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Tide-storm-dominated shelf sequence of the Neoproterozoic Blaini Formation and its implications on the sedimentation history of Krol-Belt, Kumaun Lesser Himalaya, India

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ABSTRACT

The diamictite bearing Neoproterozoic Blaini Formation constitutes a significant lithostratigraphic unit of the Lesser Himalayan sedimentary pile. These diamictite bearing horizons have implication for the genetic evolution of the Krol-belt. Detailed lithofacies and palaeocurrent analyses of the Blaini Formation suggest that the sediments belong to two distinct facies associations. These are: Strom Dominated Facies Association and Tide Dominated Facies Association. The Strom dominated Facies Association overlies a transgressive lag deposit and comprises offshore, offshore transition and subtidal facies. The Tide Dominated Facies Association, on the other hand, comprises intertidal to supratidal facies.

The Blaini succession in the Nainital area overlies the Nagthat siliciclastics, deposited in a barrier island set-up having a sharp to erosional contact. The Nagthat Sea gave way to shelf sedimentation of the Blaini times. The high-energy tide-storm condition of sedimentation in the basin had witnessed moderate to low energy conditions intermittently, wherein diamictites were emplaced through down slope re-sedimentation of cohesive debris flow. The debris was originated by intermixing of extra-basinal and intra-basinal clasts along with hinterland sediments, which were transported in response to some tectonic adjustments during the terminal stages of Blaini sedimentation. Subsequent tectonic stability and quiescence gave way to thick stromatolitic carbonate succession during the Krol times. The Krol-belt as such is evolved in three distinct cycles of sedimentation, distinguished as the Jaunsar-Simla, the Blaini and the Krol cycles.

INTRODUCTION

The Krol Belt, made up of tectonically detached synformal basins, extends over a stretch of about 300 km from Solan in Himachal Pradesh to Nainital in Kumaun (Fig. 1). The Belt comprises lower argillo-arenaceous Simla-Jaunsar and upper argillo-calcareous Mussoorie Groups (Auden 1934; Valdiya 1980). The Neoproterozoic Jaunsar Group is subdivided, in an ascending order, into Mandhali, Chandpur and Nagthat Formations, whereas Blaini, Krol and Tal formations, in an ascending order, constitute the Neoproterozoic to early Cambrian Mussoorie Group (Valdiya 1980).The Simla Group, exposed in Himachal Pradesh only, has been considered to be coeval with Jaunsar Group (Bhargava 1976).

The southern limit of the Krol-belt is marked by the Main Boundary Thrust (MBT), along which it has been thrust over the Siwalik Supergroup so that its southern fringe is split up into schuppen structure.The northern limit of Krol-belt is defined by the Ramgarh-Chail Thrust, along which Ramgarh-Chail Group has been thrust over it (Valdiya 1988).

Attempts towards understanding the depositional environment of the Blaini Formation have been made ever since 1888 when Oldham proposed a glacial origin for the Blaini diamictites and considered them to represent northern counterparts of Permo-Corboniferous Talchir Boulder Beds of the Peninsular India (Oldham 1888). Oldham's view was subscribed by a number of later workers including Auden (1934) and Bhargava (1972). However, Holland (1908) though supported the glacial origin, proposed Blaini diamictites to represent Proterozoic rather than the late Palaeozoic glaciation. On the other hand, Bhatia (1975) and Jain (1981),

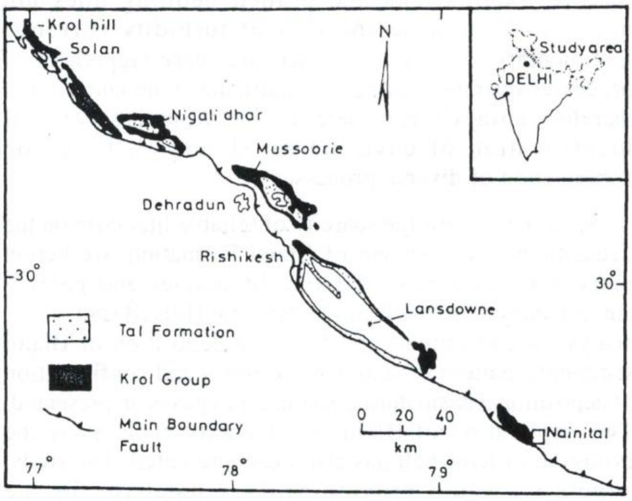

Fig. 1: Extent of the Krol Belt in Lesser Himalaya, India

among others, suggested a glaciomarine environment as they claimed drop-stone structures in diamictites and association of varvites with them. Another school of thoughts led by Ghosh et al. (1966), Rupke (1968), Valdiya (1973) and Niyogi and Bhattacharya (1971) proposed a submarine slumping and turbidity origin for the Blaini as they interpreted graded bedding, scour structures and parallel laminations in deeper shelf conditions to be exclusive of turbidites. Tangri and Singh (1982), however, proposed a shallow tidal sea for the deposition of Blaini diamictites. Recently, and Pant and Goswami (1998) have carried out detailed lithofacies analysis of parts of the Blaini Formation and suggested tide-storm dominated shelf conditions for the sedimentation.

The models proposed earlier, except the shallow marine ones, however, can not be taken as true representatives of the whole Blaini Formation for they pertain to sedimentology either solely of diamictites or, at the most, of diamictites and the laminated shales only without any attention to other lithounits. As a matter of fact, diamictites constitute merely 3% of the total stratigraphic thickness of the Blaini Formation. Moreover, glacial models are based on and stemmed from correlation of Blaini diamictites with the Permo-Carboniferous Talchir Boulder Beds. Such a correlation, however, is no more tenable as the recent fossil finds in Infra-krol (uppermost Blaini), Krol and Tal sediments have established Neoproterozoic age for the Blaini Formation (Azmi 1983; Bhatt and Mathur 1990; Tewari et al. 2001). Also, no evidence of glacial transport or deposition could be recorded in diamictites. Advocates of glaciomarine model, on the other hand, have misinterpreted tectonic features like enveloping of clasts by foliation planes as drop-stone structures and laminated mud-flat and offshore deposits of shelf affinity as varvites. The turbidity models, likewise, fail to record any evidence of the fluidal rheology of diamictite emplacing material, which is an essential character of turbidity currents (Lowe 1979; Shanmugam and Moila 1995, 1997). The occurrence of scour structures, parallel laminations and graded bedding does not necessarily indicate the role of turbidity currents. Sedimentary structures, in fact, are mere signatures of processes operated during that particular time and should, therefore, always be considered to infer the process, whereas identification of environment should be based on combination of diverse processes.

Keeping in view the scarcity of reliable literature on the depositional environment of Blaini Formation, we herein present an account of detailed lithofacies and palaeocurrent analyses of the Blaini in Nainital Hills. Based on our analysis a conceptual model for the deposition of Blaini sediments, pattern of sediment dispersal and configuration of depositional basin during Blaini times has been presented. The implication of Blaini sedimentation vis a vis the evolution of Krol-belt has also been attempted. The study, hopefully, would provide primary database for the understanding of sedimentation history of the Krol-belt.

GEOLOGICAL SETTING

Representing southeastern extremity of NW-SE tending five *en echelon* synformal Krol-basin *viz* Korgai, Nigalidhar, Mussoorie, Landsdowne and Nainital, the sedimentary succession of Nainital synform tectonically rests on 1900±100 Ma old Amritpur Granite (Trivedi et al. 1984). The Amritpur Granite is exposed only in the narrow southeastern end of the synform. The much tightened and faulted synform is thrust southwards over Siwaliks along the MBT to constitute what is known as the Krol Nappe (Auden 1934; Bhargava 1972). The Krol nappe, in turn, is thrust over by a succession of metamorphics associated with granites, called the Ramgarh Nappe, along the Ramgarh thrust. The Nainital synform has been dismembered into two unequal parts by roughly NW-SE trending Nainital fault. The larger northern part is made up of Nagthat-Blaini-Krol rocks, which exhibit northward overturning folds, whereas relatively narrow southern part is constituted of Blaini-Krol-Tal rocks and exhibits south–vergent overturned folds (Valdiya 1988). Tectonic adjustments have also resulted in development of NW-SE trending northern Bhawali anticline and southern Ayarpatta syncline (Valdiya 1988). Our lithological sections are placed over the Bhawali anticline with limbs variably dipping between 10^0 and 60^0. Core of the Bhawali anticline is largely occupied by extensive lava flows of the Nagthat Formation. Oldest sedimentary rocks in the area are quartzarenite, slate, siltstone and associated penecontemporaneous basic lava flows of the ±1900 m thick Nagthat Formation, which is overlain by the ±1700 m thick Blaini Formation with a sharp to locally erosional contact. Finally, thick carbonate sequence of Krol-Tal formations transitionally succeeds the Blaini Formation (Table 1; Fig. 2).

The Blaini Formation in Nainital area is divided into four members (Valdiya 1980; Pant and Goswami 1998) (Table 1). The lowermost *Bhumiadhar Member* consists of a basal diamictite horizon followed up by ±500 m thick sequence of shale, siltstone, greywacke, quartzwacke, litharenite and quartzarenite. This is followed up by ±1000 m thick quartzarenite, quartzwacke, and siltstone and shale sequence of the *Lariakantha Member*, which, in turn, is succeeded by diamictites, slates, siltstones, and lenticular pink siliceous dolomitic limestone of the *Pangot Member*. Finally, the grey carbonaceous–pyritous slates and siltstones of the *Kailakhan* (*Infra-Krol*) *Member* constitute the uppermost unit of the Blaini Formation.

Owing to complex structural set-up the rocks of the Nainital area are highly deformed, with great intensity in argillaceous rocks of Bhumiadhar, Pangot and Infra-Krol members. In the present study, therefore, due considerations have been given to the structural and lithological constraints. All the measurements are taken after due tectonic correction.

Table 1: Stratigraphic and tectonic set-up of the Nainital Hills (Valdiya 1980; Pant and Goswami 1998)

Time	Time rock unit	Formal unit	Stratigraphic unit	Lithology	Thickness
Cambrian	MUSSOORIE GROUP	Tal Formation			
NEOPROTEROZOIC		----------------------Transitional contact--------------------------------			
		Krol Formation			
		---------------------- Transitional contact ------------------------------			
		BLAINI FORMATION	Kailakhan Member	Variegated ash grey, brownish grey to black carbonaceous shales	±200
			Pangot Member	Diamictite, purple-green slates, pink dolomite	±20
			Lariakantha Member	White, pink, grey, purple, brown and fawn quartzarenite, sublitharenite and quartzwacke, often pebbly, purple-olive green slates and conglomerate	±1000
			Bhumiadhar Member	Greyish brown to grey, black slates, siltstone, greywacke, quartzwacke, lithicwacke	±500
-- Sharp Contact --					
Neoproterozoic	Jaunsar Group	Nagthat Formation			±1900
-- Thrust --					
1900±100ma	Amritpur Granite				
-- MBT --					
Siwalik Supergroup					

LITHOFACIES ANALYSIS

The present lithofacies analysis was carried out following Walker (1984) and Reading (1996). Keeping in view the general palaeogeographic setting and trends of the units, the study is based on parameters such as, composition, grain size, geometry of individual units, primary sedimentary structures and palaeocurrent. In all, twelve lithofacies were identified in the Blaini Formation and assigned to specific sub-environments of deposition, based on inferred depositional processes (Fig. 3-6). The general trend of the palaeoshoreline was established as NW-SE, on the basis of trend of lithofacies and channel axes and palaeoflow pattern. The northerly oriented palaeocurrent modes were considered to represent the offshore and southerly oriented ones to represent onshore currents. This is in agreement with the deductions made by Valdiya (1980), Singh (1985), Shukla and Pant (1996), Pant and Goswami (1996, 1998) and Pant and Shukla (1999).

