Characterization of Marine Interval within Neoproterozoic Cave Temple Arenite, Badami Group

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by

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Dedicated to

My friends &

My parents

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CERTIFICATE

This is to certify that **Mr. ENJAMAMUL HAQUE** of M.Sc. Final Year, 2019, bearing Exam Roll Number **MGEO194023** and Registration Number **128256** of **2014-15**, has worked under my guidance in the Department of Geological Sciences and completed his M.Sc. Thesis Dissertation entitled **"Characterization of Marine Interval within Neoproterozoic Cave Temple Arenite, Badami Group"** which is being submitted towards the partial fulfillment of his M.Sc. Final examination in Applied Geology in Jadavpur University.

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"Geologists have a saying- Rocks remember"

-Neil Armstrong

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Abstract

Meso- to Neoproterozoic Kaladgi Basin, located on the north-western fringe of the western Dharwar craton, is comprised of deformed, older Bagalkot Group and the overlying undeformed, younger Badami Group, exposed mainly in the western and central portion of the Basin. The terrestrial sedimentary units overlying the Chitradurga Schist Belt and/or Peninsular Gneiss in the southeastern margin of the western portion of the Kaladgi Basin, is characterised by multistoried conglomerate and sandstone with some occasional finer shale to siltstone bodies, belonging to the basal Kendur Conglomerate Member and Cave Temple Arenite Member of the Badami Group. The entire succession comprises of three cycles within which lower and upper part is considered to be fluvial in origin but the middle one comprised of fluvial to marine interval, with a transitional unit, in between Amply preserved primary structures, enable one to apply state-of-the-art facies analysis scheme for the entire succession, which revealed major seven genetic facies, combined in to two distinct facies associations. The first of which represents fluvio-marine transitional association, characterized by intercalating occurrences of both unidirectional traction current and bidirectional wave induced current generated facies. The other association is entirely marine, with its thoroughly wave induced texturally matured sedimentary bodies. It covers a wide paleogreographic range within marine realm, ranging from beach foreshore to offshore. Deposition apparently took place in an open wave-influenced shelf, frequently experiencing storm activities. Sequence architectural studies delineate broadly about the sea-level changes during the deposition of this marine interval. The stacking pattern actually give a sense about, the overall transgression and regression of this western sector of Badami group. The overall marine encroachment towards land from the west side is depicted by correlating of synthetic section found at different locations. The whole succession documents several coarsening upward parasequences, distributed ina fashion to depict an initial deepening upward trend followed by a shallowing upward trend with an intervening shale-rich maximum flooding zone. Resting over the lowstand fluvial wedge, the marine transgression is initially slower, leading to the development of a thick transitional interval. Following transgressive systems tract (TST) culminates into a MFZ, and in turn is followed by the normal regressive highstand systems tract (HST). Unconformably overlying fluvial sediments of the topmost cycle, marks the termination of the sequence of middle cycle. Presence of mat-induced primary structures within the studied interval, not only attest the marine origin of that

particular studied area, also gives a clear picture about the upper shoreface to middle shoreface paleogeography of the basin.

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INTRODUCTION

1.1 Introduction

Sediments and sedimentary rocks make up 75 % of earth surface. Though they contribute for only 5% of the total earth’s crust within a few 100 meters thickness of sedimentary rocks there lies thorough geological history featuring every minute details, regarding the process of formation, energy condition, depositional environment and provenance. In Indian subcontinent Precambrian sedimentary basins hold an account for a lion’s share of intricate geological information of how surficial processes shaped and curved the cratonic face of primordial, antediluvian earth. Within these Precambrian basins mainly two major types are identified within Indian shield during Proterozoic time. The older commonly deformed and highly metamorphosed, basins are generally of Paleoproterozoic age, represented by Aravalli-Delhi-Bijawar-Sausar-Sakoli etc. The other comparatively less metamorphosed as well as less deformed ones show Meso to Neoproterozoic age, represented by Cuddapah-Vindhyan-Kaladgi-Bhima, although recent discoveries of Paleoproterozoic age of Vindhyan (Rasmussen et al., 2002; Ray et al., 2002) preclude its Mesoproterozoic age. Never the less these sedimentary field basins of Meso to Neoproterozoic are also known as ‘’Purana Basins’ of India.

Kaladgi Basin is one of the Purana basin of India situated in south-western part of Indian shield. It is confined between 73º to 76º30’E longitudes and 15º30’ to 17ºN latitude covering area of about 8300 square km extending over Bijapur, Belgaum, Bagalkot and Dharwar districts of Karnataka and Kolhapur and Sangi districts of Maharashtra. Presumably a higher aerial extend is expected as the basin is covered in eastern and southern side by Deccan Trap Volcanics. The Kaladgi Basin earns its name after a place called Kaladgi which is placed almost in the central part of the basin and around which rocks of these basin had first observed. There are some controversies regarding the structural thickness of Kaladgi Basin. According to Kale (1991) geophysically estimated maximum thickness is about 7000 mts. among which only 2800 mts. is exposed, distributed along the total extent of the basin. Whereas according to Jayaprakash et al. (1987) the total thickness of entire Kaladgi Supergroup is 4527mts. The basin is saucer shaped with east-west stretching in which direction it is about maximum 200 kms long compared to the maximum 100 km long N-S direction (Hegde et al., 1994).

1.2 Previous Works

There are several ideas regarding the origin of Kaladgi Basin due to the similarity and outcrop distribution between Kaladgi and Gondwana Basin it has been considered to be a graben like basin (Hegde et al., 1994). Jayaprakash et al. (1987) attributed the initiation of Kaladgi basin to a set of lineaments trending E-W Hegde et al. (1994) inferred that the Kaladgi basin probably initiated through E-W trending rough faults over the Precambrian basement rocks, which is supported by the presence of an E-W trending about 10km long fault along the present southern boundary of the Kaladgi basin (Foote, 1876). Radhakrishna and Vaidyanathan (1997) considered Kaladgi as an “epicratonic” basin which have formed over already stabilized Dharwar craton(cratonisation of Karnataka had occurred by 2500 my). The mature orthoquartzite sediment has likely to be derived from the stable Dharwar craton.

1.2.1 Stratigraphy

The name “Kaladgi Series” was originally coined by Foote (1876) for the rocks deposited in an intracratonic basin around the town Kaladgi. Initially the Kaladgi Series was divided into a lower and upper series by Foote mainly by lithology and structure. Foote included that the sandstones around Badami and other similar horizons as the uppermost division of lower Kaladgi Series. Later workers described the Kaladgi Series as almost horizontal series of sedimentary rocks resting unconformably on the crystalline schist and gneisses of the Dharwar system. Pascoe (1949) and Krishnan (1982) rearranged the classification into a four-fold division considering lithology as well as grade of deformation. Nautiyal (1996) classified the Kaladgi sediments on the basis of metamorphism, tectonic cycle and igneous activity of the Precambrians. A sheared unconformable contact of the Kaladgi with the underlying Dharwars has been postulated (Nautiyal, 1996). Another unconformable contact between the lower and upper Kaladgi Series has been identified on the basis of which a new group has been recognized (Viswanathiah, 1968). There has been a controversy regarding the recognition of this new group. Recent work has considered the existence of Badami as an younger group within the Kaladgi, separated by an angular unconformity. Viswanathaiah (1977) classified the younger Precambrian sediment of this area (excluding Badami sediments) into Kaladgi and Badami Groups with a clearly recognizable unconformity between them. Kaladgi Group represents a more deformed as well as metamorphosed and is about 1400mts thick breccia-conglomerate-quartz, arenite-argillite-carbonate assemblage, whereas Badami represents a mildly metamorphosed and less deformed gentle dipping quartz-dolomite assemblage (Viswanathaiah, 1977). The recent and most popular classification of Kaladgi Basin has been put forward by Jayprakash et al. (1987), where Kaladgi gets the status of super group which is subdivided into a lower Bagalkot and upper Badami Group, with an angular unconformity within them (Table. 1). Petrologically the composition of quartzite between these two groups differ significantly (Radhakrishnan and Vaidyanathaiah, 1997). These two groups occupied relatively different positions within the Kaladgi basin, while Bagalkot Group is restricted in the eastern part of the basin bordering the Badami Group, the Badami Group is mainly exposed in western part of the basin .

Kaladgi Super Group is divided into lower Bagalkot and upper Badami Group. Badami Group is subdivided further into lower Kerur Formation and upper Katageri Formation. Kerur Formation is subdivided into four members, from bottom to top, which are Kendur Conglomerate, Cave Temple Arenite, Halgeri Shale and Belikhindi Arenite . Main attention in this thesis paper is given on the Cave Temple Arenite member.

1.2.2 Lithology

As stated earlier Badami Group shows less metamorphism and deformation compared to Bagalkot Group. The total succession is made up of sandstones mainly with limestone and rare shale and conglomerate (Table. 1). The basal thin Kendur Conglomerate member is characterized by matrix supported polymictic lensoid bodies, followed by Cave Temple Arenite member which is quartz arenitic with coarse to medium grain size. This member shows overall fining upward trend with several cycles within. Each cycle itself shows fining upward trend as well. Overlying Halgeri Shale and Belikhindi Arenite Member made up a minor proportion of the group. The Kerur Formation, consisting of the above mentioned members are followed by Katageri Formation, made up of a thin shale and overlying limestone unit. The conglomerate and sandstone members show very coarse to medium grain size with poor sorting as well as angularity. Internally the sandstones are characterized by trough cross-stratification with tens of meters set thickness. Both the shales on the other hand are characterized by planar lamination, rare wave ripples and reddish colour. The only limestone member of the group, Konkankoppa Limestone member, is characterized by dark colour, wave features and fine grain size.

1.2.3 Depositional Environment

Overall the Kaladgi Basin is considered to be an intra-cratonic one initiated over Dharwar Super Group (Hegde et al., 1994). Badami, being the younger counter part, deposited over meta- sedimentary Bagalkot Group of rocks, which is evident by the presence of quartzite and vein quartz pebbles within Kendur Conglomerate member, the basal member of Badami Group. Internal structures and cyclicity within the Cave Temple Arenite clearly indicate its marine origin. Shales clearly depic deposition in condition under wave influence. Geochemical studies of these shales indicate a shallow marine origin. Konkankappa Limestone also indicates shallow marine depositionas setting. Gowda et al. (1980) considered the limestone member to be deposited in a shallow marine agitated environment under high pH and CO_2 condition. The dark colour indicates a closed marine condition for this limestone (Radhakrishna and Vaidyanathaiah, 1997).

1.2.4 Age

In absence of reliable geo-chronological age data, the identification of micro-fossils within the Proterozoic segments are the common procedure for any “Purana Basin”. The basement has been dated as 3.29-2.6 Ga on the basis of Rb-Sr ratio using [$^{87}Sr/^{86}Sr$] vs. [$^{87}Rb/^{86}Sr$] plot (Jayaram et al., 1983; Rao et al., 1999). Bagalkot Group has been assigned a Middle Riphean age on the basis of stromatolite assemblage (Garuraja, 1983; Raha et al., 1982; Viswanathaiah, 1975). Subsequently Badami Group is considered to be post Middle Riphean. Sandstones in Badami Group enriched in a variety of organic micro-fossils, about 22 taxa of Coccoidal nanofossils with diameter- micron along with some Acritarchs have been identified.

1.3 Badami Group At The Western Sector Of Kaladgi Basin

The western sector of the Kaladgi Basin holds the Badami Group chiefly, overlying the Archean basement of Chitradurga Schist Belt, at places with a thin layer of lowermost Salgundi Conglomerate Member of Bagalkot Group in between. The Badami Group of rocks, though extensively developed, is represented by only the lower portion of the Kerur Formation, namely the Kendur Conglomerate and Cave Temple Arenite Member. Overlying members of the Kerur Formation as well as the Katageri Formation are not developed in this sector. Hence, study in this thesis paper concerns mainly with the Cave Temple Arenite Member only. The field work was carried around Belgaum, Karnataka at several places, namely Sirur, Bhantmuri ghat, Islampur, Gujanal, Kadapgatti-Yogikolla, Kakati, Bhantmuri and Bhutramatti, at the western part of the western sector of the Badami Basin. Bhutramatti and Islampur are situated north of Belgavi having a distance of20kms and 30kms, respectively(fig 1.1). Gujanal is placed towards north-east of Belgavi and is 25 kms from there. All the places are characterized by the presence of the Cave Temple Arenite Member. There is fluvial and marine margin at Kakati located north of Belagavi.

These areas showed beds which were dipping 25º towards west. Petrographically two distinct varieties are reconized within the total succession,. While the lower portion of many sections starts off with a texturally immature sandstone interval, followed by intercalation between texturally matured sandstone and siltstone bodies. The lower interval, wherever found, is thoroughly trough cross-stratified and made up of several fining upward cycles, with an overall fining upward trend also. Overlying texturally matured interval is characterized mostly by tabular cross stratified sandstone bodies as well as very fine silty ripple laminated bodies. The interval shows initial fining and then coarsening trend. The whole studied stretch, initial fining and then coarsening trend. The whole studied stretch, in turn, is overlain erosionally by a texturally immature coarse sandstone interval. All total there are 3 major cycles from bottom to top where the middle one comprising of matured sandstone bodies is the focal point of this study.

