Chapter 4

Facies Analysis of the Keonjhar Quartzite

4.1. Introduction

Facies analysis remains the basic methodology for the reconstruction of depositional setting of the Keonjhar Quartzite. Conventional principles for facies analysis have been adopted here. The Keonjhar Quartzite succession is classified into a number of lithofacies based on lithological criteria. Each facies represents a distinctive lithological entity and the depositional process has been interpreted based on the characteristics of individual facies type (Walker 2006). *Facies Associations* have been reconstructed based on the natural association of two or more facies in the succession (Miall 1996). Facies Associations are interpreted in terms of different subenvironments which in turn collectively lead to the understanding of the depositional setting. Vertico-lateral distribution of facies association in the study area further has been represented in terms of *facies sequence*. Facies sequence in turn leads to the reconstruction of *systems tracts, base level changes* with time and *sequence* development (Catuneanu 2006)**.** Ghosh and Chatterjee (1990) based on facies analyses suggested mainly braided fluvial depositional setting and subsequently a fluvial-beach and shallow marine from grain-size analyses (Ghosh and Chatterjee 1994). The facies classification presented here differs considerably from their findings.

4.2. Facies description

Sedimentary facies classification in the Keonjhar Quartzite has been based on criteria such as: composition, grainsize, grain shape, grading bedded geometry and sedimentary structures which include surface structures and internal structure of the individual beds. In present study include only surface outcrop of the sedimentary rocks. Following nine facies have been identified:

a) Matrix-supported cobble-pebble conglomerate facies (F1)
b) Clast-supported cobble-pebble conglomerate facies (F2)
c) Wavy bedded pebbly sandstone facies (F3)
d) Fine chip pebble conglomerate facies (F4)
e) Coarse massive sandstone with pebble float facies (F5)
f) Pebble lag facies (F6)
g) Trough cross stratified medium-grained sandstone facies (F7)
h) Plane-laminated medium-grained mature sandstone facies (F8)
i) Plane-to-wavy medium-to-fine-grained sandstone facies (F9)

4.2.1. Matrix-supported cobble-pebble conglomerate facies (F1)

Description

This facies mainly consists of sandy–to-muddy matrix-supported cobble-to-pebble conglomerate deposits (Fig. 4.1). This facies is basically defined by a polymictic matrix-supported conglomerate. Clast size in conglomerates varies from 2.1cm to 25 cm. Clasts are generally angular to subangular and haphazardly oriented in nature. Clasts of the conglomerate mainly consist of white vein quartz, black chert, jasper, grey chert and altered feldspar components. Internally, the conglomerate is non-graded and massive.

Weak planar stratification observed locally in the upper part of some conglomerates. Weak distribution grading has also been observed locally that are not laterally persistent. The conglomerates occur in shallow sheet-like bed geometry.

Conglomerate bed thickness varies from 30 cm to 65 cm. The upper bounding surfaces of the conglomerates are flat to gently wavy in nature.

Fig.4.1. Field photograph of Matrix-supported cobble-to-pebble conglomerate facies (F1) from Keonjhar Quartzite. Note clasts are completely supported in a fine-grained matrix.

Interpretation

Matrix predominance in conglomerate indicates deposition from cohesive debris flows. Absence of gradation also supports debris flow where flows are laminar in nature and grains are supported by the cohesive matrix strength (Lowe 1979). Debris flow is distinguished from mud flow by their low content of clay material and by the presence of sandy matrix. The sheet-like bedding geometry with matrix-supported texture is commonly inferred to as a product of a catastrophic flow (Nemec and Steel 1986). Random orientation of the clast and their angular to subangular nature indicates a shorter transportation.

4.2.2. Clast-supported cobble-pebble conglomerate facies (F2)

Description

This facies is pebbly to cobbly, clast-supported conglomerate (Fig.4.2). Clasts ranges in size from 3.5 cm to 15 cm. Clasts are subangular to subrounded in nature.

Clasts are haphazardly oriented. About 90% of clasts consist of vein quartz, black and white chert. Matrix proportion is very low (<10%) and is mainly sandy in nature. The facies is internally massive and do not reveal any size grading. This beds locally shows wave reworked top bounding surface. Lower bounding surfaces are planar and non-erosive in nature. The maximum bed thickness of the facies measured is 90 cm.

Interpretation

The clast-supported conglomerate facies was likely to be deposited from a cohesionless debris flow (Nemec and Steel 1986). The absence of size grading, internal cross strata and sheet-like geometry suggest deposition from non-Newtonian laminar flow. Wavy upper bounding surface signifies that the mass-flow deposits travelled down to the wave-reworking zone of shallow shelf environment.

Fig. 4.2. Field photograph of Clast-supported cobble-to-pebble conglomerate facies (F2) from Keonjhar Quartzite.

4.2.3. Wavy bedded pebbly sandstone (F3)

Description

This facies is characterized by sandstone with dispersed pebbles (Fig. 4.3A). Beds are internally massive. The pebbles are poorly sorted. Pebbles are mainly subrounded to rounded in nature with size ranging from 2 cm to 8.5 cm. They are haphazardly oriented with no size gradation. The maximum bed thickness is 10 cm. The beds show wavy geometry with low amplitude and large wave length wave forms (Fig. 4.3B).

A.

B.

Fig. 4.3. Field photographs of Wavy bedded to massive pebbly sandstone facies (F3) from Keonjhar Quartzite A. Pebbly sandstone with dispersed pebble; B. Massive pebbly sandstone beds showing wavy geometry.

Interpretation

Massive pebbly sandstones are likely to be deposited from high-energy bedload deposits (Middleton and Hampton 1976). Internally this facies is massive in nature, with wavy upper bounding surface. Wavy upper bounding surface suggests reworking by waves after deposition (Hill et al. 2003). The wavy nature influenced by the shallow water wave and pebble dominancy suggests storm, or enhanced tidal current condition.

4.2.4. Fine chip pebble conglomerate (F4)

Description

This facies is characterized by fine chip pebble supported conglomerate (Fig. 4.4). Pebbles are subrounded to well-rounded in nature. The beds show sheet-like geometry. Bed thickness varies between 13 cm to 35 cm. Pebble conglomerate is internally massive in nature and shows wavy upper bounding surface.

Fig. 4.4. Field photograph of Fine-chip pebble conglomerate facies (F4) from Keonjhar Quartzite.

Interpretation

The fine-chip pebble conglomerate internally massive is likely to be a product of cohesionless high-density flow (Lowe 1979). Rounded to well-rounded pebble suggests pebbles were derived from pre-existing wave-reworked sediment source. Wavy top is the indication of deposition in shallow water above wave base environment during storm events.

4.2.5. Coarse massive sandstone with pebble float facies (F5)

Description

The facies is essentially coarse-grained sandstone with randomly oriented dispersed pebble floats (Fig. 4.5). The pebbles range in size from 1.5 cm to 5.2 cm. The beds are massive in nature without internal stratification. Floating pebbles are angular to subangular in nature and are randomly distributed within the poorly sorted coarse-grained sandy matrix. Beds attain maximum thickness of about 35 cm. The beds are bounded by the planar surface boundaries. Locally pebbles show higher clustering near the middle part of beds.

Interpretation

This facies is dominantly coarse sand-size grade and massive in nature. The massive sand with pebble floats is likely to be the product of sediment-gravity flow/high-density sandy debris flow (cf. Nemec and Steel 1984). Massive sandstone devoid of sedimentary structure supports their deposition from the high-density sandy debris flow. Such deposits with evidences of wave reworking on top could be the products of cohesionless debris flow / storm-surge deposits from subaerial fan head to shallow shelf.