BHUMIADHAR MEMBER

Lithofacies I: Matrix supported conglomerate

Sedimentological attributes

Made up exclusively of grey diamictite, 1 m to 4 m thick units the lithofacies occupies basal part of the Bhumiadhar succession. It overlies the Nagthat Formation with a sharp contact, which occasionally appears irregular, probably due to local relief. Granule to boulder-sized clasts of the diamictite is subangular to well round in shape. More than 80% of the total clast population of diamictite is pebble sized and approximately 60% of the total clast population being sub-rounded to sub-angular (Fig. 7a). Compositionally, the clast population consists of grey, pink, white, maroon and purple quartzite, vein quartz, feldspar, carbonate, siltstone and shale, embedded in poorly sorted greywacke matrix. Argillite clasts are essentially granule to boulder sized and subangular to angular in shape. The concentration of clasts in the

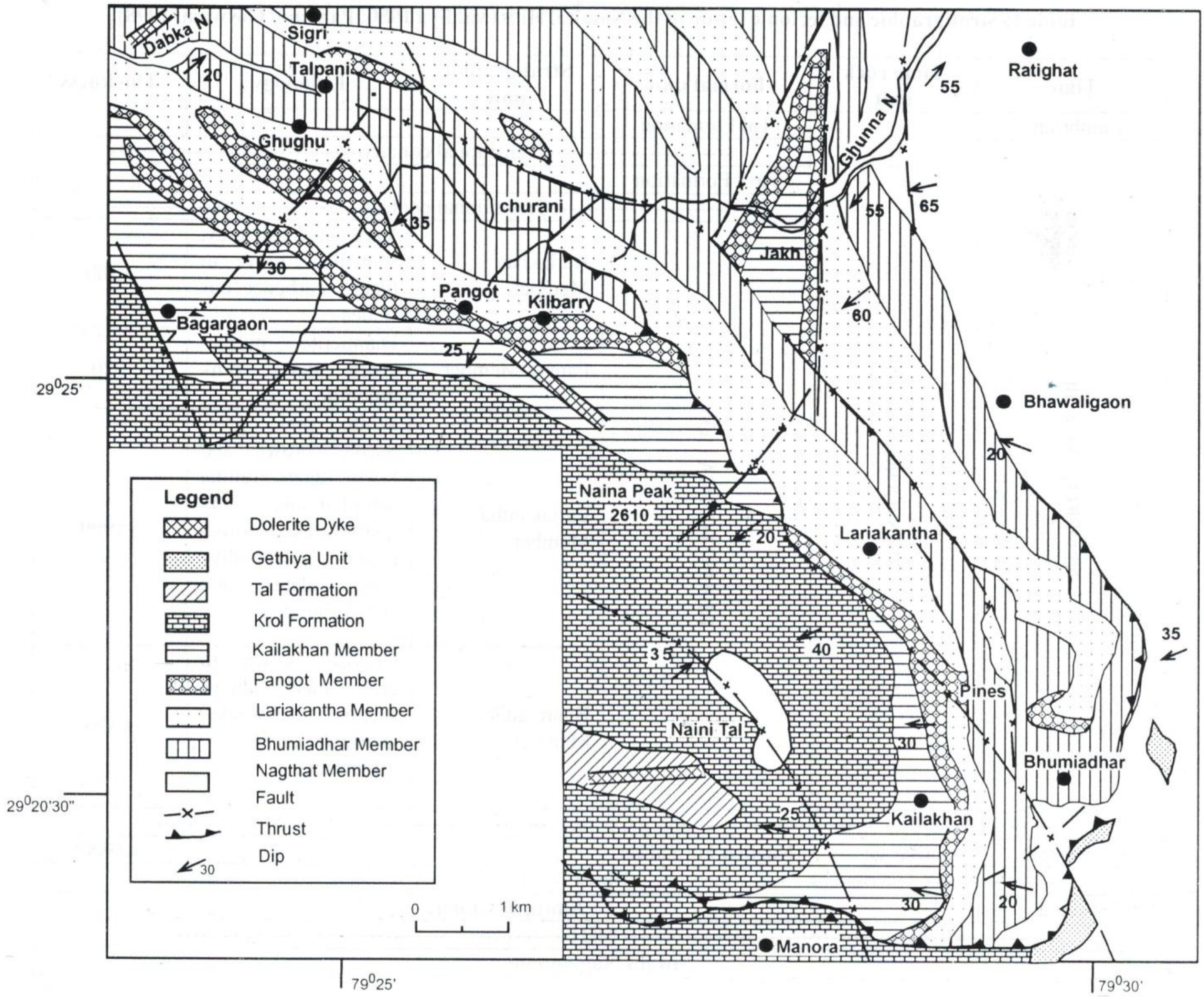

Fig. 2: Geological map of the Nainital Hills showing distribution of the Blaini Formation

lithofacies, generally, decreases stratigraphically upwards. The diamictite also contains pyrite crystals, and often is limonite-stained. Diamictite horizons also show some syn-sedimentary deformational structures. The upper contact of the lithofacies with the bounding lithofacies is also sharp.

Interpretation

The lithofacies sharply overlying the regressive Barrier-Island system sediments of the Nagthat Formation (Shukla and Pant 1996) is considered to represent the basal transgressive lag deposit (Clifton 1981). Sharp, slightly irregular base with gentle local relief may represent the transgressive disconformity. The very fact that the constituent clasts, except the shale flakes, of diamictite are compositionally akin to the pebbles recorded in the underlying Nagthat Formation indicates that diamictite is essentially derived from the reworking of the existing substrate, with no or negligible addition of extrabasinal sediments (Massari and Parea 1988). The sub-rounded to sub-angular shape of clasts and the dominance of one single clast size implies that they had already been subjected to some sort of abrasion and winnowing process for an appreciable time, probably the continuous swash and backwash activity at the Nagthat coast. Argillite clasts, on the other hand, represent intrabasinal clasts reworked during transgression.

The bulk of matrix is considered to be intrabasinal. In fact, during the landward migration of shoreline, the intertidal and upper subtidal region was eroded in order to maintain a relatively steep concave-upward shoreface profile and the eroded material, subsequently, was intermingled with gravels, dispersed at the coast, to deposit diamictites as transgressive lag deposits (Bruun 1962; Schwartz 1967).

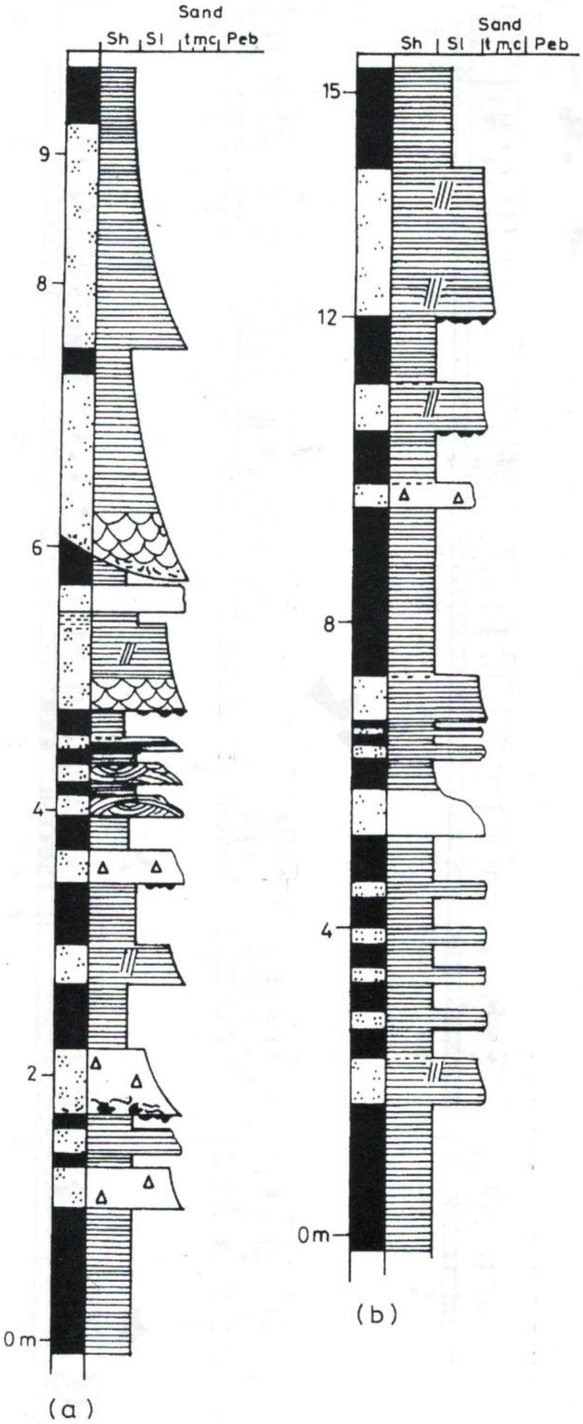

Fig. 3: Litholog of the Bhumiadhar Member in Gethia-Bhumiadhar Section. (a) 1.25 km along Pines-Lariakantha road (b) 4.3 km at Nainital-Bhowali road.

The poor sorting, occurrence of pyrite crystals and the deformational structures altogether suggest that diamictite were deposited via freezing *en masse* of a plastic material (Johnson and Rahn1970; Shanmugam 1997), which locally led to oxygen-deficient conditions.

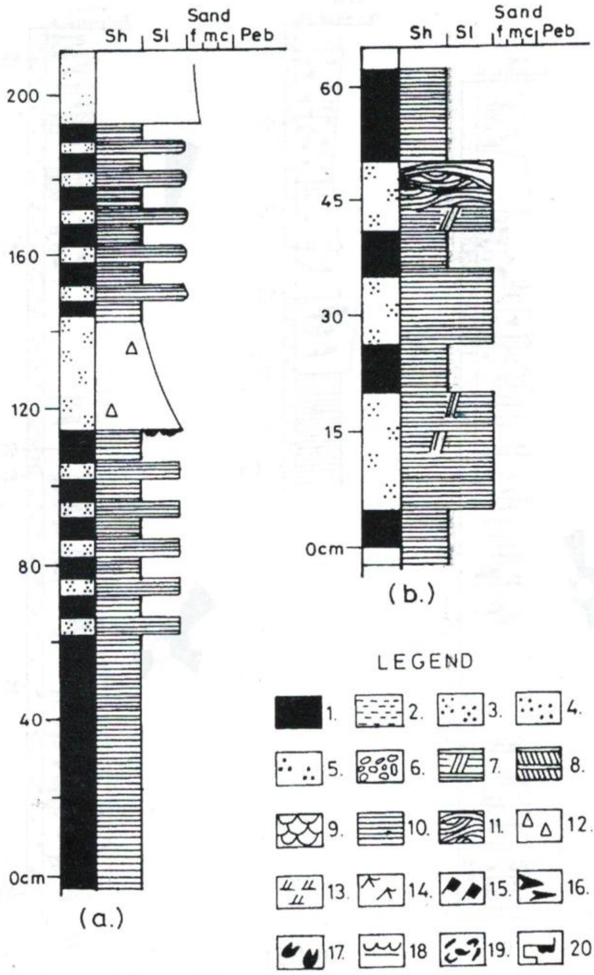

Fig. 4: Sedimentological logs of the Bhumiadhar Member. (a) 500 m (b) 200 m east of Bhumiadhar.

