of depositional environments, in which these structures could have been formed and preserved. Noticeably, up to this stage, baring the pedogenic calcretes, there is a complete lack of any other carbonate deposition and the entire lithocolumn can be considered as a product of matured braided river system, producing point bar and lacustrine deposits in semi-arid condition. This lower half of the succession including argillaceous lithofacies including nodules and concretions, arenaceous lithofacies and calcrete lithofacies are comparable with Upper Karoo strata of Tuli basin, South Africa (Bordy and Catuneanu 2001). Here, the lithouints showing interbeddings of mudstone, calystone and siltstone with arenaceous units are considered to be a suspension in interchannel stagnant pools; the argillaceous strata may show a deposition from ephemeral lakes; the paleosol features like calcrete, concretions and rhizoliths indicate that the landscape was stable over a long period (Bordy and Catuneanu 2001)

Major change in the environmental condition is clearly reflected by the nature and pattern of afterward deposits covering almost upper half of the succession. During this period, the environment was dominantly alkaline as the carbonate sediments are the main products. The fluctuation from non-alkaline to alkaline environment is represented by alternate horizons of clays and nodular limestones at Salbardi area as well as complete lack of terrigenous materials. The bedding geometry of the calcareous unit, viz. nodular limestone and chertified limestone, indicate a sheet flood environment (Fig. 13c). The closer of the Lameta sedimentation took place probably with the beginning of lava eruption which caused tremendous reduction of surface water bodies (Fig. 13d). The intraformational breccia having micritic matrix and larger clasts of contemporaneous basalt and preexisting rocks of the Lameta succession though indicates the extension of earlier prevailing alkaline flat environment; however, the depositing medium was viscous than the normal stream currents. Similar breccias are also reported from the Karoo fluvial strata (Bordy and Catuneanu 2001).

The dominance of micritic limestone is also reported from the Licho Formation, Balbuena Subgroup of the Cretaceous-Paleocene Salta Group, northwestern Argentina, and is interpreted to be the deposits of lacustrine to fluvial–lacustrine flood plains (Marquillas et al. 2005). The micritic limestone with chert nodules of the La Yesera Formation of the same group is reported to be a characteristic of shallow subaqueous environment (Marquillas et al. 2005). The source of carbonate in fluvial setting happens to be biochemical and physiochemical precipitations, as well as supply of the calcium from the preexisting source (Glass and Wilkinson 1980). The possibility of preexisting source for various types of carbonates in the present successions is being completely ruled out as the underlying thick piles of Gondwana succession is devoid of limestone. Precipitation through biochemical process is also unsupported as no algal remain has been indentified in thin sections. Therefore, it is interpreted that the carbonates were initially deposited by chemical precipitation followed by their silicification due to physico-chemical processes in different climatic conditions, producing nodular and chertified limestones.

Both nodular nature and chertification of the limestones seem to be post-depositional changes. The nodular nature may be formed mechanically by flowage of semiconsolidate sediments (Pettijohn 1984). In the present rocks, the internodular spaces are noticed to be filled with chert which is secondary in nature. The chertification of limestone in non-marine condition is normally considered as a post-depositional process due to siliceous solution (Pettijohn 1984; Sengupta 1996). A decrease in temperature and alkalinity (pH >8) increases the solubility of silica in water and in alkaline lakes, silica may precipitate from sodium silicate gels, produced during weathering of rock forming silicates (Sengupta 1996). The same is considered be an acceptable process for the chertification of limestones as the entire unit is highly calcareous and devoid of silicate minerals; therefore, replacement by silica solution was probably the main cause for chertification.

Beds and lenses of chert, as well as chertified limestones are reported from fluvial–lacustrine deposits, Durham Triassic basin, North Carolina (Bain and Harvey 1977). They interpreted that the precipitation of chert in Durham Triassic basin is due to seasonal fluctuation of alkalinity due to periodic dryness of the lake causing rotting of vegetation that reduced the alkalinity and facilitated chert precipitation (e.g. Peterson and Von der Borch 1965). Carbonate–chert facies of Oligocene–Miocene, lacustrine, Medicine Lodge Beds of Southwest Montana, USA, revels that chertification of the limestone and stromatolitic bioherms is due to replacement diagenesis of carbonates during and/or after deposition (Flores and M'Gonigle 1991). Abundant chert beds are reported from the Lower Oligocene, lacustrine Valledoria Member of the Elephant Formation, Angola, Sardine, and are interpreted to be formed due to increased hydrothermal circulation; however, the sources of silica for these cherts were volcanic ash which was supplied through fallout (Sowerbutts 2000). The sources of silica for the present chertified limestone is, however, not clear but there is a possibility from the volcanic dust as the overlying successions are a result of extensive volcanic activity producing Deccan basalt.

Conclusions

Detailed field investigations, megascopic and microscopic studies of Late Cretaceous Lameta sediments exposed at three nearby areas reveal fluvial–lacustrine environment of depositions.

- Lithofacies associations are identified in the successions, i.e. arenaceous in lower part, argillaceous in middle and calcareous in upper part.
- The sedimentation of the arenaceous sediments starts with visible break in deposition after termination of Gondwana; however, the sediment source was probably the same. The energy condition was fluctuating during the deposition as high during green sandstone and low during bioturbated sandstone.
- Argillaceous lithofacies, in general, show a clam and quite water condition of lacustrine set-up. However, periodic recharge of lakes is evident by intermittent thin horizons of coarse-grained sandstones.
- Pedogenic activities represented by rhizomorphic calcrete and nodular calcrete beds show subaerial, low gradient, alkaline-flat environment.
- A change of physico-chemical conditions resulting to alkaline flood plain environment is well represented by nodular micritic limestone. It shows an upward increase in chertification resulting to distinguishable chertified limestone. High condition of silica might have got its sources from volcanic ash as a precursor of huge volcanic activity resulting to overlying regionally exposed Deccan basaltic Trap.

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