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Combined tide and wave influence on sedimentation of Lower Gondwana coal measures of central India: Barakar Formation (Permian), Satpura basin

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Abstract: The coal-bearing Barakar succession of the Satpura basin is typical of the Gondwanan coal basins of peninsular India, in that it has previously been interpreted as continental in origin. The succession comprises three main facies associations, which are documented within this paper. Medium- to fine-grained muddy sandstone deposits of 5–75 m thickness are reinterpreted as tidally influenced delta deposits. Mudstone deposits of 3–20 m thickness with subordinate sandstones, coals and carbonaceous shales are reinterpreted as delta top deposits, and medium to coarse sandstones of 3–38 m thickness are interpreted as braided delta-top channels. The evidence for tidal influence arises from documentation of bidirectional cross-strata, tidal bundles, tidal rhythmites and periodic variation in foreset thickness. The recognition of tidal deposits indicates marine depositional conditions and significantly changes existing palaeogeographical models. This in turn has important implications for our understanding of the depositional setting and distribution of the Permian coals that occur across much of the southern supercontinent. Furthermore, to the best of the authors' knowledge, coal-bearing tidal-delta deposits have not previously been described from continental interior basins.

Keywords: Gondwana, coal, hummocky cross-stratification, deltaic sedimentation, intertidal sedimentation.

The Permian strata of the coal-bearing Barakar Formation of the Satpura Gondwana basin, India (Fig. 1) were deposited in an intracontinental basin and have previously been ascribed a non-marine origin based on the absence of marine fossils, and the similarities of some of the sediment bodies to fluvial deposits (Casshyap 1970, 1973, 1979; Casshyap & Qidwai 1971; Rai & Shukla 1977; Casshyap & Tewari 1991; Veevers & Tewari 1995; Peters & Singh 2001; Ray & Chakraborty 2002). Accordingly, it has been suggested by most previous studies that the Satpura basin was geographically restricted from oceanic waters and that tidal reworking had no effect on the deposition of the Barakar strata (see Ray & Chakraborty 2002).

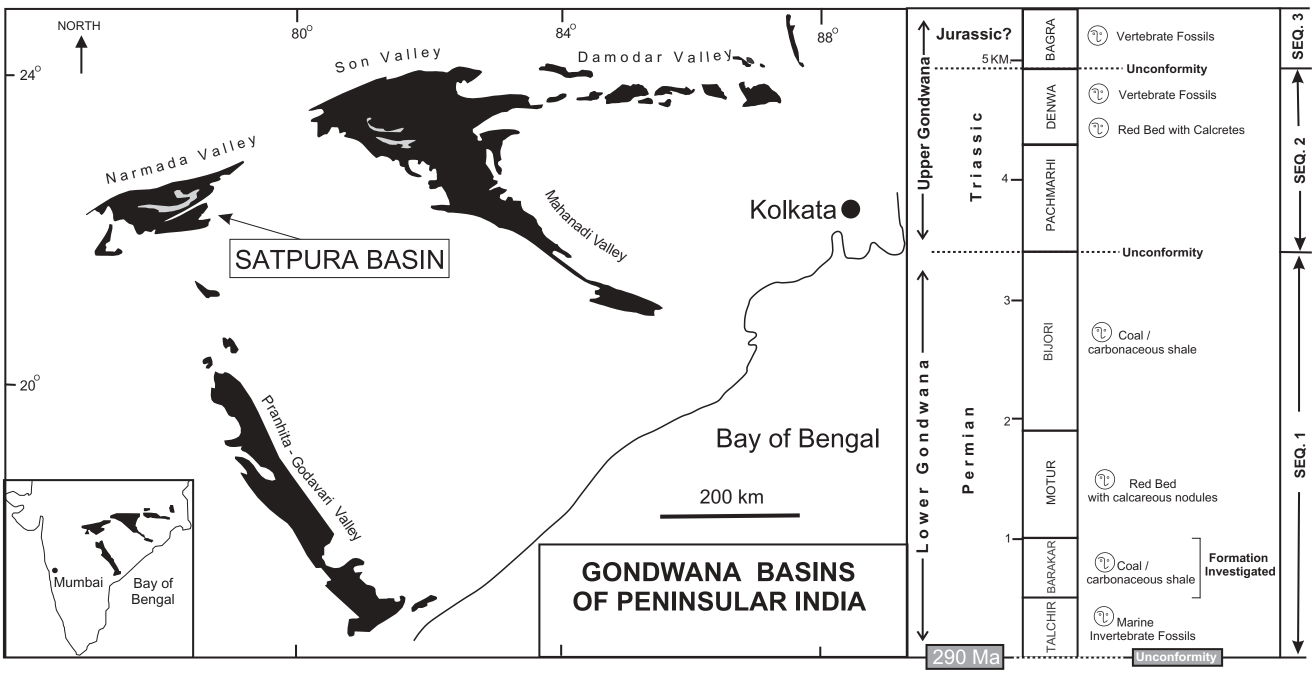


Fig. 1. Outcrops of the Gondwana basins in the peninsular India. (Note their occurrence along three distinct belts following the present-day valleys of Narmada–Son–Damodar, Pranhita–Godavari and Mahanadi rivers.) Stratigraphy of the Satpura basin fill is also shown along with key features of individual stratigraphic units. The present study is confined to the Barakar Formation of the Satpura basin. Inset shows the Indian peninsula.

Although marine fossils have not been recognized, possible marine influence during Barakar sedimentation has been proposed by several workers based on the presence of wave-generated structures in the sandstones, trace fossils and high boron contents of the coal (see Veevers & Tewari 1995; Biswas 1999; Gupta 1999, 2000). However, wave-influenced deposits may also form in exclusively continental domains (e.g. lakes and fluvial flood basins), and their formation in a marine realm can only be ascertained if they are associated with tide-influenced deposits (e.g. Brettle *et al*. 2002). Recognition of tidal signatures in strata affected also by fluvial processes is not as straightforward as in open marine strata (Shanley *et al*. 1992; Brettle *et al*. 2002). This paper describes combined tide- and wave-influenced facies from the Barakar Formation of the Satpura Gondwana basin indicating marine influence during sedimentation in a continental interior deltaic setting and suggesting that the basin was connected to oceanic waters during Barakar sedimentation.

In recent years, tide- and wave-influenced deposits that demonstrate marine influence in intracontinental settings have been recognized in association with several coal-bearing successions (Kvale & Archer 1990; Shanley *et al*. 1992; Archer *et al*. 1994, 1995; Greb & Archer 1995; Kvale & Mastalerz 1998; Michaelsen & Henderson 2000; Brettle *et al*. 2002). Tidal influence in ancient continental deposits has been recognized mostly from estuarine successions deposited in incised valleys overlying sequence boundaries (see Boyd *et al*. 1994; Kvale *et al*. 1997; Shanmugam *et al*. 2000; Brettle *et al*. 2002). Discriminating between deposits of tidally influenced deltas and tide-dominated coastal mud flats in the rock record is often difficult. Kvale & Mastalerz (1998) have interpreted the tidal deposits associated with the Pennsylvanian sequences of the USA as products of a prograding, coastal tidal flat and associated tidal channels seaward of a coal-forming mire. Unambiguous tidal deposits associated with tidally influenced deltas are rarely documented from intracontinental basins (Kvale *et al*. 1997; see Willis & Gabel 2003 for an example).

Identification of tidal signatures within a continental succession has manifold significance: (1) tidal deposits are unambiguous evidence of marine influence; (2) their recognition allows reconstruction of the broader palaeogeography of the basin, revealing the transition between alluvial and marine domains (Dalrymple *et al*. 1992; Shanley *et al*. 1992; Kvale & Barnhill 1994; Brettle *et al*. 2001), as well as estimation of the inland extent of the tidal influence in ancient settings; (3) it facilitates chronostratigraphic correlation between marine and alluvial strata, leading to an improved sequence stratigraphic interpretation of the continental succession (Shanley *et al*. 1992).

During the Permian, India was a part of the Gondwanan supercontinent. The term Gondwana stems from a number of Upper Palaeozoic and Mesozoic formations within the Satpura basin which display shared geological features with the age-equivalent strata in South America, Africa, Antarctica and Australia (‘Gondwana beds’, Medlicott 1873; Suess 1885). There have been many attempts to construct palaeogeographical and palaeoclimatic maps of the Gondwana supercontinent at different geological periods showing land–sea distribution, topography and climatic belts (e.g. The Paleogeographic Atlas Project, University of Chicago; Paleomap Project, University of Texas). Thus, besides documentation of an ancient tide-influenced deltaic succession, this study has broader implications for the Gondwanaland palaeogeography and connectivity of the central Indian craton with the Tethyan oceanic water masses.

Geological background

The Indian Gondwana

The Gondwana strata of peninsular India record resumption of sedimentation during the Permo-Carboniferous period after a long depositional hiatus that began in the Proterozoic. In peninsular India Gondwana successions are preserved in a number of discrete, intracratonic basins that record a depositional history up to the Cretaceous (Veevers & Tewari 1995; Fig. 1). Deposition in most of the basins, however, had ceased by the Triassic. These successions share the faunal and floral characteristics of the Gondwana strata of South America, South Africa, Australia and Antarctica, and also resemble one another lithologically. The successions start with basal diamictite and glacial outwash deposits, passing up to coal-bearing siliciclastic deposits with *Glossopteris* flora overlain by Triassic red beds with calcretes (Hobday 1987).

The Gondwana basins of peninsular India are intracratonic in nature surrounded by Precambrian terranes (Fig. 1). The basins crop out along the present-day ENE–WSW-trending Namada–Son–Damodar valley, the NNW–SSE-trending Pranhita–Godavari valley and the NW–SE-trending Mahanadi valley (Fig. 1). There is a general consensus that these basins originated under a bulk extensional regime, as a result of failure of the attenuated crust along pre-existing zones of weakness imparted by Precambrian structural grains (Chatterjee & Ghosh 1970; Naqvi *et al*. 1974; Mitra 1994; Biswas 1999; Acharyya 2000).