Lithofacies II: Carbonaceous shales

Sedimentological attributes

The 2 m to 6 m thick units of the lithofacies constitute the bulk of Bhumiadhar Member. It consists of black to dark grey carbonaceous shales with thin (up to few centimeters) lenses of fine-grained greywacke. The proportion of sandy lenses within the argillites gradually increases in the stratigraphically upper levels where it, sometimes, occurs as sandy sheets. The shales as well as the greywackes of the lithofacies are highly micaceous. The lithofacies is characterised by extensive limonite staining. 2-3 mm long pyrite cubes are frequently disseminated all through the lithofacies and, occasionally, being segregated as thin veins The lithofacies generally shows gradational or sharp lower and gradational upper contact with the bounding lithofacies.

Interpretation

The thick succession of shale of this lithofacies indicates deposition in very low energy condition whereas the thin sandy units suggest intermittent, short-lived phases of

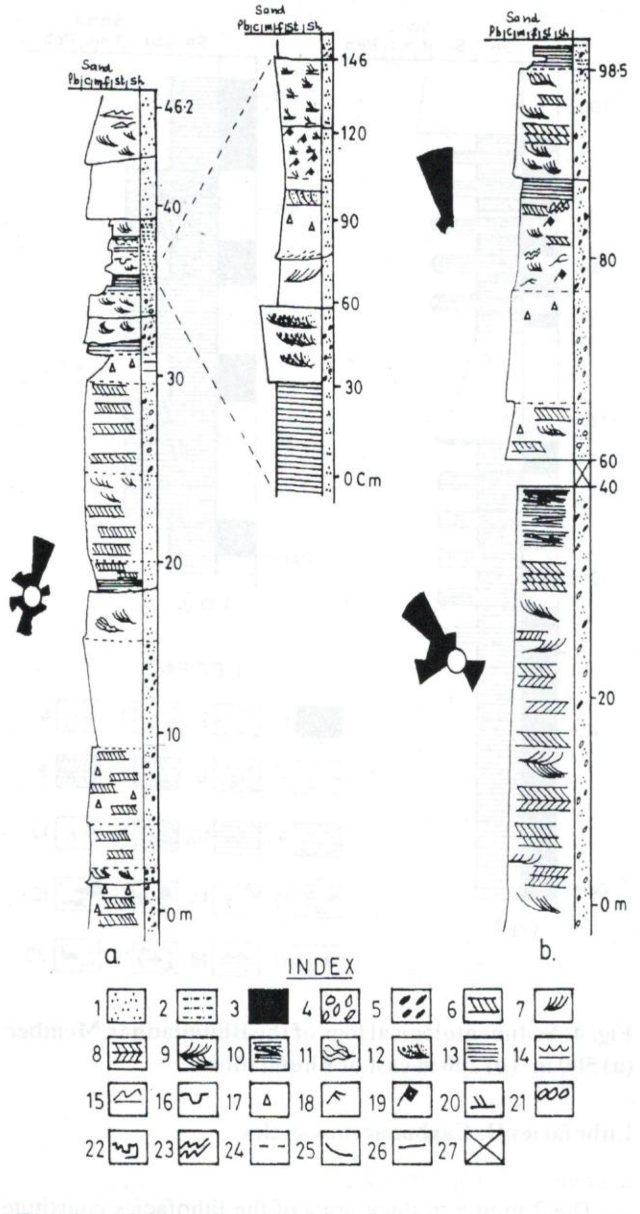

Fig. 5: Litholog of the Lariakantha Quartzite along (a) Nauniya Binayak-Binayak Section (b) Binayak-Badanthali section showing lithofacies variation, distribution of sedimentary structures and palaeocurrent directons. Index 1: Quartzite, 2: Silty Shale, 3: Shale, 4: Pebbles, 5: Mud Flakes, 6: Planar cross beds, 7: Trough Cross beds, 8: Herringbone Cross beds (Planar), 9: Herringbone Cross-beds (Trough), 10: Low angle discordance surfaces, 11: Deformed cross bed foresets, 12: Graded Cross bed foresets, 13: Parallel laminations, 14: Wave ripples, 15: Current ripples, 16: small channels, 17: Graded beds, 18: Lenticular bedding, 19: Flaser bedding, 20: Climbing ripple cross laminations, 21: Pebble imbrications, 22: Load structures, 23: Convolute bedding, 24: Gradational contact, 25: Erosional contact, 26: Sharp contact, 27: Unexposed sequence.

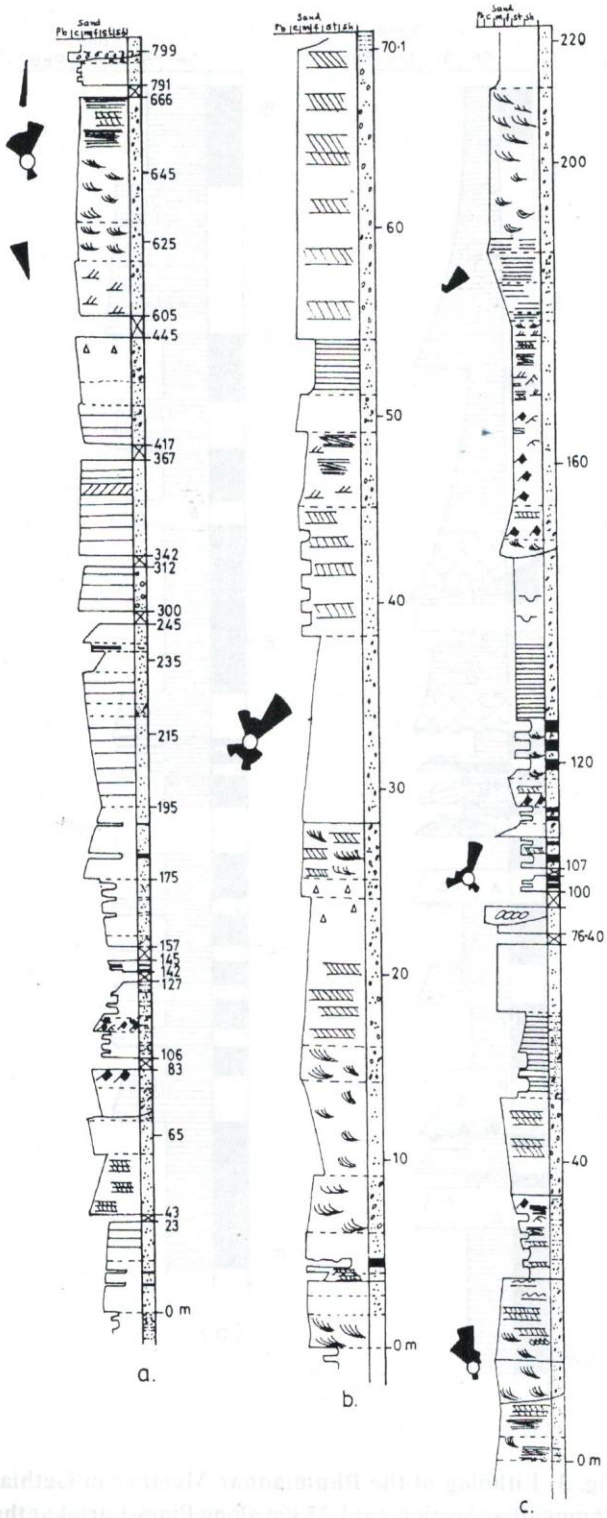

Fig. 6: Lithofacies of the Lariakantha Quartzite along Kilberry-Kunjakharak Sections (a) Binayak-Badanthali (b) Kunjakharak-Nauniya Binayak (c) Badanthali-Nauniya Binayak showing lithofacies variations, sedimentary structures and palaeocurrent patttern. The index is same as in Fig. 5.

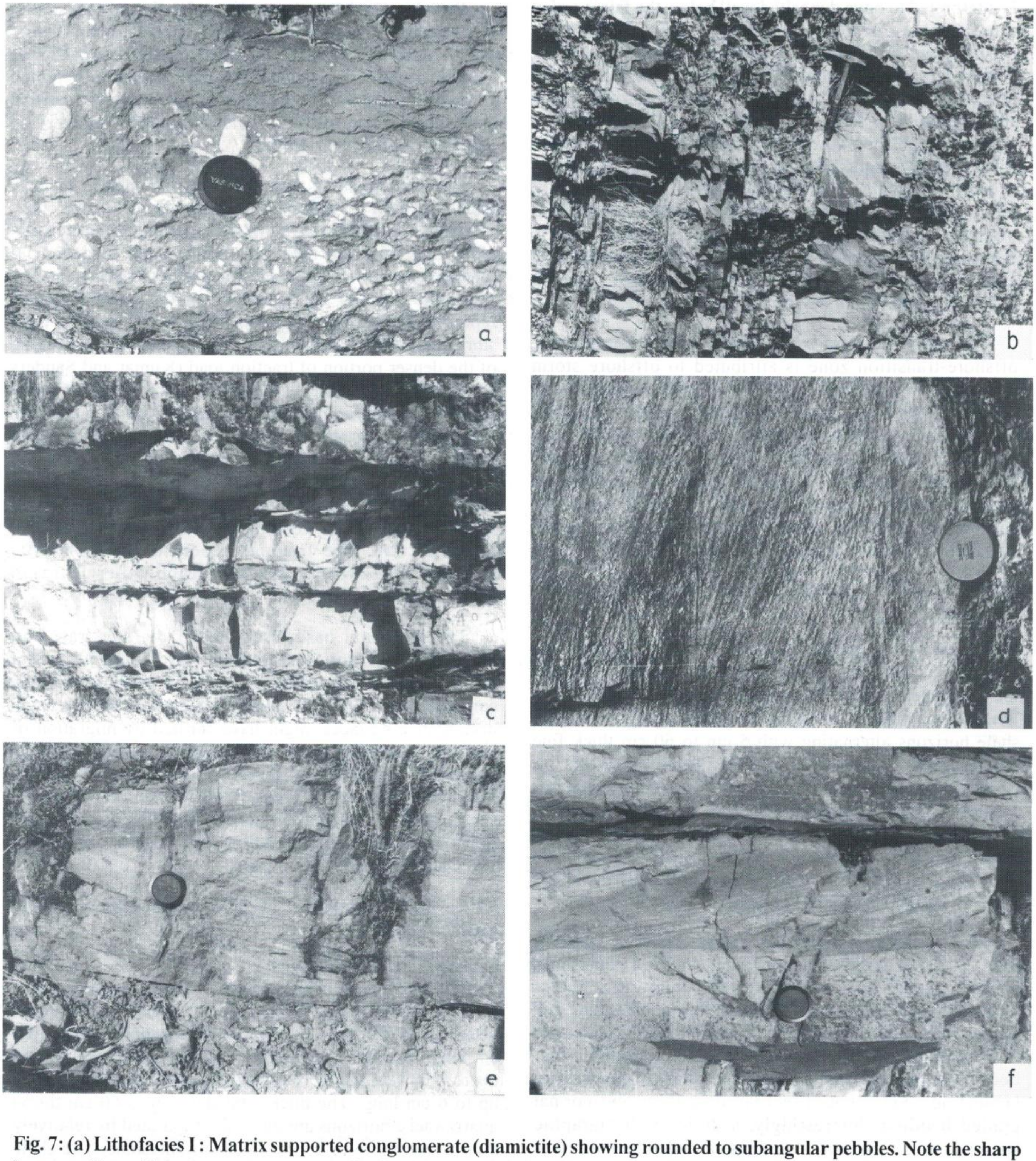

Fig. 7: (a) Lithofacies I : Matrix supported conglomerate (diamictite) showing rounded to subangular pebbles. Note the sharp lower and transitional upper part exposed at Lariakantha road. (b) Lithofacies III: Interbedding of sand and shale showing lateral pinching and swelling near Bhumiadhar village. (c) Lithfacies A Sandstone and shale interbeddding. Note the loadcasted under surfaces of the sandy units exposed south of Naunuya. (d) Lithofacies B showing planar cross bedding in gritty quartzite exposed north of Nauniya Binayakvv. (e) Large scale trough cross bedding in lithofacies B showing size gradation along the foresets and ripples towards top of the units developed north of Binayak. (f) Deformed cross-bed foresets seen in lithofacies B, developed on the western face of Badanthali ridge.

relatively high-energy conditions. The lithofacies, as such, is interpreted to have deposited well below the fair-weather wave base but near to the storm wave base i.e. the proximal offshore and distal offshore-transition zone. Prave et al. (1996) interpret the shales of such a succession as the hemipelagites and sandstones as the distal portions of the storm beds. The lensoid sandy beds probably indicate channelling of storm-currents into rip channels or deposition at rip channel mouths (Massari and Parea 1988). A number of workers (Banks 1973; Johnson et al. 1978) have also reported similar facies from the proximal offshore to distal offshore-transition zone of Late Precambrian to Early Cambrian succession of north Norway. The abundance of carbon and pyrite in the lithofacies suggests sedimentation in an oxygen-deficient environment.

