RECONSTRUCTION OF FLUVIAL BARS FROM THE PROTEROZOIC MANCHERAL QUARTZITE, PRANHITA-GODAVARI VALLEY, INDIA

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ABSTRACT

Reconstruction of bars in ancient fluvial deposits is crucial in interpreting the channel pattern and its paleohydrauluics. Excellent outcrops of the Late Proterozoic alluvial deposit of the Mancheral Quartzite around Ramgundam (1848'N 7925'E) provides opportunity for such reconstruction. The Mancheral Quartzite is a 30-76 m thick, pebbly, coarse-grained sandstone and conglomerate sequence. Several braided fluvial facies and an alluvial plain aeolian facies are well developed in the Mancheral Quartzite at Ramgundam. The planar cross-bedded bar facies overlie major erosional surfaces and is characterised by complex interlayering of 30-120 cm thick planar cross-beds and 5-15 cm thick trough cross-beds.

A number of low-angle downcurrent inclined cross-bed bounding surfaces indicate accretion at the bar lee during deposition. Thickening of the cross-bed sets in down-paleoflow direction , the presence of well-developed alternate coarse- and fine-grained foresets and counter current ripple lamination at the toe of the cross-beds denote flood stage accretion of the bedforms into the adjacent pools. Lateral transformation of the larger planar cross-sets to cosets of smaller cross-beds, truncation by smaller trough cross-beds showing flow at high angle to those of the larger planar sets and thin muddy sandstone denote modification/deposition at falling water stage.

Combined paleocurrent data from all planar cross-beds show a mean south-westerly orientation, which is assumed as the local channel direction. Paleocurrent data from the bar sequences (both planar and trough cross-beds combined) indicate downcurrent, oblique or symmetric accretion of the bars with respect to the local channel direction and are inferred to document lateral or mid-channel braid bar deposits.

Thickness of the bar sequences suggest shallow depth of the channels (~ 2.5 m). Discharge was characterised by rapid and pronounced flow fluctuation. Internal organisation of the bars are intermediate in character between topographically differentiated large braid bars and simple lingoid dunes that commonly characterise many shallow sand-bed braided channels.

INTRODUCTION

Bars are principal depositional elements within rivers. Although most of the rivers show presence of lateral, upstream and downstream accretion of the bars (Bristow & Best, 1993) different channel types are characterised by a dominant bar type (Bluck 1979, Hazeldine 1983a,b; Miall 1994, Wills 1995). Reconstruction of the bars from the ancient alluvium, therefore, serves as an important tool for paleoenvironmental analysis and reconstruction of paleochannel characteristics.

A variety of bars differing in scale and morphology has been documented from the ancient alluvium (Rust & Jones, 1978; Cant & Walker, 1978; Bluck, 1980, Hazeldine 1983b, Kirk 1983, Roe & Harmansen 1993, Wizevich 1992, Wills 1993, Miall 1994 and others). Such studies have become more popular with increasing use of the techniques of architectural element analysis (sensu Miall 1985). However, few of these studies dwell on the details of the internal sedimentary structures that can provide important paleohydraulic information other than the dominant migration direction of these features. This paper presents a detailed account of the inferred bar sequences from the Proterozoic alluvial deposits of the Mancheral Quartzite. It also presents estimates of the paleohydrologic parameters and attempts to present a generalised model for the reconstruction of shallow braid bars from ancient fluvial deposits.

GEOLOGICAL SETTING

The Pranhita-Godavari Valley Basin is one of the major Proterozoic basins of India which exposes two linear belts of Proterozoic rocks flanking an axial belt of Permo-Jurassic Gondwana rocks (Fig. 1). The Sullavai Group is the youngest group of the Proterozoic sequence exposed in this basin (Table I). The Mancheral Quartzite, a constituent of the Sullavai Group, is very well exposed around Mancheral and Ramgundam in the south-western Proterozoic belt (Fig. 1). In the Ramgundam section the Mancheral Quartzite unconformably overlies the rocks of the Middle Proterozoic Pakhal Group and is overlain by the Venkatpur Sandstone (Table 1). In and around Mancheral, the fluvial sequence of the

Mancheral Quartzite erosively overlies Ramgiri Formation of the Sullavai Group and gradationally passes upward through a transition zone of flat-bedded sabkha-playa sediments into the erg sequence of the Venkatpur Sandstone (Chakraborty 1991a, 1994).

The Mancheral Quartzite comprises poorly sorted, coarse-grained pebbly sandstones and minor conglomerates. Typically 1 - 6 m thick, salmon red, fine- to very fine-grained sandstones occur at different stratigraphic levels and comprise a subordinate part of the Quartzite sequence. The sandstones and conglomerates of the Mancheral Quartzite are interpreted to have been deposited from high-gradient braided streams and the well-sorted, fine-grained sandstone interlayers are the product of fluvial-aeolian interactions in the distal part of the sandy braidplain (Chakraborty 1991b; Chakraborty & Chaudhuri 1993). The facies recognised within the Mancheral Quartzite are summarised in Table II and Figure 2 shows the vertical log through a well exposed section of the Quartzite. Details of the coarse-grained planar cross-bedded sandstone facies (facies 6 in Table II) is discussed below.

RECONSTRUCTION OF BARS IN THE MANCHERAL QUARTZITE

Fluvial bars are defined as depositional high within the channels that might become partially exposed during the falling river stage (Miall, 1981; Bridge, 1985; Roe & Harmansen 1993). In modern braided rivers definition of bars has been strongly influenced by the channel dimension. Both a simple bedform (Collinson, 1970; Smith, 1971) and a large periodic to quasi-periodic 'macroform' with complex erosional and depositional history (Cant & Walker, 1978; Bluck, 1976, 1979; Crowley, 1983) have been designated as bars. The 'bars' within the braided streams include a hierarchy of bed configurations e.g., (in increasing scale) individual bedforms (2-D or 3-D), small 'unit' bars, bar complexes or sandflats and mature vegetated islands (Walker & Cant, 1984).

In view of the morphological complexities involved and difficulty of their recognition in the ancient record, Miall (1981) proposed a simple classification of the fluvial bars into three categories: (a) gravely, planar or massive bedded bars, (b) sandy, simple foreset bars, and (c) compound bars of sand or gravel. Recognition of the first two categories may be easier, but recognition of the compound bars requires reconstruction of the paleobar morphology and involves lateral tracing of set or coset of strata, identification of the different order of bounding surfaces and working out the paleocurrent pattern of these structures (Bluck, 1976, 1979). The concept has been successfully applied to the analysis of several ancient fluvial deposits (Bluck, 1980; Allen, 1983; Hazeldine, 1983a,b; Kirk, 1983; Steel & Thompson, 1983; Wizevich, 1992 and many others). The 'bars' inferred in this study are mostly compound type as defined above.

The bar succession

The inferred bar succession of the Mancheral Quartzite comprises predominantly of coset of planar cross-beds (facies-6, fig. 3) with minor amount of small trough cross-beds (facies-5) and laterally impersistent layers of muddy fine-grained sandstone (facies-7). The succession has an overall F-U trend but may show local C-U trend (fig. 2).

The Quartzite succession at Ramgundam area are organized in several channel-fill sequences. Each channel-fill sequence is marked at its base by a major erosional surface that are flat to concave-up and can be laterally traced for up to several hundred meters. The surfaces may show local relief of up to a few meters (Chakraborty, 1991a; see also fig. 8 Chakraborty & Chaudhuri, 1993). The dominantly planar cross-bedded succession described below is separated by a major erosion surface from the underlying trough cross-bedded sandstone of facies-4 (fig. 2). Elsewhere in the Ramgundam Gutta (hill) the bar succession overlie the conglomeratic sandstone (facies-2) or may directly overlie the unconformably underlying Pakhal Limestone. Details of the primary structures, internal bounding surfaces, facies architecture and paleocurrent of the bar succession are well exposed in several outcrop section described below.

Hierarchy of bounding surfaces

Most prominent bounding surfaces observed within Mancheral Quartzite, as already mentioned, are those marking the base of the channel-fill sequences. These are designated first order bounding surfaces. Section 1, 2 and 3 described below show this surface as a basal erosion surface underlying the bar succession. Within the overlying planar cross-bedded succession most prominent bounding surfaces are the erosional base of the larger, solitary or compound planar cross-sets. These surfaces are irregular to flat and are either sub-parallel [redacted] or at low-angle to the first order bounding surfaces. These surfaces are designated second order bounding surfaces and are most prominently displayed in section-1(fig. 4). It should be noted, however, that within the limits of available outcrop sections these two surfaces have not been found to mutually truncate each other. First order surfaces are easily recognized because they separate distinct facies sequences and are laterally much more extensive than the second order surfaces. For example in section-4 (see below) although the first order surfaces are not exposed the erosional lower bounding surfaces of the larger planar cross-beds in this section facilitate easy recognition of the second order bounding surfaces. Internal reactivation surfaces within the cross-sets or the intraset boundaries of compound cross-sets constitute the third order bounding surfaces within the Mancheral bar succession. The shape of the third order surfaces are highly variable and have been found to change from convex-up to concave-up within the same set.