The glacio-marine Talchir Formation and the overlying coal-bearing Barakar Formation represent the lower part of the Indian Gondwana succession and show more or less uniform lithological associations in all of the basins. The Barakar Formation is the primary resource of coal in India (Veevers & Tewari 1995). With the exception of the Talchir Formation, the Indian Gondwana succession has been previously interpreted as representing deposits of alluvial settings with a few lacustrine intervals (Fox 1931; Robinson 1967; Raja Rao 1982, 1983, 1987; Casshyap & Tewari 1991; Veevers & Tewari 1995).

Tectonostratigraphic setting of the Satpura basin

The Satpura basin is the westernmost Indian Gondwana basin. Cropping out along the ENE–WSW-trending Narmada valley (Fig. 1), it contains the depositional record of longest stratigraphic range between the Permian and Cretaceous. The basin is rhomb-shaped and elongate in an ENE–WSW direction (200 km long, 60 km wide). The Satpura basin is now considered to have a ‘pull-apart’ origin and is filled with *c*. 5 km thick siliciclastic sediments (Fig. 1; Biswas 2003). Three major unconformity-bounded units can be recognized in the succession (Fig. 1). The distinguishing feature of the lowermost sequence is the presence of coal or carbonaceous shale within alluvial and lacustrine strata (Peters & Singh 2001). The upper two units represent ‘red beds’ deposited entirely in an alluvial setting (Casshyap & Khan 2000; Maulik *et al*. 2000). These are rich in calcretes and vertebrate fossils (Bandyopadhyay 1999). The lowermost unit includes the glacio-marine Talchir Formation at its base (Casshyap & Qidwai 1974), which is overlain by the coal-bearing Barakar Formation, the subject of the present paper (Fig. 1).

Study area and methods

The Barakar Formation is dominantly exposed along the southern margin of the Satpura basin with a single outcrop at the eastern part of the northern margin (Fig. 2). There are seven discrete outcrop belts of

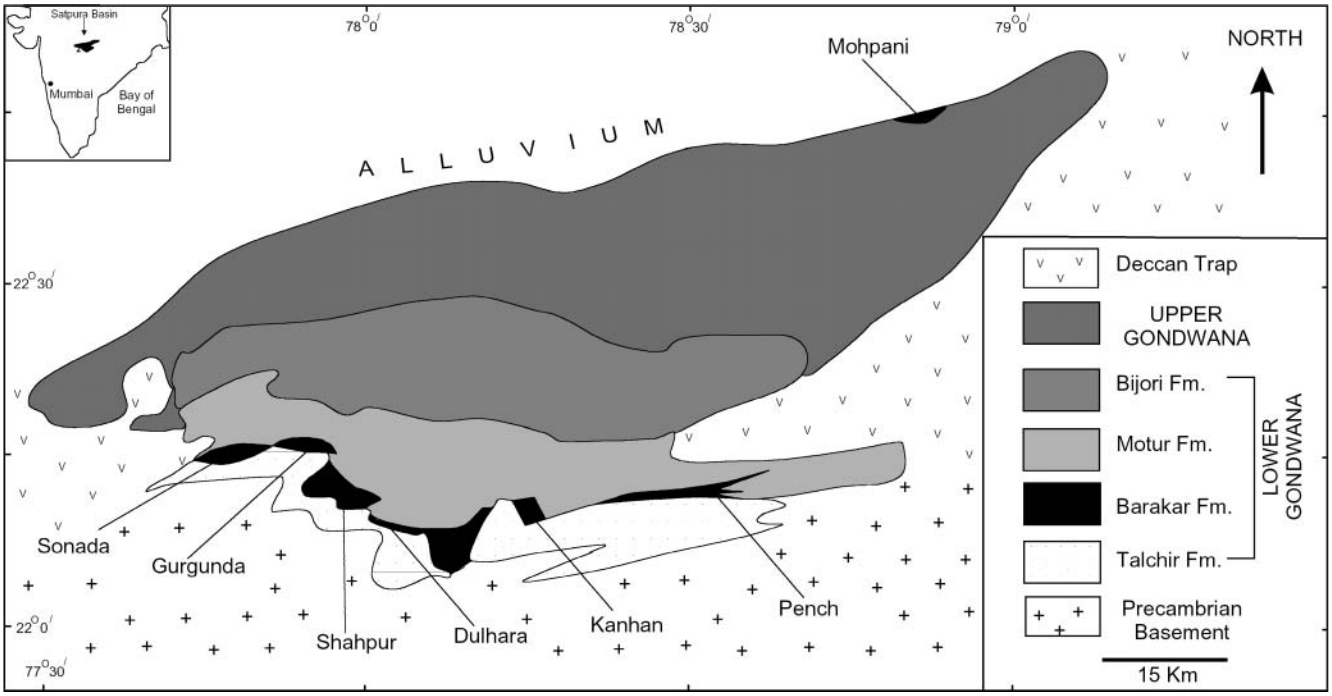


Fig. 2. Geological map of the Satpura basin. The names of the studied coalfields of the Barakar Formation are also shown. The seven discrete outcrops of the Barakar Formation are bounded by faults. Inset shows the Indian peninsula.

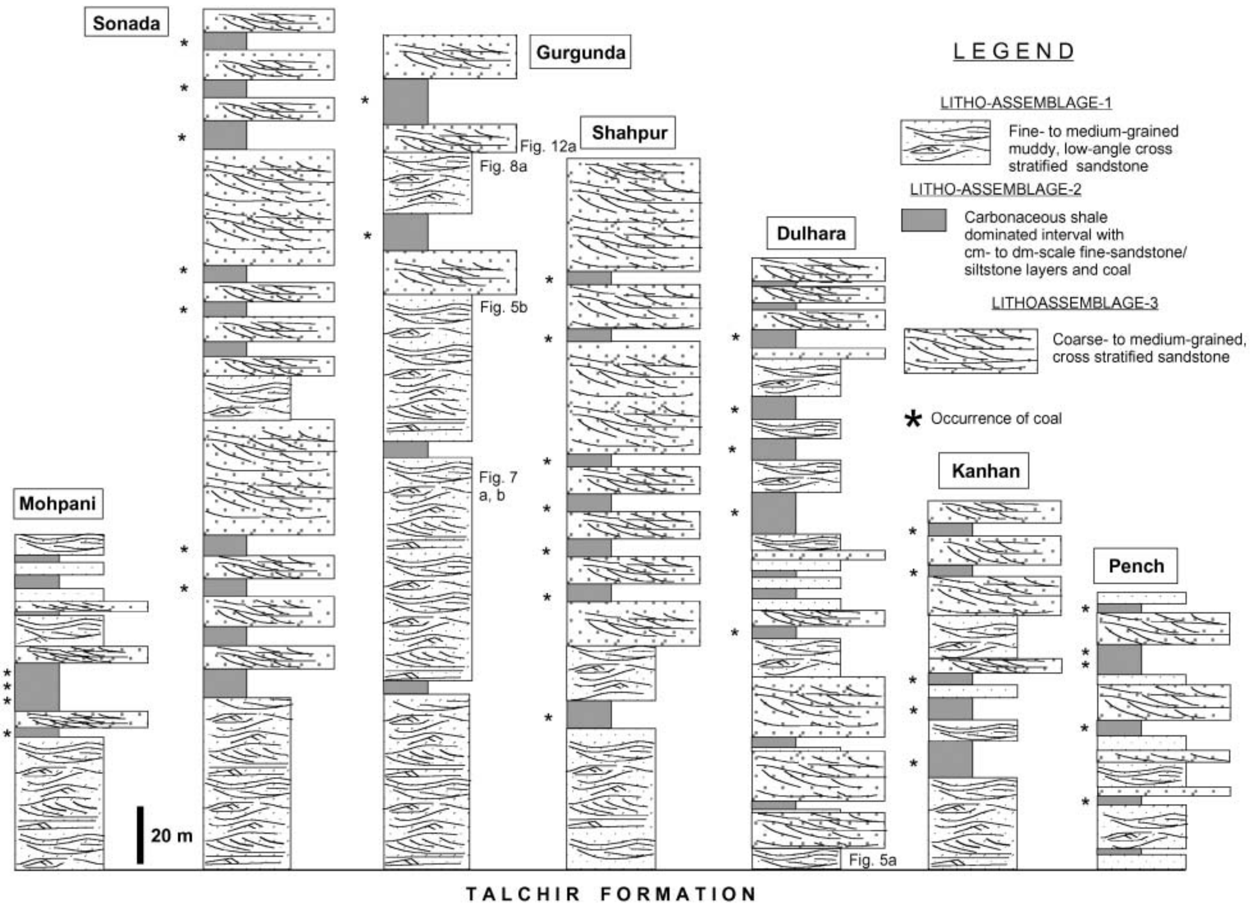


Fig. 3. Lithological logs of the Barakar Formation occurring in the seven coalfields of the Satpura basin. It should be noted that three principal lithological assemblages constitute the Barakar Formation in all the coalfields. The location of the coalfields is shown in Figure 2. Asterisks mark occurrence of coal. Location of facies photographs in successive figures is shown.