A.

B.

Fig. 4.5. Field photographs of Coarse massive sandstone with pebble float facies (F5) from Keonjhar Quartzite A. Coarse massive pebble float sandstone with wavy top facies (F5); B. Coarse massive sandstone with dispersed pebble floats.

4.2.6. Pebble lag facies (F6)

Description

The facies is defined by thin rounded to well-rounded pebble train deposits (Fig. 4.6). This facies mainly occurs interbedded with mature quartzarenite facies. Clasts mainly consist of vein quartz and black chert. They are haphazardly oriented and rounded to well-rounded in nature. The pebble lag facies lacks any size grading. The thickness of the pebble lag beds variesfrom 11 cm to 25 cm. Beds are laterally extensive. Gently wavy geometry of the beds follows the wavy top surface of bottom substrate for the lags.

Fig.4.6. Field photograph of pebble lag facies (F6) from Keonjhar Quartzite.

Interpretation:

Pebble lag facies often are interbedded with the mature quartzarenite facies and suggests deposition from bedload traction (Miall 2016). Pebbles are basically rounded to well-rounded in nature which supports wave reworking as well as recycling from source. Such coarser lag deposits draping the wave-reworked mature arenite beds are likely to be formed from erosion of the alluvial deposits along the beach scarp and subsequent fair-weather winnowing of fine-grained fraction by wave action (Orton and Reading, 1993).

4.2.7. Trough cross-stratified medium-grained sandstone facies (F7)

Description

This facies mainly composed of coarse-to-medium-grained sandstone with randomly dispersed pebbles (Fig. 4.7). Beds are moderately sorted. The facies is dominated by medium-scale trough cross-bedding. Lower bounding surfaces of beds are generally undulating to gently erosive. Individual thickness of the beds varies between a wide range from 20 cm to more than 2 metre. Trough axes dominantly dip towards a WSW direction. Trough axes dip direction suggests the facies was controlled by unidirectional currents. This facies occurs as sheet-like beds.

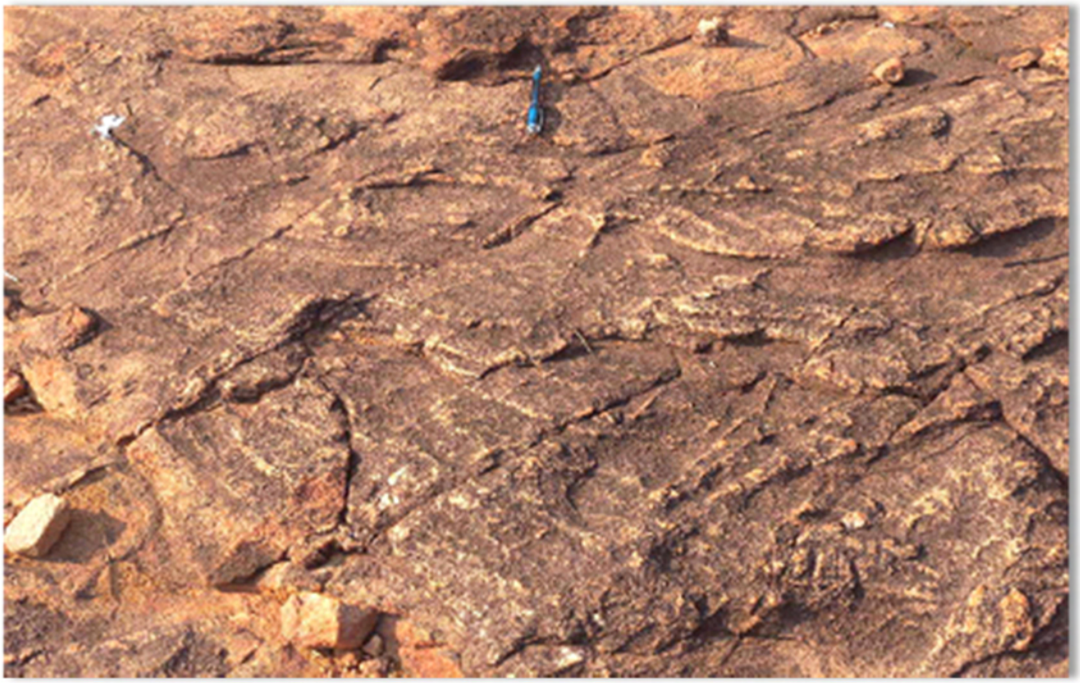

Fig.4.7. Field photograph of Trough cross-stratified medium-grained sandstone facies (F7) from Keonjhar Quartzite.

Interpretation

Trough cross-stratified sandstones are likely to be the products of moderate to high flow strength fluid-gravity flow which formed three-dimensional dunes (Miall 1996). Trough cross-stratification is generated due to the migration of the dunes. Sets of cross-strata are likely to constitute cosets in a subaerial mid-fan channel braid bar depositional setting.

4.2.8. Plane-laminated medium-grained mature sandstone facies (F8)

Description

This facies is defined by medium-to-fine–sandstone with plane lamination (Fig. 4.8).The thicknesses of the sandstone beds varies widely and attains maximum up to 50 cm. Plane-laminated sets show low-angle truncations. The sandstone bed interbedded with layers of fine grain sandstone upto 2 cm to 5cm thick with wavy ripples.

Fig. 4.8. Field photograph of Plane-laminated medium-grained mature sandstone facies (F8) from Keonjhar Quartzite.

Interpretation

Plane lamination within the medium-grained sandstone suggests deposition under high-energy condition of upper flow regime (Miall 1978). Horizontally, bedded and planar low-angled cross-stratified sandstones reflect the traction current (Mueller and Corcoran 1998) under upper flow regime (Eriksson 1978, 1979; Fedo and Cooper 1990).

4.2.9. *Plane-to-wavy bedded cross-stratified medium-to-fine-grained sandstone facies (F9)*

Description

This facies is essentially composed of medium–grained sandstone. The sandstones are well sorted in nature. The beds are represented by medium-to-thick bedded cosets of cross strata with mega-rippled top (Fig. 4.9A, B). Individual cosets of the megarippled beds vary in thickness from 25 cm to more than a metre and define the compound bedsets that are seprated by small-scale wave ripples formed in medium-to-fine-grained sandstones and are interbedded with the thick wavy beds.

Interpretation

This facies is dominated by the plane- to wave-dominated medium-grained mature sandstones that are likely to be deposited from bedload transport in wave-agitated environment (Swift et al. 1971). Plane laminated-to-wavy bedded medium-grained sandstone facies reflect medium-to-high energy condition of deposition within wave base in foreshore to shoreface depositional settings. Sets of cross-strata arranged in cosets represent tidal cycles and forms the building units of tidal bars (Reineck and Singh 1973).

Fig. 4.9. Field photographs of mega-rippled sandstones in the Keonjhar Quartzite: A. Wavy bedded medium-grained sandstone facies (F9); Wavy bedded thick cosets form the flank of tidal bar compound strata. B. Internal bedsets of cross-strata in wavy bedded structure of medium-grained sandstone facies (F9).

Table 4.1. Summary of characteristics of the major lithofacies of the Keonjhar Quartzite.