Description of the outcrop sections

Section - 1 (Fig. 4)

The northern end of the section is marked by a triangular unit comprising a 70 cm thick, partly deformed planar cross-set (marked 'L') and an overlying thin unit of rippled, fine-grained sandstone (8-25 m, fig. 4). This triangular unit is overlain to its north, by a coset of planar cross-sets with set boundaries dipping to the north. Whereas to the south second order bounding surfaces overlying this deformed cross-bed are inclined downcurrent. Combined together the second order bounding surfaces in this section define a form set geometry (sensu Anatase et. al., 1997). South of the set 'L', three major downcurrent inclined second order surfaces accommodate three planar cross-sets (marked 'A', 'B' and 'C' in fig. 4). These second order surfaces are inclined 3°-8° towards south with respect to the first order bounding surface at the base of the section. Each of the three sets thickens considerably (about 10 times in case of the set 'A') as they migrate over the downcurrent dipping basal erosional surfaces. However, the basal erosional surfaces of sets 'A' and 'B', in their downcurrent extremity become flat to slightly concave-up producing a scoop-like shape. Consequently, the overlying cross-sets have a lenticular set geometry. At the northern end the lower bounding surface of set 'A' (as well as an internal reactivation surface) descend stepwise as it erodes down into the underlying sequence (between 15-27 m, fig. 4). Note finer-grained parallel laminaset lap over the step-like reactivation surface at its upcurrent end and counter current ripples are present in the thickest part of set 'A' (between 27-30 m, fig. 4). Inclination of the foreset laminae of the set diminishes in the downcurrent direction and ultimately evolve into concave-up, channel-form layers near its downcurrent termination (34-43 m, fig. 4). The top of the channel-form layers have been dissected by several small trough cross-beds. Overlying set 'B' also thicken as it migrates over a downcurrent inclined surface. Upcurrent part of the set 'B' is dominated by avalanche foresets with few intervals containing reactivation surfaces whereas in the downcurrent part it evolves into a compound set (fig. 5). The reactivation surfaces in the upcurrent part of set 'B' are convex-up whereas at the terminal part of the set, the third order (intraset) bounding surfaces become very gentle, slightly convex-up, and sub-parallel to the underlying concave-up (second order) bounding surface (46-55 m, fig. 4). Similar to set 'A', the downstream margin of set 'B' is also dissected by small trough cross-beds containing coarse-grained sandstone with dispersed granules. Paleocurrent measurements from the small trough cross-beds indicate paleoflow direction at high angle to that of the large planar sets. Near its downcurrent termination set 'B' and overlying trough cross-beds are capped by a 15 cm thick unit of rippled, muddy sandstone of facies 7 (52-62 m, Fig. 4). In the central part of the section (around 35 m, fig. 4) smaller planar cross sets with granules and pebbles overly set 'B'. Near the southern end of the section, set 'B' is succeeded by another downcurrent dipping second order surface overlain by a planar cross-beds (set 'C') that also thicken in the downcurrent direction.

Section - 2 (Fig. 6; exposed north of section-1)

A basal sheet conglomerate seperates the planar cross-stratified succession from the underlying sequence of facies 4 rocks. The section is dominated by superposed sets of large planar cross-beds with a persistent west- south-westerly flow. Planar sets are tabular to wedge-shaped and are characterised by alternate coarse- and fine-grained avalanche foresets with rare or common counter current ripples. In the downcurrent direction, some of the foresets become finer grained, their inclination decreases and some evolve into compound cross-beds. Some other planar sets laterally pass into ripple-laminated and small trough cross-bedded zones. Shallow channels (up to 30 cm deep) cut into top of the planar sets and are filled with small trough cross-beds. Paleoflow directions of these trough cross-beds are at high angle to that of the planar sets (fig. 6).

Section - 3 (Fig. 7; south of section-1)

Compared to sections 1 and 2 coarse-grained, small trough cross-bedded units are volumetrically more abundant in this section. Large planar cross-sets interlayer with or laterally pinch out within trough cross-bedded units at different stratigraphic levels. The troughs show flow both to the Southwest and east (fig. 7). Several rippled muddy sandstone units (upto 23 cm thick) occur in the sequence and are often associated with the low-angle planar cross-beds having convex- up foresets (near the southern margin of the section).

Section - 4 (Fig. 8; located between section 1 and 3)

The section, about 50 m in the inferred downstream direction of section 1, contains three different orientation of outcrop faces and allows a three dimensional reconstruction of the depositional architecture. Organisation of facies in the two parallel north-south trending faces is essentially similar to those in other sections, Second order bounding surfaces are generally irregular, but some of these surfaces are distinctly dipping to the Southwest or south-east. Consequently some of the planar cross-sets thicken in the downcurrent direction (north and west wall of the exposure). Cosets of smaller cross-sets with oblique paleoflow direction, interlayer with or erode down into the larger planar sets. Concentration of granules and pebbles locally define coarsening-upward trend (southern end of eastern wall). The east-west trending section shows large planar sets migrating oblique to the streamwise direction, and thickening in the directions outward from the axial part of the exposure (fig. 8).

Interpretation of the sections: Planar cross-beds that dominantly comprise the bar succession were probably deposited by migrating 2-D dunes (Ashley, 1990). Bedforms were both simple and compound type, later one with superposed smaller bedforms. Similar planar cross-bedded succession is common in many modern and ancient braided fluvial deposits (Collinson, 1970; Smith, 1970; Banks, 1973; Bluck, 1976; Cant, 1978; Hazeldine, 1983a, b; Roe, 1986;). Paucity of grained sediments and low directional variability of the planar cross-beds both within and between the exposures (Figs. 4,6,7 and 8) support deposition in low sinuosity bedload streams (Willis, 1993). Transition of solitary planar sets downcurrent into compound cross-sets (Figs. 4 and 6) presumably formed by the migration of smaller bedforms at the falling river stage and are reported to be common feature of braided Platte river (Blodgett and Stanley, 1980). Reactivation surfaces indicate frequent fluctuation of flow depth and velocity. Change in the shape of the reactivation surfaces from convex-up to concave-up (set 'B', fig. 4) probably represent a progressive lowering of the flow stage (Jones & McCabe, 1980). Erosional truncation of the set or coset of planar cross-beds by lenticular, trough cross-bedded units (Figs. 4, 6 and 8) is inferred to represent the divergent, shallow, low-stage channels that dissected the bar tops. Rippled fine sediments (Figs. 4 and 7) probably record deposition in slough channels on emergent bar tops (cf., Bluck, 1976).

Many of the planar cross-beds of the above described sections show a remarkable tendency to thicken downcurrent as they migrate over the inclined bounding surfaces (sets 'A', 'B', 'C' in fig. 4; sets in the north and west wall of fig. 8 and also a few sets in the fig. 6 and 7). In order to leave behind a net deposit of cross-stratified sediment migrating bedforms must climb-up in the downcurrent direction (Rubin & Hunter, 1982; Rubin, 1987). Consequently 3°-8° southward dip of the set bounding surfaces within Mancheral bar succession must imply presence of sloping primary depositional surfaces. In the overall context of the braided river origin of the Mancheral Quartzite, inclined surfaces of these sections (particularly in section -1 ,fig. 4), are inferred to represent the lee slope of downcurrent accreting fluvial bars. Straight crested dunes grew larger as they migrated down the bar-lee into deeper water of adjacent pools (cf., Hazeldine, 1983a, b; Kirk, 1983; Willis 1993).