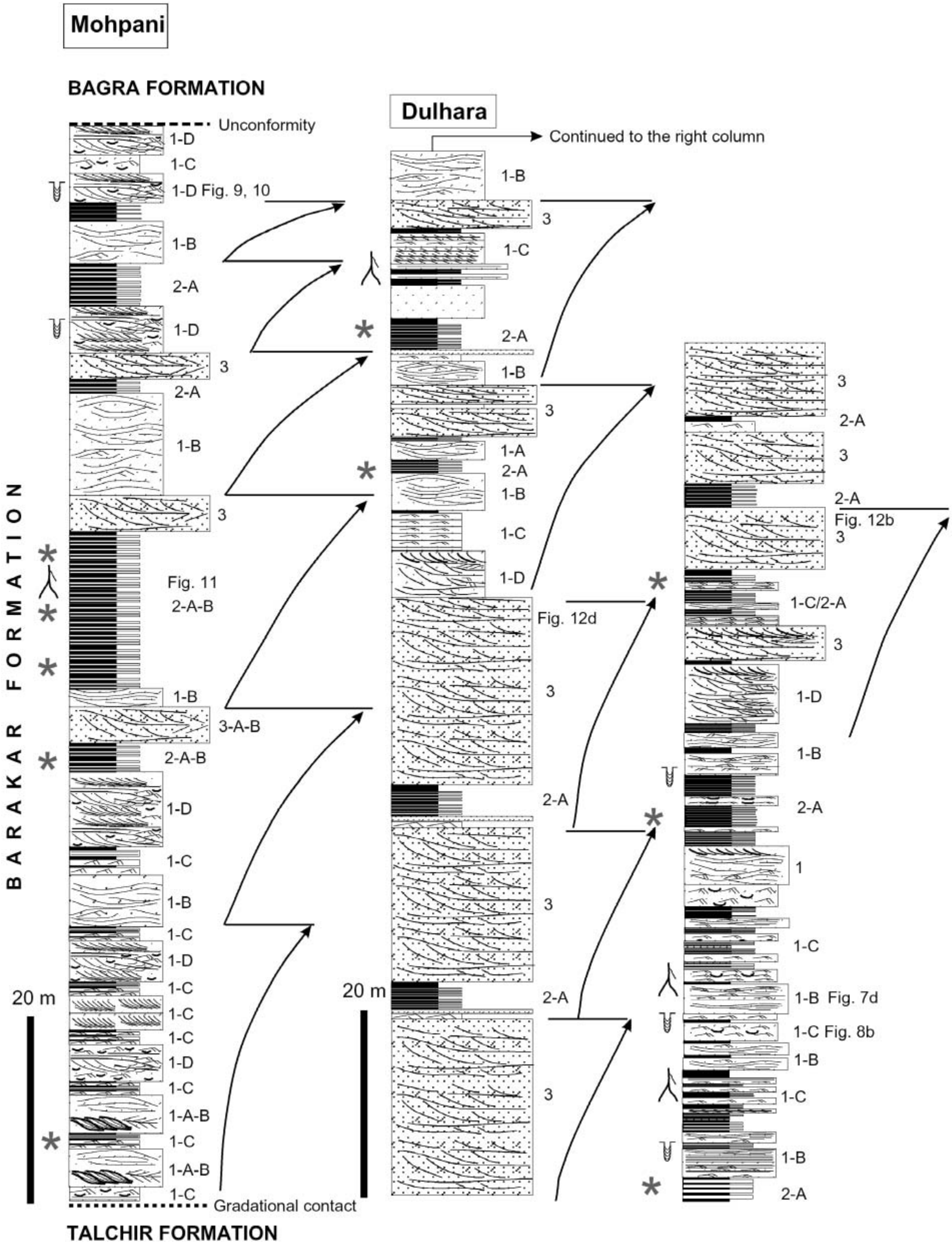
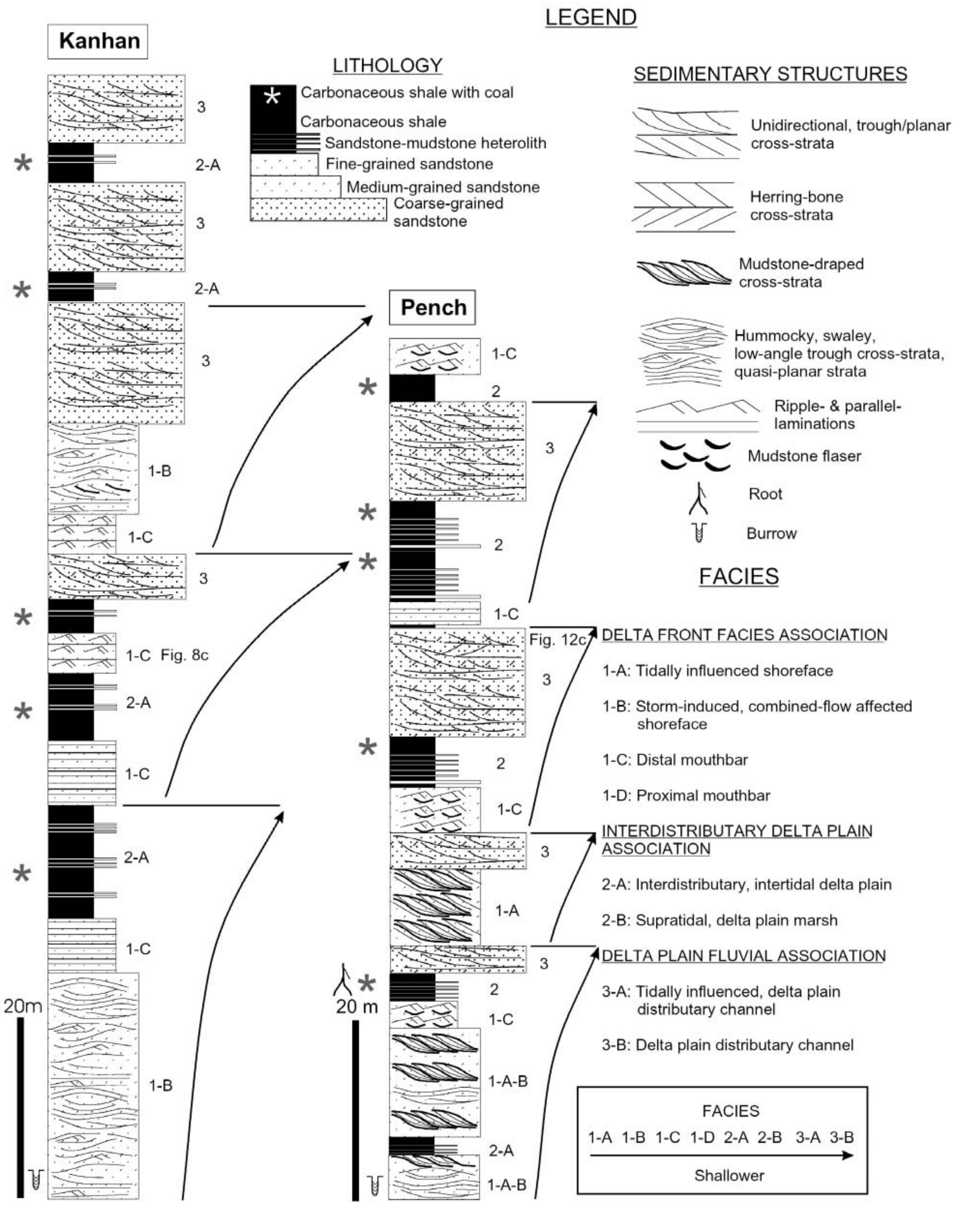


Fig. 4. Sedimentological logs of the Barakar Formation in four coalfields of the Satpura basin. It should be noted that eight different facies constitute the Barakar strata in all of the coalfields and their successions define a number of progradational cycles (marked by arrowhead lines). Asterisks mark occurrence of coal. Location of the coalfields is shown in Figure 2.

Barakar strata, which are bounded by faults and designated by the names of the coalfields situated within them: Mohpani, Sonada, Gurgunda, Shahpur, Dulhara, Kanhan and Pench (Fig. 2). The regional, structural strike of the basin fill strata is NW–SE and the regional dip (*c.* 5°) is northerly with a general thickening of the basin fill in the same direction. The structural dip was caused by rollover of hanging-wall strata during synsedimentary, tectonic faulting (Biswas 2003). The present study is based on river sections in the seven above-mentioned coalfields that continuously expose 95–300 m of Barakar strata (Fig. 3). The rock successions were examined for preparation of sedimentological logs, characterization of facies and their stacking pattern, as well as facies-specific palaeocurrent measurements. Stratigraphic correlation between



individual logs is not possible as the outcrops are bounded by faults and a suitable marker horizon or palynological data are lacking.

Sedimentology of the Barakar succession

Borehole data and outcrop studies reveal that the Barakar succession of the Satpura basin is composed of three broad lithological assemblages (Fig. 3) that occur repetitively and are interdigitated: (1) 5–75 m thick medium- to fine-grained, muddy sandstone bodies; (2) 3–20 m thick mudstone-dominated packages with variable proportions of centimetre- to decimetre-scale, fine- to medium-grained sandstone, carbonaceous shale and coal; (3) 3–38 m thick coarse- to medium-grained sandstone bodies with scoured bases. The sandstone bodies have previously been interpreted as braided fluvial channel deposits with the coal-bearing, mudstone-dominated intervals representing inter-channel floodplain environments or peat-forming mires (e.g. Ray & Chakraborty 2002).

Based on lithology, primary physical sedimentary structures and their associations, eight facies have been identified in the Barakar succession. These have been grouped into three facies associations, which are described below (Fig. 4). The three facies associations broadly correspond to the three broad lithological assemblages mentioned above (Fig. 3).