Lithofacies	Characteristics	Interpretation
1. Matrix-supported cobble-pebble conglomerate facies (F1)	Polymictic matrix-supported conglomerate, haphazardly oriented clasts, internally non-gradation and massive nature, The upper bounding surface of the conglomerate facies is flat to wavy in nature.	Matrix predominance indicates deposition from a cohesive debris flow. Non gradation supports debris flow where flows are laminar in nature and grains are supported by the cohesive matrix strength (Lowe 1979).
2. Clast-supported cobble-pebble conglomerate facies (F2)	Pebbly to cobbly clast-supported conglomerate with mainly sandy in nature, internally massive, undulating erosive top bounding and planar bottom surface, shallow sheet like beds, lacks size gradation. Interlayered with thick mature trough cross-stratified sandstone layer.	Deposited from cohesionless debris flows, deposition is mainly causedby non-newtonian laminar flow. Wavy geometry within clast-supported conglomerate is a shallow marine reworking signature.
3. Wavy bedded to massive pebbly sandstone (F3)	Pebble supported sandstone medium to coarse grained, internally massive, with a wavy nature, lacks size grading.	High-energy bedload deposition presumably by storm episodes, reworking by waves after deposition.
4. Fine chip pebble conglomerate (F4)	Fine chip pebble- supported conglomerate, clasts rounded to well-rounded, sheet like geometry, thin- bedded, internally massive, wavy upper bounding surface.	Likely to be products of cohesionless high-density flow. Pebble roundness, wavy top surface suggest wave reworking, presumably during storm events.
5. Coarse massive sandstone with pebble float facies (F5)	Coarse-grained sandstone with randomly oriented dispersed pebble floats, massive without internal stratification, angular to subangular pebbles, bounding surfaces planar.	Massive sand with chaotic pebble floats are products of sediment gravity flow/ high-density sandy debris flow (Nemec and Steel 1984). cohesionless debris flow / storm-surge deposits from subaerial fan head to shallow shelf.

Table 4.1. Continuation……

6. Pebble lag facies (F6)	Rounded to well-rounded pebble train lag deposits, interbedded with mature, weak wavy distribution observed within the pebble lag.	Pebble lag facies interbedded within the mature quartz arenite facies suggest deposits from bedload lag from high-energy flows, coarser lags formed from erosion of the alluvial deposits along the beach scarp and fair weather winnowing fine-grained fraction by wave action (Orton and Reading 1993).
7. Trough cross stratified medium-grained sandstone facies (F7)	Coarse-to-medium-grained sandstone with pebbles, moderately sorted, dominated by sets of trough cross-strata, gently erosive lower bounding surfaces.	High-energy bedload deposits sets and cosets of cross-strata represent braid bars in subaerial mid fan distributaries
8. Plane-laminated medium-grained mature sandstone facies (F8)	Plane laminated, medium-to-fine- grained arenites, well sorted, and internally finely plane- parallel laminated sets. Each bed consists of cosets with low angle discordance between successive sets. Interbedded with layers of fine grain sandstone up to 2-5cm thick with wavy ripples.	High energy bedload deposits. Plane lamination within the medium grain sandstone suggests deposition under high energy condition of upper flow regime (Miall 1978, 1985). Horizontally, bedded and planar low-angled cross-stratified sandstones reflect the traction current (Mueller and Corcoran 1998) under upper flow regime (Eriksson 1979; Fedo and Cooper 1990). Discordance between sets indicates beach lamination character.
9. Plane-to-wavy bedded cross-stratified medium-to-fine-grained sandstone facies (F9)	Medium–grained well sorted mature arenites, beds include medium-to-thick bedded cosets of cross strata with megarippled top individual cosets of the megaripple with varying thickness from 25 cm to more than a metre define the compound bedsets separated by fine sandstone with small-scale wavy ripples. .	Compound bed form represents tidal sand bars made up of amalgamated bedset of megarippled sandstones. Megarippled beds represent cosets of starta with trough cross-stratified sets from tidal cycles.

4.3. Facies associations

Facies associations represent particular sedimentary depositional environment (Walker 2006, Walker et al. 2008). Miall (1985) defined the concept of ‘facies association’ in terms of geometry, scale, and lithofacies assemblages. Nine lithofacies identified from the study area have been grouped into following four facies associations (Fig. 4.10, Table 4.2).

4.3.1. Matrix-supported conglomerate dominated lithofacies association (FA1)

This facies association includes F-1, F-2, F-7 of primarily slope-related subaerial mass-flow (cohesive) to subaerial braid plain (Fig. 4.10A, B). This cohesive debris flow deposits represent the most proximal part of a subaerial fan setting. The subaerial mass flow deposits accumulate in incised valleys within feeder channels of the alluvial fan and fan slope-to base of slope. This facies association is very well exposed at the lower part as Asurkhol Member. This facies association attains a maximum thickness of about 25 meters.

4.3.2. Clast-supported conglomerate dominated lithofacies association (FA2)

This facies association includes F-2, F-7, F-4 and F-1 lithofacies (Fig. 4.10C). This facies association is also dominated by mass-flow (cohesionless) and high-energy high-density deposits and is likely to represent medial part of a suabaerial fan and braid plain depositional setting. This facies association is likely to represent alluvial fan and braided plain depositional setting in fan delta type environment where coarser beds from braid plains or base of the fan slope extend subaqueous into shallow shelf. This facies association constitutes thickness of about 12 meters in the Asurkhol Member in fault slices west of FA-1.

4.3.3. Coarse-to-medium-grained pebbly sandstone dominated lithofacies association (FA3)

This facies association represents F-3, F-4, F-5 and F-7 lithofacies (Fig. 4.10D, E, F). This facies association is dominated by wave-reworked pebbly sandstone, chip conglomerate, sandstone with floating pebbles, with interbeds of trough cross-stratified sandstone. Deposits from coarse-grained debris-flow and sandy debris flow with interbedded trough-cross-stratified cosets of sand bars indicate a transition from slope-derived mass-flow and braid plain fluvial deposits similar to FA-2 extending into shallow marine wave reworking zone of foreshore. The evidence of such wave-reworking suggests that braid plain is likely to be the subaqueous parts of a fan delta\braid delta.

4.3.4. Thick-bedded trough to planar cross-stratified mature sandstone dominated lithofacies association (FA4)

This facies association represents F-9, F-8, and F-6 lithofacies (Fig. 4.10G, H). Wavy bedded compound cross strata with plane-laminated mature sandstone indicate deposition in wave\tide-dominated shelf setting. The absence of coarse sandstone with pebbles indicates a shallow marine outer shelf depositional environment. Pebble chip conglomerates and pebble lags are likely to be deposits from storm events on the shelf.

Table 4.2. Summary characteristics and interpretation of major lithofacies association.

Facies association	Stratigraphic location	Lithofacies assemblage	Description and interpretation
A. Matrix-supported conglomerate dominated lithofacies association (FA1)	Lower part of Asurkhol Member	Matrix-supported cobble-Pebble conglomerate facies (F1), Clast-supported cobble-pebble conglomerate facies (F2) and Trough cross stratified medium grained sandstone facies (F7)	Facies association attains a maximum thickness ~25 meters. This cohesive debris flow deposits represent the most proximal part of a subaerial fan setting. The subaerial mass flow deposits accumulate in incised valleys within feeder channels of the alluvial fan slope-to-base-of-slope.
B. Clast-supported conglomerate dominated lithofacies association (FA2)	Upper part of Asurkhol Member	Clast-supported cobble-pebble conglomerate facies (F2), Trough cross stratified medium-grained sandstone facies (F7), Fine chip pebble conglomerate (F4) and Matrix-supported cobble-pebble conglomerate facies (F1)	This facies association constitutes thickness 12 meters in one thrust slice. This facies association is likely to represent alluvial fan and braid plain depositional setting in fan delta type environment where coarser beds from braid plains or base of the fan slope extends subaqueous into shallow shelf.
C. Coarse-to-medium-grained pebbly sandstone dominated lithofacies association (FA3)	Middle part of Keonjhar Quartzite, near Kankana village	Wavy bedded to massive pebbly sandstone (F3), Fine chip pebble conglomerate (F4), Coarse massive sandstone with pebble float facies (F5) and Trough cross stratified medium grain sandstone facies (F7)	Deposits from coarse-grained debris-flow and sandy debris flow with interbedded trough-cross-stratified cosets of sand bars indicate a transition from slope-derived mass-flow and braid plain fluvial deposits. The evidence of such wave-reworking suggests that braid plain is likely to be the subaqueous parts of a fan delta\braid delta.
D. **Thick-bedded trough to planar cross-stratified mature sandstone dominated lithofacies association (FA4**	Upper part of Keonjhar Quartzite, near Paranapani village	Plane-to-wavy bedded cross-stratified medium-to-fine-grained sandstone facies (F9), Plane laminated medium grained mature sandstone facies (F8) and Pebble lag facies (F6)	Wavy bedded compound cross strata with plane-laminated mature sandstone indicate deposition in wave-\tide-dominated shelf setting.