1.4 Scope of Work

With the aim set at beginning the following work plans are proposed:

1. Selection of locations and attitude study of beds in Deshnur, Marihal and Benchinmardi areas.

2. Detail facies analysis in Cave Temple Arenite Member of Kerur Formation and petrological study of facieses.

3. Interpretation of depositional processes from the facies attributes.

4. Determination of facies which are found to be associated with each other throughout the succession.

5. Documentation of vertical and lateral transition of facies and facies association.

6. Reconstruction of palaeogeography and palaeoenvironment of deposition.

1.5 Procedures

For execution of the self-imposed task the following work procedure was adopted.

 Identification, documentation and measurements of various sedimentary structures and their mutual relationship.

 Identification and characterization of different facies and their distribution.

 Distribution of different facies association both laterally and vertically.

 Vertical logging of these facies in available good section in order to demonstrate facies sequence pattern.

1.6 Equipment

Extensive fieldwork was the mainstay of the present work. For field purpose toposheets (bearing no. 48 I/9 and 47 L/12), hammer, clinometers, bran ton-compass, scales, tapes and camera were used. Well known methodologies like vertical logging were used most frequently. Petrographic studies made on reflected light microscope in direct correlation with specific field attribute that augmented the study. Specification of instrument used for petrographic studies in laboratories is given below.

1. LEICA DMLP microscope .

2. Canon 150 IS, Canon 120 IS camera for taking microphotograph .

SUPERGROUP	GROUP	SUBGROUP	FROMATION	MEMBER	THICKNESS(m.)
KALADGI SUPERGROUP	BADAMI		Katager	Konkankoppa Limestone	85
				Halkurki Shale	67
			Kerur	Belikhindi Arenite	39
				Halgeri Shale	3
				Cave-temple Arenite	89
				Kendur Conglomerate	3
	Angular Unconformity				
	BAGALKOT	SIMIKERI	Hoskatti	Mallapur Intrusive	7
				Dadanhatti Argillite	695
			Arlikatti	Lakshanhatti Dolomite	87
				Kerkalmatti Haematite Schist	42
				Niralkeri Chert-breccia	39
			Kundargi	Govindkoppa Argillite	80
				Muchkundi Quartzite	182
				Bevinmatti Conglomerate	15
		Disconformity			
		LOKAPUR	Yadhalli	Argillite	58
			Muddapur	Bamanbundi Dolomite	402
				Petlur Limestone	121
				Jalikatti Argillite	43
			Yendigere	Naganur Dolomite	93
				Chikkshelikere Limestone	883
				Hebbal Argillite	16
			Yargatti	Chitrabhanukot Dolomite	218
				Muttalgeri Argillite	502
				Mahakut Chert-breccia	133
			Ramdurg	Manoli Argillite	61
				Saundatti Quartzite	383
				Salgundi Conglomerate	31
Non-conformity					
Granitoids, gneisses and metasediments					

Table 1: Stratigraphic succession of Kaladgi basin

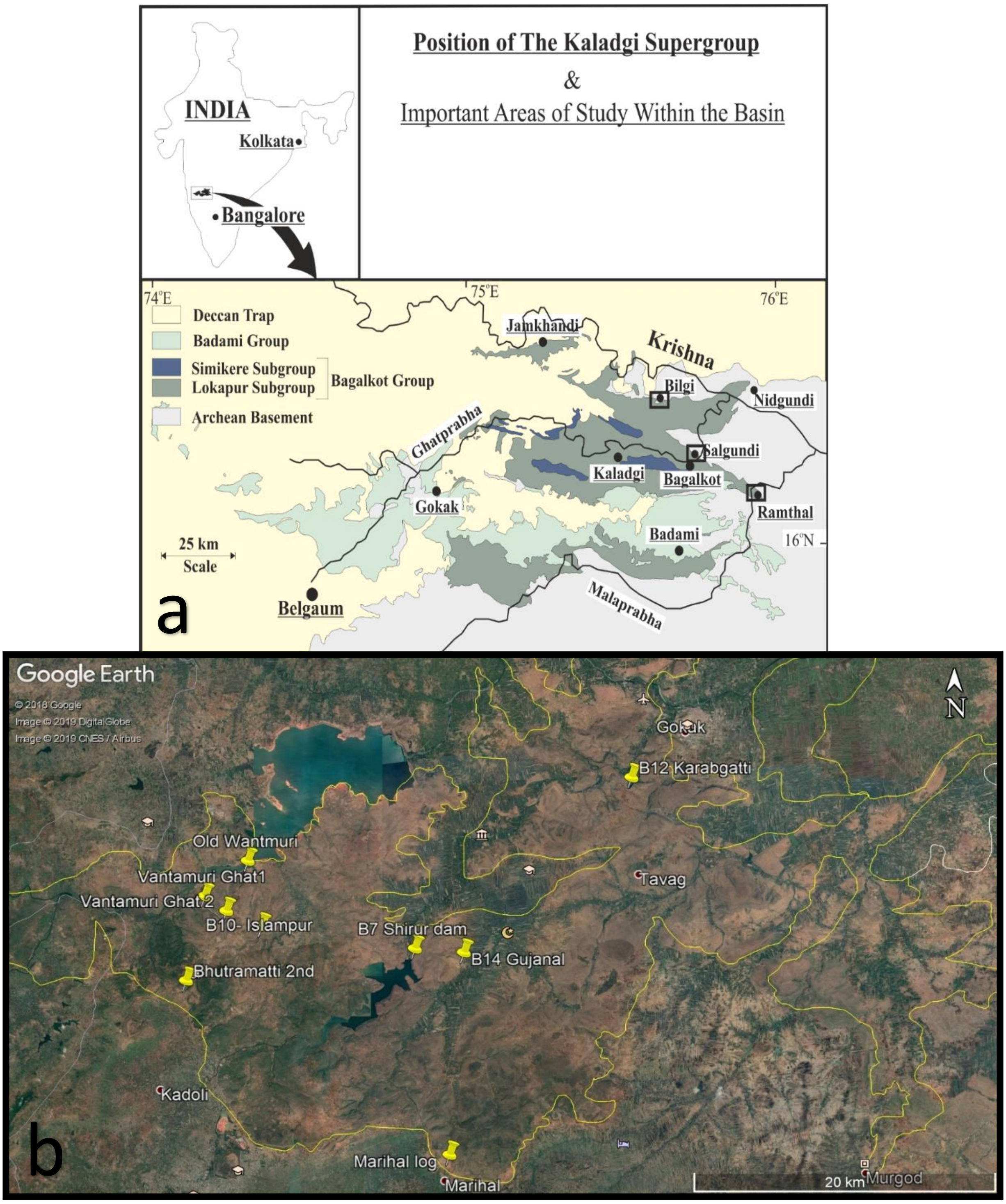

Fig.1.1 Introduction : a) Geographic Location and lithologic map of Kaladgi Basin (after Jayaprakash et.al., 1987). b) Location of the studied sections in the Kaladgi basin, with traced the boundary of the basin.

Chapter 2

FACIES ANALYSIS

An organized classification of the rocks deposited in an ancient sedimentary basin is an essential prerequisite to understand the modes of deposition therein. Therefore a detailed facies analysis is needed which deals with the genetic aspects of co-existing rocks for the above mentioned goal (Miall, 1980; Hallam, 1981; Walker, 1984; Reading, 1996).

In this study focus have been drawn to establish the marine paleogeography and sedimentological niche within the Neoproterozoic succession of Badami group of sediments in the western part of Kaladgi Basin, Karnataka. The ultimate goal is the reconstruction of the paleogeography and paleodepositional environment of the studied succession in terms of paleo-hydrodynamics and depositional agents. Keeping that in mind attempts had been made, in this thesis paper, to carry out the state-of-the-art facies analysis. Primarily, facies classification is based upon criteria such as lithologies, overall geometry, internal structures and nature of bounding surfaces of the sedimentary bodies (Walker, 1983), along with some basic petrographic characters, like mineralogical and textural maturity, which are also very much informative to delineate genetically different facies. State-of-the-art facies analysis not only encompasses erection of different genetically related facies, but also takes into account their distribution in time and space along with the nature of contact among themselves, to reveal a unique paleogeographic model for the studied area. Overall the studied interval suffered metamorphism, but primary structures, like trough cross-sets, decapped hummocks, ripple cross strata and planar laminations, are adequately preserved.

The Kerur Formation in the western sector of the Badami Basin shows a multistoried appearance overall. The total succession shows three distinct cycles, while the lower and upper cycle is entirely fluvial in nature, part of the middle cycles shows evidences of deposition under standing water body. In this thesis paper, main emphasis is given on characterization of the marine interval within the middle cycle. A transitional unit is found all across the studied stretch beneath the marine interval, which is also studied in detail.

2.1 Facies in the studied succession :

An unified facies classification covering all the exposed rock bodies in this area is done on the basis of lithology, texture and internal structures along with their body geometry, association and inter-relationship among themselves. Eight facies have been identified, which are described below in detail.

2.1.1 Facies A: Thoroughly trough cross-stratified sandstone facies:

This facies is characterized by fine to medium sand-sized tabular bodies of internally thoroughly trough cross-stratified sandstone unit(fig 2.1A). Both the bases and tops of such bodies are sharp, while the bases are sharper and erosional in nature. Rarely some planar laminated part underlies the thorough trough cross-stratification. Overall reduction in trough set thickness is discernible. Unidirectional ripple laminations, with long asymptotic toes, are often encountered on top of such bodies with markedly reduced grain size, hence a normal grading is discernible. Locally some thin reddish mud partings are found to intercalate the sandstone bodies of this facies. Desiccation cracks on thin discontinuous mudstone partings are also common. Commonly, this facies is seen to be overlain by ripple laminated fine sandstone facies (described later).

Interpretation: The presence of thorough trough cross-stratification clearly designated this facies as a fluid-gravity flow-product, where traction current is the sediment-transporting agent (Miall, 1992). Long asymptotic toes of the foresets indicate high amount of suspension fall-outs. Presence of trough cross-stratification, nonetheless, pointed towards dune migration, under unidirectional flow conditions. The normal grading as well as transformation from trough cross strata to ripple lamination indicate waning nature of a high energy flow. The initial high energy conditions are depicted by erosional bases of such bodies, along with rare presence of planar laminations underneath.

2.1.2 Facies B : Tabular cross stratified sandstone facies:

This facies is characterized by internally tabular cross-stratified bodies with broadly lenticular to tabular body geometry showing sharp upper and lower contact (Fig2.1B). Two distinct varieties can be distinguished based upon textural attributes and overall body geometries. One subfacies is characteristically broadly lenticular in body geometry with coarse sand-sized, poorly sorted grains showing a few oversized pebbles reclining on the bases of the foresets. The second subfacies, on the other hand, shows tabular body geometry with moderately sorted medium sand-sized grains (Fig2.1 B). While the former subfacies shows restricted occurrence and mainly associated with trough cross-stratified facies, showing consistent area-wise palaeocurrent direction, the second subfacies shows considerable distribution associated with hummocky cross-stratified and wavy parallel-laminated facies (described later) with opposite palaeocurrent direction to that of the former subfacies (area-wise).

Interpretetion: Large-scale tabular cross-strata represent avalanching of sediments along the lee-side of large aqueous bars under the influence of current (Collinson and Thompson, 1989; Blatt et al.,). From its textural immaturity as well as association the former subfacies clearly appears to be a product of in-channel high energy traction current. Conformable palaeocurrent direction with the dominant in-channel traction flow products pointed towards transverse bar origin (Smith, 1970; Olsen, 1988; Reading, 1996; Best et al., 2003; Labourdette and Jones, 2007). The latter subfacies, on the other hand, represents a product of current nonetheless, but of more stable and comparatively lower-energy flows, such as wave-induced currents. Textural maturity and association renders a standing water body origin plausible. Opposite palaeocurrent direction is probably produced by the migration of standing water body bars towards shoreline.

Facies C: Planar laminated sandstone facies:

This facies is generally characterized by medium to fine grained sandstone having tabular geometry and internal planar laminations. It is bounded by erosional surface both at the top and bottom. No definite trend of grain-size change is discernible within these bodies(fig 2.2A). Two distinct subfacies can be erected, depending upon their position with respect to the major erosional surfaces and associations. While the former one overlies major erosional surface and in turn almost always is overlain by trough cross stratified sandstone bodies, the latter variety used to occupy position just beneath the major erosional surfaces and overlies trough cross-stratified and/or tabular cross-stratified sandstone bodies with erosional contact. The latter variety shows parting lineations and rare rill marks on bedsurfaces. Petrographically the latter variety appears to be much more matured texturally than the former one.

Interpretation : Such bodies certainly indicate higher flow regime planar beds deposited under shooting tractive current (Cant and Walker, 1978). Position of such bodies, belonging to the former subfacies, over major erosional surfaces attests the presence of shooting flows towards the initiation of channel filling (Bose et al., 2008). On the other hand, planar laminated units with parting lineation and rare rill marks are likely to represent a beach environment (Sarkar et al., 2008).

2.1.4 Facies D: Ripple laminated facies: This facies is characterized by internally ripple laminated, cm-scale bodies made-up of fine sand to silt-sized material. Body geometry appears to be broadly lenticular with sharp but non-erosional bases. Two distinct subfacies are discernible, one shows unidirectional ripple laminations, while in case of the other, bidirectional ripple laminations are found.