Facies association 1: medium- to fine-grained, muddy sandstone. Facies 1-A. Description. This facies comprises 4–10 m thick sandstone bodies showing decimetre- to metre-scale bidirectional and unidirectional, bundled cross-stratification (Figs 4 and 5). Bundling is defined by periodic mudstone drapes on the surfaces of medium-grained sandstone foresets and toesets (Fig. 5b). In longitudinal profile, the foresets are concave-up in shape, and have thicknesses between a few millimetres and 1.5 cm in their thickest part. The mudstone drapes contain very finely comminuted plant debris. The thickness of the drapes dominantly ranges between 2 and 4 mm; however, draping laminae as thin as 0.3 mm, and in one instance as thick as 7 mm, have also been observed. Within a set, mudstone-draped foresets occur as bundles that alternate with bundles of foresets draped by 0.5–5 mm thick very fine sandstone laminae similar to those described by Allen (1981) from the Cretaceous Folkestone beds (see also Eriksson & Simpson 2000). The draping laminae continue downcurrent for several metres subhorizontally beyond the foreset and coalesce to form a horizontal set of pinstripe laminae underneath the cross-set (Fig. 5b). The pinstripe lamina-set comprises millimetre-scale alternation of sandstone and mudstone. Within a pinstripe lamina-set, there is repetitive alternation of mudstone-rich and sandstone-rich intervals (Fig. 5b). Rarely, mudstone drapes occur in pairs, up to 5 mm apart

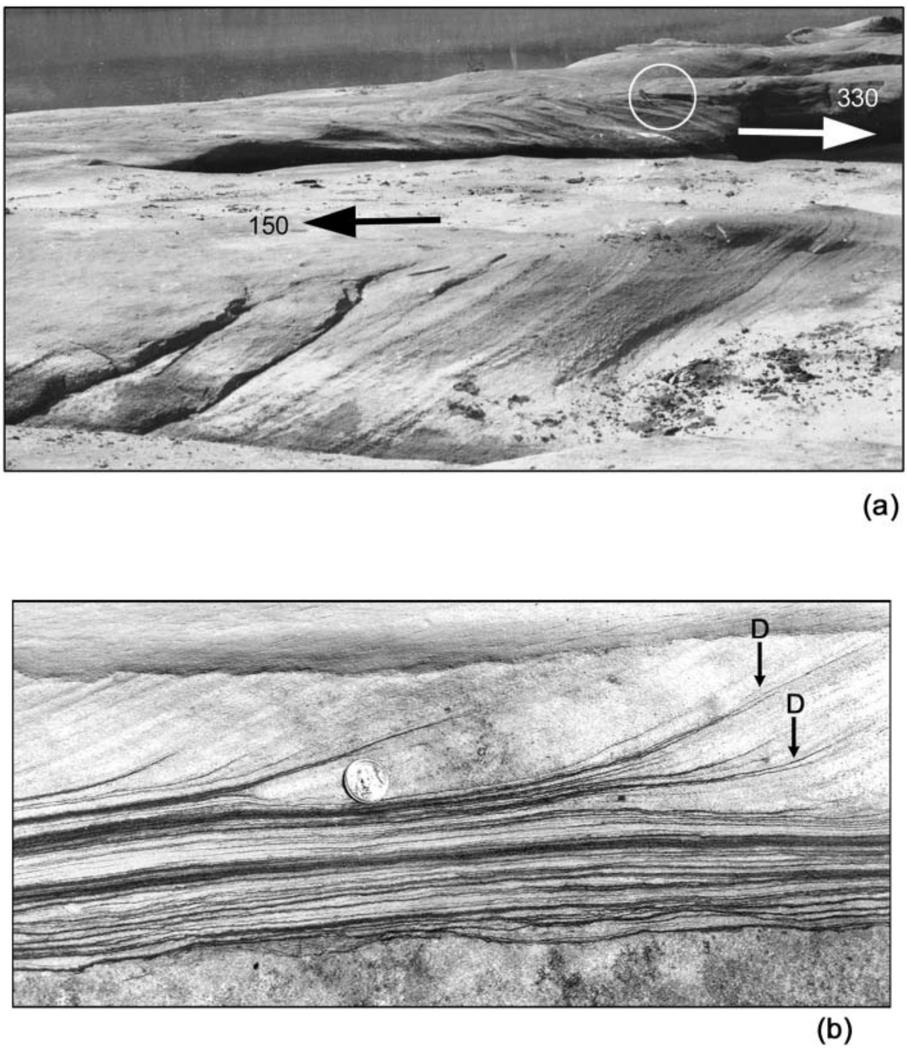


Fig. 5. Two sets of cross-stratification showing opposing palaeocurrent direction (**a**) and a cross-set with periodic mudstone drapes (**b**) in lithofacies 1-A. In (**b**), periodic mudstone drapes of variable length on the foreset and toeset surfaces that coalesce downdip forming cyclic mudstone-rich intervals in the toeset deposit should be noted. D, double mudstone drapes. Hammer and coin (diameter 2 cm) are for scale. Locations of the photographs are shown in Figures 3 and 4.

(Fig. 5b). Within the pinstripe lamina-set very small ripples occasionally occur encased between a pair of mudstone drapes. These ripples are oriented in the opposite direction to the cross-strata.

A thickness plot of 275 successive foresets (including the mudstone- and fine-sandstone drapes) of a cross-stratified set betrays thick–thin alternations and shows a sinusoidal variation defining seven prominent cycles that contain a total of 223 laminae with an average of 33.2 laminae per cycle (Fig. 6).

Interpretation. Cyclic occurrences of bundles of mudstone-draped foresets in alternation with bundles of fine sandstone-draped foresets suggest unidirectional but periodically fluctuating flows. This periodicity is also reflected in the repetitive alternation of mudstone-rich and sandstone-rich intervals in the pinstripe lamina-set. Mudstone and fine-sandstone drapes on the foresets again point towards smaller-order flow fluctuations resulting in alternate traction sedimentation of foresets (higher flow stage) and suspension fallout of drapes (lower flow stage). It is also evident that mudstone drapes formed during slack water stages at specific periods, whereas fine-sandstone drapes were formed in other periods. It is inferred that the strata-sets were developed under the influence of periodically fluctuating tidal currents (see Allen 1980, 1981; Visser 1980; Homewood & Allen 1981; Yang & Nio 1985; De Boer *et al*. 1989; Nio & Yang 1991; Eriksson & Simpson 2000). The presence of bidirectional cross-stratification is also indicative of deposition under the influence of tidal currents. A tidally influenced, subtidal shoreface environment is favoured over that of a tidal channel because the sandstone bodies do not show basal scouring.

Each individual foreset and the associated drapes may be considered to represent high water and slack water stages of one tidal fluctuation (flood or ebb). Bundles with mudstone-draped foresets formed during the neap tide period and so did the mudstone-dominated intervals of the associated pinstripe lamina-set. In contrast, the bundles with fine sandstone-draped foresets and the sandstone-dominated intervals of the pinstripe lamina-set formed during the spring tide period (see Allen, 1981). The conspicuous alternation of thick and thin foresets indicates that tide was semi-diurnal in nature (Fig. 6). The periodicity of 33.2 laminae per cycle (Fig. 6) represents *c*. 16.6 days, denoting the spring–neap–spring cycle (Archer 1995). The tidal currents associated with these bedforms were dominantly unidirectional, representing either ebb or flood. However, rarely there might have been deposition during subordinate phases, and that is why the estimated spring–neap–spring cycle (16.6 days) is slightly higher than the ideal periodicity of 14.75 days.

Facies 1-B. Description. Sheet-like, medium-grained, amalgamated sandstone bodies of 5–25 m thickness represent this facies (Fig. 4). Internally the beds show low-angle (<10°) cross-strata that in bedding plane exposures appear as shallow, metre-scale, intersecting sets of troughs showing multidirectional dip azimuths in single outcrops (Fig. 7a). The cross-strata at places are draped by convex-upwards parallel stratification (Fig. 7b). Symmetric and asymmetric metre-scale hummocky and swaley bedforms (wavelength 5–10 m, amplitude 0.3–0.5 m) are also common (Fig. 7c). In places these are internally made up of ripple lamination (quasi-planar lamination; see Arnott 1993). In addition, there are decimetre-scale, sheet-like beds with sole marks and displaying progressive vertical variation in structure from low-angle parallel lamination (parting lineated) to ripple lamination (Fig. 7d; see Myrow & Southard 1996; Myrow *et al*. 2002). Mudstone clasts and plant litter often mark the interfaces of the sandstone beds. In places the beds are bioturbated.

Interpretation. The cross-stratification style and dimensions indicate a combined-flow origin (Arnott & Southard 1990; Van de Meene *et al*. 1996; Myrow *et al*. 2002), and the presence of hummocky cross-stratification and quasi-planar lamination suggests deposition from storm-generated flows under transitional upper-stage plane bed conditions (Arnott 1993). Superimposition of unidirectional currents on the storm-generated oscillatory flow resulted in a combined-flow structure that could sustain low-relief bedforms internally showing unidirectional, low-angle cross-strata with variable azimuths instead of typical, symmetrical, hummocky cross-stratification. The beds showing progressive vertical transition from parallel to ripple lamination also reflect combination of storm waves and downwelling sediment-laden currents. These are interpreted as wave-modified turbidites (see Myrow *et al*. 2002). It is thus inferred that the sandstone bodies were formed in a wave- and current-influenced shoreface setting.

Facies 1-C. Description. This facies is represented by 3–8 m thick, tabular to convex-upwards sediment bodies consisting dominantly of fine- to medium-grained, muddy sandstone with subordinate mudstone-rich intervals (Fig. 4). Decimetre-scale bedding characterizes the facies. Individual beds persist laterally for more than 20 m before pinching out. The mudstone-rich intervals show single sandstone ripple trains or isolated ripples (wavelength 5–15 cm, amplitude 0.5–3 cm) encased within mudstone. Bioturbation and plant litter are common. Based on the internal structures of the sandstone-rich intervals, two subfacies are recognized.