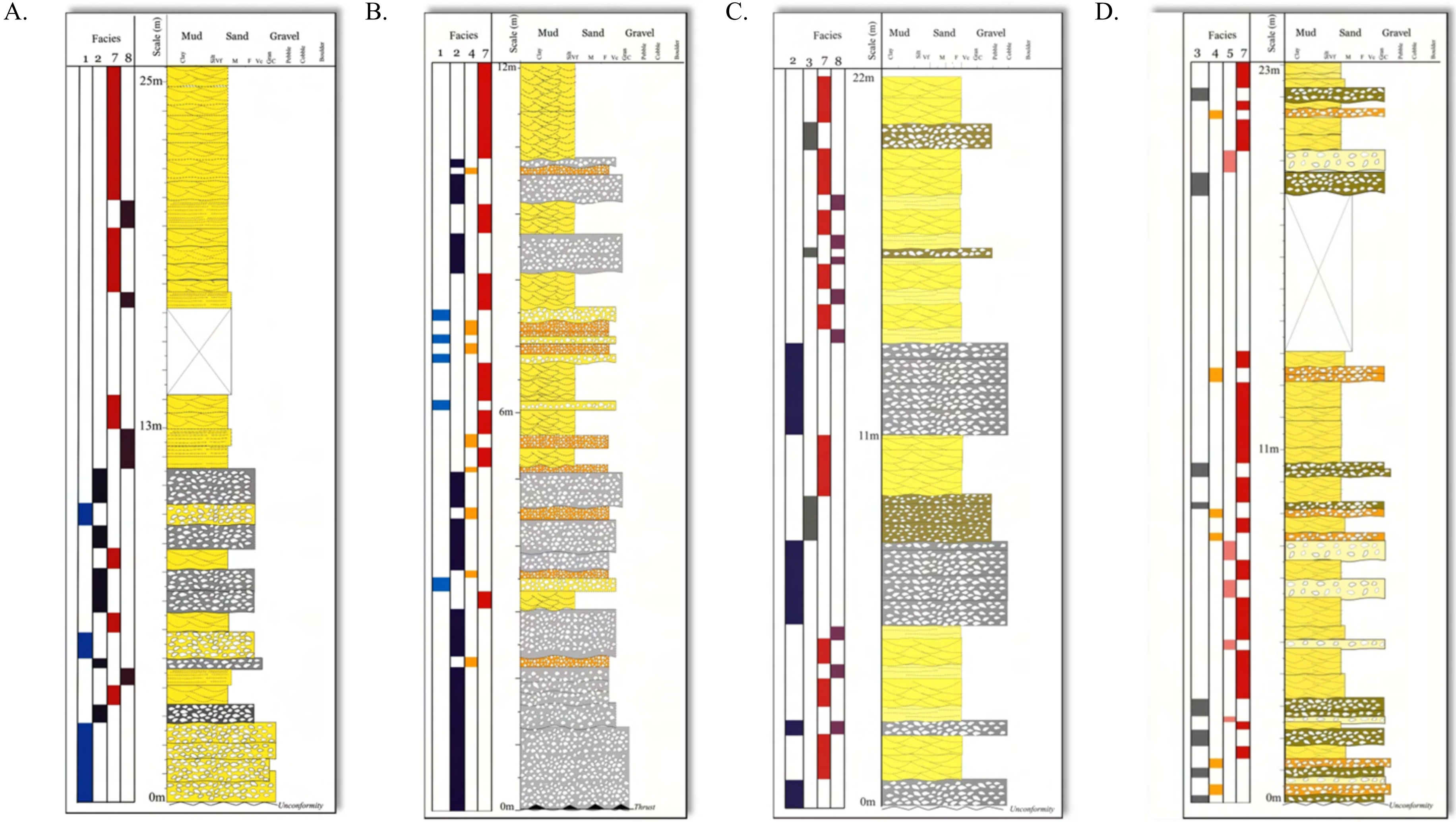

Fig. 4.10. Lithofacies associations from proximal to distal direction in Keonjhar Quartzite. A. Proximal alluvial fan association in Asurkhol section; B. Proximal alluvial fan association in Kankana section; C. Midfan braid plain to fan-delta association south west part of Kankana section; D. Subaqueous parts of a fan-delta\braid delta Hatidari section.

Fig.4.10. continuation…….