The introduction of great volume of sediments in the offshore-transition zone is attributed to offshore storm currents (Harris and Eriksson 1990). Parallel laminations of the lithofacies might have been formed as the plane bed from suspension clouds generated by storms. However, the low angle discordance surfaces as well as the parallel laminations could also have generated by the migration of low-amplitude bed-forms, as a result of bed load traction and sediment fallout during passage of an overriding turbulent suspension current (Paola et al. 1989).

Lithofacies III: Shale alternating with fine-grained sandstone

Sedimentological attributes

The 1.5 m to 3 m thick lithofacies units generally overlie the lithofacies II of the Bhumiadhar Member (Fig. 7b). The lithofacies is made up of 15 cm to 1 m thick grey, micaceous shale horizons alternating with 5 cm to 60 cm thick fine grained, grey micaceous wacke or arenite horizons (Fig. 7b). Repetition of such units at different intervals characterises the lithofacies. The thickness of sandy horizons, generally, increases upwards. Shales of the lithofacies are characterized by parallel laminations. The sandy horizons succeed the argillites with sharp or erosional base, and individual beds show lateral pinching and swelling.

The lower bedding surface of sandy horizons is generally load casted. The basal part of such horizon sometimes contain papery thin mud flakes and mud curls. Other sedimentary structures of sandy horizons include, flute and groove casts, often accentuated by loading, on the underside of basal units, up to 4 cm thick planar and trough cross-beds, hummocky cross-stratification (HCS), parallel laminations, low angle discordance surfaces and normal graded bedding. Interestingly, a definite stratigraphic sequence of sedimentary structures can often be noticed in sandy horizons ¾ mud chips in the basal part followed up successively by cross-beds, parallel laminations, low angle discordance surfaces and, finally, hummocky cross-stratification. The lithofacies indicates ENE directed palaeocurrent and shows gradational mutual contacts with the bounding lithofacies.

Interpretation

Based on rhythmic alternations of shale and sandstones, this lithofacies is interpreted to have deposited in offshore-transition zone, below the fair-weather wave base but above the storm wave base. Such alternations have been reported from the middle to proximal part of the offshore-transition zone by a number of workers (Hamblin and Walker 1979; Duke 1985; Prave et al. 1996).

The parallel laminated shale are interpreted to have deposited during the fair-weather conditions (Lowe 1982; Shanmugam 1997) through storm generated suspension cloud and sharp/erosional based fine sandy horizons are interpreted to imply episodic storm deposits (Duke 1985). The mud clasts in the basal part of the sandy horizons represent the storm lag deposits, ripped-up during the peak storm and re-deposited *en masse* in response to the freezing of the denser portion of traction load (Kumar and Sanders 1976; Mutti and Nilsen 1981). The sharp/erosional based sandy horizons with flute and groove casts on the underside and mud clasts in the lower portion of basal beds indicate sudden and erosive emplacement of sand into an environment dominated by quiet mud deposition. The presence of load casts on the lower bedding surface of basal sandy unit and graded bedding upwards further strengthens the deduction. The frequent repetition of such units suggests that storms followed each other in rapid succession.

The erosional base, scouring of the substrate and occurrence of cross-bedding up wards suggest initial deposition of sediments from powerful offshore directed currents (Duke 1985). The parallel laminations and low angle discordance surfaces might have formed by migration of low-amplitude bed forms under oscillatory or combined flow conditions (Reineck and Singh 1980; Swift et al. 1983). Similarly, hummocky cross-stratification also indicate aggradation and/or translation in a combined or oscillatory flow regime (Dott and Bourgeois 1982; Swift et al. 1983; Allen 1985; Nottvedt and Kreisa 1987).

Lithofacies IV: Fine- to medium-grained pebbly quartzwacke

Sedimentological Attributes

The lithofacies consists of 3 m to 8 m thick units of fine to medium grained, poorly sorted, grey, micaceous, occasionally pebbly, quartzwacke. The pebbles are up to 2 cm long, rounded to well- rounded grey, white and purple quartzites, vein quartz, feldspar, siltstone and shale flakes up to 6 cm long. The thickly bedded (up to 60 cm thick) quartzwacke horizons are generally separated by relatively thin horizons (up to 25 cm thick) of siltyshale. The shale shows parallel laminations.

The beds of the quartzwacke horizons laterally pinch and swell and generally show load casts on the underside of basal beds, which sharply overlie shale beds. Occasionally, thin mud clasts are also recorded in the basal part of sandy units. Internally, the quartzwacke manifests graded beds. The characteristic feature of this lithofacies is the development of hummocks and swales on the top of quartzwacke beds (Figs. 3 and 4). The spacing (as measured between successive hummocks or successive swales) is between 90 cm and 2.8 m and the height of hummocks (as measured vertically between the swale and corresponding hummock) being 20 cm to 50 cm. The wackes also manifest faintly developed parallel laminations in the lower part of the unit.

The lithofacies shows sharp lower and gradational mutual contact with the bounding lithofacies. It, generally, overlies the Lithofacies III of the Bhumiadhar Member.

Interpretation

On the basis of its position above the proximal offshore-transition zone facies and dominance of hummocky cross-bedded sandstone over the parallel laminated shale, this lithofacies is interpreted to have deposited near, but below the fair-weather wave base (Hamblin and Walker 1979). The lithofacies, as such, is considered to represent the uppermost part of offshore-transition zone.

The parallel laminated shale is interpreted to have deposited during the periods of quiescence, mainly from storm generated suspension clouds. Sharp bases of sandy horizons and occurrence of mud clasts within suggest strong unidirectional current. The graded beds and load casts in the wacke indicate rapid deposition of sediments. Planar laminations in the lower part of sandy units are considered to have formed in response to rapid deposition of suspended sand and silt in slowly moving water during the waning phases of storms (Kriesa 1981). The occurrence of hummocky cross-beds on top of sandy units suggests marked role of oscillatory or combined flow.

The dominance of storm units over the fair-weather units suggests that the depositional basin was frequently struck by more energetic storms, probably because of relatively shallower depth (Hamblin and Walker 1979; Massari and Parea 1988). Moreover, Brenchley et al. (1993) considers such sequences as amalgamated sandy sequences and interprets them to be products of multiple storm events. As such, only the lower portion of each storm-deposited sequence is preserved as is also corroborated by Massari and Parea (1988) and McCrory and Walker (1986) for near fair-weather wave base storm deposits of Southern Alps, Italy and southern Alberta, Canada respectively. The absence of fair-weather sedimentation in storm beds of near fair-weather wave base region has been attributed to scouring away by subsequent storms (Leithold and Bourgeois 1984).

LARIAKANTHA MEMBER

Lithofacies A: Quartzwacke Interbedded with Siltyshale

Sedimentological Attributes

The 4.5 m to 5.3 m thick units of lithofacies comprise of grey to purple, fine to medium grained, poorly sorted quartzwacke interbedded with dark grey to black siltyshale. The 15 cm to 2.5 m thick quartzwacke horizons of the lithofacies succeed the 5 cm to 20 cm thick siltyshale horizons with sharp or erosional bases (Fig. 7c). The individual beds of the quartzwacke generally show lateral pinching and swelling and contain papery thin mud clasts within; concentration of mud clasts in the lithofacies being greater in the eastern part of the study area as compared to the western part, where it also contains mud pebble conglomerates at the base of the sandy horizons (Figs. 5 and 6).

The highly micaceous sandy horizons of the lithofacies are often marked by load casts on the underside of basal beds (Fig. 7c). The sandy horizons of the lithofacies occasionally manifest trough and planar cross-beds with graded foreset laminae. Papery thin mud flakes also lie parallel to the foreset laminae of cross-beds. The set height of the cross-beds ranges between 2 cm to 25 cm in the western part and 6 cm to 30 cm in the eastern part of the area. The arenaceous horizons, additionally, show parallel laminations, low angle discordance surfaces, normal size grading and isolated flute and groove casts often accentuated by loading. The siltyshale of the lithofacies shows parallel laminations. The lithofacies displays NNW to NNE directed palaeocurrent.

The lithofacies constitutes the basal part of Lariakantha Member and generally shows gradational mutual contacts with the bounding lithofacies and an upward coarsening character.

Interpretation

On the basis of its position above the offshore sediments and alternations of fine to medium grained, poorly sorted cross-bedded quartzwacke with subordinate siltyshale, the lithofacies is interpreted to have deposited in lower to middle shoreface subenvironment of deposition. Analogous facies from Late Precambrian Sakaergardnes Formation of Norway and Early Proterozoic Uncompahgre Group of south-west Colorado have also been interpreted to represent the lower to middle shoreface environment of deposition by Levell (1980) and Harris and Eriksson (1990) respectively.

The repetition of sand and siltyshale alternations in varying scale is related to the operations of alternating high and low energy conditions, probably storm and fair-weather conditions of varying periodicities. During storms much sand was eroded from upper shoreface and foreshore regions, taken into suspension by turbulent water and, eventually, re-deposited in deeper parts of the basin with greater amount in lower to middle part of the shoreface (Reineck and Singh 1980). The abundance of mud clasts, erosional bases of sandy horizons with mud pebbles in the basal part, flute casts, load casts and graded beds collectively suggest erosion followed by rapid deposition of sand onto water saturated mud in response to respective peak and waning phases of storm activity.

Occurrence of cross-beds with seaward directed palaeocurrent may be attributed either to storm enhanced rip currents (Gruszczynski et al. 1993) or to storm generated geostrophic currents (Walker 1984; Duke 1985), which cause the bottom currents to move offshore. General increase in the set height of cross-beds in eastern extension of the lithofacies suggests stronger current activities in the eastern part of the basin, probably related to the eastward shallowing of the basin. The mud clasts recorded in the lithofacies are considered to have generated at the height of storm when semi-consolidated sediments were ripped-up, carried-in by rip currents and, ultimately, re-deposited (Mazzullo 1971).

The parallel laminations and low angle discordance surfaces, so frequently recorded in the lithofacies, characterise many storm-generated deposits (Howard 1971; Kumar and Sanders 1976; Howard and Reineck 1981), and might have formed by the migration of low amplitude bed forms under oscillatory or combined flow conditions (Reineck and Singh 1980; Swift et al 1983) or they represent the waning phases of the storm when storm suspended sand and silt rapidly drop from the suspension, in very slowly moving water (Kreisa 1981).

Lithofacies B: Cross-bedded quartzarenite

Sedimentological attributes

The lensoid units of the lithofacies, ranging in thickness from 4 m to 6.7 m, are made up of medium to coarse grained, well sorted, grey to purple grey, thickly bedded, pebbly quartzarenite. The lithofacies also contains a lot of mud flakes and mud clasts.