2.1.4.1 Subfacies D_1:Unidirectional Ripple laminated sandstone:

Bodies of the former subfacies are rare in occurrence, often patchy, but invariably overlie the trough cross-stratified facies. Such bodies are mostly sandstones, varying between medium to fine sand-size, though some rare siltstone bodies are also discernible(fig 2.3A). Grains are moderately sorted, sub-angular to sub-rounded. Rarely, bedding surfaces contain current ripples (Fig.2.3A.), with few 5mm height and 8cm wavelength.

Interpretation: This facies represents product of ripple migration under lower flow-regime condition (Harms and Fahnestock, 1965; Simons et al., 1965). From the extent of textural maturity as well as nature of internal laminations first subfacies appears to be product of unidirectional traction currents. This facies typically marks the terminal period of channel filling. As water depth and velocity within channel decreases, larger dunes, previously moving on the channel floor, are replaced by the smaller scale ripples (Harms et al., 1975).

2.1.4.2 Subfacies D_2: Bidirectional Ripple laminated sandstone: The second variety overlies both the trough cross-stratified as well as the hummocky cross-stratified bodies (described later), and is mostly fine sandy to silty in nature, with well sorted subrounded grains. Bedsurfaces are replete with wave, combined as well as interference ripples (Fig.2.3.B). Rarely, some superimposed ripples are also found (Fig 2.3B).

Interpretetion: The above mentioned facies represent deposition under wave influence within standing water body. Extent of textural maturity also supports the contention. Presence of combined flow ripples pointed towards deposition under unidirectional current with some wave component . Interference as well as superimposed ripples, on the other hand, indicates deposition under wave generated current influence . Presence of such bodies over trough as well as hummocky cross-stratified bodies, clearly shows their deposition at the waning stage of storm activity .

2.1.5 Facies E: Swaley or Hummocky cross stratified coarse to medium grained sandstone facies:

This facies is characterized by coarse to medium sands-sized, moderately sorted sandstone characterized internally by hummocky cross-strata and externally by broadly lenticular to tabular body geometry with slightly convex-up tops. Bases of such beds sometimes replicate the underlying bedsurface and hence are sharp but non-erosional, in other occasions they are erosional. Tops of the beds are less sharp. Swaley cross-strata are the dominant internal structure, at least towards the lower portion of the succession, with rare hummocks, almost always decapped. Often a massive part underlies the swaley cross-stratified part. Occasionally, a ripple laminated part overlies the swaley cross-stratified portion with sharp contact. Rarely some large-scale combined flow ripples are encountered on top of such bodies. A faint normal grading is discernible. Amalgamations of such bodies are quite common.(Fig 2.4 A)

Interpretation : Hummocky or swaley cross-strata of wave length larger than 1m indicate strong wave action; possibly storm (Bose et al., 1997). Sharp transitions to overlying ripple laminated facies indicate sharply waning nature of the parent flow. Body geometry, dimensions and contacts of such swaley cross-stratified bodies with underlying and overlying ripple laminated facies pointed towards their origin under large, sharply waning waves with huge wavelength (Bose et al., 1997). Faint normal grading supports the waning nature of the flow. Erosive nature of the bases, as evident from the mud clasts, pointed towards comparatively shallower water condition. As swaley cross-strata dominate over hummocks in the lower part of the succession, the water depth appears to be shallow. Presence of decapped hummocks further attests the contention. Storm waves accord well with such a sharply waning waves with huge wavelengths.

2.1.6 FACIES F: Wavy Parallel laminated siltstone:

This facies is basically identified by parallel laminated siltstone. The overall laminae are laterally persistent bodies of siltstone and showing a wavy nature. It is characterized by very fine silty particle. (Fig 2.4 B)

Interpretation: Presence of mm-scale wavy parallel lamination within the siltstone beds clearly indicates deposition under wave influence (Reineck and Singh, 1980).

2.1.7 Facies G: Planar laminated shale:

This facies is characterized by internally planar laminated, laterally persistent bodies of shale, with well-developed fissile planes and local laterally extensive silt stringer. Laminae are usually mm-scale, though locally no primary structures are discernible. This facies is encountered all across the studied stretch, occupying basal position of the succession(Fig 2.5 A &B)

Interpretation : Planar laminae suggest settling of sediment from suspension under calm and quite condition. Energy level must be low to form this type of facies and water stagnancy is prerequisite condition.

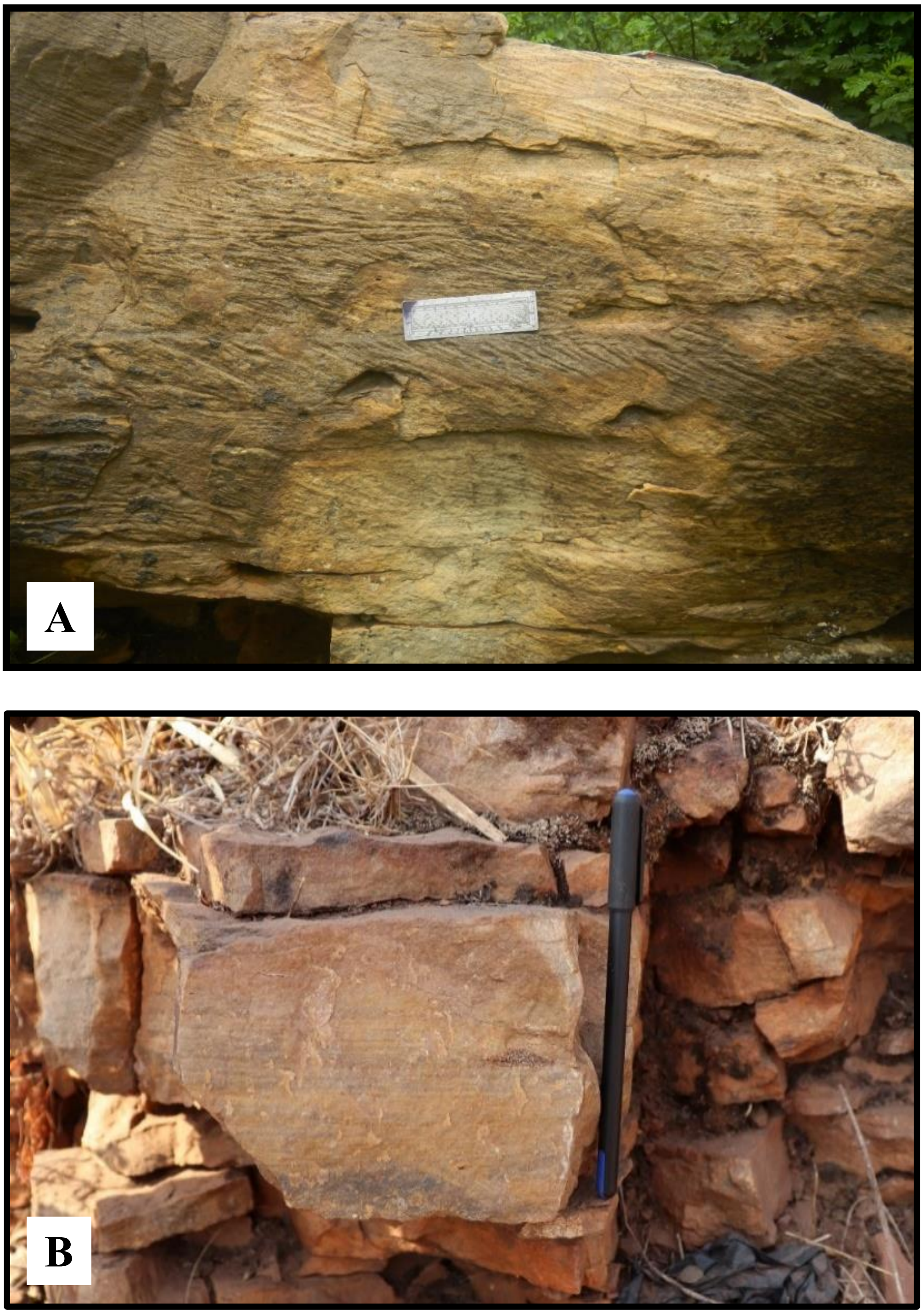

Fig.2.1 Facies analysis :A) Facies A,Thoroughly trough cross stratified sandstone facies. B)Facies B,Tabular cross bedded sandstone facies

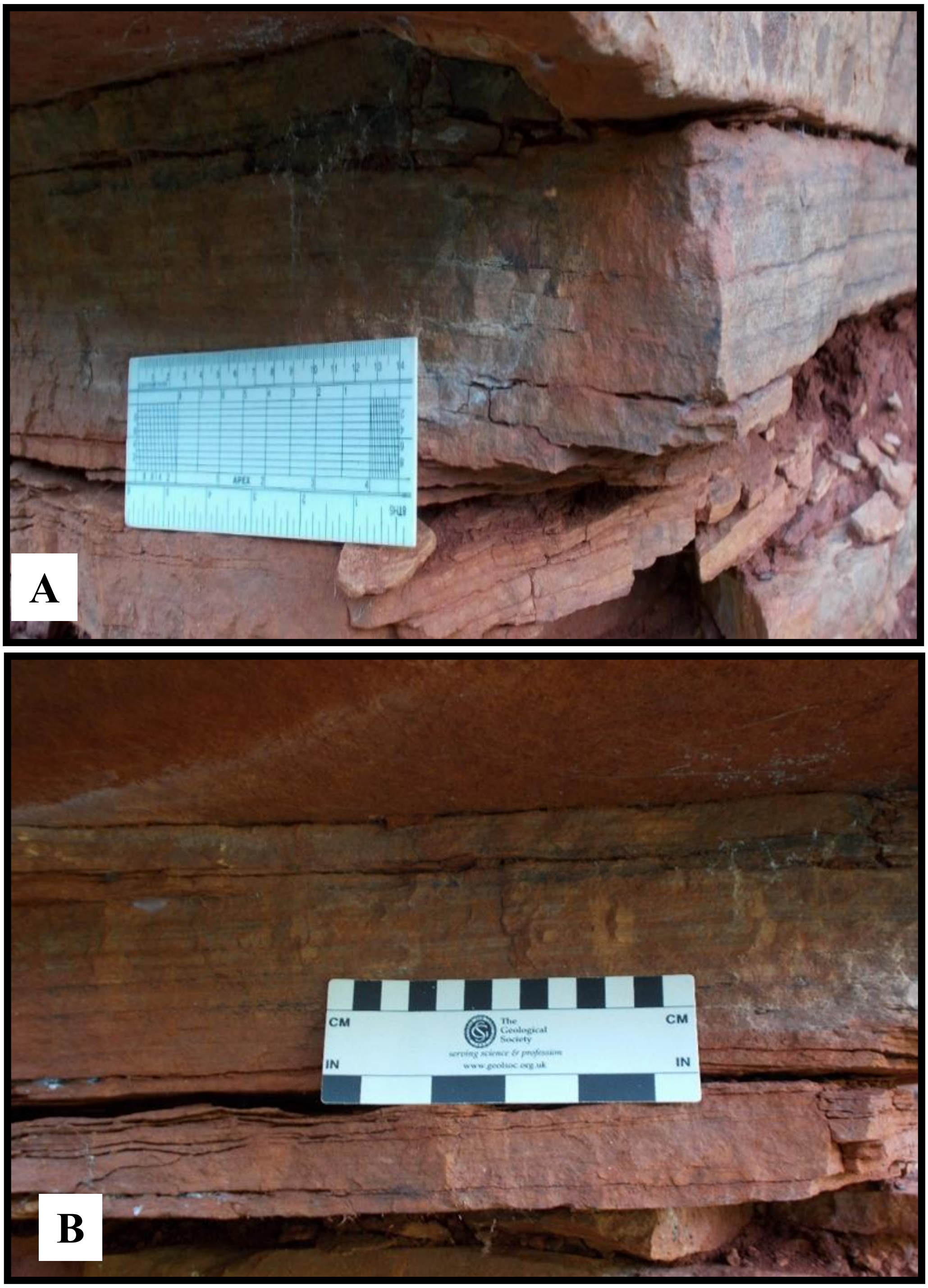

Fig.2.2 Facies analysis：A) Facies C Planar laminated sandstone. B)Facies C, Planar laminated sandstone.