One of the most remarkable feature of section-1 is the downcurrent transition of a thick planar cross-bed (set 'A') into a concave-up trough-shaped lamina set (Fig. 4). Similar features have been earlier reported from sandy and gravely braided rivers and have been variously interpreted as channel-fill in between two bars (Ramos et al. 1986) or as pool-filling structure (Sigenthaler & Huggenberger, 1993).The second order bounding surface at the base of the set defines a scoop-shaped depression with a steep, upcurrent margin and slightly concave-up downcurrent end. Set 'A' filling the scour shows systematic variation in the foreset geometry. Shallow upcurrent part shows parallel laminae (18-23 m, set 'A', fig. 4), thickest central part shows angular foreset and counter-current ripples and at the downcurrent end it forms trough-like laminae. The variable foreset geometry is best explained by invoking the depth ratio concept (depth of water:depth of basin or scour being filled by a bedform, Joplin, 1965; fig. 9). At the upstream margin of the scour pool, the flow was shallow (high depth ratio) and formed upper regime plane beds. As the bedform prograded into deeper waters of the scour pool, increased bedform height (lower depth ratio) ensured formation of angular foresets. The increased bedform height also produced well-developed flow separation at the lee of the bedform and back-flow eddy formed regressive ripples at the toe of the foresets. As the bedform approached the other end of the scour, due to decreasing depth of the scour, foresets became low-angle, tangential. Eventually it formed laminae sub-parallel to the upcurrent-dipping base of the scour resulting in trough-shaped lamina (Jopling, 1965; fig. 9).

The above interpretation supports the inferred existence of deeper water pools in front of the depositional high represented by the sequence of deformed cross-bed (set 'L') and overlying fine sandstone in fig. 4. The second order surface at the base of overlying set 'B' has a similar geometry. The bounding surface at the base of set 'C' though incompletely exposed hints at similar trend. These surfaces are inferred to represent the successive positions of the advancing pool in front of a bar. It is apparent from fig. 4 that the scour pools migrated both laterally and vertically and depth of the successive scours varied. Formset-like geometry (cf., Anastase et al, 1997) of the onlapping second order surfaces across the deformed cross-set (set 'L') in figure 4, probably indicate that the deformed cross-set and the overlying fines acted as a depositional high or core of the bar sequence preserved in this section. The up-dip migrating planar sets to the north of the section probably denote upcurrent accretion of the bar core (Miall, 1985; Bristow, 1987; Bristow & Best, 1993). The scours, defined by the scoop-shaped to down-dipping second order surfaces, in the lee of the inferred bar core probably represent positions of migrating pool structures. Similar bar-pool units have been reported from modern braided rivers as well as scaled laboratory models (Bluck, 1976; Bristow et al 1993; Clifford 1993; Ferguson, 1993; Ashmore, 1993). Pools were probably formed at the flood-stage and dune bedforms encroached upon them as the discharge fell (Clifford, 1993). Progradation of the bar was probably achieved through the migration of the scour pool and the accretion of the pool-filling cross-stratified units on to the bar lee. As the river stage fell smaller superposed bedforms overtook the larger dunes forming compound cross-beds and eventually shallow channels dissected the emergent bars. Less commonly fine-grained sediments formed on top of the exposed bars to be partly removed during a subsequent flood when a new scour was formed at the lee of the existing depositional high. Local concentration of coarser material within the smaller trough cross-bedded units probably reflect winnowing action of shallow flows over emergent bars (Bluck, 1976). Two fine grained sandstone units are preserved in section 1 (13-17 m and 52-62 m in fig. 4). Assuming that the fines accumulated at the top of the bars, occurrence of these two units roughly at the same stratigraphic level above the first order bounding surface, indicate positive relief of the bar (with respect to the base of the channel) maintained its existence over several flood and low-stage flow of the river.

It is interesting to note that the shape of successive scoop-shaped second order bounding surfaces in figure 4 has remarkable similarity with the computer generated sediments formed on top of the exposed bars to be partly removed during a subsequent flood when a new scour was formed at the lee of the existing depositional high. Local concentration of coarser material within the smaller trough cross-bedded units probably reflect winnowing action of shallow flows over emergent bars (Bluck, 1976). Two fine grained sandstone units are preserved in section 1 (13-17 m and 52-62 m in fig. 4). Assuming that the fines accumulated at the top of the bars, occurrence of these two units roughly at the same stratigraphic level above the first order bounding surface, indicate positive relief of the bar (with respect to the base of the channel) maintained its existence over several flood and low-stage flow of the river.

It is interesting to note that the shape of successive scoop-shaped second order bounding surfaces in figure 4 has remarkable similarity with the computer generated scalloped cross-bedding (fig. 17, Rubin, 1987). In the computer generated cross-bed bounding surfaces cyclically scoop down into underlying deposits (as the second order surfaces in fig. 4). Rubin (1987) postulated that such structures are produced due to migration of bedforms undergoing large and rapid fluctuation of height. Such change in bedform height has also been reported from different depositional settings including the Brahmaputra River (Coleman, 1969). Changing height of the fluvial bars in response to imposed flow condition when combined with downcurrent accretion are likely to produce features similar to those generated by computer simulation.

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A variety of scours have been reported from modern rivers (see Slater, 1993). Two commonest type of scours in braided streams are riffle-pools and confluence scours (Keller & Melhorn, 1978; Ashmore, 1993). Flow convergence can be inferred from section 3 and 4, but similar evidences are absent in section 1 (fig. 4) which preserves the scour structures. Therefore, there is no first hand evidence to relate these features to confluence scours. Correlation of these features with riffle-pool sequences is problematic because the relationship between the riffles and braid bars are not very well understood (written communications, Ellen Wohl and Nicholas Clifford, 1994). Although it is not known if the riffles evolve into braid bars or not, presence of an elongated pool flanking the braid bar is well documented from the modern braided rivers (Ashmore, 1993, Ferguson, 1993). Close association with depositional high, low height and evidences of periodic migration and filling-up by unidirectional, downstream accreting 2-D dunes suggest that the scour structures of Mancheral bar succession probably represent bar-pool units (cf., Ashmore, 1993). Development of strong eddy currents during the high flood at the lee of the channel bars possibly provided the driving mechanism for the formation of these scours. However, data from the two-dimensional outcrops of Mancheral Quartzite is inadequate for precise process-based interpretation of these scour structures.

PALEOCURRENT AND BAR TYPES

Azimuths of planar cross-beds in each of the exposures show a very consistent mean towards south-west (Figs. 4, 6, 7 and 8) and is inferred to reflect the mean channel direction (Rust, 1972; Bluck, 1976). The small trough cross-beds, within and between exposures show much greater dispersion (a spread of up to 220°) as compared to that of the planar sets (a maximum spread of about 100° about the mean). This paleocurrent pattern is consistent with the origin of small trough cross-bed from shallow, divergent flows that dissected the bar top at the low stage of the river (cf. Bluck, 1979).

Paleocurrent pattern in the section-1 indicates dominant flood-stage accretion of the bar to the south-west along the channels. The smaller cross-beds show a more westerly flow direction (Fig. 4). This is inferred to indicate deposition as a mid-channel bar that during the falling stage accreted more towards the right (west) bank of the local channel (Bluck, 1976; Hazeldine, 1983b).

Disposition of large planar cross-beds in section-4 (Fig. 8) indicate accretion of larger bedforms away from each other and down into the deeper channels on both the flanks of a topographic high in the river and is typical of mid-channel braid bars (Bluck, 1980, pp. 33-37; Allen, 1983; Bristow, 1993a). Erosively overlying troughs in this section show a higher spread but symmetrical orientation with respect to the inferred mean channel direction. This pattern is also consistent with the mid-channel bar interpretation of the section.

In section-3 (Fig. 7) some of the larger planar cross-beds initially thicken downcurrent and then pinch out laterally into cosets of smaller trough cross-beds. Whereas the planar cross-beds show consistent flow to south-west the trough axes show much greater variation with stronger modes towards east or southwest. This probably indicates flow convergence at the lee of the larger bedforms and preferential growth of the bar to the east (left bank of local channel) during the low stage. Section-2 (Fig. 6) contains similar sequences but paleocurrent pattern indicate preferential low-flow stage accretion to the west (right bank of local channels).

Summarising the data from the sections it can be inferred that most of these bars developed as mid-channel depositional features with dominant flood-stage accretion in the downstream direction. During the low stage, flow either converged at the lee of the larger 2D bedforms or bars (section 3) or flowed obliquely over the bars either towards the right (section 1 and 2) or left (section 4) bank of the stream. Low-stage accretion of the bars towards alternate banks suggests a transformation from mid-channel to lateral bars (Bluck, 1976; Hazeldine, 1983b).

DEPTH OF THE PALEOCHANNELS

Rippled, fine-grained sandstones in fig. 4 are inferred to have formed at the top of the emergent bars. Two fine-grained sandstone units (at 13-17 m and 52-62 m in fig. 4) are about 190 cm above the basal first order erosion surface (the inferred channel base). Therefore, [illegible] one estimate of the relief of the preserved bar in this section is 190 cm. The height of the bars provide the minimum estimate of the bankful channel depth (Allen, 1983). Accordingly the depositional channels were at least 2 m deep.