Basal part of the lithofacies is generally conglomeratic and grain size in the lithofacies decreases upwards. Upper part of the lithofacies is characterized by large scale (30-70 cm thick), high angle (up to 30°), planar and trough cross-beds (Fig. 7 d, e, and 8a), with a lot of reactivation surfaces (Fig. 7e), mud pebbles and synsedimentary deformation structures (Fig. 7f). The foresets of cross-beds, varying in thickness from 0.4 cm to 5 cm, internally manifest normal down dip size grading. Many of the foresets show concentration of mud pebbles along their surfaces. The lithofacies also manifests parallel laminations, low angle discordance surfaces, very thin graded beds and crude pebble imbrications. The lithofacies is characterized by poly-modal palaeocurrent, prominently directed towards NNE-NNW and SSW-SSE (Fig. 5 and 6). In the eastern part of the study area, the lithofacies also shows 18-40 cm wide and 3.2-13 cm deep, roughly NE-SW trending channels filled with well rounded to sub-rounded, up to 2 cm long pebbles of quartzite, vein quartz and siltstone.

At some places, particularly in the eastern part of the area, the lithofacies shows development of current, wave modified current and wave ripples. The wave ripples, sometimes, are superimposed by current ripples. The ripples indicate ENE-WSW to NNE-SSW directed wave action and NE and SW directed palaeocurrent. The lithofacies generally shows erosional lower and gradational upper contact with the bounding lithofacies.

Interpretation

On the basis of medium to coarse grain size, well sorted grain texture and steep angles of the cross-bed foresets this lithofacies is interpreted to be of subtidal (Upper shoreface) bar origin. McCubbin (1982) also reports such types of foresets in upper shoreface from Cretaceous Gallup Sandstones of New Mexico. The morphology and dimensions of the cross-beds suggest that bars be of sand wave origin (Dalrymple et al. 1978; Allen 1980). Migration of these bed of foreset dip are also consistent with those usually found on the bar lee sides (Massari and Parea 1988). The cross-beds, as such, are interpreted to represent the bar lee deposits marking landward or seaward migration, where different phases of tidal cycle facilitating foreset erosion on the crest to lee face, under the influence of currents, are represented by reactivation surfaces (Allen 1980; De Mowbray and Visser 1984). This phenomenon is quite common in upper shoreface regime (Harris and Eriksson 1990). The deformed foresets with mud clasts indicate rapid sedimentation under high-energy conditions.

The polymodal palaeocurrent may be attributed to interaction of storm-enhanced rip and longshore currents and storm generated geostrophic currents. The prominent seaward and landward directed current modes positively indicate conclusive role of storm generated geostrophic currents (Morton, 1981). Powerful role of longshore currents in upper shoreface zone has also been discussed by DeCelles (1987).

The basal conglomeratic horizon of the units may indicate peak of storm erosion followed by sudden traction deposition and the overlying cross-bedded horizons may indicate current activity during the waning phases of storm. The mud flakes and mud pebble conglomerates in the lithofacies are considered to represent the storm lag deposits. Small erosional channels occurring in the eastern extension of the lithofacies may represent high angle scours of Leithold and Bourgeois (1984) or gutter casts of Aigner (1985) and may be related to storm enhanced rip currents. Such storm enhanced rip current channels in inner bar zone are quite common under moderate storm conditions, such as the Polish Baltic coast (Gruszczynski et al. 1993). The absence of such channels in the western extension of the lithofacies indicates that storms hit the eastern part of the basin more vigorously, probably because of the shallowing in the eastern part.

The presence of wave and wave modified current ripples in the eastern part of the study area indicates variations in velocities and confirms the role of wave activity even in deeper parts of a shallow marine environment (Niedoroda et al. 1989; Thorne et al. 1991). Moreover, the general absence of these structures in western part of the study area further strengthens the inference that the basin was progressively shallower towards the east.

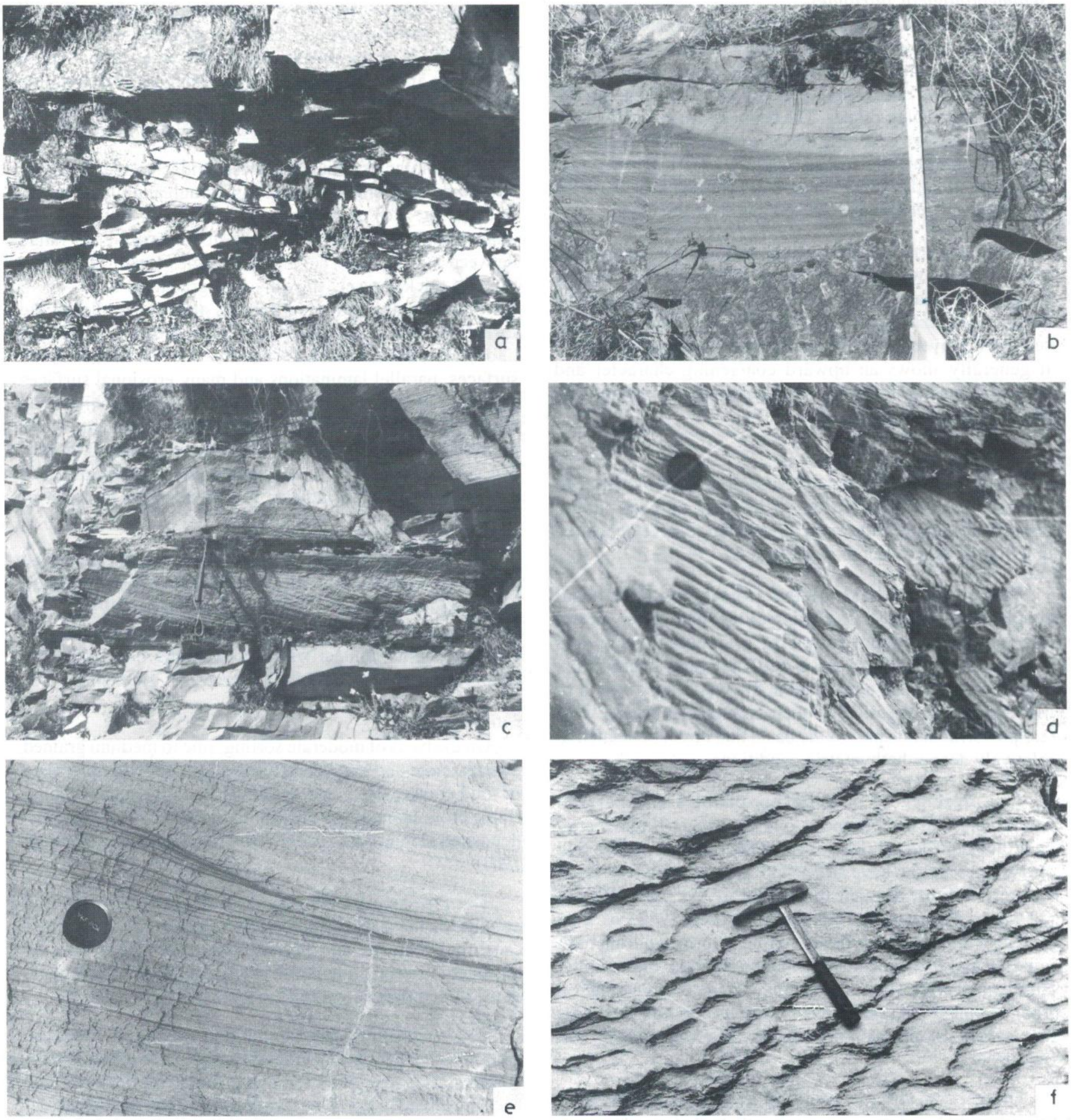

Fig. 8: (a) Lithofacies B showing very large scale cross-bed sets having sharp contact with overlying gritty quartzite, developed north of Nauniya Binayak. (b) Small scale channelised sandstone body developed in thinly laminated silt stone and quartzite incised in lithofacies D as seen near Nauniya Binayak. (c) Planar Cross-bedded sandstone developed in lithofacies D exposed about 3 km. north of Binayak. (d) Prolific development of wave and wave modified current ripples in lithofacies D, seen near Kilberry. (e) Lithofacies P3 showing laminites in pink dolomitic limestone exposed near Rajgarh village. (f) Lithofacies P3 showing sinuous ripples near Rajgarh village.

Lithofacies C: Massive to parallel laminated quartzarenite

Sedimentological attributes

The 3.2 m to 4.9 m thick units of lithofacies are composed of medium to coarse grained, thickly bedded, moderate to well sorted, white grey or purple quartzarenite. The quartzarenite is occasionally pebbly and also contains few mud flakes and clay-drapes. The beds (25 cm to 1 m thick) of the lithofacies are generally massive (structure less) or show parallel laminations in the upper part with low angle discordance and parting lineations. The thick beds of the lithofacies in general are stacked one over the other.

In the eastern part of the study area the lithofacies quite often begins with an erosional base followed up by conglomerates and eventually by medium to coarse grained pebbly quartzarenite. The lithofacies, being rich in segregated layers of heavies, contains micaceous minerals. It generally shows an upward coarsening character and erosional or sharp lower and gradational upper contact with the bounding lithofacies.

Interpretation

On the basis of medium to coarse grain size, moderate to well sorting, concentration of heavies and low angle discordance this lithofacies is interpreted to have deposited in a high-energy beachface setting.

The erosional base of the lithofacies with basal conglomerate suggests beginning of the high-energy event, during which medium to coarse grained sediment was winnowed away leaving a gravel lag (Cudzil and Driese 1987). The absence of such a package in the western extension of the lithofacies suggests that such high-energy events were less powerful in this part of the basin that might be related to relatively deeper bathymetric conditions.

The presence of mud flakes, pebbles and parallel laminations and discordances together suggest high-energy conditions during the deposition of the lithofacies. The thin clay-drapes might have deposited during relatively slack water conditions through the fallout of the fine sediment put into suspension during storms (Allen 1982) or they represent intertidal clay-drape couplets, formed during both low-tide and high-tide slack-water conditions. The parallel laminations with discordances may suggest sedimentation from sediment charged flows driven by vigorous currents that buried the pre-existing sandwaves (Chakraborty and Bose 1990).

The general absence of storm generated structures in these beachface deposits may be attributed to extensive reworking by the dominating tidal currents (Soegaard and Eriksson 1985).

Lithofacies D: Ripple cross-laminated quartzarenite Interbedded with silty shale

Sedimentological attributes

The 2.4 m to 5.3 m thick lithounits consist of fine to medium grained, moderately sorted, purple, purple grey or pink pebbly quartzarenite interbedded with subordinate grey to purple, occasionally micaceous siltyshale. The sandy units also show ubiquitous mud clasts disseminated all through the lithofacies with a drastic increase in concentration in the eastern part of the area. The 4 cm to 7 cm deep and 20 cm to 40 cm wide, NNE to SSW trending channels filled with mud clasts at the base, becoming fine sandy upwards, are common in the lithofacies (Fig. 8b).

The lithofacies abounds in flaser and lenticular bedding, climbing ripple cross-laminations, trough and planar cross-beds (Fig. 8c) and herringbone cross-beds in the quartzarenites. The set thickness of the cross-beds range between 5 cm to 40 cm having steep angles (up to 23°), 2 mm to 1 cm thick foresets showing size gradation in the down current direction. Flat mud pebbles also lie parallel to the foreset laminae. The lithofacies also shows thin graded bedding, convolute bedding, low angle discordance surfaces, parallel laminations and many erosional surfaces of localised nature. Upper part of the quartzarenite units manifest prolific development of wave, current, wave modified current ripples and interference ripples (Fig. 8d). The ripple index (1.1 – 1.5), rounded sinuous crest and their extensive bifurcation indicate the wave origin for most of the ripples.