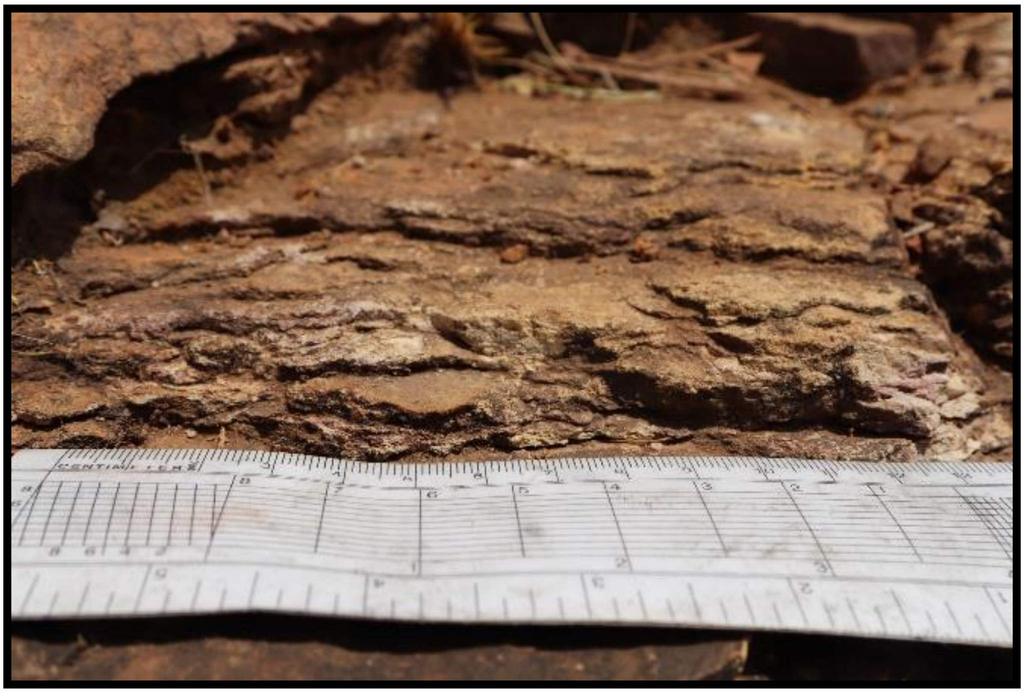

Fig.2.3 Facies analysis : A) Facies D_1 Unidirectional ripple laminated facies laminated sandstone. B)Facies D_2,Bidirectional ripple laminated facies.

Fig.2.4 Facies analysis : A) Facies E ,Swaley and Hummocky cross stratified sandstone facies B) Facies F, Wavy parallel laminated siltstone

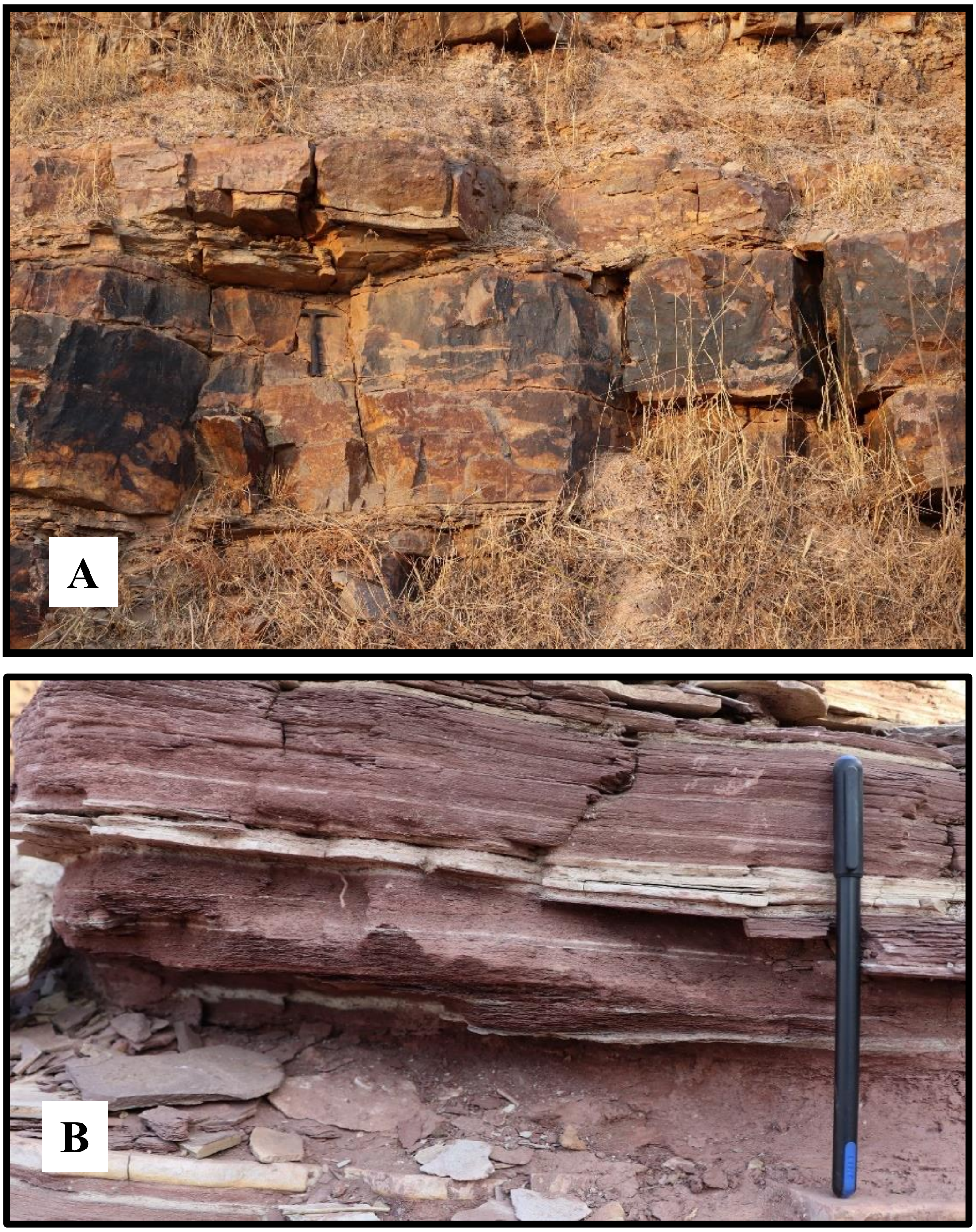

Fig.2.5 Facies analysis : A) Facies G,Planar laminated shale **B**)Facies G, Planar laminated shale

Chapter 3

FACIES ASSOCIATION AND SEQUENCE ARCHITECTURE

The state of art Facies analysis is inevitably an important and necessary tool for understanding the processes of sedimentation and variations in energy conditions. On the other hand, association of different facies together, tells something about the paleogeographies of deposition , and in turn about the ultimate environment of deposition. To infer consecutive and gradual changes in paleogeographies of different genetically related facies in time and space, one has to study the three-dimensional variations of facies associations. The ultimate goal regarding the clear understanding of the evolution of a basin, can only be achieved through systematic step-by-step analysis of the sediment deposited therein, following the aforementioned pathway. After the identification of different genetically related facies in the previous chapter, this chapter documents their association as well as distribution in time and space. For meaningful depositional environment or palaeogeographic extrapolation, grouping of genetically related facies, into facies assemblages, is done depending upon the more sensitive parameters, like body geometry, thickness, its position with respect to major erosion surfaces, pebble composition and more importantly, association (Collinson, 1969; Miall, 1980; Hallam, 1981; Walker, 1984; Reading, 1986). Such an association differs from each other in the total combination of facies within them, their mutual proportions, internal organization and body geometries, although a facies can be shared by different associations. In other words, a facies, whether authigenic or allogenic, may be a commoner in one association and aberrant in another; some may be exclusive for one association, though perhaps not common in occurrence (Mukhopadhyay, 2012). The combination of the commoners and the exclusive genetic facies within such natural associations provides the most dependable interpretation of palaeogeography and depositional environment. This chapter thus evolves through assimilating all significant field aspects to establish several paleogeography-based facies associations and to study their distribution in time and space, along with their petrographic properties, with the ultimate aim to gain insight about the evolution of the basin. The study has been perceived on visual appreciation of both lateral and vertical transitions, but is framed here on the basis of measured vertical facies successions at seven different locations of the field area, moving successively downslope away from the basin-margin, almost along the paleo-flow direction (from east to west and north-west broadly), as much as the outcrops permit.

3.1 Facies Associations:

It is pertinent to recall that the studied interval of the Kerur Formation of the Badami Basin comprises of marine and fluvio-marine transitional sedimentary successions, bounded below by fluvial sediments of Kerur Formation. The transitional and marine sediments possibly represent parts of Cave Temple arenite, Belikhindi Arenite and Halgeri Shale Members. The work spreads over about 30 km stretch along the western margin of the western sector of the Badami Basin (Fig. 1b), covering about 15 km present day basin margin stretch, between Bhutramatti and Sirur and , as well as 10 km basin interior stretch from Marihal, at southern margin, to Kadapgatti-Yogikolla in the north. The study documents total range of paleogeographic variation, both along and across the depositional dip direction amply through its excellent exposure quality. Hence, a holistic facies association scheme can be coined safely encompassing the variations encountered within the studied stratigraphic interval.

Overall eight facies have been found over this field area on the basis of grain size, grain shape, sorting, primary structure, current direction. From these facies, overall two broad facies association can be categorized. These are described below:

3.1.1 Facies association I:

This facies association, although occupy smaller proportion among the total studied succession, stands apart from other facies associations, having a unique facies assemblage. It comprises of six different facies, i.e., facies A, B, C, D_1, D_2 and E (mentioned earlier in Chapter-3). The association is dominated by facies A, B, D_1 and D_2 with less frequent occurrence of facies C, and E. two distinct packages are found to alternate within this association. The first package is chiefly made up of thoroughly trough cross stratified, normally graded sandstone bodies of facies A with highly lenticular body geometry, made of coarser to medium sand sized sediments, and very poor to moderate grain sorting indicate deposition through unidirectional traction current. Migration of three dimensional dunes represents fluvial channel fill deposits. They are often bounded below by poorly sorted planar laminated sandstone of facies C showing medium to coarse sized sand grains and above this some unidirectional ripple laminated sandstone of facies D_1 are also found within coarse sand sized sandstone body matted by unidirectional current ripples on the bed surface. Unidirectional ripples generated by some current action above the poorly sorted lensoid sandstone bodies again indicate fluvial condition. The normal grading as well as transformation from trough cross strata to ripple lamination indicate waning nature of the flow, in accordance with the gradual filling of the channel. The initial high energy conditions are depicted by erosional bases of such bodies, along with rare presence of planar laminations of facies C underneath. Distinct channel fills can be identified made thoroughly of trough cross stratified sandstones of facies A, sometimes along with facies D_1 on top, with thickness of trough sets decreasing upward. This assemblage is accompanied by presence of occasional facies B bodies, with rare presence of unidirectional ripples on bed surface. Such bodies used to show conformable paleocurrent data with that of the facies A hence they can be safely identified as the transverse barforms. This facies B sometimes transits upward to thoroughly trough cross stratified facies A through a sharp erosional contact indicating migration of channel fill deposits over the bar forms. This indeed represents fluvial depositional setting.

The second package of the association is characterized by comparatively matured, medium sand-sized sandstone bodies with plenty of wave-generated structures within. Trough cross stratified facies A bodies are present within this package also, but in lesser proportion. Bidirectional ripple laminated facies D_2 bodies form about the same proportion as facies A. The ripple laminated bodies are tabular in geometry. Presence of bidirectional interference ripples, combined ripples and tabular body geometry indicate deposition through wave induced traction currents within a standing water body. Facies B is also observed along with both large tabular cross stratified bodies and smaller low angle tabular cross stratified bodies made of medium to fine sand along with rare presence of planar laminated, well sorted, medium sand sized sandstone of facies C underneath, formed under high energy shooting flow within shallow water column. This indicates a waning energy, while textural maturity of sediments and presence of combined ripples on the surface of facies B indicate reworking under wave influenced depositional environment. Occasional presence of parting lineations on the bed surface of large tabular cross stratified sandstone of facies B and shallow trough cross stratified bodies of facies A again indicate high energy flow in very shallow water. Facies A and B are rarely topped by highly lensoid swaley or hummocky cross stratified, moderately to poorly sorted, coarse to medium sand sized bodies of facies E with erosional base. These are products under storm generated waves within shallow marine regime. Presence of bidirectional ripple laminated sandstone of facies D_2 on top of facies A, B, C and E implies waning nature of wave induced current. Even wave ripples and combined ripples are preserved on top surface of facies A, B and E which indicate deposition under wave and wave influenced current in a shallow marine environment. Altogether these assemblages infer a marine facies group.

Because of alternations between unidirectional traction-dominated and bidirectional wave-dominated packages and its position just beneath the thick, entirely wave featured marine stratigraphic segment (discussed below) in most of the suuccessions, this facies association is identified as transitional between the fluvial and marine environments, namely fluvio-marine transitional facies association, where fluvial assemblages decrease and marine assemblages increase upward both in thickness and frequency of occurrence.