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It is difficult to make similar estimate for the succession in fig. 6, because of lack of preserved depositional topography. However, minimum height of the low-stage channels, presumed to be flowing over emergent bars, from the basal first order erosion surface is about 90 cm (south-western end of fig. 6). Assuming this value to reflect the thickness of the emergent bar/bedform in this section the minimum estimate of the channel depth should be

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Flow depth can also be estimated employing well known hydraulic relationship

$$H = 0.086\, d^{1.19} \qquad \text{(Allen, 1968)} \;\ldots\ldots\ldots\ldots\ldots\ldots\ldots\; (1)$$

where H is the mean dune height and d is depth. The calculated value of depth (d) can be further modified by incorporating compensation for (i) compaction of sand due to burial, c and (ii) variation in depth between straight and sinuous reaches, c′. The modified flow depth is given by

$d_m = cc'd$ (Khan, 1987) .... (2)

Values of c range from 1.1 to 1.2 and that of c' range from 0.585 to 1.0 (Khan, 1987 and the references therein). The mean thickness of planar cross-beds were calculated for section 1, section 2 and 117 measurements collected from throughout the Ramgundam area(Table III). The flow depths calculated by eq. 1 and 2 for the succession preserved in section 1 (fig. 4) range between 146 and 272 cm and that for section 2 varies between 97 and 181 cm. The average channel depth estimated for the Mancheral braided system (on the basis of facies 6 planar cross-bed thickness) range between 92 and 145 cm. The calculated values tally closely with the values estimated from the bar morphology and thus supports the reconstruction of the bar morphology discussed earlier.

TOWARDS A MODEL FOR SHALLOW BRAIDED RIVER BARS

Bars have been the focus of many sedimentological studies which aimed at deciphering the distinctive signature of its depositional processes (Williams & Rust, 1969; Smith, 1971,1974; Bluck, 1976, 1979; Cant, 1978, Brierly, 1991; Bristow 1993a among many others). Slater (1993) and Bristow et al (1993) recently pointed out that other features of stream beds, notably scours of different types, having high preservation potential and sedimentological implications, have received little attention from the sedimentologists. These scours include both quasi-regular riffle-pool sequences (Keller & Melhorn, 1978; Clifford, 1993) and more irregular confluence and constriction scours (Mosley, 1976; Best, 1986; Ashmore et al., 1992). Recognition of scour pools within Mancheral Quartzite underlines the importance of these features as an essential element of the ancient braided river deposits and provides an actualistic basis for constructing braided bar facies model.

The common features that characterise the bar sequences in the Mancheral Quartzite are:

a) Presence of a sequence of planar cross-beds above a major erosion surface and paucity of the fine grained sediments in the succession.

b) Downcurrent thickening of some of the larger planar cross-beds as they migrated over downcurrent dipping second order bounding surfaces.

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~~a) Presence of a sequence of planar cross-beds above a major erosion surface and paucity of the fine grained sediments in the succession.~~

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c) Transition of the simple planar cross-beds into compound cross-beds or into coset of smaller trough cross-beds in the downcurrent direction.

d) Presence of shallow channels that down cut into the top of the larger bedforms and are filled with small trough cross-beds. Flow in these shallow channels were at high angle to that forming the larger cross-sets.

e) Low dispersion of paleocurrent measured from large planar cross-beds both within and between exposures. In contrast direction from the smaller trough cross-beds show higher dispersion.

These features are collectively inferred to indicate

1) Bars dominantly comprised large 2-D dunes.

2) Presence of a 'depositional high ' or bar and a deeper water pool in its lee comparable to the 'pool-bar' units described from modern braided rivers and scaled laboratory models (Ashmore 1993). In comparatively deeper channels, these scour pools were well developed and in current parallel sections reveal a 'spoon-shaped' geometry (cf. Ashmore 1993, pp 131). In shallower channels, pools had a lower depth and the lower bounding surfaces of the 2-D dunes (the inferred bar-pool interface) are either subparallel or subtends a

small angle with the first-order bounding surfaces at the base of the sandbody (the inferred channel base).

3) The bar sequences in the Mancheral Quartzite were formed during rapidly fluctuating flow conditions. During low-flow stage smaller bedforms initially developed at the lee of the larger bedforms (Blodgett & Stanley 1980) but as water level fell further, bedforms/bars were dissected by shallow divergent flows.

4) Mancheral river channels had a low sinuosity. Bars were mostly mid-channel type. During the low flow condition some of the bars accreted either to the left or right bank of the stream channels.

5) Mancheral fluvial system was characterised by contemporaneous existence of both shallow and deeper channels similar to the different order of coexisting channels in the braided streams (Bristow & Best 1993).

Bluck (1976,1979) recognised multiple topographic levels within braid bars and termed them platform, supra-platform bar head, bar head lee and bar tail. A hierarchy of bounding surfaces inferred to have developed due to lateral migration of these topographically differentiated bars were used by Hazeldine (1983a,b) to reconstruct a 10 m thick bar sequence. A hierarchy of simple periodic to complex quasi-periodic bedforms are known to exist within braided channels and consequently scale and internal organisation of the bar succession is expected to vary considerably. The scale of bedform considered as braid bar is probably strongly influenced by the scale of the channels in which they exist and varies from simple dunes to large channel islands (see Smith, 1978; Miall, 1981). However, existence of pool-bar units, convergence of flow at the lee of the bars, dissection bars or larger bedforms at low-stage, coexistence of multiple orders of channels and presence of mid-channel bars with flow on both sides of the depositional high are typical of most of the braided rivers independent of their scale or size of the bed load (Smith, 1970; Rust, 1972; Bluck, 1976; Cant, 1978; Bristow, 1987; Ashmore, 1993; Ferguson. 1993). Recognition of these features provide the key to the reconstruction of the bars in the Mancheral Quartzite. Simpler internal organisation and lower thickness of the bar succession in the Mancheral Quartzite appear to reflect the lack of multiple topographic levels and simpler morphology of the bars. The bars of Mancheral Quartzite are probably intermediate in character between large topographically differentiated bars and simple bedforms that occur within braided channels.

In many respects Mancheral bars are analogous to the bar sequences described by Roe & Hermansen (1993) from the Precambrian fluvial deposits of northern Norway. As pointed out by them unstable sandy bank and absence of cohesive fines in the overbank areas (see Chakraborty & Chaudhuri, 1993 for description of overbank deposits of Mancheral Quartzite) of these Precambrian rivers favoured channel widening in response to increased flood discharge resulting in high width:depth ratio. Shallow channels resulted low height of the bars (Roe & Hermansen 1993, their fig. 4,8). Internal organisation of these Norwegian bars notably the downcurrent thickening of the larger cross-sets, up or downcurrent transition of these larger sets into cosets of smaller cross-sets, erosional dissection of the top of the larger sets and low paleocurrent variability bears striking resemblance to the Mancheral bar sequences. However, the grain size of these Norwegian sequences is much finer that may account for abundance of plane beds with parting lineation and sigmoidal cross-sets in the succession. The coarser grained deposits of the Mancheral Quartzite contain a very few of these features.

CONCLUSIONS

Well exposed sections of the planar cross-bedded facies of the Mancheral Quartzite allows reconstruction of the shallow braid bars that characterised the precursor channels. These sequences reveal:

i) sets of cross-beds with downcurrent inclined bounding surfaces denote accretion of bedforms in the front of the depositional highs (bars) into the adjacent pools;

ii) scoop-shaped second order bounding surfaces and overlying sets or cosets of planar cross-beds are inferred as pool-filling sequences;

iii) the bar successions were characterised by fluctuating flow, flow convergence at the lee of the bars/bedforms and dissection of the bar tops;

iv) depositional channels had a low sinuosity and bars were mostly mid-channel type

v) different lines of evidences suggest a bankful channel depth of about 2.5 m.

Acknowledgement

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b. Geological map of the area around Ramgundam.

c. Location of sections 1 to 4 and vertical log (fig. 2) through the bar succession in the blown-up outcrop map of Mancheral Quartzite at Ramgundam Gutta

Figure 2. Vertical log through a representative section of Mancheral Quartzite, Ramgundam Gutta. For location of the log see fig. 1c. The vertically stripped rose shows paleocurrent data from facies 2 and rose with horizontal stripes shows data from facies 4. For all the rose diagrams N= number of data and C= consistency ratio.

Figure 3. Coset of planar cross-beds in a bar sequence. Hammer handle is 34 cm long.

Figure 4. Detail outcrop diagram of the section-1, Ramgundam Gutta. Circled numbers (1,2,3) denote the different orders of bounding surfaces. 'A', 'B' and 'C' mark the large planar sets referred in the text. Note counter current ripples at the thickest part of set 'A' and concentration of coarser material near the top part of the section. North direction of the paleocurrent arrows coincides with the north direction of the section shown in the bottom left. The rectangle marks the position of fig. 5.