Subfacies-I comprises parallel-laminated muddy sandstone showing millimetre-scale interlaminations of mudstone and fine sandstone (Fig. 8a). Mudstones contain very finely macerated, black organic debris. The thickness of the sandstone laminae ranges between 1 and 8 mm and that of the mudstone laminae between 0.5 and 3 mm. The sandstone laminae commonly occur

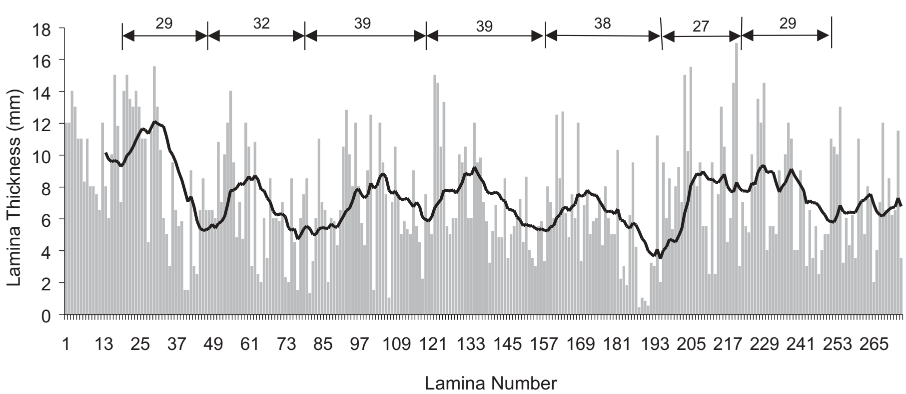


Fig. 6. A thickness plot of 275 successive lamina from the set of cross-stratified bundles shown in Figure 5b. The trend line (bold line), drawn with a moving average of 14, depicts seven cycles of average periodicity 33.2 laminae per cycle.

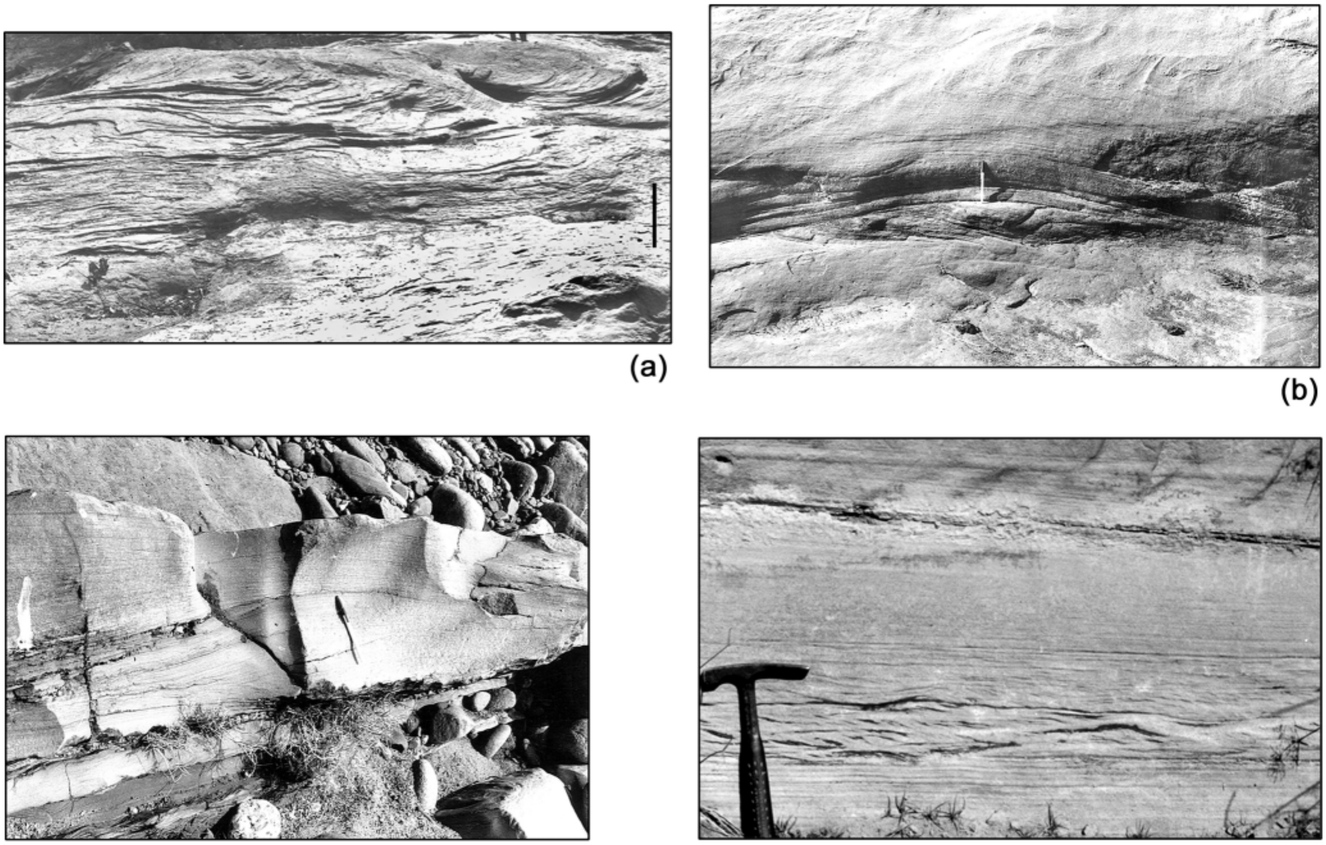


Fig. 7. Sedimentary characteristics of facies 1-B. (**a**) Intersecting, low-relief troughs. The multidirectional azimuths of the low-angle strata sets should be noted. (**b**) A low-angle, cross-stratified formset draped by convex-upwards, parallel stratification. (**c**) Scour-and-drape type hummocky cross-stratification. (**d**) Parallel lamination grading into climbing-ripple cross-lamination and vice versa, followed by amalgamated sets of parallel lamination with low-angle discordances. Pen is 15 cm long. Vertical line in (**a**) represents 1.5 m. Locations of photographs are shown in Figures 3 and 4.

in thick–thin pairs. Within a bed there is progressive vertical variation in the thickness of sandstone and mudstone laminae resulting in alternate sandstone-rich and mudstone-rich intervals (Fig. 8a). The sandstone-rich intervals are always thicker (up to 15 cm) than the mudstone-rich intervals (up to 3 cm).

Subfacies-II comprises fine-grained, muddy sandstone showing ripple bedding with discontinuous mudstone flasers and drapes (Fig. 8b). Ripples are asymmetric, their foresets are often oppositely oriented and show mudstone-draped reactivation surfaces (Fig. 8c). Some of the ripples display chevron, draping and offshooting laminae (see De Raaf *et al*. 1977). Subfacies-II rarely contains up to 15 cm thick sets of unidirectional cross-strata with periodic mudstone drapes, which are at places oppositely oriented.

Interpretation. Millimetre-scale interlamination of sandstone and mudstone in the parallel-laminated, tabular-bedded sediment bodies of subfacies-1 coupled with the absence of parting lineation indicate deposition from suspension in relatively calm water. The rhythmicity of lamination and the periodic lamina-thickness variation resulted from rhythmic fluctuation in the rate of suspension settlement. It is inferred that these deposits formed from suspended sediment plumes such as those observed in delta mouths (Wright & Coleman 1974; Wright 1977). The effluent plumes generated from fluvial discharges interact with the basinal agents (e.g. tide and wave) to develop different orders of rhythmicity in the lamination as observed in subfacies-I. A similar facies has been discussed at length by Brettle *et al*. (2002). Subfacies-I is interpreted as tidally influenced distal mouthbar deposits that are commonly observed in deltaic settings (see Wiseman *et al*. 1986; Nemec 1995; Brettle *et al*. 2002).

In contrast to subfacies-I, subfacies-II bears imprints of sedimentation under the influence of traction currents developing ripple cross-lamination. Temporal fluctuation in flow intensity is evidenced by mudstone flasers, mudstone drapes on the foresets and reactivation surfaces. The presence of oppositely oriented foresets suggests influence of tidal currents. Chevron, draping and offshooting laminae within some of the ripple-bedded sandstone beds signify effects of wave-induced oscillatory current. Subfacies-II is interpreted as representing deposition in the mouthbar front that was subject to tractive reworking by basinal agents during periods of low fluvial discharge (see Brettle *et al*. 2002).

Facies 1-D. Description. This facies is dominantly represented by 5–8 m thick fine- to medium-grained sandstone bodies with thin interbeds of sandstone–mudstone heterolithic beds (Fig. 4). The sandstone bodies show metre-scale, unidirectional, angle-of-repose, cross-strata with periodic, sigmoidal reactivation surfaces (Fig. 9). Within a set, the angle-of-repose foresets grade downcurrent into low-dipping (*c*. 10°) compound cross-strata ('downcurrent dipping cross-strata'; see Banks 1973) that become subhorizontal in the downcurrent direction, forming long toesets where sandstones are interlayered with mudstone-rich intervals showing starved, asymmetric sandstone ripples (Fig. 9). The compound cross-strata are internally made up of decimetre-scale cross-strata that are often oppositely oriented and draped by