3.1.2 Facies association II:

The facies association is characterized by well sorted, texturally matured sandstone bodies, with broadly lenticular to tabular body geometries. Although the association is chiefly arenaceous, local concentration of silty to clay material is common, especially towards middle portion of the interval. This association is made up of facies B, A, E, F and G, with subordinate amount of faciesD_1, D_2 and C. Thoroughly trough cross stratified bodies of facies A are normally graded, with well sorted medium sized sand sediments, concave base and lensoid body geometry. They gradually transit into ripple laminated facies D_2 and occasionally up to finer sediments of facies F and G. The bed surface of both facies A and medium grained sandstone of facies D_2 have been found matted with bidirectional combined flow ripples or multiple set of interference ripples. This clearly indicates a waning flow and deposition under wave induced current or wave action within a standing water body. Presence of wavy parallel siltstone infers deposition from suspension load under wave action, where planar laminated shale is the product of suspension fallout within standstill deep water, below wave base. Hence, a lower shoreface paleogeography is evident. Facies F and G co-exists as alternating interbeds of shale and siltstone with occasional presence of ripple laminated very fine sand to siltstone of facies D2 and rare facies C bodies. This area clearly indicates deposition from alternate suspension fall out and traction current. Hence, a paleogeography between fair weather and storm wave base can be inferred (Ref). Rare planar laminated bodies refer to allochthonous high energy flows generated from shallower part of the shelf, owing to storm activities. Large tabular cross stratified, well sorted, medium sand sized sandstone bodies of facies B are present with interference ripples and combined ripples on bed surface, indicating subaquous marine bars, moving towards the shore under wave influence. Presence of swaley and hummocky cross stratified bodies of facies E along with erosional base above trough cross stratified bodies and ripple laminated bodies indicate storm induced deposits at shallow shelfal region. Presence of decapped hummocks indicates further reduction in depth. Presence of ripple laminated bodies with plenty of bidirectional as well as interference ripple pointed towards waning nature of the storm events, leading to the deposition of low energy ripple laminated portion, towards shallower depth, as inferred from the presence of interference ripples. Alternate trough cross stratified bodies reflects deposition under unidirectional wave generated currents, in areas above the breaker zone. Paleocurrent directions acquired from these troughs indicate shoreward movement of the subaqueous dunes. Planar laminated sandstone of facies C can be observed rarely beneath both the trough and tabular cross stratified bodies and above the swaley cross stratified bodies, having sharp but non-erosional contact between them. Scarcely some entirely planar laminated comparatively thinner bodies are found having parting lineations on bed surface and scours and gutters at the base. Such bodies imply deposition from high energy shooting flow generating turbulent eddies. A beach paleogeography can be inferred. Succession comprised of facies assemblage of facies G, F, D_2, C, A, D1 and E can be found together in a coarsening upward package of sediments where gradual transition from facies G and F with occasional presence of D_2 occurs up to facies C, A and D_1 respectively with more frequent occurrence of facies E towards the upper part. This package is a product of shallowing up system tract within a marine standing water body and presence of combined and wave ripples on top of bed surfaces of several facies support the marine origin. While hummocks are found with comparatively finer sediments of deeper part, increased occurrence of decapped hummocks and swales infer shallower part affected by storm-weather wave base.

Altogether the facies assemblages of this association represent a marine environment and its deposits within a standing water body under the influence of wave and storm induced current. Paleogeography varies from beach foreshore to lower shoreface, below the storm weather wave base.

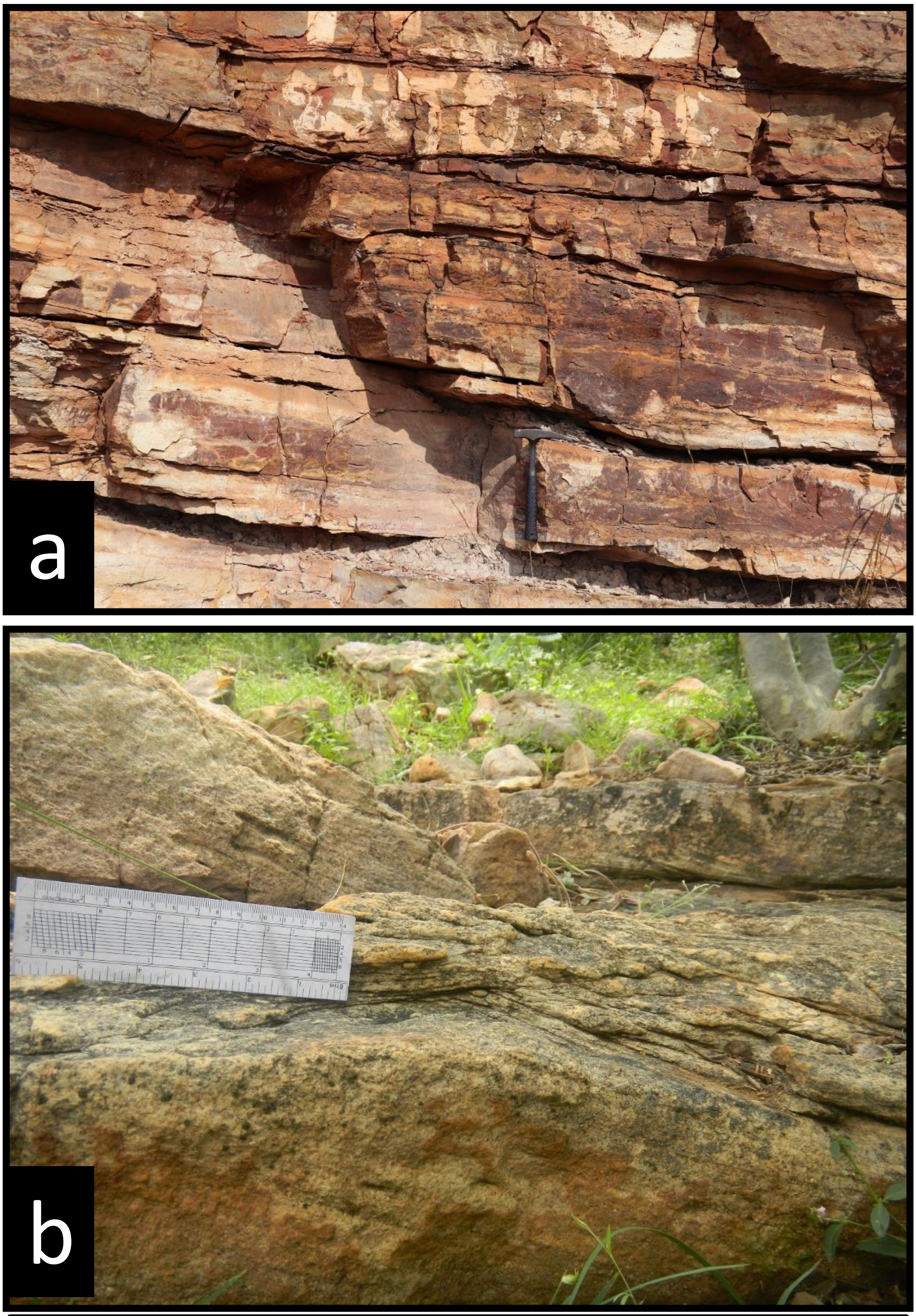

Fig. 3.1.1 Facies association: a) Gradual waning up succession by tabular cross stratified facies followed by planar laminated shale facies b) Bidirectional ripple laminated indicating wave induced current features

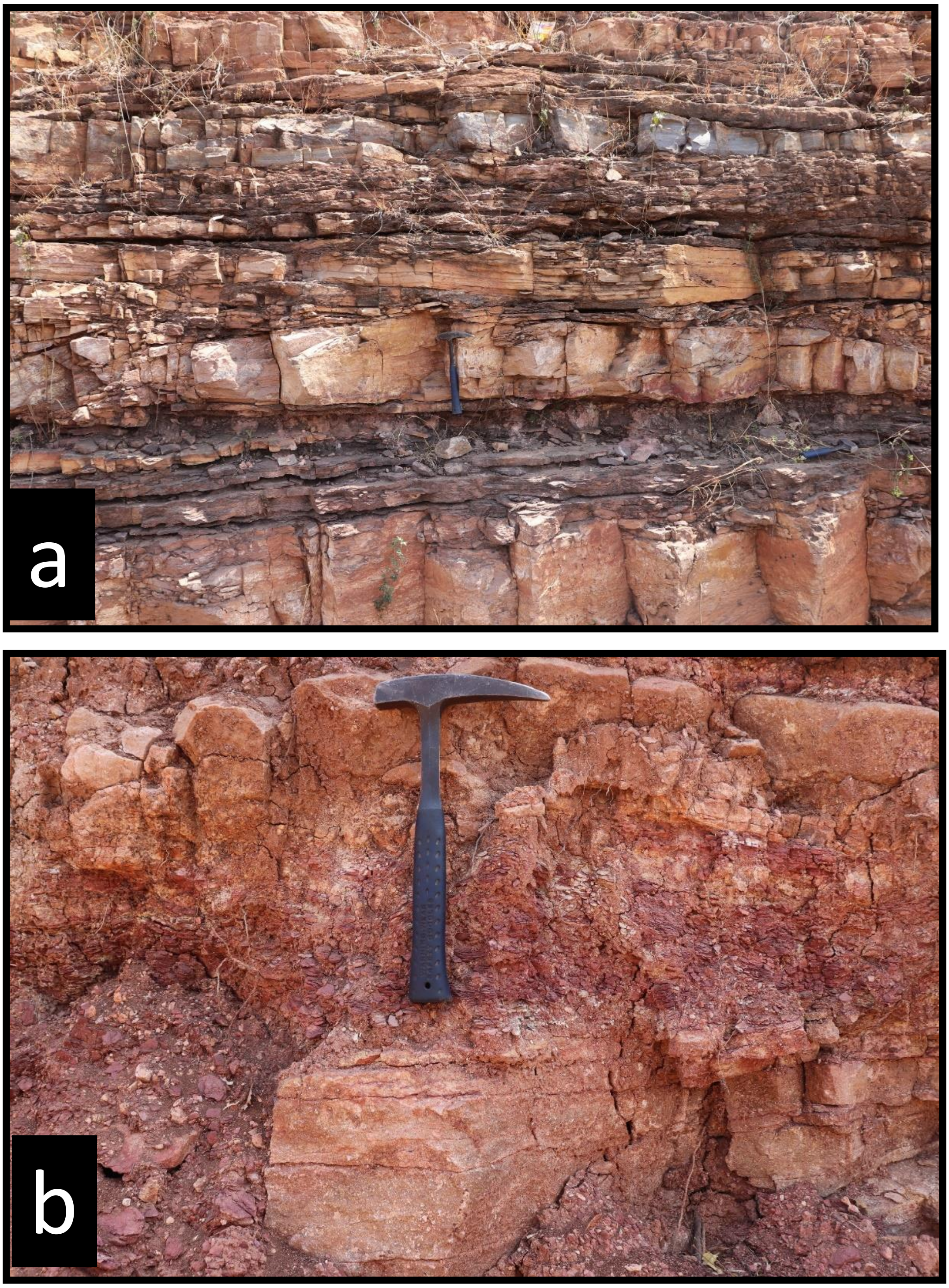

Fig 3.1.2 Facies association: a) Shallowing upward trend showing parasequence. b) parallel laminated shale to siltstone facies.

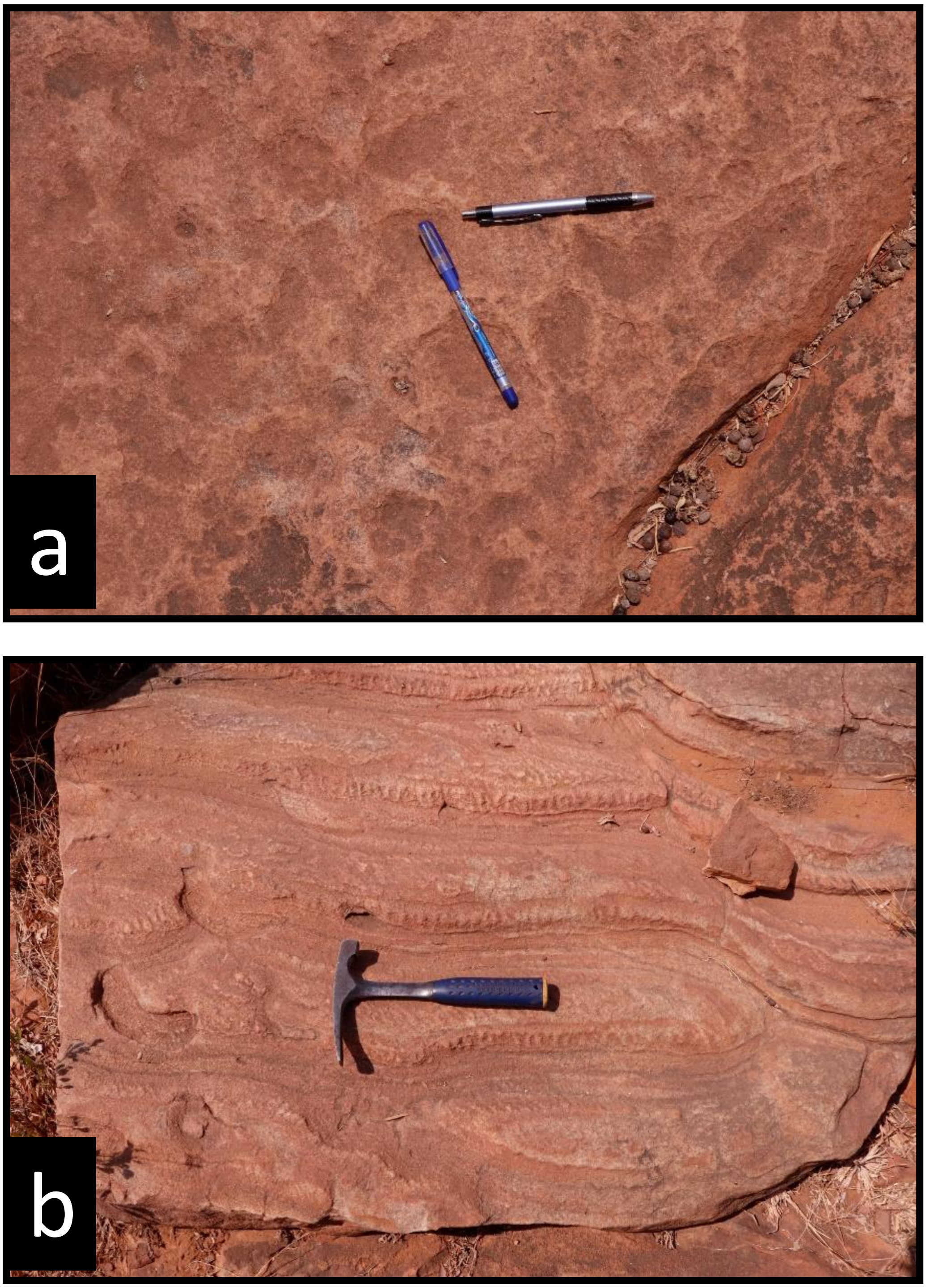

Fig 3.1.3 Facies Association: a) Interference ripple showing two direction on bed surface. b) Ladder back,indicative of bi directional wave generated current

3.2 Sequence Architecture:

Sequence architecture is a methodology that provides a framework to study the pattern of distribution of different elements of any depositional setting, facilitating paleogeographic reconstructions and understanding the trends of changes trough time and space. This framework explains changes in stratal stacking patterns in response to the varying accommodation space creation and sediment supply rate, through time. Stratal stacking patterns enable determination of the order in which strata were laid down, and explain the geometric relationships and the architecture of sedimentary strata. The sequence stratigraphic framework also provides the context within which to interpret the evolution of depositional systems through space and time. This analysis is improved by integration of process sedimentology with an understanding of the geometries and scales of the component depositional elements.