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Figure 6. Detail outcrop diagram of the section-2, exposed north of section-1 (see fig. 1c for location). Note different orders of bounding surfaces marked by circled numbers. The first order bounding surface lined with lag conglomerate at the base of the section overlies a sequence of smaller trough cross-beds of facies 4.

Figure 7. Detail outcrop diagram of section-3 described in the text (see fig 1c for location). Note planar cross-beds merge laterally or interlayer with smaller trough cross-beds. At the southern end basal first order surface overlies facies 4 small trough cross-beds. North for the paleocurrent arrows coincides with the north of the outcrop. Rectangle marks the position of fig. 3.

Figure 8. Fence diagram showing the details of section-4. Note divergent accretion of large planar sets and locally coarsening upward trend within small trough cross-beds (indicated by the inverted arrow, east wall). Paleocurrent arrows are plotted with respect to the north direction shown in the top right corner of the fence diagram.

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Table - I

Age	Supergroup/ Group	Formation Mancheral Area	Formation Ramgundam area	Broad Lithology & sedimantary structures	Depositional Environment
Perm. – Early Creta.	Gondwana Supergroup	Talchir Formation	Talchir Formation		
	....	*Angular Unconformity*	....		
PROTEROZOIC	GODAVARI SULLAVI GROUP	Venkatpur Sandstone (48 m +)	Venkatpur Sandstone	Red, fine to medium-gained, well-sorted sandstone with meter-scale planar cross-beds and flat beds	Erg and erg-margin deposits (Chakraborty 1991a)
		Mancheral Quartzite (76 m)	Mancheral Quartzite (23 m) ? ? ? ? Ramgiri Formation (456 m+)	Mancheral Quartzite: Purple to red, coarse-grained pebbly sandstone and conglomerate; F-U sequences; interlayered fine-grained sandtone units with adhesion structures	Braided fluvial with interlayered aeolian units (Chakraborty & Chaudhuri 1993)
		Ramgiri Formation (250 m +)		Ramgiri Formation: Red conglomerate and pebbly arkose; conglomerates reverse graded; sandstone cross-bedded; laterally extensive, sheet-like sedimentation units	Distal alluvial fan-braided river (Chakraborty 1991b, 1994)
		—— *Angular Unconformity* ——			
	SUPERGROUP PENGANGA GROUP	Sat Nala Shale	Mulug Subgroup		
		Chanda Limestone	PAKHAL GROUP *-Disconformity-*		
		Pranhita Sandstone	Mallampalli Subgroup		
	....	*Angular Unconformity*	....		
Archean (?)		Gneissic Basement Complex	Gneissic Basement Complex		

TABLE - II

Facies No.	Brief Description	Paleocurrent	Interpretation
1	Matrix or clast-supported, pebble to boulder conglomerate; beds 11-140 cm thick & show CU or CU-FU trend; MPS of individual beds varies from 5-84 cm; beds show MPS:BTh positive correlation; few clast-supported beds show clast imbrication & crude horizontal stratification; pervasive hematitic cement locally present; grades upward into trough cross-bedded sandstone of facies 4	Imbrication in few beds show SW'ly transport	Viscous to non-cohesive debris flow or hyperconcentrated flood flow deposit on alluvial fans
2	Poorly sorted pebbly sandstone to sandy conglomerate; sandy conglomerate massive; pebbly sandstone cross-bedded; 4-40 mm clasts dispersed throughout the x-bedded units; cross-sets 8-60 cm thick; occasional sigmoidal foresets; soft-sediment deformations common; facies occurs near the base of the channel-fill sequences; interlayered with facies 3 & grades upward into facies 4	Exposure mean direction varies from 251°-296°; dispersion locally high	Rapid deposition from sediment-laden, high velocity flow in shallow channels.
3	Medium- to coarse-grained sandstone with large trough cross-beds; set thickness >45cm; >30 m wide in bedding plane exposures; occur interlayered with facies 2.	Consistent mean flow towards 291°	Deposition from large 3-D dunes in deeper parts of the channels
4	White to grey, fine to very coarse-grained sandstone with few pebbles; 2-15 cm thick trough cross-beds ubiquitous; cosets of troughs form sheet-like sandbodies bounded by pebble-strewn flat erosional surfaces; sandbodies 30-81 cm (av. 50 cm) thick and traceable in strike-parallel direction for 80-110 m; gradationally overlain by facies 7 or 8; at places facies 6 erosively overlies this facies unit.	At Ramgundam exposure mean direction varies from 151°-244°; overall mean 215°; at Mancheral mean direction 006°	Deposition from small 3-D dunes in shallow, wide channels occurring at the higher topographic levels/ proximal floodplain of braided streams
5	Red to reddish brown coarse-grained sandstone locally with granules and small pebbles; 2-10 cm thick trough cross-beds; cosets 5-25 cm thick; occur always as lenticular units interlayered with facies 6 and often fill shallow scours overlying large planar set/coset	Exposure mean varies from 118°-275°; flow was usually at high angle to that of the enclosing planar cross-beds of facies 6	3-D dunes in small, low-stage channels dissecting top of larger bedforms/bars in braided rivers.
6	Deep brown to purple, coarse-grained sandstone locally with granules & small pebbles; planar cross-beds 10-130 cm thick; cosets 50-160 cm thick; planar sets tabular to lenticular and often evolve downcurrent into compound cross-beds; downcurrent inclined set/coset boundaries; counter current ripples & reactivation surfaces common; interlayered facies 5 and 7.	Dispersion is locally high, overall flow consistently SW; exposure mean direction from large planar cross-beds varies from 204°-284°	Deposition from migrating braid bars that experienced rapid fluctuation of flow depth & velocity
7	Red to purple fine-grained muddy sandstone/ mudstone; usually ripple laminated; interference ripple marks, shallow channels, pools & desiccation cracks common; lenticular units upto 15 cm thick; interlayered with or overlie facies 6 & 4.	Variable ripple orientation.	Deposition in pools/sluggish channels on bar tops or higher topographic levels of braided streams
8	Typically salmon red, v. fine to medium grained, well-sorted, well-rounded sandstone; abundant adhesion structures; aeolian strata comprise ~ 40% of the facies succession; 5-25 cm thick, lenticular aqueous units of massive/faintly cross laminated sandstone; ferricrete layers at places; in Mancheral area polygonal salt-ridge structures common; gradationally	highly variable paleowind direction measured from adhesion cross-laminae.	Aeolian/aqueous deposits or weathering profile material in the highest topographic levels of the overbank areas of braided rivers

Table - III

Section no. / Location	**Number of data**	**Mean Height of dunes (H) (cm)**	**Bankful Channel depth $d_{bf} = cc'[H/0.086]^{1/1.19}$ (cm)**	**Remarks**
Section-1 (fig. 4); Ramgundam Gutta	9	54.55	145.7 to 271.7	Height of reconstructed bar 235 cm.
Section-2 (fig. 6); Ramgundam Gutta	10	33.66	97.01 to 181.01	Min. height of reconstructed bar 90 cm.
All data from facies 6; Ramgundam area	117	31.65	92.20 to 143.28	—