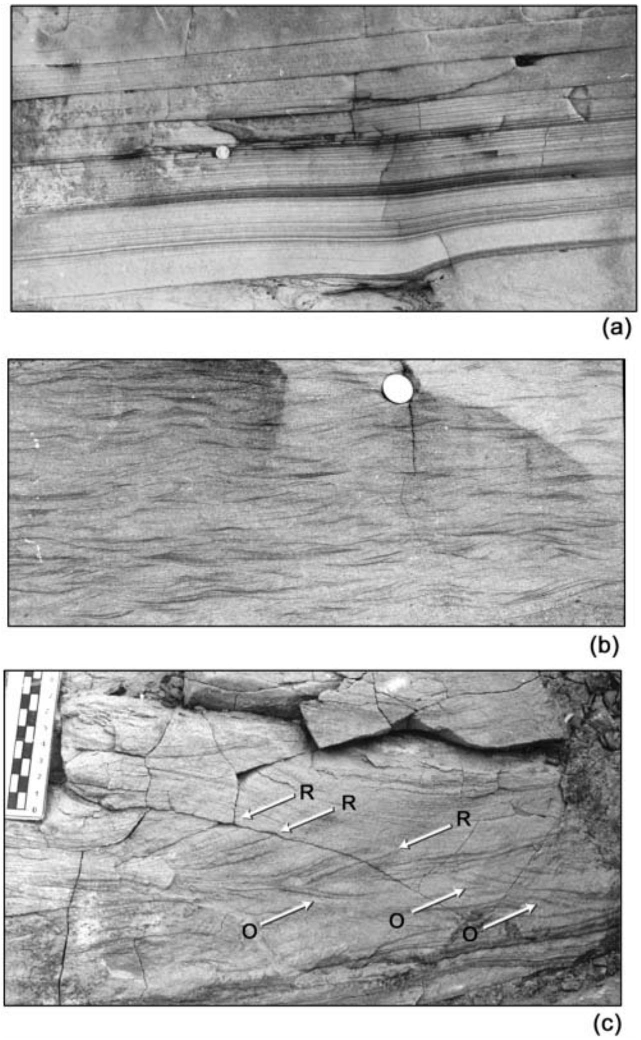


Fig. 8. Sedimentary characteristics of facies 1-C. (**a**) Parallel stratification showing millimetre-scale interlamination of fine sandstone (bright) and mudstone (dark) layers. The progressive vertical variation in the thickness of sandstone and mudstone laminae resulting in successive sandstone- and mudstone-rich intervals should be noted. (**b**) Ripple cross-lamination with mudstone drapes (dark) on the foresets and set-bounding surfaces. The reactivation surfaces (R) and oppositely oriented ripple foresets (O) in (**c**) should be noted. Coin diameter 2.5 cm. Locations of photographs are shown in Figures 3 and 4. Small divisions of scale bar represent 1 cm.

mudstones (Fig. 10). The bounding surfaces of the compound cross-strata are also locally draped by mudstones up to 5 cm thick. Burrows, mudstone clasts and symmetric, wave ripples are locally present. The interbedded sandstone–mudstone heteroliths show isolated asymmetric sandstone ripples encased within mudstone, and sediment-filled, synsedimentary cracks are present in them. This facies commonly alternates with facies 1-C and 3-B (Fig. 9).

Interpretation. Large-scale, unidirectional cross-strata suggest high-velocity traction currents and high sediment flux. Periodic reactivation surfaces and transition from simple to compound foresets reflect temporally fluctuating discharge. The stratification style is inferred to represent large-scale, solitary, compound bedforms (bars) driven by strong unidirectional currents. Presence of mudstones in the toesets is indicative of suspension settlement in the bar front and oppositely oriented cross-strata suggest tidal reworking. Rare occurrence of sediment-filled cracks suggests near-emergent conditions. The features are reflective of bars observed in the river mouths of deltas (Wright & Coleman 1977; Wright 1977). This facies is interpreted as deposits of proximal mouth bars (Mellere *et al*. 2002) fed by fluvial channels of variable discharge, which underwent reworking by tide and wave during periods of low fluvial discharge.

Facies association 2: carbonaceous shale with interbedded sandstones and coals. Facies 2-A. Description. This facies is dominantly represented by 5–20 m thick mudstone-dominated packages with minor sandstone and heterolithic interbeds (Figs 4 and 11). The heterolithic units show interlayering of sandstone and mudstone defining flaser, wavy and lenticular bedding, as well as pinstripe stratification. One stratification style usually grades into another vertically within a single bed (Fig. 11a). The sandstone interlayers range in thickness from a few millimetres to several centimetres. The thicker sandstone layers are dominantly rippled (wavelength 5–20 cm, amplitude 1–4 cm) whereas the thinner layers are generally flat. In thicker layers, ripple lamination occurs as cosets representing climbing ripple cross-lamination with discontinuous mud flasers (flaser bedding) or continuous mud partings (wavy bedding). These are replaced by mudstone-enclosed, laterally linked form sets (Fig. 11a and b), laterally disconnected form sets and flat layers (Fig. 11a) as the thickness of the sandstone layer decreases. In profile, the ripples are symmetrical and asymmetrical and the internal lamination styles suggest a combined-flow origin (Fig. 11). At places the successive sandstone layers within a heterolithic bed show opposite orientations of cross-lamina (Fig. 11b). Within individual heterolithic packages, the sandstone/mudstone ratio, along with the bedding type, varies cyclically upwards, giving rise to alternate sandstone-dominated and mudstone-dominated intervals (Fig. 11a). Desiccation cracks are abundant (Fig. 11c) and ladder-back ripples, plant litter and rootlets are common. Burrows are present.

Interpretation. Although not uncommon in other sedimentary environments, sandstone–mudstone alternations displaying flaser, wavy, lenticular and pinstripe beddings along with desiccation cracks and ladder-back ripples are the most common characteristic features of the tidal flat system, signifying periodic flow fluctuations (Reineck & Wunderlich 1968; Reineck 1972). Reversal of cross-lamina orientations within successive, clay-draped, sandy ripples demonstrably indicates periodically fluctuating, reversing flows. Cyclic occurrence of sandstone-dominated and mudstone-dominated intervals are considered to represent spring and neap tides, respectively (Williams 1989; Dalrymple *et al*. 1991; Tessier 1993; Greb & Archer 1995; Archer & Johnson 1997; Choi *et al*. 2001) Tidal currents presumably interfered with wave-induced oscillatory currents to result in combined-flow ripples with their characteristic internal lamination style (Harms *et al*. 1982). The presence of desiccation cracks and significant amount of mudstone suggests intermittent emergence and presence of appreciable muddy suspended load in an upper, mixed flat setting. A tidally influenced interdistributary delta plain environment is thus inferred for lithofaces 2-A, as it is associated with deltaic deposits described above.

Facies 2-B. Description. This facies comprises interlaminated to interbedded, dark grey to black carbonaceous claystone and coaly stringers that often grade vertically and laterally into economically exploitable coal seams (Fig. 4). In the measured sections (Fig. 4), the thickness of this facies ranges between 0.2 and 1 m. Subsurface drilling, however, revealed occurrence of

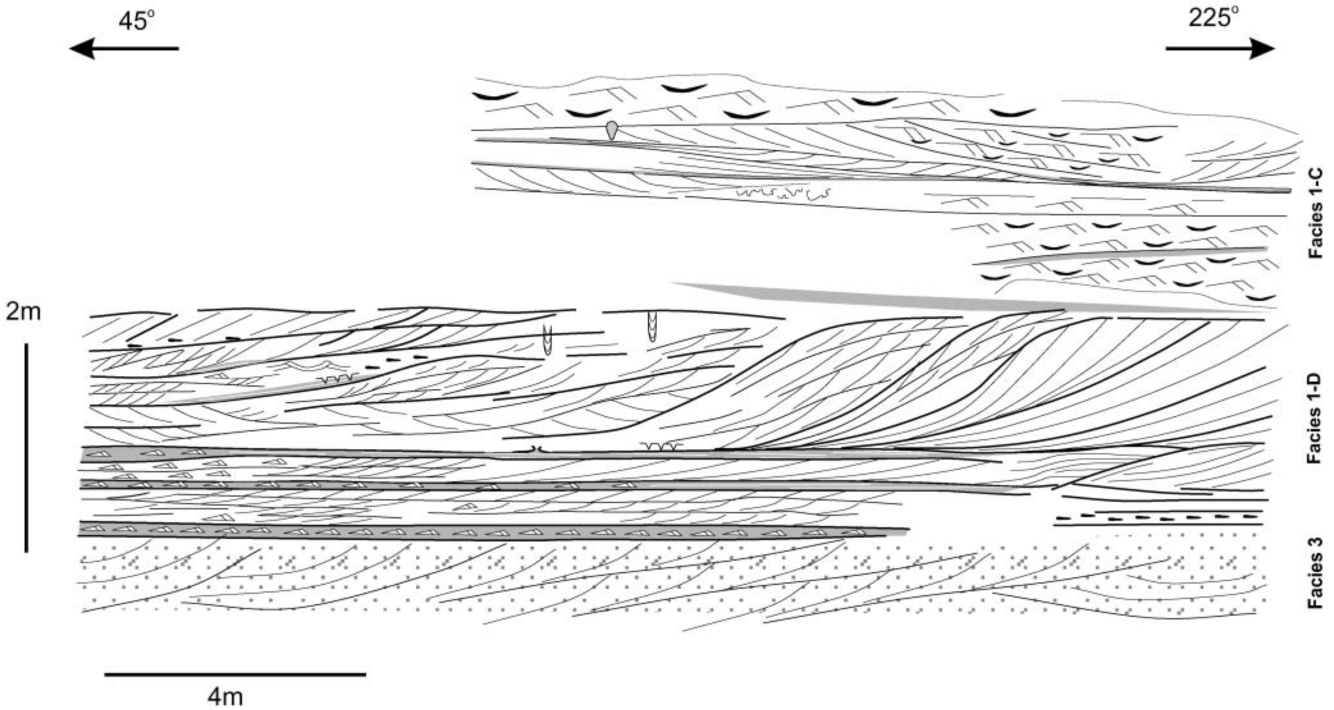


Fig. 9. Field sketch of a facies 1-D sediment body sandwiched between deposits of facies 1-C and 3. Noteworthy features are: (1) large-scale, unidirectional cross-strata with sigmoidal reactivation surfaces; (2) lateral transition of simple cross-strata to compound cross-strata; (3) occurrence of oppositely oriented cross-strata in the compound foresets; (4) mudstone drapes on some of the compound foresets; (5) alternation of subhorizontal beds of small-scale cross-stratified sandstone and mudstone-rich heterolith just above the facies 3 sandstone body, which represent the distal toesets of the compound cross-stratification. Location is shown in Figure 4.