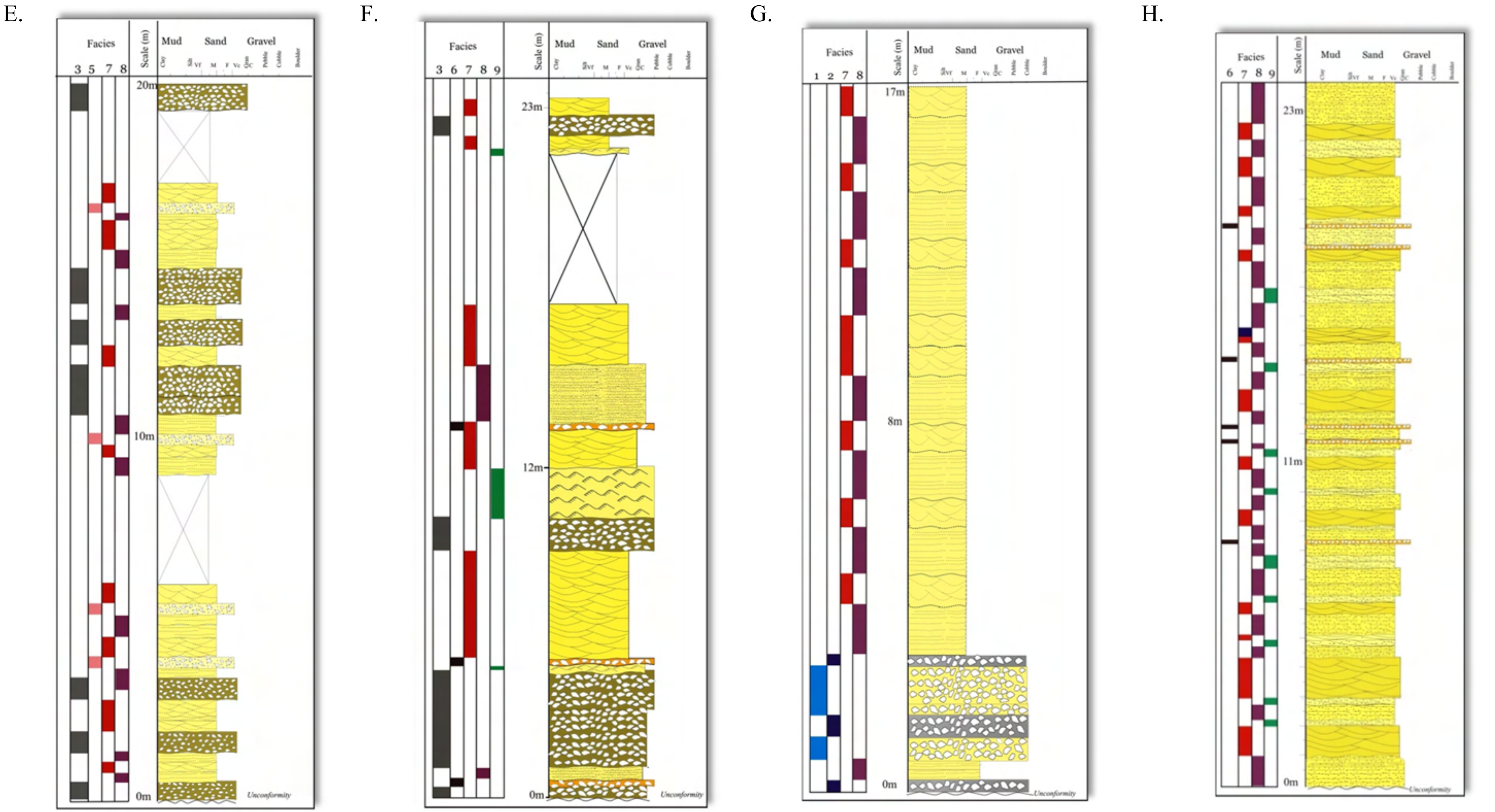

Fig. 4.10. E. Subaqueous parts of a fan-delta\braid delta west of Kamalpur section; F. Subaqueous parts of a fan-delta\braid delta Belpahar section; G. Wave-\tide-dominated shelf Jaipur section; H. Wave-\tide-dominated shelf Paranapani section.

4.4. Facies sequence and depositional environment

The ~715 m thick sedimentary succession can be subdivided into a number of facies sequences from vertico-lateral distribution of facies associations. The generalized lithofacies association represents conglomerate-pebbly sandstone-sandstone of upward-fining cycle. The upward-fining successions in the Keonjhar basin displays rapid changes of the mass-flow conglomerate- dominated proximal subaerial fan to coarse-grained stratified high-energy midfan braided fluvial facies in the lower parts. The upper 3/4th part of the section is mainly represented by amalgamated sandwave deposits of shallow shoreface to foreshore depositional setting. The facies association (FA1-FA2-FA3-FA4) stacking pattern suggests such changes from alluvial fan to shallow marine shelf depositional environment (Fig. 4.11).

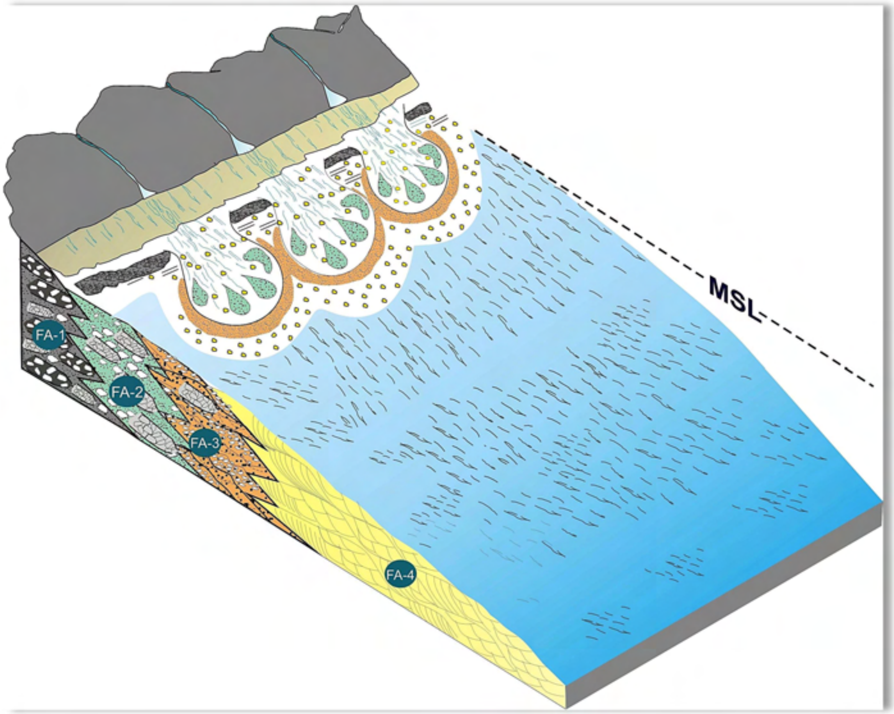

Fig.4.11.Schematic depositional model for the Keonjhar Quartzite. Subaerial fan to fan-delta and open shelf depositional setting. FA 1: Proximal alluvial fan association, FA 2: Midfan braid plain to fan delta association, FA 3: Subaqueous parts of a fan-delta\braid-delta association, FA 4: Wave-\tide-dominated shelf association. The vertico-lateral facies transition suggests retrogradational stacking pattern and coastal onlap for the shelf association.

An alluvial fan deposit of the Keonjhar Quartzite is very well exposed lower part of the Asurkhol Member. The alluvial fan type deposits are dominated by matrix-supported cobble-pebble conglomerate facies (F1), clast-supported cobble-pebble conglomerate facies (F2) and trough cross stratified medium-grained sandstone facies (F7). Proximal part of the subaerial fan is represented by cohesive debris flow deposits. Shallow or rapid water flow across this alluvial fan deposits resulting in thin-bedded layers of trough cross-stratified medium-grained sandstone, a high energy deposits occurred within cohesive debris flow deposits. The subaerial mass flow deposits accumulate in incised valleys within feeder channels of the alluvial fan slope-to base of slope.

Subaerial braid plain association is dominated by trough cross-stratified medium-grained sandstone facies (F7), fine chip pebble conglomerate (F4) and matrix-supported cobble-pebble conglomerate facies (F1) are rarely interbedded.

This type of deposit is very well exposed upper part of the Asurkhol Member and dominated by clast-supported cobble-pebble conglomerate facies (F2), trough cross stratified medium-grained sandstone facies (F7), fine chip pebble conglomerate (F4) and matrix-supported cobble-pebble conglomerate facies (F1).

A shelf deposit in the Keonjhar Quartzite is well exposed near Paranapani village with FA-4 facies association. The shelf deposits are dominated by mainly three facies with evidences of wave reworking and higher textural and mineralogical maturity. Plane-to-wavy bedded cross-stratified medium-to-fine-grained sandstone facies (F9), plane-laminated medium-grained mature sandstone facies (F8) and pebble lag facies (F6) of facies association 4 represents the shelf deposits. This lithofacies stacking pattern suggests with upward fining succession and indicates an early stage of transgressive sequence.