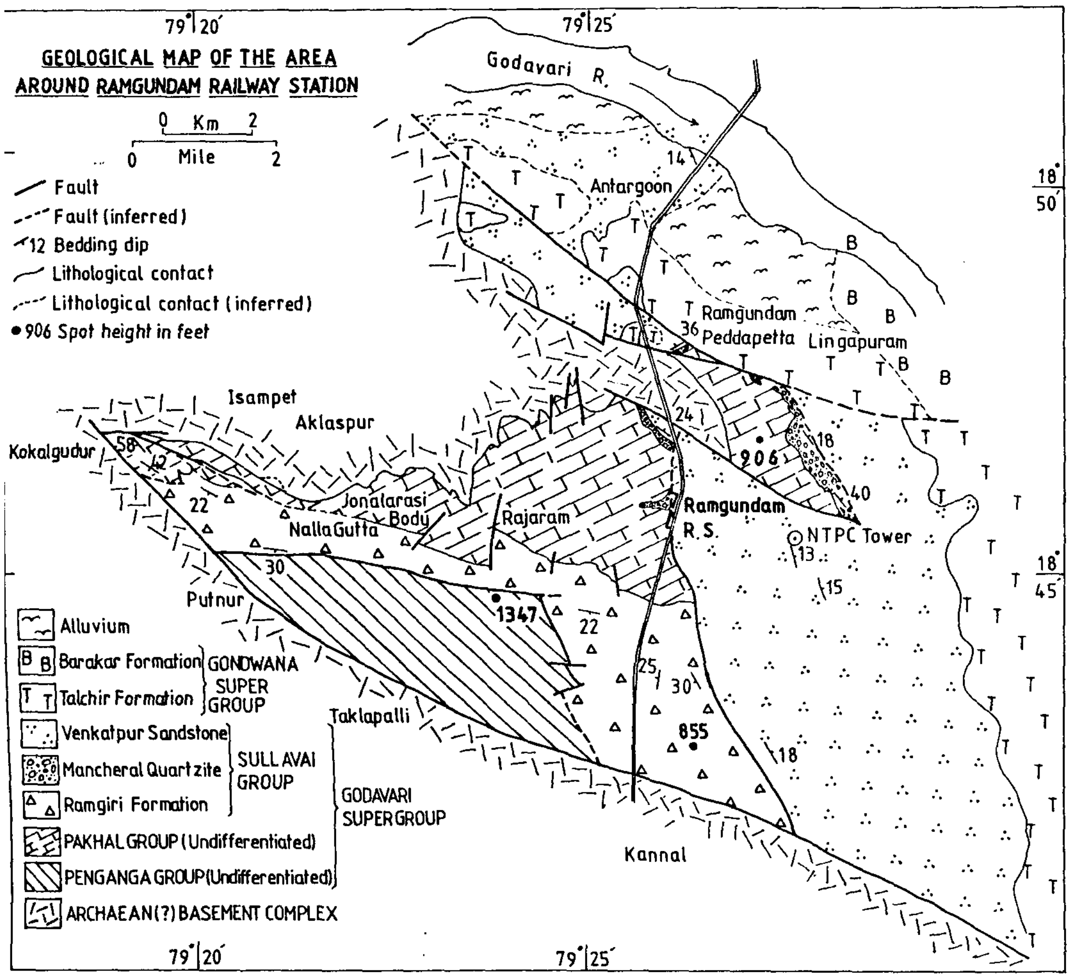
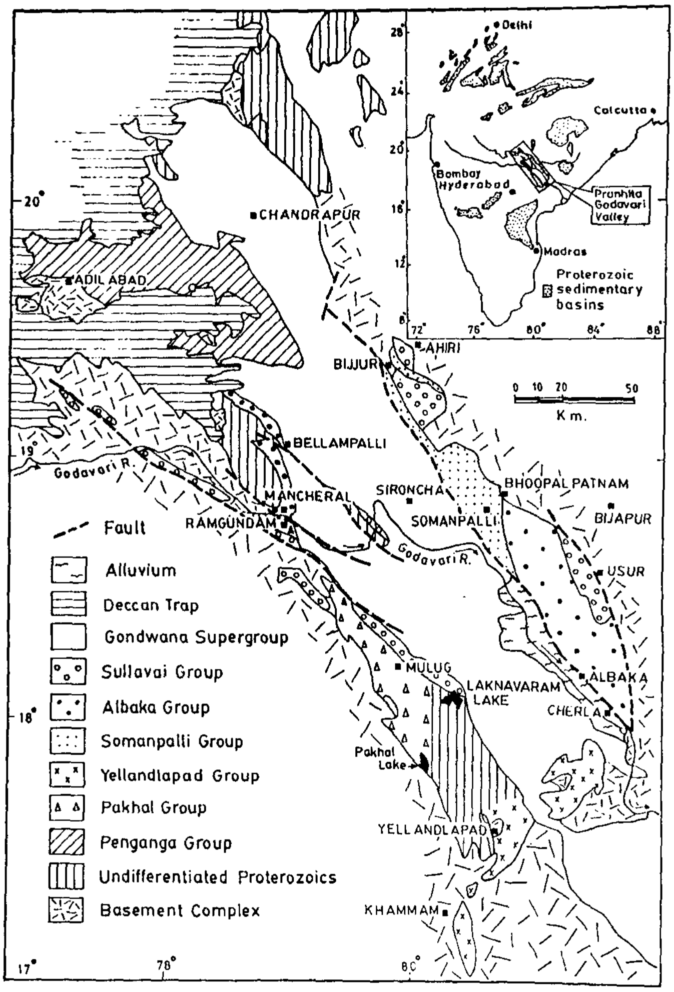

GEOLOGICAL MAP OF THE AREA AROUND RAMGUNDAM RAILWAY STATION
0 Km 2
0 Mile 2
Fault
Fault (inferred)
12 Bedding dip
Lithological contact
Lithological contact (inferred)
● 906 Spot height in feet
79° 20′
79° 25′
18° 50′
18° 45′
Godavari R.
Antargoon
Ramgundam
Peddapetta
Lingapuram
Isampet
Aklaspur
Kokalgudur
Jonalarasi Body
NallaGutta
Rajaram
Ramgundam R.S.
NTPC Tower
Putnur
Taklapalli
Kannal
906
1347
855
14
36
24
18
40
13
15
58
42
22
30
25
B
T
Alluvium
Barakar Formation
Talchir Formation
GONDWANA SUPER GROUP
Venkatpur Sandstone
Mancheral Quartzite
Ramgiri Formation
SULLAVAI GROUP
GODAVARI SUPERGROUP
PAKHAL GROUP (Undifferentiated)
PENGANGA GROUP (Undifferentiated)
ARCHAEAN (?) BASEMENT COMPLEX

fig 1b



Delhi
Calcutta
Bombay
Hyderabad
Madras
Pranhita Godavari Valley
Proterozoic sedimentary basins
28°
24°
20°
16°
12°
8°
72°
76°
80°
84°
88°
0
10
20
50
Km.
20°
19°
18°
17°
78°
80°
CHANDRAPUR
ADILABAD
AHIRI
BIJJUR
BELLAMPALLI
Godavari R.
MANCHERAL
RAMGUNDAM
SIRONCHA
SOMANPALLI
BHOOPALPATNAM
BIJAPUR
USUR
Godavari R.
MULUG
LAKNAVARAM LAKE
ALBAKA
CHERLA
Pakhal Lake
YELLANDLAPAD
KHAMMAM
Fault
Alluvium
Deccan Trap
Gondwana Supergroup
Sullavai Group
Albaka Group
Somanpalli Group
Yellandlapad Group
Pakhal Group
Penganga Group
Undifferentiated Proterozoics
Basement Complex

Fig. 1a

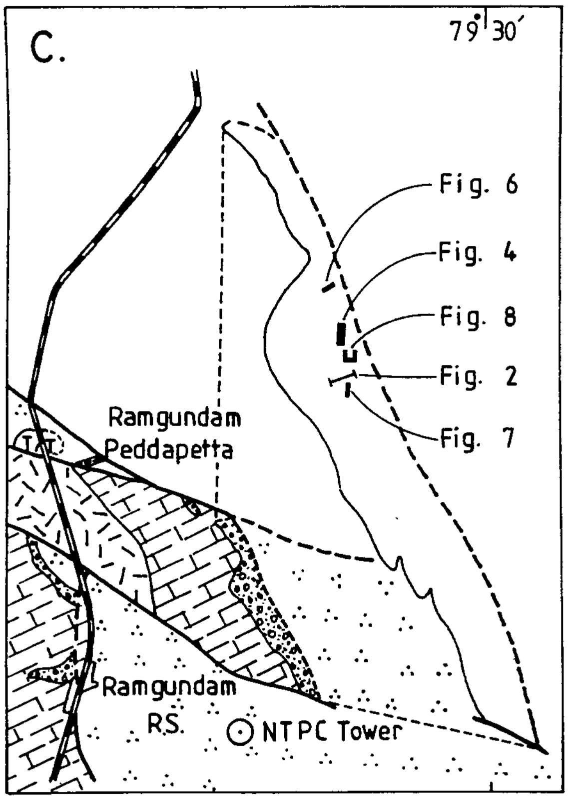

C.
79°30′
Fig. 6
Fig. 4
Fig. 8
Fig. 2
Fig. 7
Ramgundam
Peddapetta
Ramgundam
RS.
NTPC Tower

Fig 1c.