Fig. 10. Internal details of the compound cross-stratification of facies 1-D. Reversals of cross-strata orientations within the compound foresets should be noted.

coal seams up to 10 m thick (Raja Rao 1983). The thickness of the coal seams varies laterally. The coal stringer/claystone ratio tends to increase towards the coal seams. Some claystones show very fine lamination. Finely macerated organic debris and leaf imprints on bedding planes are very common. The coal is generally dark and partly shining with a moderate specific gravity showing interlayering of vitrain–clarain and vitrain–durain bands with very little fusain. Approximate maceral composition is vitrain 40%, clarain 48%, durain 10% and fusain 2%. The rank of the coal ranges from medium-volatile bituminous (mvb) to high-volatile B-bituminous (hvBb) (Raja Rao 1983).

Interpretation. High organic carbon content of facies 2-B points towards accumulation of fine-grained, terrigenous sedi-

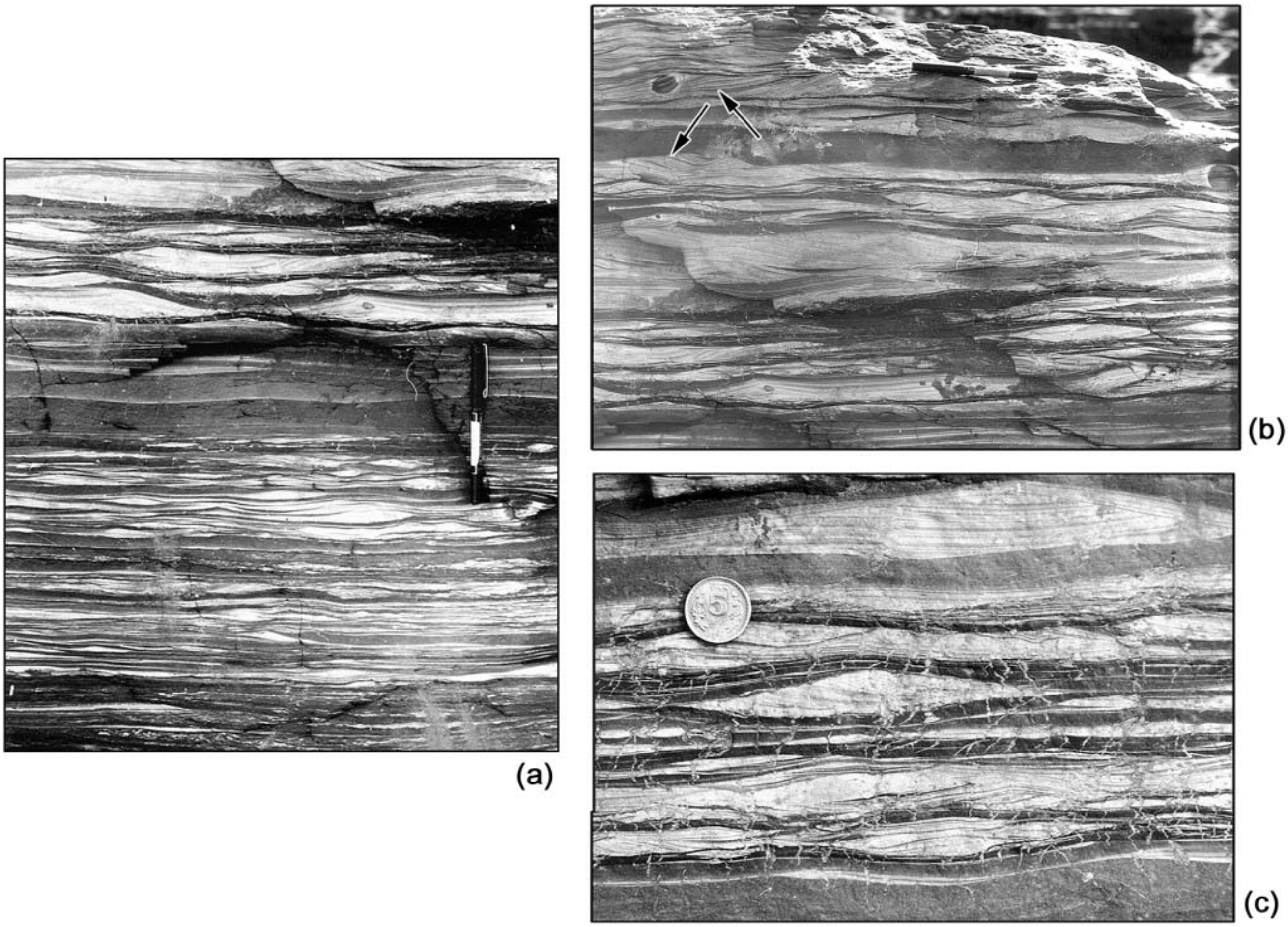


Fig. 11. Sedimentary characteristics of facies 2-A. Noteworthy features are the different varieties of sandstone (bright)– mudstone (dark) heterolithic bedding and their vertical transition in (**a**), the internal lamination styles of the ripple forms and oppositely oriented cross-laminae (marked by arrows) in (**b**) and profuse desiccation cracks confined to the mudstone layers in (**c**). Locations of the photographs are shown in Figure 4. Pen is 15 cm long; coin diameter is 2 cm.

ments along with plant debris in a marsh environment. Thick coals presumably developed in low-lying peat mires that used to remain starved of siliciclastic input for a considerable period and sustained accumulation of vegetal matter, but underwent episodic burial by siliciclastic deposits that led to transformation of the organic debris into coal. Occurrence of this facies in association with tidal-flat deposits (facies 2-A; Fig. 4) suggests a supratidal marsh environment in the interdistributary areas of the delta plain (Breyer & McCabe 1986).

Facies association 3: coarse-grained sandstone. Facies 3-A. Description. This facies is represented by 3–15 m thick coarse-grained sandstone bodies showing cosets of decimetre-scale planar and trough cross-strata. The sandstone bodies have scoured, concave-upwards lower bounding surfaces (Fig. 12a). Within cross-sets, convex-upwards reactivation surfaces are common and planar cross-strata are often oppositely oriented (Fig. 12b and c). This facies is interpreted together with facies 3-B described below.

Facies 3-B. Description. This facies is represented by 3–38 m thick, multistoreyed, sheet-like (width/thickness ratio >50), coarse-grained sandstone bodies with scoured, concave-upwards lower bounding surfaces marked by mudstone clasts (Fig. 4). The storeys are characterized by cosets of decimetre-scale planar and trough cross-strata. Basal parts of the storeys show large down-current-dipping compound cross-strata that are usually overlain by cosets of planar and trough cross-strata (Fig. 12d).

Interpretation of facies 3-A and 3-B. The coarse-grained nature of the facies 3-A and 3-B sandstone bodies, their concave-upwards, erosional lower boundaries and abundance of planar and trough cross-strata suggest deposition in fluvial channels (Collinson 1996). Compound cross-stratification is inferred to represent downcurrent-accreting fluvial bars (Haszeldine 1983) such as those observed in braided rivers (Miall 1988; Bristow & Best 1993). The sheet-like geometry of the sandstone bodies also suggests deposition in low-sinuosity, braided rivers (see Ray & Chakraborty 2002). However, the presence of herring-bone cross-stratification and periodic reactivation surfaces signifies that some of the channels were tidally influenced, implying their connection to the marine realm. Facies 3 is thus inferred as delta plain distributary channels, with facies 3-A representing upper parts of the delta plain lying beyond the reach of tide and facies 3-B representing the lower delta plain.

The Barakar depositional regime

The Barakar Formation of the Satpura basin and the other Gondwana basins of peninsular India is traditionally considered