The eastern extension of the lithofacies also shows well preserved mud cracks. The lithofacies generally shows polymodal with prominent NNE-NNW and SSW directed palaeocurrent. The lithofacies has gradational lower and erosional upper contact with the bounding lithounits. The lithofacies displays an upward decrease in grain size.

Interpretation

On the basis of moderate sorting, fine to medium grained quartzarenite and silty shale alternations showing presence of mud cracks, flaser and lenticular bedding, and climbing ripple cross-laminations the lithofacies is considered to have deposited in intertidal zone (Mixed flat) (Reineck and Singh 1980).

The presence of the small scale channels with mud pebbles at the base becoming fine sandy upwards, other erosional features and herringbone cross-beds may be attributed to strong tide-storm activity in the intertidal zone, in the mixed flats and along the tidal channel.

The prominent landward and seaward directed palaeocurrents probably indicate pronounced effect of tidal currents. The size gradation along the foreset laminae has been attributed to the wave swash and backwash in intertidal zone (Clifton 1969; Eriksson 1977; Reineck and Singh 1980; Reinson 1984; Cudzil and Driese 1987). The preservation of current and wave modified current ripples in the upper part of the units in the lithofacies indicate variations in the velocities, and reworking is considered to be related to emergence and superimposition of wave processes (Reineck and Singh 1980). The high sinuosity of the ripples may be attributed to relatively high energy and decreasing depths (Allen 1980).

The presence of mud cracks and higher concentration of mud clasts in the eastern part of the study area, points to subaerial exposure for a longer period of time as compared to the western part. This may be related to the shallowness of the basin in eastern part.

PANGOT MEMBER

Lithofacies P1: Finely laminated siltstone – shale

Sedimentological Attributes

The lithofacies comprises grey and purple shale interbedded with similar coloured siltstone. The grey and purple silt stone and shale are intimately associated with each other and grade into each other vertically as well as laterally. The lithofacies also shows inter -bedding with the pink dolomite.

The shale of the lithofacies shows parallel laminations. The associated siltstone sometimes particularly in the western part of the area, shows flute casts, which suggest ESE directed current directions. In addition, again in the western part of the study area, the siltstone also shows climbing type trough and planar cross-laminations, parallel laminations and graded beds.

The lithofacies generally shows gradational lower and upper contact with the bounding lithofacies.

Interpretation

The intimate association of the lithofacies with the subtidal-intertidal sediments of the Lariakantha Member suggests sedimentation in tide affected coastal environment with great influx of suspended material. Therefore, on the basis of general absence of sandy material in the lithofacies and its gradational contact with the mixed flat sediments (lithofacies- D of Lariakantha Member), This lithofacies is interpreted to have deposited in mud flats of the Intertidal zone. (Reineck and Singh 1980). Extensive mud flat sediments have been reported from modern German North Sea Tidal flats (Reineck 1975).

The purple shales containing abundant iron oxide (hematite) suggest oxidising conditions and intermittent exposure during the deposition. Moreover, the alternations of shale and siltstone indicate alternating low and relatively moderate energy conditions. Synthesis of these deductions also points to the deposition in the mud flat.

The occurrence of flute casts at some places indicates scouring of the substrate in response to relatively stronger energy episodes. The palaeocurrent direction as suggested by these flutes indicates strong longshore current. The occurrence of current formed structures in western extension of the lithofacies suggests slightly higher energy in western part of the basin, probably in response to shallower depth in this part. The planar laminations are considered to have formed from suspended material of turbulent water (Reineck and Singh 1980). The presence of thin graded units suggests rapid deposition of sediments from suspension clouds.

Lithofacies P2: Diamictite

Sedimentological attributes

The lithofacies comprises 4cm to 10m thick units of diamictite. Randomly oriented sub-rounded to well-rounded, pebble sized clasts of quartzite, vein quartz and chert, and sub-angular to sub-rounded pebble to boulder sized siltstone, shale and carbonate embedded in argillaceous, sandy or carbonate matrix. At places, carbonate cement is also noticed. The diamictites generally lack sedimentary structure except for local thin graded units, crude pebble imbrication and slump folding. The pebble imbrication shows NNE to NE directed current activity. The three dimensional reconstruction of the diamictite horizons although is not possible owing to terrain limitations, the integration of morphological information on different dip and strike sections indicate that these horizons mostly are channel like with depth not exceeding about a meter and width in the order of tens, sometimes a few hundreds, of meter. The cannels are carved through underlying sandstone, silty shale or dolomite. Diamictite horizons sometimes are intervened by lenticular argillaceous and sandy pockets. At places, the diamictites show inter bedding with well-sorted quartzites or with siltstones or even with shale; the siltstone and shale are parallel laminated. The diamictite, occasionally, shows interfingering with the pink dolomite.

The lithofacies generally shows sharp or erosional lower contact and gradational upper contact with the bounding lithofacies.

Interpretation

It is not clear as whether the thick massive diamictite units are the result of single depositional event or represent amalgamations of many thinner beds. However, on the basis of intervening argillaceous and sandy horizons it is inferred that the diamictite units are products of amalgamation of different episodes of sedimentation (Eyles et al. 1988). Moreover, the diamictite horizons are channel, locally sheet, like and, as such, are inferred to have emplaced by some mass flow mechanism. The massive nature of diamictite also suggests accumulation by down-slope re-sedimentation of unstable pile as cohesive debris/mud flow (Johnson and Rahn 1970; Hampton 1975; Lowe 1979; Johnson 1984; Postma 1986).

Compositionally, the diamictites show bimodality of both clasts and matrix. The quartzose clasts are mainly pebble sized and argillite clasts are cobble to boulder sized. The matrix is mainly argillaceous sand and carbonate. Moreover, the clasts are by and large sub-angular to sub-rounded. Also, the pebbles of diamictite are similar to those encountered in underlying Lariakantha and Bhumiadhar members. It is, thus, inferred that these clasts were already dispersed at the coast and, as such, were subjected to continuous winnowing processes to attain sub-angular to sub-rounded shape. The converging lines of evidence, thus, suggest that the pre-existing clasts at the coast were intermixed with argillaceous sand and/or carbonate as a result of sudden introduction of such material. The argillaceous sandy material might have been introduced from the intertidal or supratidal regions in response to excessive erosion related to some unusually high-energy event such as storm. The calcareous material was carried in from the carbonate flats. The tectonic upheavals of the coast and hinterlands might have triggered sedimentation at the coast. The larger argillite clasts in the diamictite are considered to represent the intrabasinal origin, ripped-up from the mud flats or from the supratidal flats at the height of storms.

The pebbly, sandy and clayey sediment available at the coast got intermixed at the height of storms and, subsequently, slid down-slope as viscous debris flow under the combined influence of gravity and off shore directed currents. The association of diamictites with well sorted quartzite horizons suggest that the debris flowed down-slope up to the subtidal region. The crude pebble imbrication, graded bedding and slump folding suggest sudden deposition of the material with some current influence.

Lithofacies P3: Pink siliceous dolomite

Sedimentological attributes

Interfingering with the underlying diamictite of lithofacies P2, or transitionally overlying the siltstone shale of lithofacies P1, this lithofacies comprises 1-15 m thick units of deep pink siliceous dolomite. The dolomite sometime shows parallel to wavy laminations (Fig. 8e), sinuous current ripples (Fig. 8f) and cryptalgal mats. The ripples indicate SSE directed palaeocurrent. The dolomite shows extensive stylolitization parallel to bedding. The tectonic deformation has rendered it foliated at places, thus obliterating the primary depositional fabric to a large extent.

Interpretation

This lithofacies clearly marks a phase of transition from clastic to carbonate depositional environment. The lithofacies is interpreted to have deposited in intertidal zone under warm (subtropical to semiarid) climatic conditions. The high MgO (16.29 to 18.56%) also suggests a warm condition for the deposition of the lithofacies.

The typical pink colour of the dolomite is attributed to the presence of ferric oxide in the lithofacies, which is indicative of strong oxidising environment (Tucker and Wright 1990). The occurrence of sinuous crested current ripples indicate paleoflow with variable energy conditions. As the occurrence of ripple marks is restricted to the western part of the study area, it is inferred that the western part of the basin was shallower as compared to the eastern part and experiencing slightly higher energy during the Pangot times.

KAILAKHAN MEMBER

Lithofacies K1: Black carbonaceous shale

Sedimentological attributes

The lithofacies comprises dark black to ash black, carbonaceous shale, being locally silty. The lithofacies also contains layers of siltstone and, sometimes, flat lenses of silty sandstone. The shales are pyritous and manifest extensive decolourisation rings and limonite staining. The silt and sitysand horizons within the lithofacies sometimes manifest load casts. The shales, siltstone and siltysand of the lithofacies being parallel laminated, wavy laminated and quite often shows discordances.

The lithofacies has gradational lower contact with the underlying lithofacies P1 of the Pangot Member and upwards it transitionally grades into marls of Krol Formation.

Interpretation

On the basis of fine grained clastics and general absence of large scale current or wave formed structures it is inferred that the lithofacies is deposited in a zone of persistent low energy (Reineck and Singh 1980). The high concentration of carbon and pyrite in the lithofacies suggests sedimentation in an oxygen-deficient (reducing environment (Tucker and Wright 1990; Harris and Eriksson 1990). It is, therefore, interpreted that the lithofacies represents mud flat to lagoonal environment of deposition .

The parallel lamination, recorded in the lithofacies, are formed from suspension (Reineck and Singh 1972) in the absence of bed load transportation in almost quiet waters (Harms and Fahnestock 1965). The wavy laminations is attributed to slightly increased energy conditions corresponding to lower part of the lower flow regime, most probably in response to restricted fetches of waves. The load casted fine sandy lenses within the shale suggest sudden incursion of the sand on to semi-consolidated muddy substrate, probably in response to higher energy condition during the storm.

FACIES SEQUENCE

Except lithofacies I all other lithofacies distinguished in the Blaini Formation are repetitive in nature and show marked lateral and vertical variation in characters. It is also clear that, no single section shows full development of all the twelve lithofacies, instead one or more of the constituents are missing in every section so that truncated cycles are very common. Most common cycles of lithofacies in the Blaini are Lithofacies II Lithofacies IV Lithofacies A Lithofacies B Lithofacies D Lithofacies P1 Lithofacies P3 Lithofacies K1 and Lithofacies II Lithofacies III Lithofacies B Lithofacies D Lithofacies P1 Lithofacies P3 Lithofacies K1. Lithofacies I occurs only at the base of Blaini succession and lithofacies P2 occurs, with erosional base, over lithofacies B, C, D, P1 or P3. Most common association of lithofacies P2 is with lithofacies P1. Nevertheless, the overall vertical sequence of lithofacies as derived from different sections comes out to be, Lithofacies I Lithofacies II Lithofacies III Lithofacies IV Lithofacies A Lithofacies B Lithofacies C Lithofacies D Lithofacies P1 Lithofacies P2 Lithofacies P3 Lithofacies K1.

The unit cycles within the Bhumiadhar and Lariakantha sequence are generally fining up. The overall grain size from shale (Lithofacies II) to sand (Lithofacies IV) in Bhumiadhar Member gives an overall coarsening up character to the sequence. Likewise, the increase in grain size from fine to medium grained quartzwacke–siltyshale (Lithofacies A) to medium to coarse grained quartzarenite (Lithofacies C) followed up by medium to coarse grained quartzarenite–siltyshale (Lithofacies D) gives an overall coarsening up character to the Lariakantha sequence (Figs. 5 and 6).