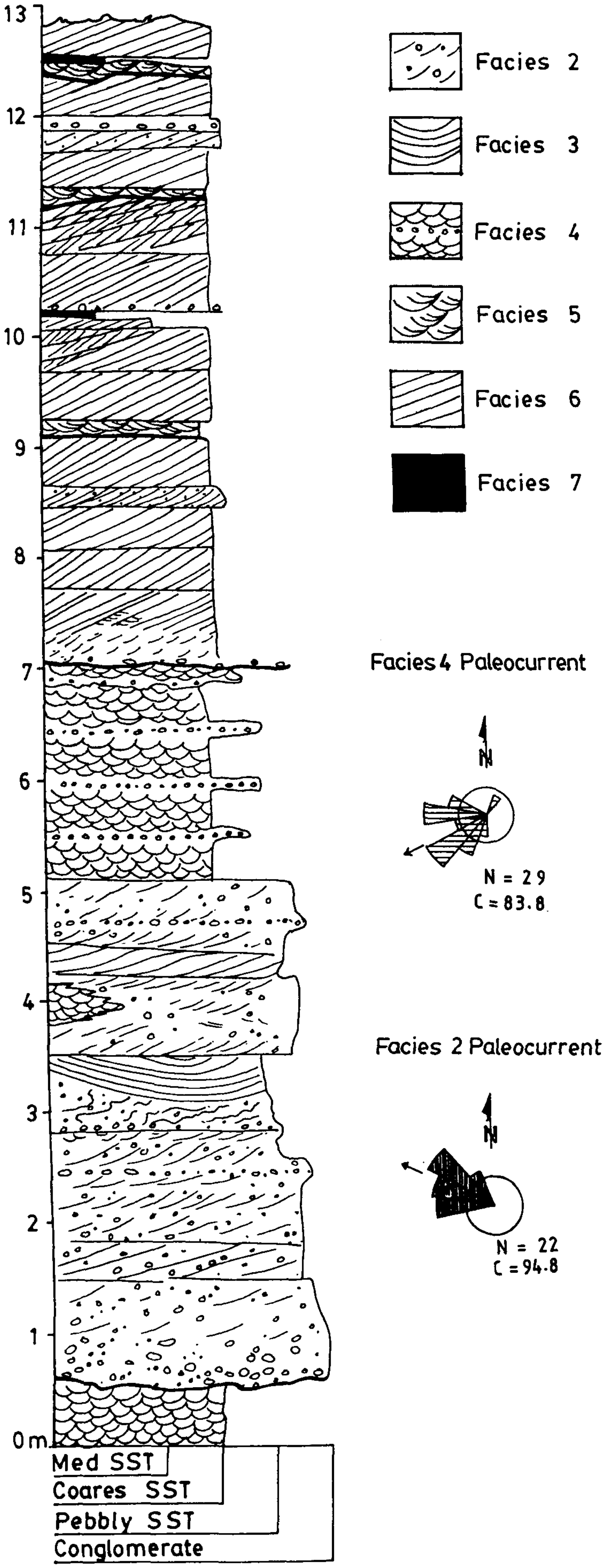

13
12
11
10
9
8
7
6
5
4
3
2
1
0m
Med SST
Coares SST
Pebbly SST
Conglomerate
Facies 2
Facies 3
Facies 4
Facies 5
Facies 6
Facies 7
Facies 4 Paleocurrent
N
N = 29
C = 83.8
Facies 2 Paleocurrent
N
N = 22
C = 94.8

Fig. 2

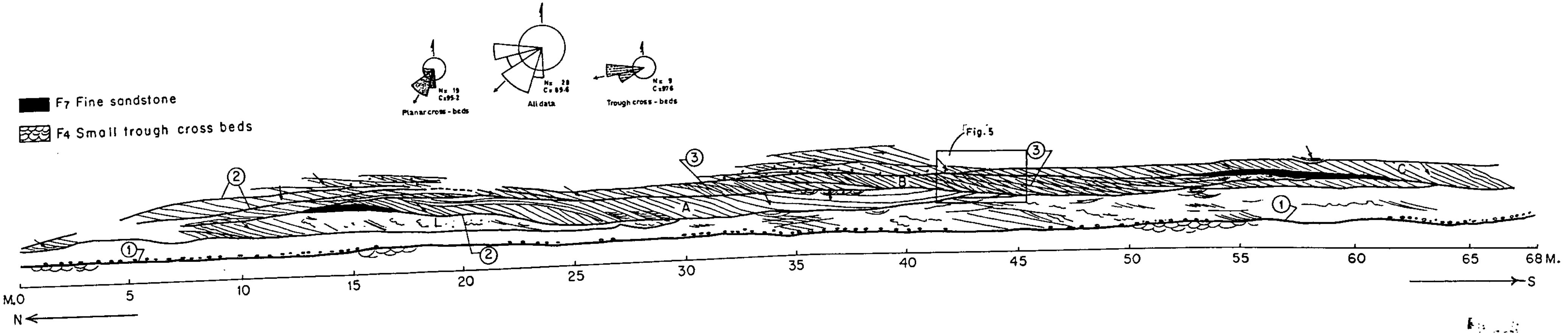
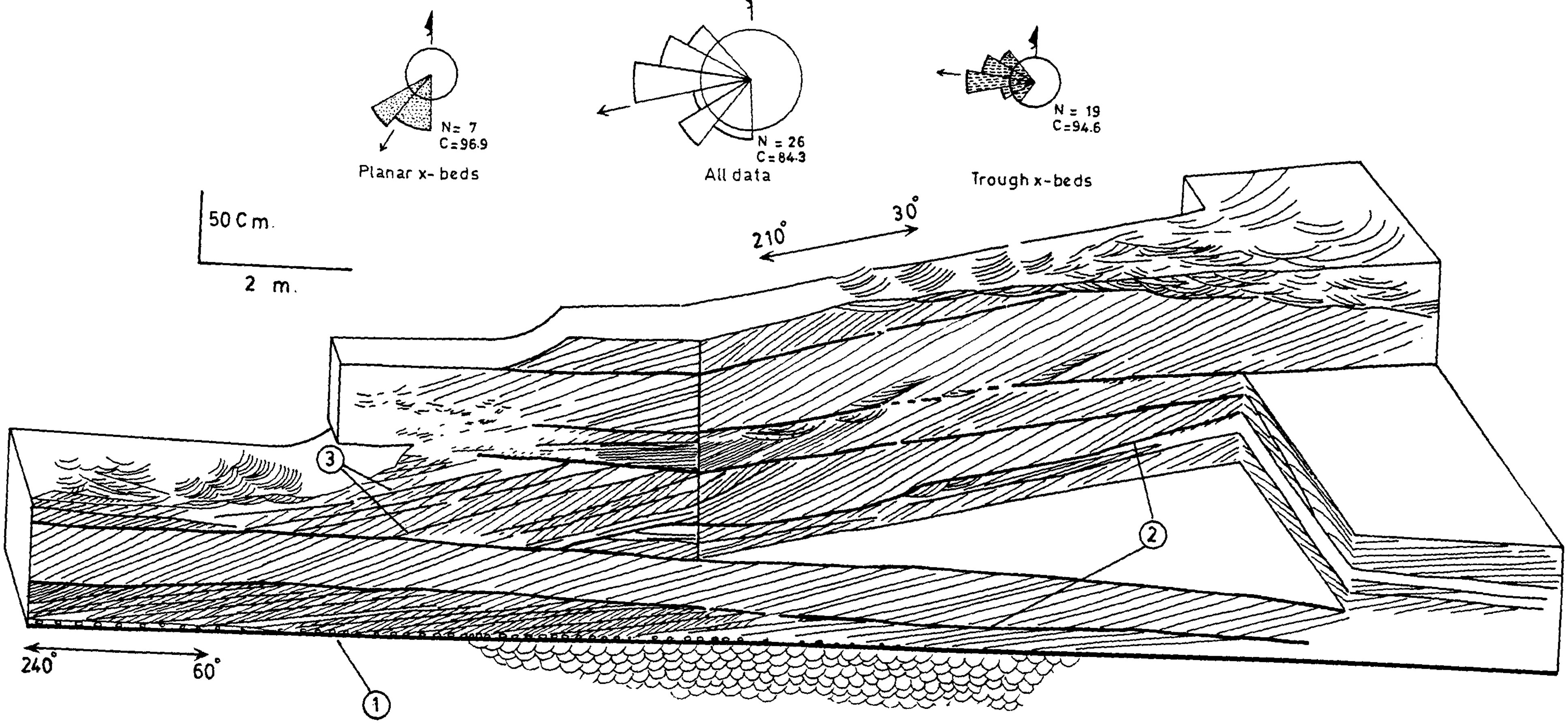

F7 Fine sandstone
F4 Small trough cross beds
N= 19
C=95·2
Planar cross - beds
N= 28
C= 89·6
All data
N= 9
C=97·6
Trough cross - beds
Fig. 5
①
②
③
A
B
C
M.0
5
10
15
20
25
30
35
40
45
50
55
60
65
68 M.
N
S

Fig 4


N= 7
C=96.9
Planar x- beds
N = 26
C = 84.3
All data
N = 19
C=94.6
Trough x-beds
50 Cm.
2 m.
210°
30°
③
②
240°
60°
①