The main tool used in sequence architectural analysis is the stacking pattern of strata and the key surfaces that bound successions defined by different stratal stacking patterns. Trends in geometric character, which combine to define stratal stacking patterns, include upstepping, forestepping, backstepping, and downstepping. A sequence architectural framework may consist of three different types of sequence stratigraphic unit, namely sequences, systems tracts (LST, TST, HST, MFS, LSW, HNR, LNR) and parasequences. Each type of unit is defined by specific stratal stacking patterns and bounding surfaces. The definition of these units is independent of temporal and spatial scales, and of the mechanism of formation.

A systems tract is “a linkage of contemporaneous depositional systems, forming the subdivision of a sequence” (Brown and Fisher, 1977). The definition of a systems tract is independent of spatial and temporal scales. The internal architecture of a systems tract may vary greatly with the scale of observation, from a succession of facies (eg., in the case of high-frequency sequences driven by orbital forcing) to a parasequence set or a set of higher frequency sequences. The FSST includes all the regressive deposits that accumulate after the onset of a relative sea-level fall and before the start of the next relative sea-level rise. The

FSST is the product of a forced regression. The LST includes deposits that accumulate after the onset of relative sea-level rise, during normal regression, on top of the FSST and the corresponding updip subaerial unconformity. The TST comprises the deposits that accumulated from the onset of transgression until the time of maximum transgression of the coast. The HST includes the progradational deposits that form when sediment accumulation rates exceed the rate of increase in accommodation during the late stages of relative sea-level rise (Fig.. The HST lies directly on the MFS formed when marine sediments reached their most landward position. A parasequence in its original definition (Van Wagoner et al. 1988, 1990) is an upward-shallowing succession of facies bounded by marine flooding surfaces. A marine flooding surface is a lithological discontinuity across which there is an abrupt shift of facies that commonly indicates an abrupt increase in water depth. The maximum flooding surface (MFS) (Frazier, 1974; Posamentier et al., 1988; Van Wagoner et al., 1988; Galloway, 1989) is a stratigraphic surface that marks a change in stratal stacking patterns from transgression to highstand normal regression. It is the paleo-seafloor at the end of transgression, and marks maximum thickness of water column.

3.2 Architectural pattern:

Finally to elaborate the sequence architectural pattern a synthesized vertical section of consecutive parasequences is produced (Fig 3.2). The section is made along the continuous roadside sections of Bhantmuri area which is located near the western margin of the western sector of Badami Basin. The synthetic section covers a ~ 4km strike-wise variation between Old Wantamuri to Bhantmuri Ghat. The section is about 21 m. thick and it is basically characterized by fine to medium sand intercalated with occasional fine shale to silty material. The beds are sub-horizontally disposed in the studied area.

The entire section is comprised of all the constituent facies of marine association, distributed along twenty seven (27) coarsening upward parasequences. The entire section is mainly made up of arenaceous facies A, B, E and D bodies, with intervening finer facies F and G bodies and rare facies C bodies. The amount of intervening fines increases steadily up to a portion, which is almost entirely argillaceous. Then again the amount of fines decreases

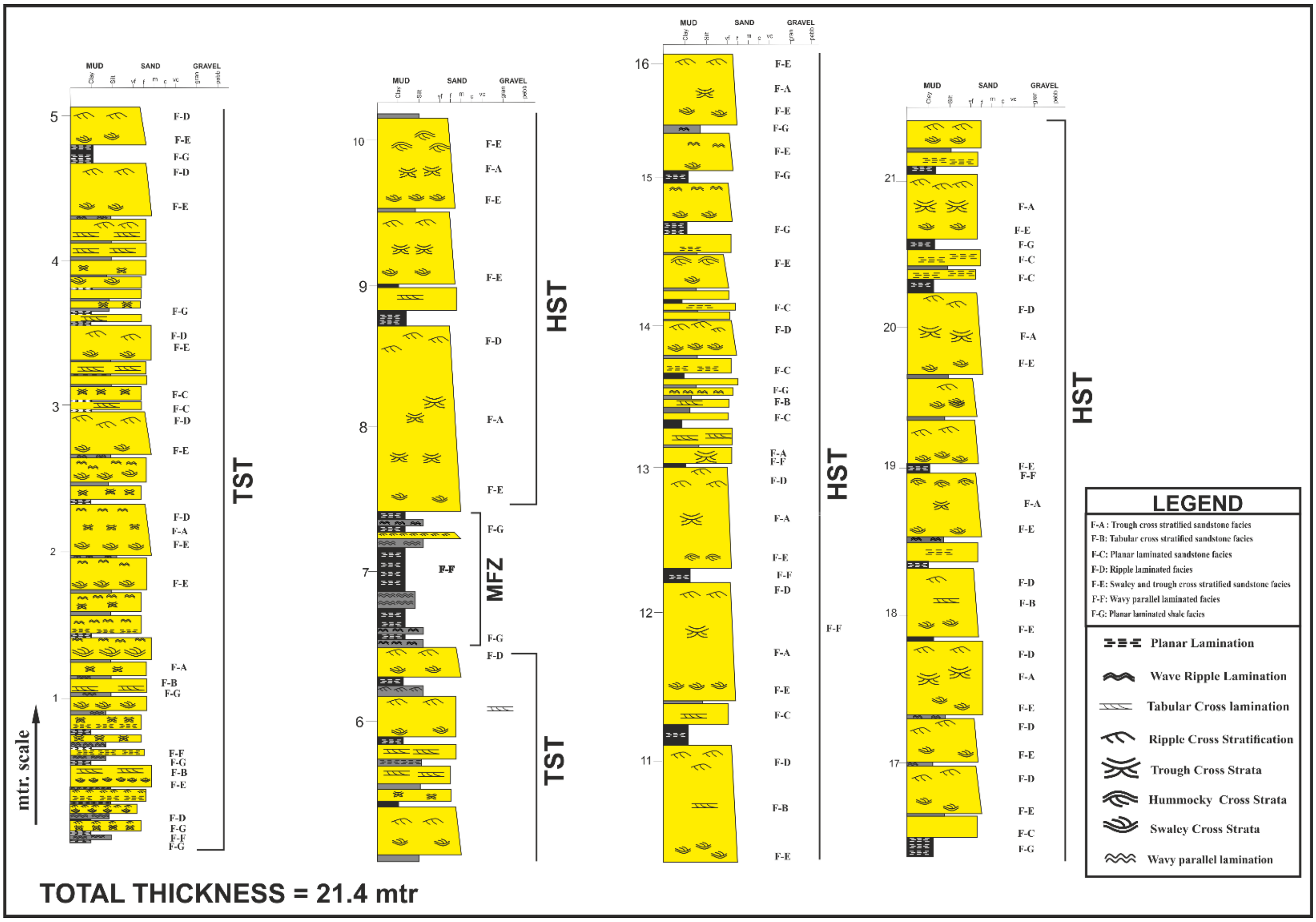

Fig 3.2 Synthetic section of Marine Succession of Bhantmuri area showing facies correlations within the vertical stacking of parasequences depicting the sequence architectural pattern.

upward. Hence, the section can be subdivided into two parts. Lower part shows an overall fining upward trend, while the upper part is coarsening upward. Each parasequence characteristically starts off with finer, either F or G facies, the amount of which decreases upward in expense of arenaceus facies A and/or E bodies, with some minor facies B bodies. Parasequences at the basal portion of the succession shows dominance of facies A, B and E with decapped hummocks and swaley cross strata. Intervening finer variety is characteristically facies F. Bed surfaces of facies A and B bodies in this part are matted with combined and interference ripples, often flat crested, indicating very shallow water depth. Often facies A and B are topped by D_1 and rarely by D_2, showing a gradual waning of traction current in a wave induced shallow environment. This assemblage is frequently interrupted by facies E crowded only with large swales and occasional facies C suggesting sudden increase in energy condition, indicating probable incorporation of exogenous sediments through storm events. Overall, an upper shoreface to marginal marine paleogeography can be inferred for the lower part of the succession. Parasequences, on the middle portion of the fining upward section, are characterized by similar facies assemblages but with greater abundance of fines, often starts off with facies G bodies. Facies A and B bodies usually changes gradually in to facies D_1, and D_2 bodies. Facies E bodies, observed here, shows decapped hummocks, along with swaley cross-stratified nature. Rare facies C bodies with erosional bases, along with facies E bodies, represent high energy products, interrupting the indigenous sedimentation periodically. Sedimentation in a comparatively deeper part of middle shoreface region can be inferred. The upper part of this portion is characterized by a facies assemblage containing ripple laminated fine sand- to siltstone of facies D_2 giving way to thicker interbeds of planar laminated and wavy parallel laminated siltstone of facies F and planar laminated shale of facies G. The increased frequency and thickness of both facies F and G along with occasional presence of hummocks and swales of facies E and planar beds of facies C infer a lower shoreface paleogeography, indicating deposition below storm weather wave base in deeper waters. This particular facies assemblage is topped by a thick column of wavy parallel laminated silt along with planar laminated shale at the topmost part of the lower portion of the succession. This thick argillaceous interval represents deepest paleogeography, probably offshore region, with fines, deposited from suspension fall-out representing indigenous sediments and occasional thin fine sandy to silty interbeds representing products of storm derived sediment gravity flows from the shelf region. The increased thickness and occurrences of finer sediments of facies F, G and D2 and decrease in occurrence of facies A, B, E and D1 suggest an overall deepening of the paleogeography transiting from beach shoreface to offshore.

The upper part of the succession starting above the argillaceous interval, is dominated by facies A and E with occasional presence of D_1, D_2, and C and rare occurrences of F and G. Immediately above the MFZ presence of swaley cross stratified thick, amalgamated sandstone bodies with erosional bases indicates very frequent occurrences of high energy storm events. This storm beds are accompanied by facies A and C which is topped by ripple laminated sandstone bodies of facies D_1 and D_2. Occasional presence of thin interbeds planar laminated shale of facies G along with ripple laminated and wavy parallel laminated siltstone of facies F again suggests deposition in the middle shoreface paleogeography, very frequently interrupted by storm events. This shallowing up parasequence set is followed by another parasequence set which shows a comparatively fining up trend where the thickness of sandstone bodies of facies A, C and E decreases along with increase in thickness of frequently occurring shale and siltstone bodies of facies F and G. This parasequence set indicates a slight deepening of water column within an overall coarsening upward succession. This is again followed by a coarsening upward stacking where facies A, B and D_1 increase not only occurrence but also in thickness, with occasional presence of planar laminated sandstone of facies C underneath. Gradual transition to ripple laminated sand- to siltstone of facies D_2 and D_1 from facies A and B at the top suggest a gradual waning of wave induced traction current within a standing water body. Rare occurrences of facies F and G in the prevailing parasequence set along with frequently preserved swales and decapped hummocks infer a shallower paleogeography. Further up in the succession presence of combined and interference ripples on the bed surfaces of facies A, B and E indicates deposition in a beach shoreface region. The overall transition from middle shoreface, between fair weather and storm weather wave base, to beach foreshore paleogeography becomes empirical.

Positioned between two basin-wide unconformity surfaces of valley fill boundary scale, the middle valley fill represents a total “sequence”. Although the upper portion of the total valley fill is studied in this attempt, it gives the general ides about the sequence building pattern in this area during the emplacement of the middle valley fill at least. The entire studied succesion depicts a story of relative sea level rise and fall, reflected by the variations in stacking pattern as well as internal constituents of these distinct sediment packages, through space and time. The lower part of the succession, showing fining upward trend, is comprised of nine (09) numbers of parasequences, with paleogeography varying from upper shoreface to lower shoreface. Hence, a deepening upward trend becomes empirical. This part of the succession, overlying the fluvial interval of the middle valley fill through an intervening transitional marine unit, can safely be ascertained as the product of a transgressive systems tract (TST), at least the top part of it. The transgression started by drowning the fluvial interval, which forms the lowstand wedge, forming over the valley fill scale unconformity surface. The transitional marine part represent the initial transgressive phase, characterized by the slower rate of sea level rise, which in turn is followed by the thick marine succession, the lower part of which amply represent the late stage of the TST. This fining upward portion is followed by a thick (~1m) argillaceous unit, indicating offshore paleogeography. Hence, this zone represents the deepest depositional setting in the whole succession, and in turn can be identified as the maximum flooding zone (MFZ) of the total sequence. Overlying coarsening upward part of the total succession shows a transition from middle shoreface to upper shoreface to beach foreshore paleogeography. Hence, a shallowing upward trend, representing normal regression, under the backdrop of reduced sea level rise rate, bcomes empirical. This portion is identified as highstand systems tract (HST). The entire marine succession is a product of transgression followed by a normal regression with an MFZ in between, not only delineating the deepest portion of the basin but also differentiates the two system tracts i.e. TST at the bottom and HST at the top.