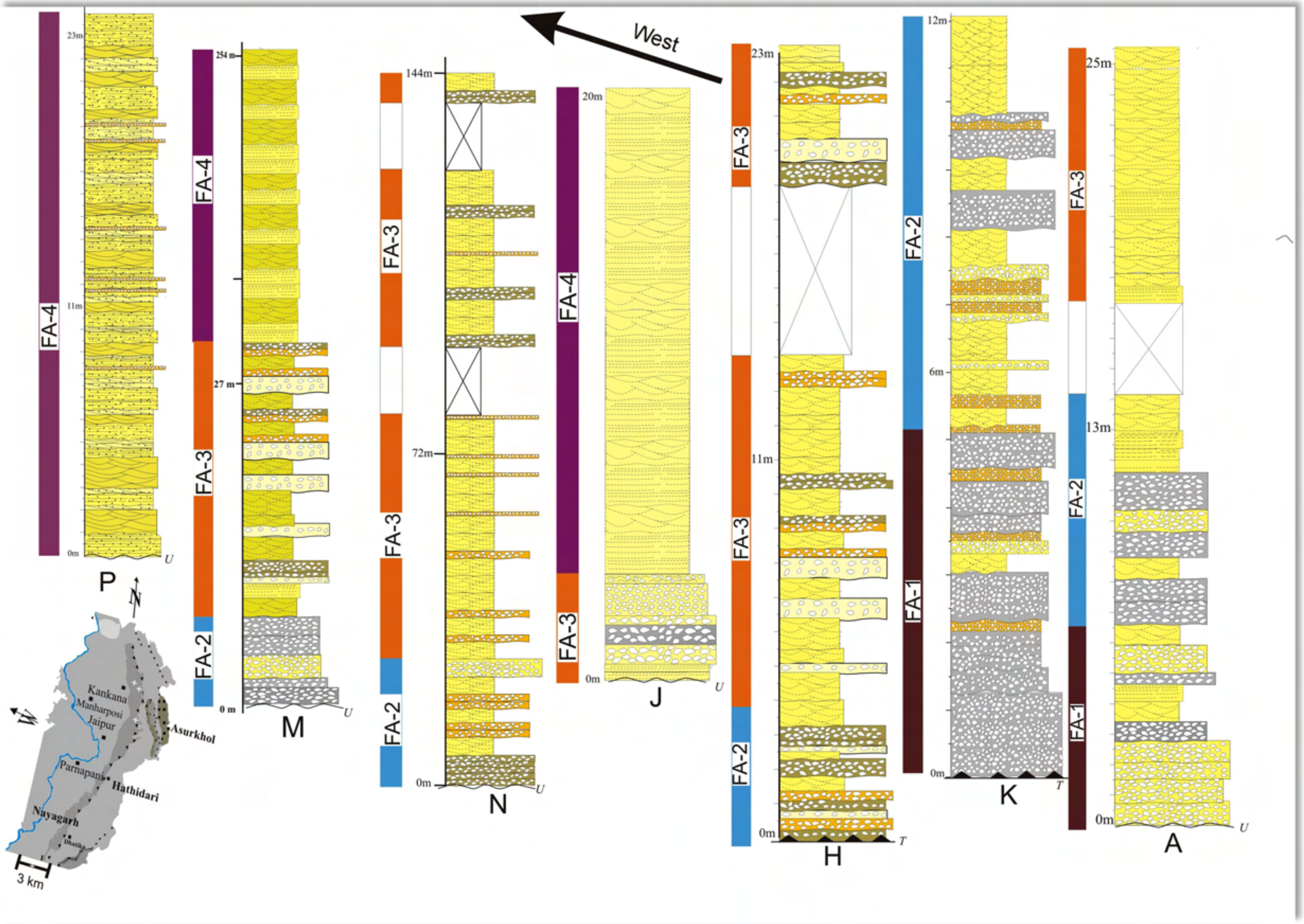

Fig. 4.12. Spatial distribution of facies sequence in Keonjhar Quartzite. Facies sequences from east to west in down dip section represents facies associations from proximal to distal parts of the depositional basin. A-Asurkhol, K-Kankana, H-Hathidari, J-Jaipur, N-Nayagarh M-Manharposi, P-Parnapani, U-Unconformity, T-Thrust. Inset outline map for locations.

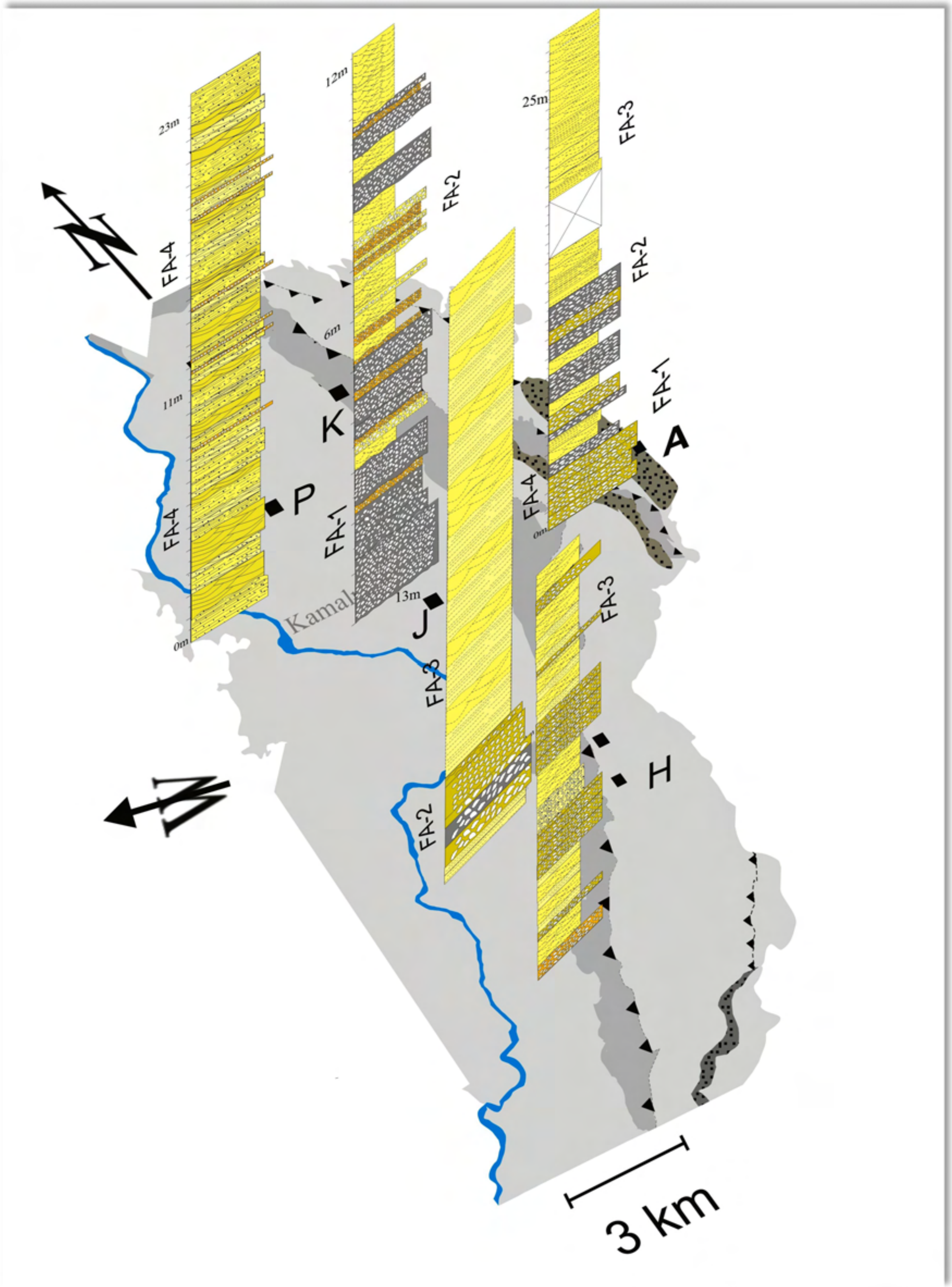

Fig. 4.13. Schematic presentation of facies sequence in spatial distribution from east to west downdip direction. Note the facies associations of proximal to distal depositional environments in facies sequences across strike from east to west.