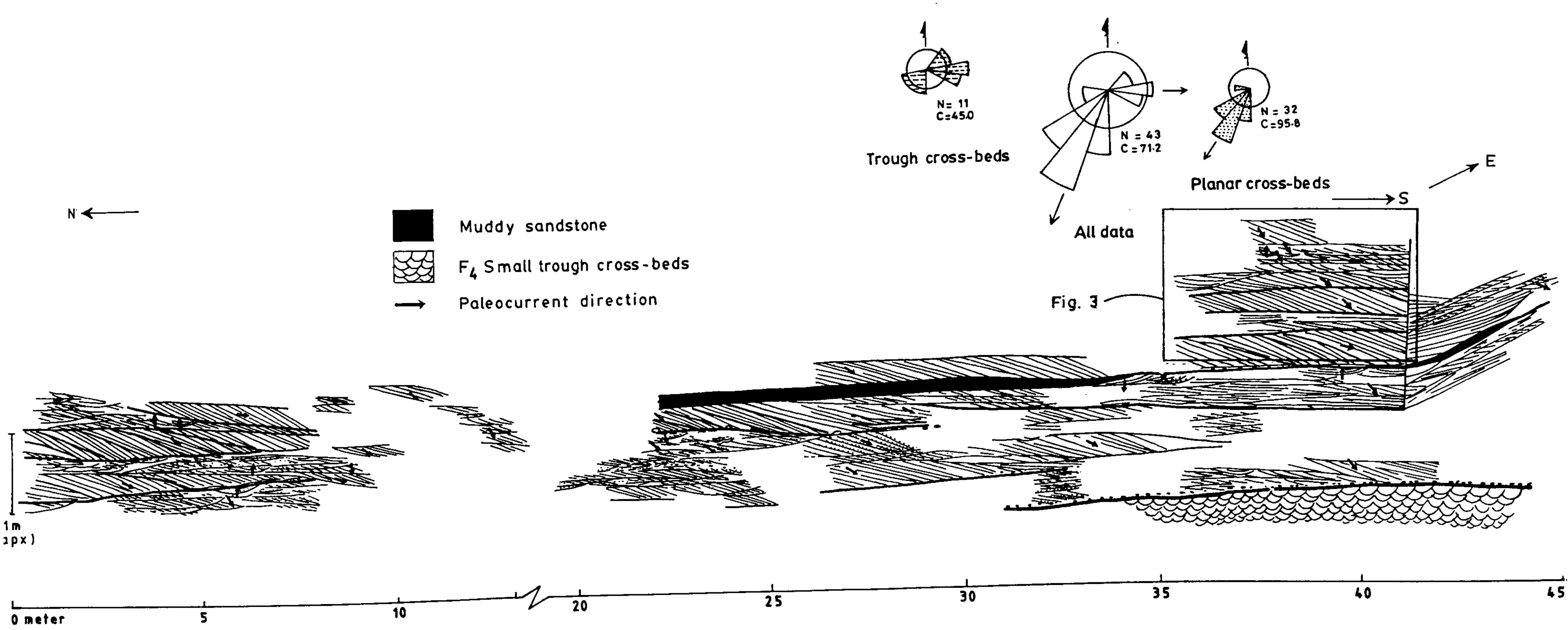
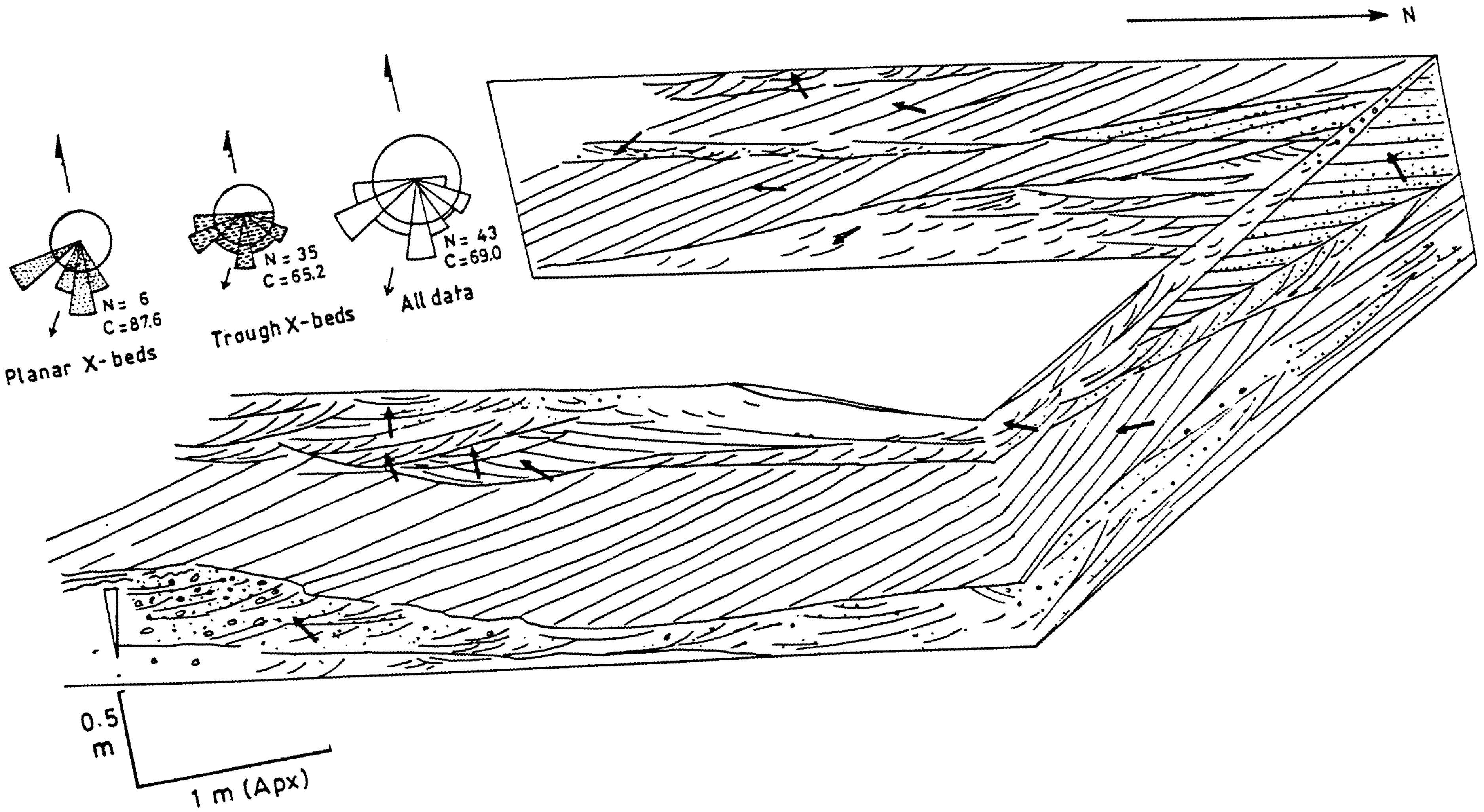
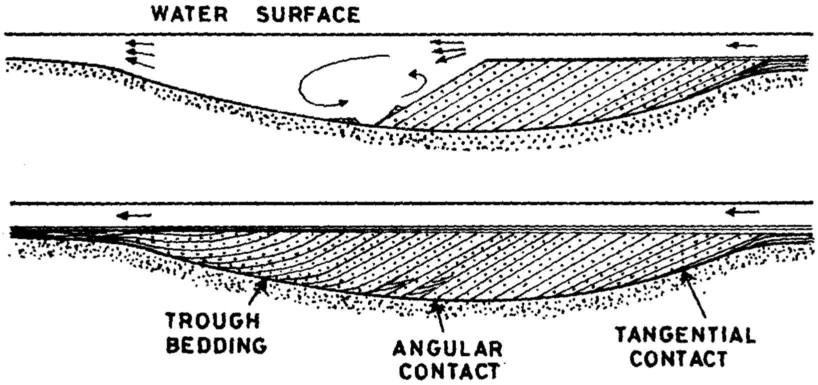

N
Muddy sandstone
F_4 Small trough cross-beds
Paleocurrent direction
N= 11
C=45.0
Trough cross-beds
N = 43
C = 71.2
All data
N = 32
C = 95.8
Planar cross-beds
S
E
Fig. 3
1m
px)
0 meter
5
10
20
25
30
35
40
45

Fig. J


N = 6
C = 87.6
Planar X-beds
N = 35
C = 65.2
Trough X-beds
N = 43
C = 69.0
All data
N
0.5 m
1 m (Apx)



After Jopling, 1965.

Fig. 9., [illegible], '98