PALAEOCURRENT ANALYSIS

Palaeocurrent analysis of the Blaini Formation is carried out considering measurements for tabular and planar cross-beds having set thickness more than 4 cm. A total of 431 readings were collected. As the regional dip of rocks in the study area is invariably more than 10°, the azimuth readings were corrected for tectonic tilt following Potter and Pettijohn (1976) and Lindhom (1991). The azimuths were measured after ascertaining the maximum inclination of the planar foresets and curvature of trough foresets on bedding plane surface.

In order to understand the pattern of sediment dispersal and complex nature of currents in Blaini shelf the palaeocurrent data was analysed in association with general NW-SE trend of the palaeoshore line (Picard 1967; Selley 1967; Dalrymple et al. 1992; Ke et al. 1996). This would also help reconstruct the palaeogeography and basin configuration during Blaini sedimentation (Greb and Chesnut 1996).

The area level analysis of the palaeocurrent (Fig. 9) shows polymodality with prominent NE, NNW and SW directions. Thus, indicating sediment dispersal through powerful offshore, oblique offshore and onshore directed currents.

The spatial distribution of palaeocurrent data displays a high degree of spatial variation, with bipolar-bimodal to polymodal pattern (Fig. 9). However, sediment dispersal was mainly towards NE, SW and NNW and to a lesser, but appreciable, extent towards SE. That is to say, the sediment dispersal was mainly through ebb, flood and longshore currents. Western part of the study area shows dispersal of sediments mainly through ebb currents, whereas in the eastern part both ebb and flood currents were almost equally powerful. Moreover, the sediment dispersal through longshore currents has been most powerful in the eastern part of the study area. These currents never show bipolarity for they behave as unidirectional fluvial currents during high-energy periods and bring about rapid migration of dunes (Davis and Fox 1972). It is, thus, quite evident that the tidal dispersal system dominated the depositional regime during the Blaini times. This suggests that the Blaini coast was a high-energy coast.

The strong spatial variability of palaeocurrent with dominance of bipolar-bimodal to polymodal modes in eastern part of the area may suggest that the basin was progressively shallower towards the east. The detailed lithofacies analysis also points to such variability in the bathymetry of the basin, particularly during the Lariakantha sedimentation.

The pattern of sediment dispersal within the coastal setting (Fig. 10) is highly variable in the subtidal domain. The palaeocurrent pattern is polymodal due to complex system of flood, ebb and longshore currents. However, the flood and ebb currents have played a major role in the deposition of subtidal sediments. Basin ward from the subtidal domain is the offshore-transition zone showing sediment dispersal only through ebb currents. This is in agreement with the fact that offshore oriented storm currents are the only currents, which can bring in bed load deposition below the fair-weather wave base (Reineck and Singh 1980). The palaeocurrent pattern in the intertidal domain also shows less variability but for the reason that, only cross-bedding data (with set thickness>4 cm) has been taken into consideration for present analysis and, hence, most of the data on the mixed flat zone, generally having small scale features, is not shown here. Neverthless, the intertidal domain shows that much of the sediment dispersal was by ebb and flood currents.

The sediment dispersal pattern for the Blaini sediments is consistent with the results of lithofacies analysis, which suggest sedimentation in a high-energy tide-storm influenced shallow marine system. In such a system, ebb currents are unusually powerful during storm events and are most responsible for the bed load sedimentation in deeper parts (Gruszczyznski et al. 1993).

DEPOSITIONAL ENVIRONMENT

Depositional environment of the Blaini Formation has been the most hotly debated problem of Lesser Himalayan geology. Most of the depositional models proposed so far pertain to investigations of diamictites only without considering their association with other lithounits of the Blaini. The over emphasised diamictites occur at two stratigraphic levels within the ±1700 m thick Blaini sequence and altogether constitute less than 3% of the total stratigraphic thickness. Lower diamictite horizon constitutes the basal unit of the lowermost Bhumiadhar Member and the upper diamictite horizon occurs above the ±1000m thick texturally and mineralogically mature sandstones of the Lariakantha Member (Pant and Goswami, 1996). The genesis of diamictites should, therefore, be viewed not only in conjunction with other lithounits of the Blaini but also in conjunction with the underlying Nagthat-Simla succession. Keeping in view the same, the present study aims at depositional environment of Blaini Formation based on integration of our data and published data of Shukla and Pant (1996) and Pant and Shukla (1999) on underlying Nagthat Formation.

The detailed lithofacies analysis of the Blaini Formation reveals that sediments were deposited in a shallow marine environment. The sedimentation took place mainly in offshore to supratidal zones of a regressive shelf. The

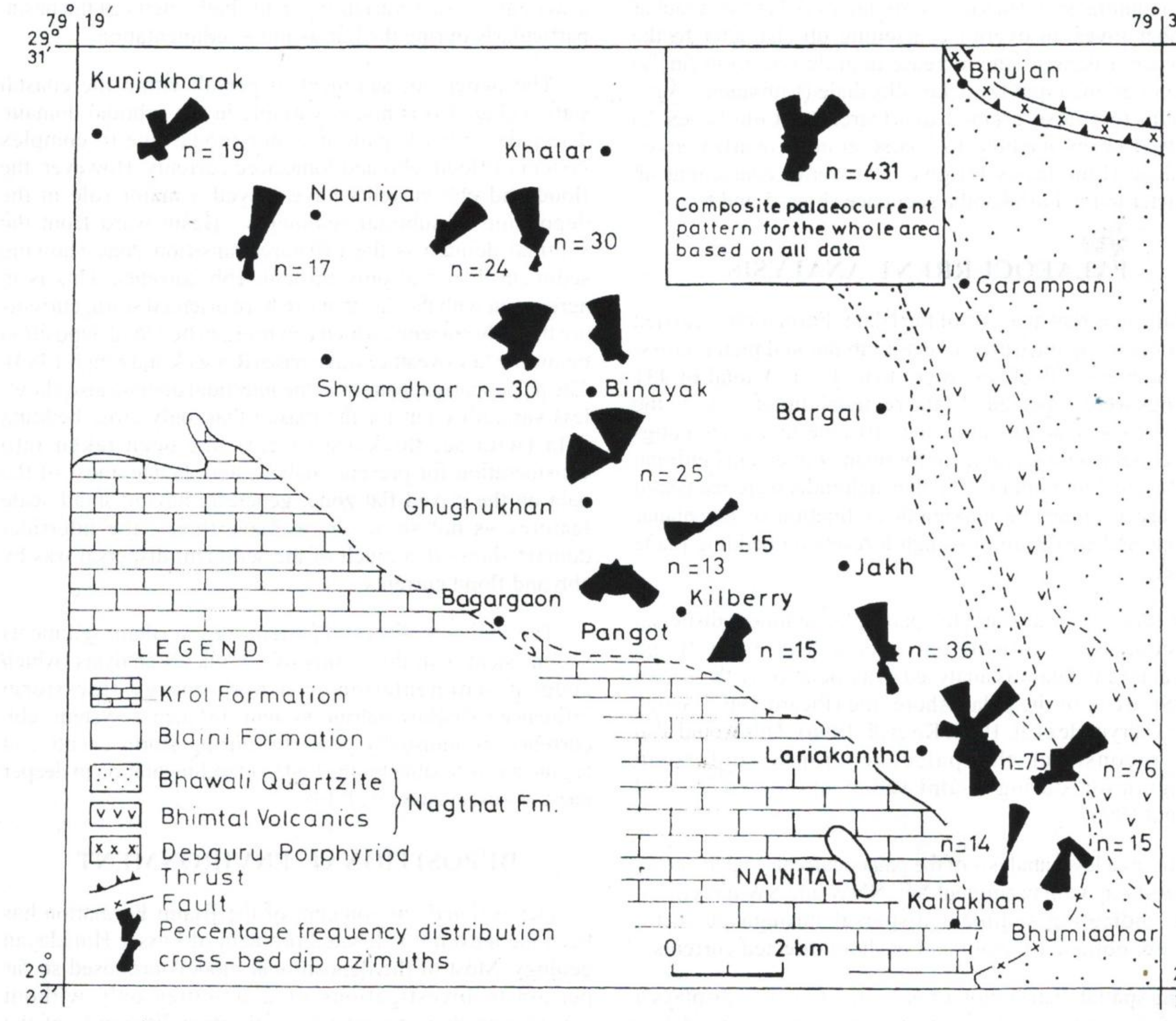

Fig. 9: Map showing spatial distribution of palaeocurrent. Inset shows a regional palaeocurrent pattern in Blaini Formation.

sedimentation of the Blaini Formation commenced with a marked transgression after the regressive Nagthat sedimentation ceased in Jaunsar basin of Nainital area. The transgression was very intense and, ultimately, caused cessation of the barrier island sedimentation of Nagthat times (Shukla and Pant 1996; Pant and Shukla 1999) and facilitated emergence of shelf conditions during the Blaini times. Transgressive lag deposits are preserved in the basal part of the Bhumiadhar sequence as diamictites (Lithofacies I). The upper subtidal and intertidal zones were, perhaps, eroded during the transgression (Massari and Parea 1988) and the eroded material was intermingled with already existing pebbles at the coast. The assimilated material, eventually, settled down as transgressive lag deposit. As in the Nainital area, the Blaini succession in other parts of the Krol-belt, such as Solan and Rishikesh, also starts with a basal diamictite horizon, followed up by black carbonaceous shales (Gaur 1971; Valdiya 1973; Tangri and Singh 1982). The sedimentological characters of these diamictites are more or less similar to our lithofacies I and II respectively. This probably implies the regional extent of transgression, which affected the whole Krol-belt. The transgression, as such, might have been related to the deepening of basin in response to some tectonic activity for it is difficult to visualize such an intense and extensive transgression in response to climatic changes (Kukal 1990). The role of tectonics during the end stages of Jaunsar (Nagthat)- Simla sedimentation has also been discussed by Virdi (1991). The overlying lithofacies of Blaini Formation, representing various subenvironments of deposition within the meso- to macro-tidal shelf setting, may be grouped into following two distinct facies associations:

(i) The storm dominated facies association, comprising lithofacies II, III and IV of the Bhumiadhar Member and lithofacies A and B of the Lariakantha Member.

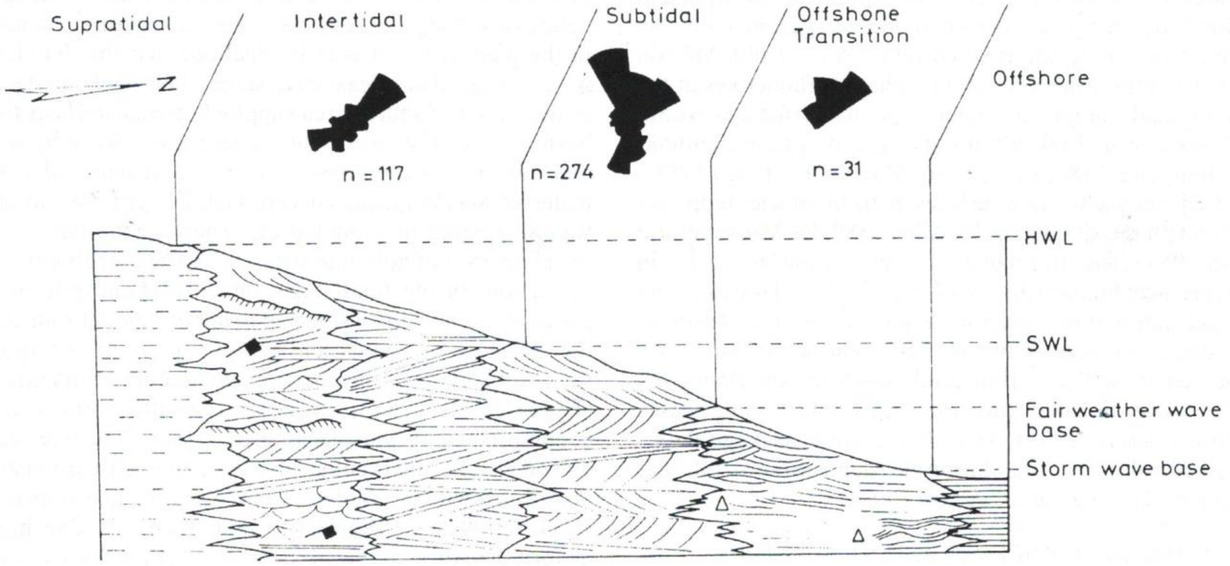

Fig. 10: Sediment dispersal pattern in different domains of the Blaini shelf.