Wavy bedded compound cross strata with plane-laminated mature sandstone indicate deposition in wave-dominated shelf setting. Thin interlayers of pebble lag within thick mature sandstone suggest storm events.

A composite facies sequence from the Keonjhar Quartzite suggests an alluvial fan-braid plain (fan delta) to shallow-marine shelf depositional setting based on facies analyses (Fig. 4.11).

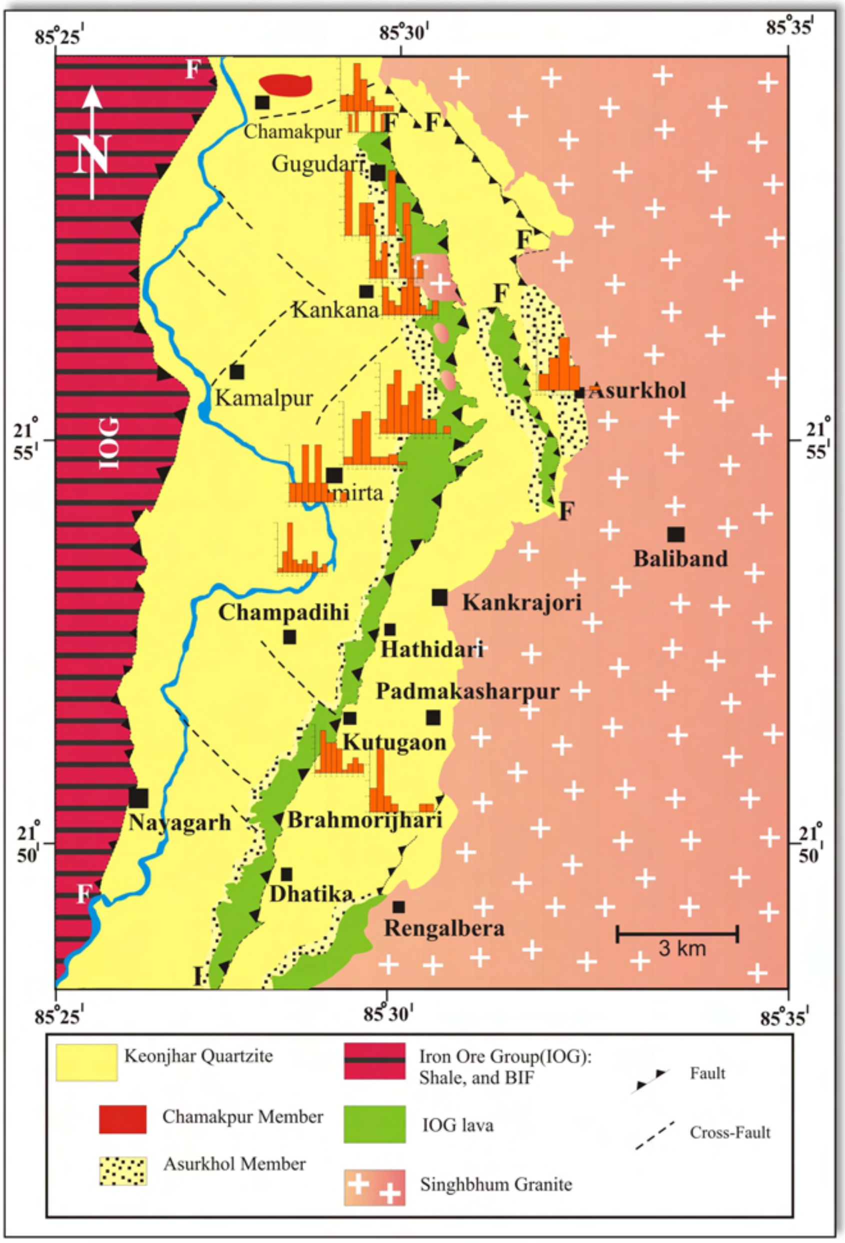

Fig.4.14. Grain-size distribution histogram pattern from conglomerate beds (ten largest clasts measured from each bed). Note enrichment of smaller fraction towards west.

Spatial disposition of facies sequences in down-dip fault blocks (Fig. 4.12, 4.13) further indicates westerly down-dip fining associations. Alluvial and fluvial facies associations occur mainly in the eastern part of the study area and facies associations of shallow shelf mature arenites dominate towards west. Grain-size distribution from conglomerates and pebbly sandstones from east to west in different thrust packages reveal that the pebble size decreases from east to west (Fig. 4.14).The relative distribution of conglomerate and arenite in successive down dip fault blocks therefore indicates a westerly paleoslope of the depositional basin.

4.5. Facies sequence development

The succession is interpreted here in terms of a 'sequence' consisting of lowstand systems tract (LST), transgressive systems tract (TST) and highstand systems tract (HST) (Fig. 4.15). The Asurkhol Member with mass-flow conglomerate-dominated proximal-midfan depositional setting is considered here to constitute the LST. The base of the LST is marked by the major unconformity and many localized channelized conglomerates are likely to be incised valley fills (IVF) from the early Falling Stage Systems Tract (FSST). The interbedded conglomerate –sandstone association of the FA-2 forms the upper part of the LST which is characterized by repeated progradational sandstone-conglomerate interbeds in a progradation normal regressive phase of the base level during terminal LST. The appearance of well sorted, clast-supported pebbly conglomerate, fine chip conglomerates and pebble lags in FA-3 with sandstone beds marks the onset of the TST. Lowest of the pebble lags or a thin bed of laterally persistent chip conglomerate mark the transgressive lag surface, FA-4 with wavy bedded sandstone and pebble lag is likely to represent the TST phase. The uppermost part of the succession dominated by mature wavy bedded sandstone of