3.3 Correlation of synthetic sections:

Besides the detailed studies of facies associations and sequence architecture, correlation of synthetic sections in five different locations has been taken in to account to portray the distribution of marine and fluvio-marine transitional successions along the paleodip direction of the basin, i.e., from east to west and north-west broadly.

The correlated section from Bhantmuri to Islampur (Fig 3.3 A.) indicates that middle valley fill go through notable changes in depositional environmental as well as paleogeographic dsposition from east to west direction. While moving from the west to east from Bhantmuri to Islampur the thickness of marine succession gets thinner progressively which indicates the west part of this studied area is deeper than that of the eastern part. So correlating the synthetic sections of these two areas give an indication of marine encroachment from west to east. The thickness of middle part of the fluvial counterpart is getting thicker from the west to east which also supports the previous encroachment direction of the sea. The marine interval onlaps over the fluvial interval from west to east direction. The intervening fluvio-marine transitional association shows considerable thickness all across the studied stretch, indicating a slow rate of initial rise of sea level (Bose et al., 2008).

Another correlation is done between sections from Kabalapur, Islampur and Godihal (Fig 3.3 B). In this correlation, a clear onlapping relation of marine counterpart over lower fluvial successions is seen which also indicates the presence of a basement high, resulting in the lower thickness of the fluvial unit, followed by a marine transgression over an uniform fluvial sediment pile.

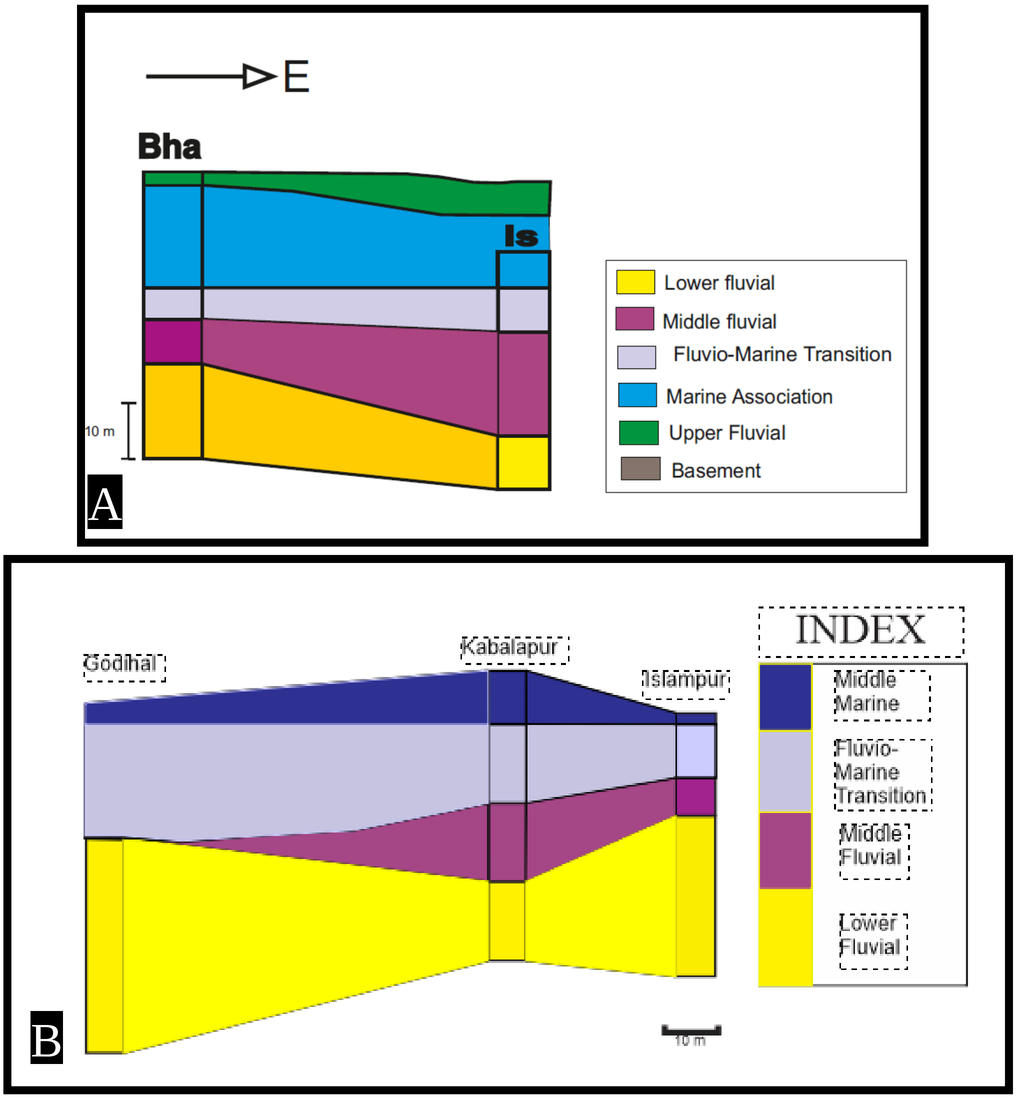

Fig 3.3 A) Correlation between Synthetic section of Bhantmuri and Islampur
B) Correlation among Synthetic section of Godihal, Kabalapur and Islampur.

Chapter 4

MAT INDUCED MACRO STRUCTURES

4.1 MICROBIALLY INDUCED MACRO-STRUCTURES OBSERVED IN FIELD AREA:

Microbes are the most abundant, varied in kind and widespread organisms (Schopf, 1999, 2002; Riding and Awramik, 2000) of the world. The effect that they may exert on sediments in their effort to eke out a living is likewise varied. Even their dead colonies respond to natural processes, like burial, overburden pressure or reaction with ambient sediment and pore-fluid, differently from other abiogenic sediment components. They contribute stability to sediment, destroy, oxidize or reduce primary minerals and also add new minerals in diverse ways. Since preservation potential of the microbes themselves is poor, especially within siliciclastic sediments, recognition of their prior existence in ancient siliciclastic rocks depends on detection of their proxy records (Schieber, 1998, 1999). The proxy depends on mode of interaction between ambient physico-chemical condition of sedimentary environment and microbiota, of widely varying living habit. Wide range of structures on bedding plane surfaces in the Proterozoic siliciclastics successions have been inferred by many as sheet colonies or mats of microbiota, responder to varied kinds of environmental processes (Schieber, 1998, 1999, 2004; Bottjer et al., 2000; Noffke et al., 2001, 2003; Eriksson et al., 2000; Bouougri and Porada, 2002; Pfluger and Gresse, 1996; Seilacher, 1999; Sarkar et al., 2006, 2008). Clues for this interpretation come from analogous structures found in modern depositional settings (Gerdes et al., 1985, 1993, 2000; Gerdes and Krumbein, 1987; Noffke et al., 1996) and also from a limited number of experimental settings using cultured mats. Progress has also been made on the subject of mineralization under direct or indirect influence of microbiota. It is now well established that, cyanobacteria-dominated microbial mats, along with a large variety of anoxygenic phototrophs, anaerobic and aerobic chemotrophs, successfully leave their foot-prints on sun-lit sedimentary surfaces through their respiration, synthesis and fermentation, and thus, concomitantly and to a lesser degree, leave their images in the sedimentary rock record. Increasing interest in modern microbial mat features formed in siliciclastic sediments is complemented by a group of sedimentary features that are being found in Precambrian clastic sedimentary rocks, emphasising on their important impact on Earth's earlier sedimentation record.

In our study area the unique structures preserved in rock record also depict a story of ancient time when life interacted with sedimentary dynamics and left behind evidences of pattern of biogenic activity and their influences on sedimentary environment and sedimentation pattern.

4.1.1 Desiccation cracks on sand:

Set of cracks retained on sandy substrate are found. Cracks terminate against each other almost at 90^o and are not isolated, rather form polygonal network, propagating continuously and maintaining almost uniform thickness along length. These shrinkage cracks result from subaerial exposure and desiccation of cohesive medium (Figure 4.1 a). Brittle fracture within sand generally is not retained but if the sand is cohesive then cracks will be retained and later will be filled by materials from overlying substrate. This cohesiveness may be imparted due to microbiotas which during their growth bind the sand particles together in a jelly like organic substance, and thus imparting the desired cohesiveness and plasticity.

According to Lachenbruch (1962) and Anderson and Everett (1964), desiccation polygons in mud or other cohesive medium seem generally to be of the orthogonal system, perpendicular cracks propagating slowly and not tending to bifurcate. Care must be taken not to misinterpret desiccation cracks as synaeresis cracks. In vertical cross-section, the profile of a synaeresis crack in sandy substrate is U-shaped. Only the mat margin is curled up. The sandy bottom remains flat. In contrast, desiccation cracks are V-shaped. In the fossil record, these cracks are preserved in sandstone even if no clay-like material was present and this is most often related to microbial polymeric films binding the sand grains together. Because of this origin, identification of desiccation cracks in sand is easy.

4.1.2 Spindle-shaped cracks (Synaeresis cracks):

Surface of medium to fine grained sandstone are found to be marked with "Spindle-shaped" cracks (Figure 4.1 b) generally developed associated with ripples (Figure 4.1 b). Sometimes they cross-cut each other at acute angle and form networks of cracks (Figure 4.1 b) or run along troughs as isolated individuals (Figure 4.1 b). Generally cracks which cut across each other, are certainly related to subsurface origin and classified as non-orthogonal cracks within less inhomogeneous and relatively less plastic medium (Lachenbruch, 1962). Synaeresis origin of the majority of spindle-shaped cracks is further corroborated by their occurrence in sediments deposited well below the sea surface (Seilacher et al., 1998). Geologic significance of synaeresis cracks was first reported by Jüngst (1934), and it was defined as the spinlde-shaped or curvilinear cracks, usually found in ripple troughs, originated subaqueously at the sediment-water interface (Wheeler and Quinlan, 1951). Considerable experimental work has been done on the subaqueous formation of cracks in clay sediments (White, 1961; Dangeard et al., 1964; Burst, 1965; Kuenen, 1965; Twenhofel, 1923).

In our study area the presence of synaeresis cracks within sandy substrate can only be attributed to the presence of microbial filaments and EPS binding the sand grains together and imparting cohesion into them.

4.1.3 Sand chips and sand clasts:

Some bed surfaces comprise of a lag of sand chips (fig 4.2 a). The chips are spherical, ellipsoidal, triangular, crescent-shaped or without any definite geometry and sometimes flattened. The chips are, however, generally rounded at their edges and have been measured up to 4 cm. along their long axis. Locally they have preferred orientation of their long axis or show imbrication implying current-aligned deposition. Some sandy surfaces even contain imprints of broken and detached sand clasts (4.2 a).

In previous works they have been also termed as Microbial sand clasts; spheroidal pliable sand clasts and are also known as 'algal balls' and 'sand balls' (Eriksson et al., 2007). Rounded or ellipsoidal shape with rounded edges imply long transportation and reworking. The sand chips or clasts can only be generated through imparting cohesion in granular sand. The chips found in field area are made of medium to fine sand and reflect strongly desiccated mat-bound sandy sediment surfaces that form rigid and curved clasts, several centimetres in their longest dimensions. They became rounded or ellipsoidal due to rolling as bed load. They resemble dried-up mud clasts formed when a thin mud layer desiccates and breaks up. The crescent-shaped (Figure 4.2 a) and flattened ones are deformed plastically and this plastic behaviour can also be explained by mat induced cohesion.

4.1.4 Palimpsest ripples:

Several medium to fine grained sandstone and siltstone surfaces are demarcated with ripple forms which replicate a previous generation of ripples from the bed underlying(fig 4.2 b). For such replication, the overlying bed has to be very thin. These are called Palimpsest (something which is newly formed and altered but still bears visible traces of its earlier form) ripples (Fig.4.2 b)Palimpsest ripples (Pflüger and Sarkar, 1996) mislead in determining the hydrodynamic condition of deposition of the bed on which they are found; rather they carry the signature of hydrodynamic conditions that prevailed during deposition of the underlying bed like a preserved memory from the immediate past. Such replication is attributed to trapping of sediment particles by filaments and EPS of microbial mat grown uniformly over ripples formed earlier (Pflüger and Sarkar, 1996; Sarkar et al., 2006). This preservation requires very low rate of sedimentation and complete cessation of erosion (Noffke, 2000).