(ii) The tide dominated facies association, comprising lithofacies C and D of the Lariakantha Member and lithofacies P1 of the Pangot Member.

Storm dominated lithofacies II, III and IV of the Bhumiadhar Member were deposited under more or less stable shelf conditions. The sedimentation mainly took place under fair-weather conditions in the form of mud. Intermittent storm events introduced sand in this zone (Duke 1985; Prave et al. 1996). The progressive increase in the sand content from offshore (Lithofacies II), through middle (Lithofacies III) to proximal (Lithofacies IV) offshore-transition zone indicates progressive decrease in carrying capacity of offshore directed storm currents. The distal part of the zone is represented by mud of lithofacies II that were deposited in rather deep, oxygen deficient condition (Harris and Eriksson 1990). The heteroliths of the lithofacies III suggest that fair-weather conditions of mud deposition were frequently disrupted by high energy storm events (Dott and Bourgeois 1982; Duke 1985; Sinclair 1993; Prave et al. 1996). The erosional/sharp bases of sandy horizons, scour structures on the underside of basal sandy beds and occurrence of cross-beds collectively suggest initial deposition of sandy units by powerful offshore directed currents (Duke 1985), whereas parallel laminations, low angle discordance surfaces and hummocky cross-stratification in the upper part of sandy units suggest deposition under oscillatory or combined flow condition (Reineck and Singh 1980; Dott and Bourgeois 1982; Swift et al. 1983; Allen 1985; Nottvedt and Kreisa 1987). The succession of sedimentary structures in lithofacies III sometimes resembles Bouma type Tacde, Tade and Tae beds. Such deviations from general facies architecture, however, do not necessarily indicate their derivation from turbidity currents and could form from bottom-current deposition, related to storms. The typical Tae beds may be considered as a deviation of turbidite beds only if the Ta unit is normally graded (Shanmugam 1997). Nevertheless, such an association of turbulent fluidal flow with the storm currents essentially suggests that the turbidity currents were related to storms. The Te beds are related to suspension mechanism during the fair-weather conditions. The sequence of heteroliths, thus, undoubtedly represents storm dominated offshore-transition zone. The lithofacies IV with thick sand and discontinuous mud alternations suggest deposition very close to, but below the fair-weather wave base. The dominance of storm units over the fair-weather units suggests that due to relatively shallower depth the depositional environment was frequently struck by powerful storms (Hamblin and Walker 1979; Massari and Parea 1988). As such, fair-weather units often were scoured away, leaving behind only the lower portion of each storm unit (Leithold and Bourgeois 1984; McCrory and Walker 1986; Massari and Parea 1988).

The storm-dominated lithofacies A and B of the Lariakantha Member were deposited in the subtidal zone. The siltyshale and sand alternations of varying scale (Lithofacies A) of the lower subtidal zone have been related to alternating fair-weather and storm conditions. The scouring/erosion of the muddy substrate followed up by load casted and graded bedded sandy units suggest sudden inception of the high-energy event followed by rapid deposition of sand onto water saturated muddy substrate. The lensoid morphology of sandy units and occurrence of cross-beds with seaward dipping foresets in this zone probably represent bed-load deposition by enhanced rip currents (Gruszczynski et al. 1993) and/or by storm generated offshore directing geostrophic currents (Walker 1984; Duke 1990). The subtidal bar unit (Lithofacies B) suggests deposition under the influence of strong rip, longshore and geostrophic currents. However, the prominent landward and seaward directed palaeocurrent modes suggest marked role of rip, geostrophic and tidal currents (Allen 1980; Morton 1981; Gruszczynski et al. 1993). The conglomerates at the base of sandy units, and other erosional structures within the lithofacies are related to peak of storm phase (Leithold and Bourgeois 1984; Elliot 1986; Massari and Parea 1988). The frequent reactivation surfaces in the lithofacies represent different phases of tidal cycle (Allen 1980; De Mowbray and Visser 1984). The strorm beds of subtidal zone are lacking in characteristic hummocky cross-stratification. However, the parallel laminations and low angle discordance surfaces recorded in subtidal sediments represent deposition under combined or oscillatory flow conditions (Dott and Bourgeois 1982; Swift et al. 1983; Allen 1985) during the waning phases of storms (Kreisa 1981). As such, the whole package shows a marked role of storms during the deposition of subtidal sediments (DeCelles and Cavazza 1992).

The tide dominated facies association includes all the three lithofacies of intertidal-supratidal region. The lithofacies C of Lariakantha Member is deposited in sand flats under high-energy conditions. Intermittent, short-lived phases of low tide and high-tide conditions are represented by clay-drapes associated with quartzarenite. The plane beds and lamination of the lithofacies suggest deposition under upper flow regime when laminations are formed either by strong swash-backwash process (Reineck 1975) or by vigorous currents burying the pre-existing sandwaves (Chakraborty and Bose 1990). The mixed flat zone deposits (Lithofacies D) with flaser and lenticular bedding, climbing ripple cross-lamination, cross beds with bipolar-bimodal palaeocurrent and many reactivation surfaces suggest powerful tidal current activity (Reineck and Singh 1980). The gradation of the crossbed foresets suggest wave swash and backwash in intertidal zone (Clifton 1969; Reineck and Singh 1980; Reinson 1984; Cudzil and Driese 1987) and the mud cracks suggest intermittent exposures of the sediments. The mud flat (intertidal–supratidal) sediments (Lithofacies P1 of the Pangot Member) also suggest intermittent exposure and deposition under oxidizing conditions. The sediments also suggest sudden phases of high-energy episodes and attendant erosion of the substrate by strong longshore currents. These events may be related to storms. The intertidal–supratidal sediments, in general, are devoid of storm generated structures. This may be related to extensive, day-by-day reworking of sediments by dominant tidal currents (Soegaard and Erikson 1985).

The areno-argillaceous system of the Blaini Formation progressively changed into a carbonate system (Lithofacies P3 of the Pangot Member). However, the source area was rejuvenated intermittently, probably in response to climatic variations. As such, diamictites (Lithofacies P2 of the Pangot Member) were emplaced in a tide-storm dominated shelf; probably as a result of downslope re-sedimentation of unstable pile of cohesive debris flow (Johnson and Rahn 1970; Hampton 1975; Lowe 1971; Johnson 1984; Postma 1986) under the influence of gravity. On the basis of subrounded to rounded nature of resistant quartzose clasts, subangular nature of soft argillaceous clasts and carbonate cementation in the diamictites, it may be deduced that the diamictites were emplaced in at least three stages. During the first stage, rejuvenation of source area supplied quartzose clasts to the basin. These clasts were, subsequently, reworked by waves and currents at the coast and, in the absence of clastic material, were embedded in carbonate cement; the carbonate was also being precipitated elsewhere in the basin. The interfingering of dolomite with diamictite corroborates this deduction. In the final stage, unconsolidated pile of this material was slid down slope up to upper subtidal zone under the influence of gravity and along way got mixed up with sand, silt and clay. The amalgamated nature of diamitctites (Eyles et al. 1988), suggests that the emplacement accomplished in various phases rather then one single episode. The intervening phases witnessed carbonate or clastic deposition. Auden (1934) has also questioned one single episode of diamictite emplacement. The highly unsorted nature of the diamictite, with a lot of sandy, argillaceous and calcerous matrix and large subangular argillite clasts probably suggest ripping and mixing up of the substrate during the flow. The highly unsorted nature of diamictites with an appreciable proportion of coarser material also suggests emplacement of material as high density flows whose denser part was deposited via freezing *en masse*. The presence of carbonate cement might have rendered diamictites the ability to stand at relatively to steep slopes of a tide-storm dominated shelf (Eyles et al. 1988). The pink dolomite (Lithofacies P3 of Pangot Member) of the Blaini indicates warm climatic condition in intertidal domain as the dolomite shows sinuous current ripples and cryptalgal mats. The carbonaceous shales (Lithofacies K1 of the Kailakhan Member) were deposited in a zone of persistent low energy, probably in a mud flat to marginal lagoonal environment. The high concentration of carbon and pyrite suggests sedimentation in an oxygen deficient environment (Harris and Eriksson 1990). The occurrence of wavy laminations indicate that slack water conditions of deposition were sometimes interrupted by slight increase in energy, probably in response to restricted wave fetches.

It is also clear from the lithofacies analysis that the Blaini shelf was progressively shallower towards the east during the Lariakantha sedimentation, whereas during the Pangot sedimentation the basin was progressively shallower towards the west. Kumar (1982), has also made similar inferences regarding the Pangot basin. Such gradual tilting of Blaini basin was probably a result of intrabasinal tectonic activity. Role of widespread intrabasinal tectonic activity during the later stages of Blaini sedimentation has also been discussed by Valdiya (1973) and Virdi (1991). The uninterrupted great thickness of the Blaini Formation (± 1700 m) suggest an equilibrium between the rate of sedimentation and subsidence of the basin.

Cessation of the Blaini sedimentation witnessed deepening of the basin and, as such, the marginal lagoonal sediments of the Kailakahn Member were overlain by the subtidal lower Krol sediments (Misra 1984). The influx of the arenaceous material to the basin came to rest with the cessation of Blaini sedimentation and the precipitation of carbonate along with subordinate argillaceous material began, giving rise to the thick sequence of the Krol Formation mainly under tidal regime.

CONCLUSION

The Krol-belt underwent a major transgression during the end stages of Nagthat sedimentation. This transgression was a response of some tectonic activity in the basin and, ultimately, changed the barrier-island system of Nagthat time into the shelf system of Blaini time. The imprints of the transgression are preserved as diamictite in the basal part of the Blaini Formation, that have also been referred to as the lower pebbly horizon. The diamictites owe their genesis to the intermingling of pre-existing substrate in response to sudden and powerful incursion of sea water onto the land. No decisive evidence of glacial or turbidity process could be recorded in diamictites.

The overlying sequence of Bhumiadhar was deposited on offshore to offshore-transition zone of a more or less stable shelf. The sediments were laid down mainly through suspension under fair-weather conditions. The low energy conditions, however, were frequently disrupted by high energy episodes of storm currents, which carried in and deposited the sandy material mainly as bed-load onto the muddy substrate either as sheets or as channels through the rip channels. Such storm events are characterised by prevalence of offshore directed unidirectional currents during the initial stages and, as such, give rise to scouring of the muddy substrate. The transportation of sand by such powerful currents gives rise to ripples or even to parallel laminations of upper flow regime. During the waning phases of storms the oscillatory or combined flow conditions persist and such structures as hummocky cross stratification and low angle discordance surfaces form.

The Bhumiadhar Member, thus, marks an important event in the evolution of the Krol Belt. The pre-Blaini sedimentaries (Jaunsar) represent a different cycle of sedimentation. Similarly, the post-Blaini carbonate succession represents another cycle of sedimentation. As such, it may be concluded that the Krol-belt registers at least three different cycles of sedimentation, which may be called the Jaunsar-Simla cycle, the Blaini cycle and the Krol cycle.

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