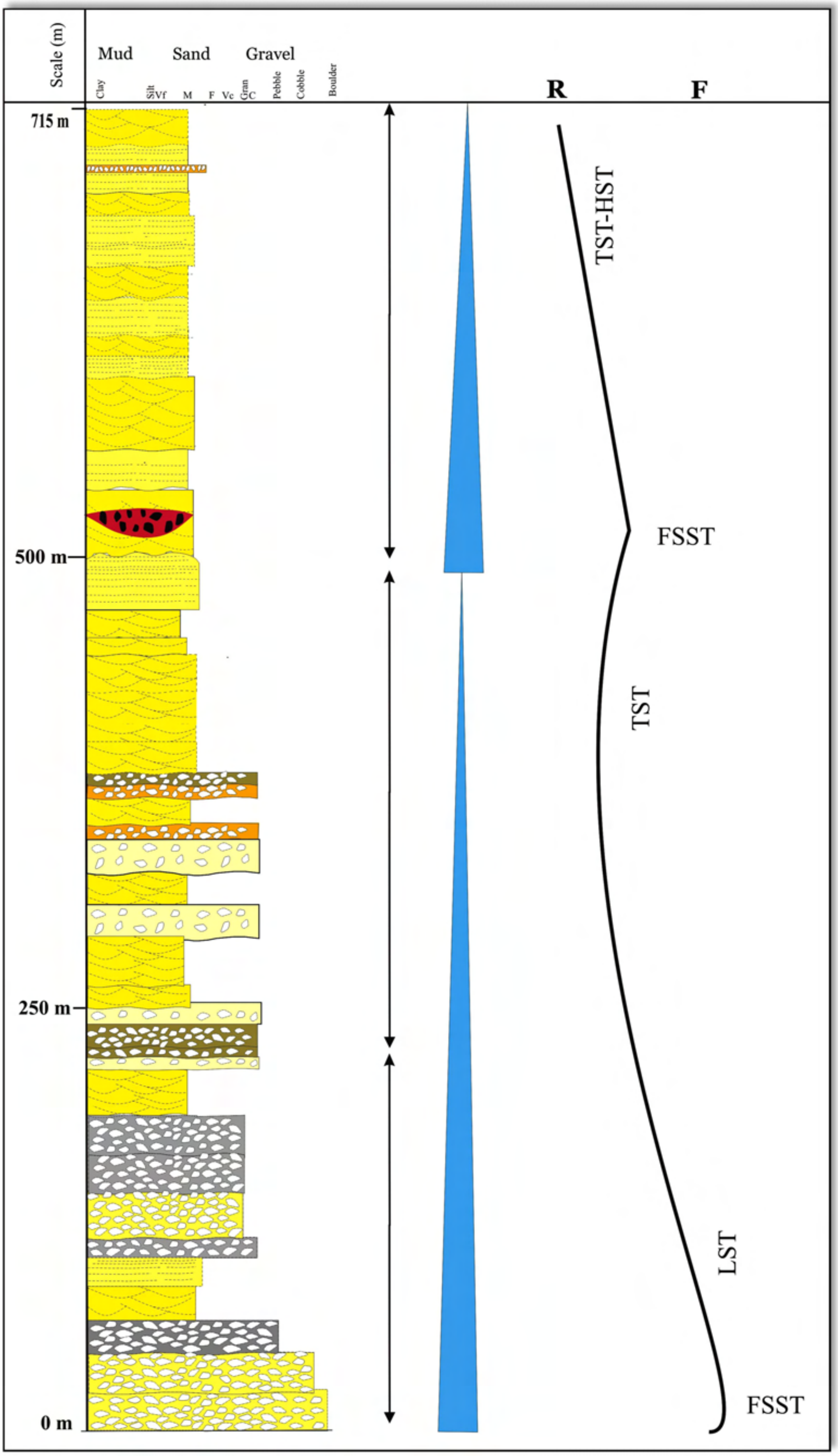

Fig. 4.15. Depositional sequence and systems tract from Keonjhar Quartzite.

subequal thickness is likely to indicate aggradational stacking pattern in the later phase of TST or early part of the HST (Fig. 4.15). The iron ore clast bearing mass flow conglomerates of the Chamakpur Member is incised into the aggradational shelf deposits of the TST and might represent a local-scale base level fall and shelf incision from local tectonics.

4.6. Paleocurrent analysis

Paleocurrent data in Keonjhar Quartzite have been obtained from cross-strata azimuths. The analysis is based on 285 measured from the study area (Fig. 4.16).Paleocurrent distribution is mainly dominant in unimodal or multimodal with a preferred direction (255º).

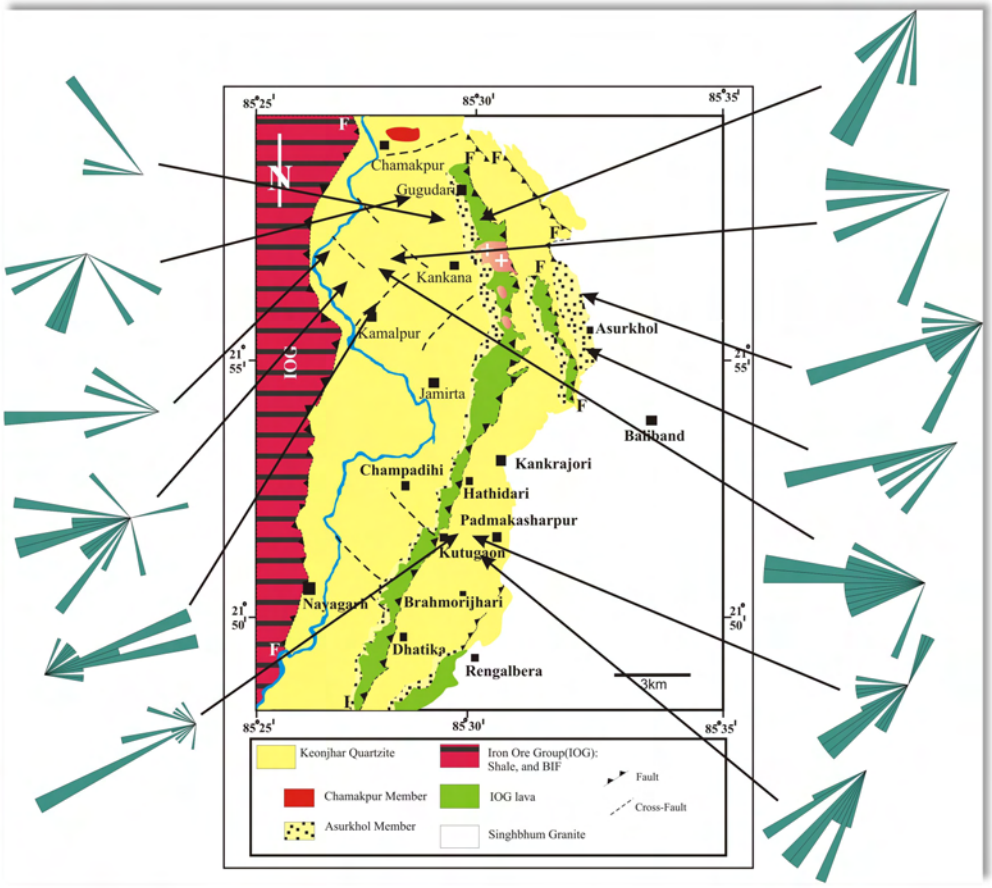

Fig.4.16. Paleocurrent distribution pattern from trough cross-stratified sandstones.

Unimodal data dominated in the Harijori, Kankana and Gugudari area with the preferred direction varies 245º to 255º (Fig.4.16). Dominantly unidirectional current in wavy bedded sandstone with evidences of bipolarity indicates that the downlapping strata of wavy bedded sandstones that are the most dominant lithology in the Keonjhar Quartzite have been influenced by strong WSW-ly directed ebb tidal current (cf. Witts et al. 2012). Alluvial and braided channel deposits mainly generated with WNW-SW direction paleocurrent, with a vector, mean direction towards WSW-ly direction. Further westward, from alluvial and braided deposits from some parts of the study area, paleocurrent distribution shows bimodal-bipolar distribution towards SW and NE directions suggesting tidal influences on fluvial distributaries in a fluvio-tidal coastal plain (cf. Witts et al. 2012). Bimodal and bipolar overall complex paleocurrent distributions are most important diagnostic criteria for tidal sedimentation, but an absence of bimodal-bipolar palaeocurrent patterns not necessarily excludes a tidal interpretation because Holocene tidal systems often are characterised by the dominance of ebb or flood flow (e.g., Terwindt 1981; Oomkens and Terwindt 1960; de Raaf and Boersma 1971; Dalrymple et al. 1990). Locally, multidirectional paleocurrent (Fig. 4.16) is also observed. Multidirectional paleocurrent is an indicator of the storm signature within the shallow marine shelf deposits (Gray and Benton 1982). Sediment dispersal patterns towards WNW to NW from paleocurrent data indicate the source from the eastern/southeastern side of the Singhbhum craton. Ghosh et al. (2016) also suggests that Singhbhum Granite batholith with enclaves of IOG-like greenstone belts is the most probable source of the Keonjhar siliciclastics.