Degree of replication may be variable. When ripples on underlying bed is replicated very prominently, the structure is called ‘transparent’ and when thicker mat growth within ripple troughs renders the ripple geometry unrecognizable, the structure is called ‘non-transparent’ (Noffke et al., 2003a). Sometimes thicker growth of mat within troughs and other

4.2 Implications:

According to previous studies different mat induced feature can be indicative of certain palaeoenvironment (Schieber et al., 2007; Eriksson et al., 1981, 2000, 2004, 2005). Retention of cracks (originated subaerially or subaqueously) within sandy substrate, load casts formed on underlying sandstone bed, patchy occurrence of preservation and erosion of bedforms, replication of underlying topography, formation and preservation of setulfs, presence of wrinkle marks and formation of sand clasts, all these signatures can only be explained through generation of cohesion within sand grains and preservation of structures due to any protecting envelop. These attributes altogether imply presence of microbial mat and cohesion and plasticity generated by EPS secreted by microbial organisms.

Generation of different kinds of cracks, along with other features described above, within sandy substrate demands genesis and growth of mat envelop formed by microbial activity. Overall, mat proliferation demands shallow water condition, with plenty of sunlight. Hence, the upper to lower shoreface paleogeography is supported by the presence of prolific growth of microbial community. Their abundance within the indigenous facies only, on the other hand, emphasizes the role of low sedimentation rate over microbial mat growth. It is well evident that prolific growth of microbial community demands lower rate of sedimentation (Seilacher et al., 1998).

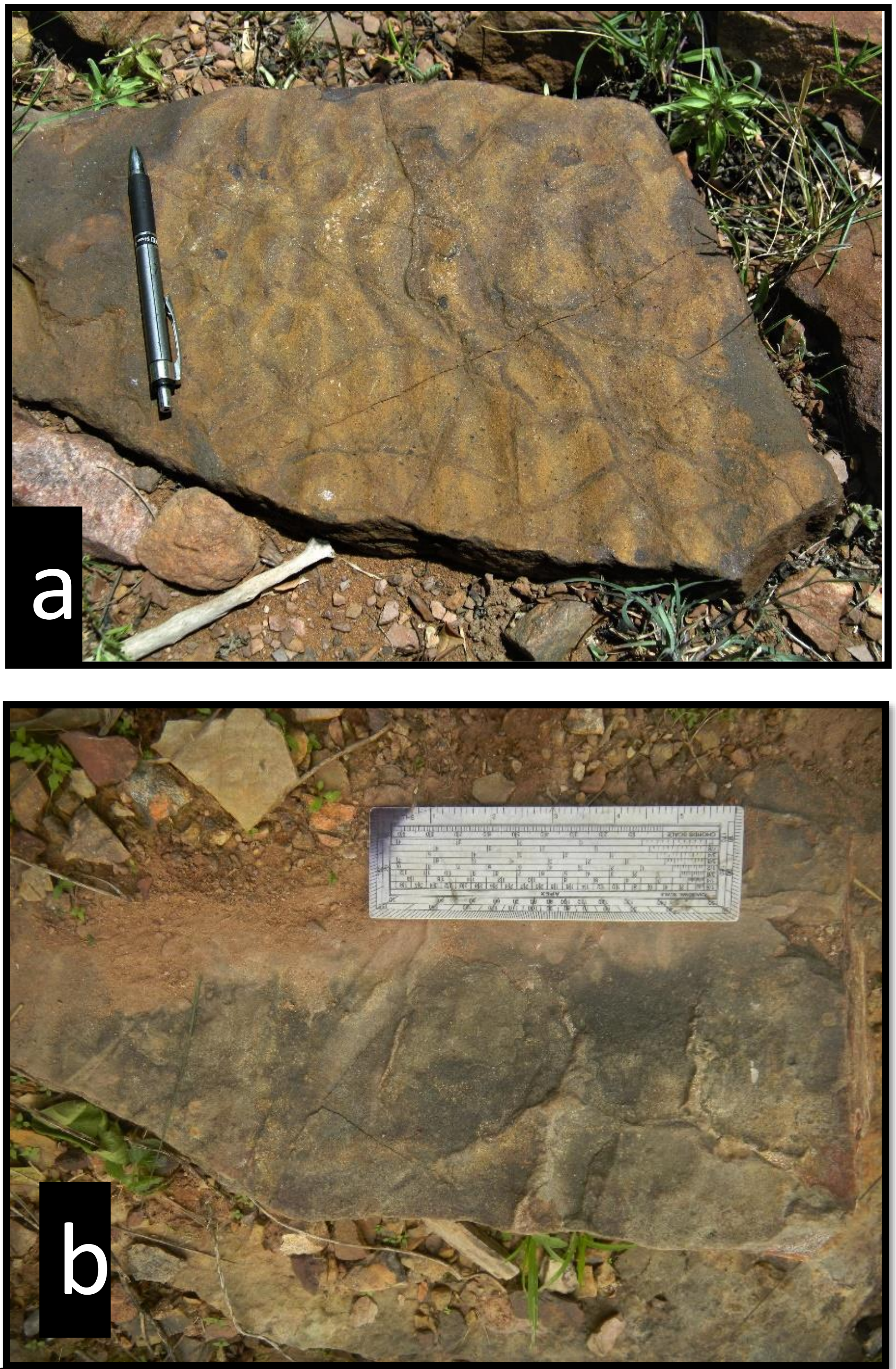

Fig.4.1 Mat induced structure: a) Dessication crack. b) Synerisis crack

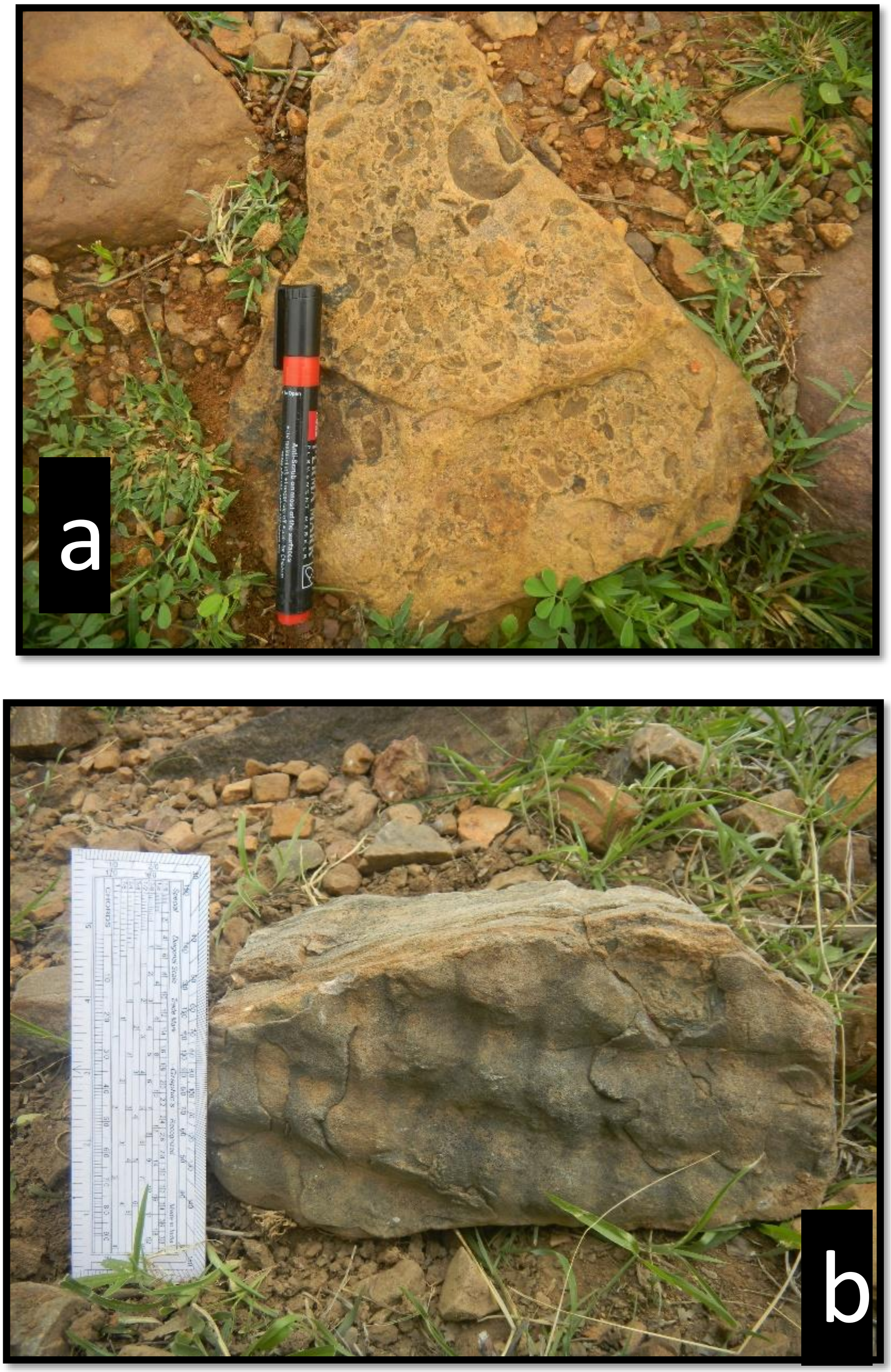

Fig.4.2 Mat induced structure: a) Sand clast. b) Palimpset ripple

Chapter 5

Discussion and Conclusion

State-of-art facies analysis and sequence architectural studies within the studied interval of Cave Temple Arenite Member on the western segment of Kaladgi Basin, extrapolate a clear picture about the depositional environment and paleogeography of the area as well as their variability in time and space. All across the studied stretch the studied Member is characteristically made up of three vertically juxtaposed sedimentary cycles. The basal and the topmost cycle is characteristically fluvial in origin, with coarse to medium sand sized texturally, as well as mineralogically immature sandstone bodies. This study concentrated on the comparatively matured, both texturally and mineralogically, sandstone interval belonging to the middle cycle of the Cave Temple Arenite Member. Although a basal fluvial unit is present laso within this cycle, study in this thesis work concentrates mainly upon the texturally matured, medium to fine sand and shale-silt sized sediments, which shows plenty of wave-induced features. The textural maturities, along with dominance of wave-induced features indicate the marine origin for the aforementioned studied interval. Detailed state-of-the-art facies analysis identified seven genetic facies, grouped mainly into two facies associations. While the fluvio-marine transitional facies association shows alternate units of fluvial and marine influence, the marine facies association covers a wide paleogreographic range within marine realm, ranging from beach foreshore to offshore. Deposition apparently took place in an open wave-influenced shelf, frequently experiencing storm activities. Detailed study on the immediate association of facies, revealed four different sub-associations, reflecting the exact paleogeographies of deposition. While the coarsest association with plenty of swaley cross-stratified amalgamated sand bodies, intercalated with thinner fine sandy to silty, trough cross-stratified or ripple laminated interbeds represents upper shoeface paleogeography, with increasing amount of fines it changes gradually towards deeper offshore area, through middle shoreface and lower shoreface areas. Occasional presence of planar laminated bodies with parting lineations on top within the upper shoreface sub-association, pointed towards local development of beaches. Plenty of interference ripples as well as superimposed ripples in that area also support the shallow water emplacement of these sediments. Indigenous sediments become finer (from fine sand- to silt- to clay-sized) as water deepens, frequented by hummocky cross-stratified and /or trough cross-stratified storm events only.

Sequence architectural analysis in the studied stretch revealed an onlapping relationship between the lower fluvial and overlying marine interval of the middle cycle. By virtue of its position between a basin-wide unconformity surface and a marine interval, the fluvial succession in the middle cycle clearly represents a lowstand wedge. The sea ingressed from the west, hence the thickness of marine interval increases westward in expense of the fluvial one. Overlapping the fluvial interval with a sharp transgressive surface, the marine interval, nonetheless, indicates a transgressive origin. Considering the adequate thickness of the fluvio-marine transitional association, the rate of transgression appears to be quite low, at least at initial stages. Identification of twenty seven parasequences pointed towards prolonged marine sedimentation. In accordance with the marine aggradational under the backdrop of punctuated sea-level rise, all the parasequences are coarsening upward. The lower part of the succession shows an overall fining upward trend, with increasing amount of intercalated fines, culminating into a thick shale-rich zone. This zone is aptly identified as the maximum flooding zone (MFZ), below which lays the product of the transgressive systems tract (TST). The following succession shows an overall coarsening upward trend, with a short zone showing fining upward trend in between. It is followed by the sediments of the topmost fluvial cycle through an erosional contact. Thus, the highstand systems tract (HST) status of the top portion of the succession becomes infallible. Overall, the middle cycle of the Cave Temple Arenite Member, represents an initial transgression, initially slow in rate, but later taking pace to inundate the valley totally. The following MFZ and HST account for the aggradation at high water stage and normal regressive stage, respectively. The sedimentation rate must be greater enough to overcome the sea-level rise rate, towards the penultimate stages of valley filling. Hence, a deepening upward trend, over a fluvial lowstand wedge, changes into a deepening upward one with the intervening maximum flooding zone, to comprise the whole depositional history of the middle cycle of Cave Temple Arenite.

Presence of microbially induced structures, further strengthen the marine origin. Some dessccaition and synaeresis cracks and plenty of sand clasts, pointed towards their deposition in parts of the upper shoreface as well as the upper part of middle shoreface.

Finally, it can be concluded that this is the first report of marine interbeds within the hitherto entirely fluvial western sector of Badami Basin. The coeval nature of the fluvial and marine intervals during the time of deposition of the middle cycle, clearly indicates the closeness of the sea, during the deposition within the chiefly continental Badami Basin.

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