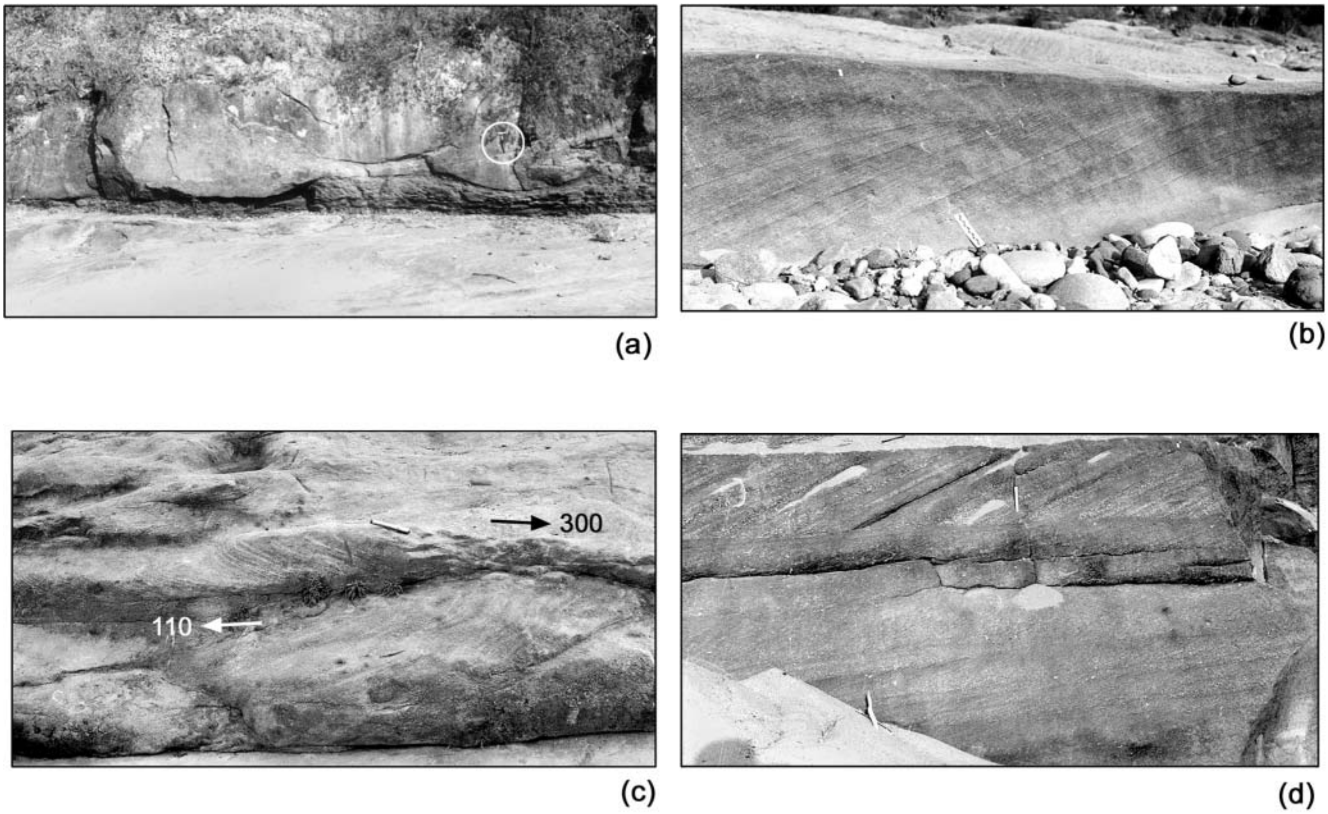


Fig. 12. Sedimentary characteristics of facies 3. (**a**) A sandstone body overlying facies 1-C. The scoured base of the sandstone body should be noted. Hammer for scale. (**b**) Periodic reactivation surfaces within a set of cross-strata; scale bar represents 10 cm. (**c**) Oppositely oriented planar cross-strata (110–300°); pen is 15 cm long. (**d**) A set of planar cross-strata overlying a set of downcurrent dipping, compound cross-strata. Locations of the photographs are shown in Figures 3 and 4.

to be alluvial in origin. There are indeed fluvial deposits within the Barakar succession of the Satpura basin represented by facies association 3. However, facies 1-A and 1-B reveal influence of tide and wave processes, implying an open marine condition, whereas facies 1-B and 1-C reflect tidal and wave reworking of fluvially discharged sediments in a shallow marine environment. It therefore follows that conditions were not exclusively alluvial. The Barakar facies successions in different coalfields of the Satpura basin show gross similarity and depict a number of progradational cycles (Figs 3 and 4). This suggests a wave- and tide-influenced, fluvio-deltaic environment for the deposition of the Barakar Formation instead of an estuarine setting (see Shanmugam *et al*. 2000). This tidal delta origin is also supported by the observation that the succession does not overlie any regional incision surface. The succession of facies associations in all the coalfields (except Mohpani, where the succession is truncated at the top by an unconformity; Fig. 3) shows a progressive dominance of the fluvial association (facies association 3) towards the top, indicating an overall progradation. The upper part of the underlying Talchir succession is represented by shallow-marine deposits and in the Satpura basin the Talchir–Barakar transition appears to be continuous (Ghosh 2003). Beds containing marine fossils have been identified within the Talchir Formation at several localities along the Son and Damodar valley as well as from the Satpura basin (Ghosh 2003), indicating an early Permian marine incursion in the form of a seaway following a relative sea-level rise (see Veevers & Tewari 1995). The Barakar fluvio-deltaic regime was established with the development of coal-forming delta-top swamp conditions, as the rate of sediment supply exceeded the rate of relative sea-level rise. The deltaic setting was characterized by braided delta plain distributary channels (facies association 3) with supratidal marsh and intertidal flat environments in the interdistributary areas (facies association 2). The delta front comprised the zone of mouthbar deposition and a wave-tide affected shoreface laterally (facies association 1). Prodeltaic deposits are not represented in the studied Barakar successions. The deltaic deposits were preserved as a result of synsedimentary, fault-controlled subsidence and the rate of subsidence probably varied from one coalfield to another, as reflected in the variable stacking pattern of the progradational packages in different coalfields (Figs 3 and 4).

Palaeocurrent data (measured from trough and planar cross-strata) of the delta plain fluvial association reveal NW to NNE river flow (Fig. 13), with minor southerly flow interpreted as the result of tidal influence. Wide dispersion of the data suggests diverging distributary channels. Migration directions of cross-strata in the delta front facies association reveal vector means oriented between NW and north. The currents are polymodal, reflecting interplay of a variety of processes in the delta front environment including tidal current reflected by the oppositely oriented data (Fig. 13). The trends of ripples in the interdistribu-

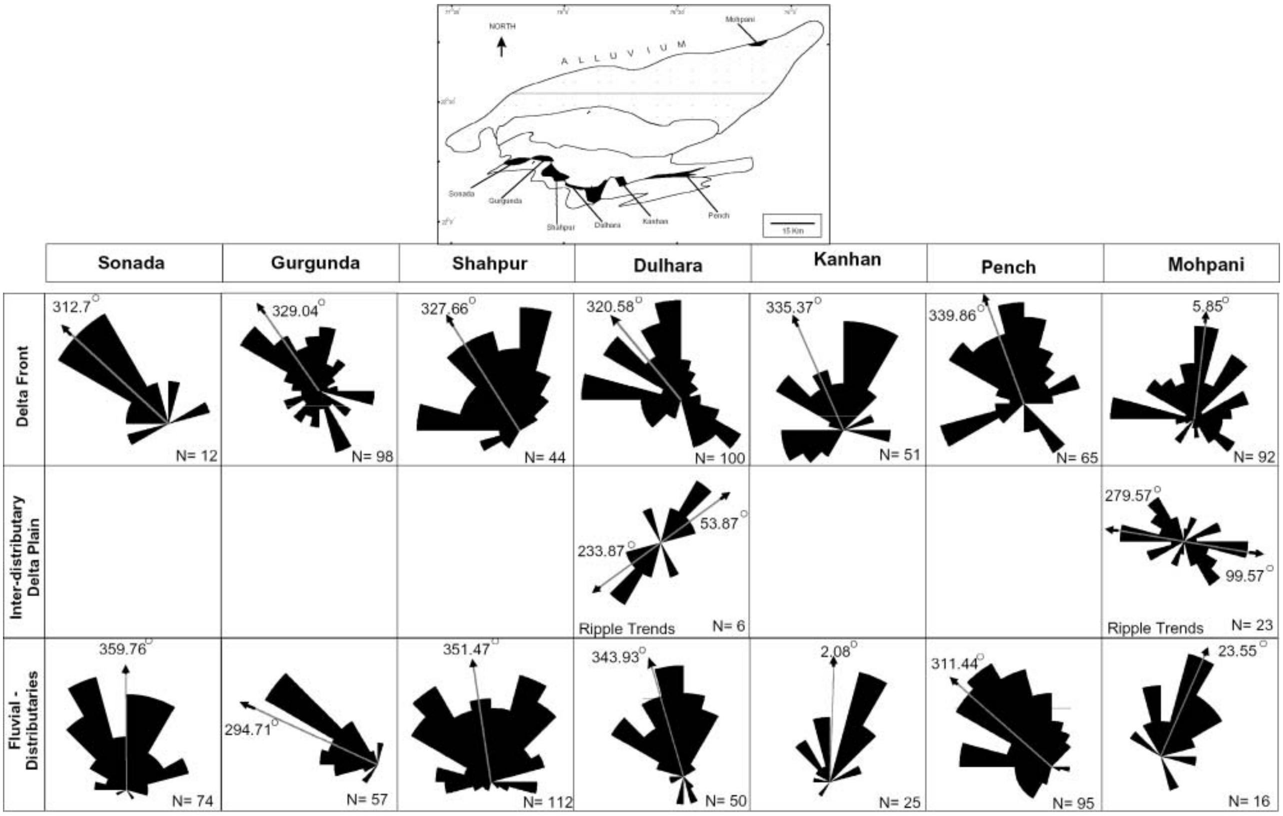


Fig. 13. Palaeoflow characteristics of the three facies associations in different coalfields of the Satpura basin. Facies association 3: delta plain distributary channels (azimuths of cross-strata). Facies association 1: delta front (azimuths of cross-strata). Facies association 2: interdistributary delta plain (trends of ripples). Locations of the coalfields are shown in the inset.

tary, tidal flat facies indicate an east–west to NE–SW shoreline orientation, nearly orthogonal to the mean of the net sediment transport directions (Fig. 13).

Conclusions

The Permian Barakar coal measures of the Satpura Gondwana basin, central India, has been interpreted by previous workers as representing a record of deposition in an exclusively alluvial setting. A prevalent notion also exists that the basin was geographically restricted from oceanic waters. This paper has identified significant proportions of tide- and wave-influenced strata within the Barakar Formation indicating a marine connection to the basin, as has been recently documented from several other coal-bearing successions of the world. A detailed facies analysis demonstrates that the strata were deposited in a tide- and wave-influenced fluvio-marine delta, which is rarely recognized in the rock record. The underlying Talchir Formation represents sedimentation in a glacio-marine setting within an intracontinental embayment (Ghosh 2003) and the present study suggests that following deglaciation the marine embayment continued to exist until the deposition of the Barakar Formation. This study suggests that the depositional dynamics of the Barakar Formation of the other Gondwana basins of peninsular India needs further re-evaluation.

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References

Acharyya, S.K. 2000. Tectonic setting and nature of the Gondwanic Indian crust. *In: Proceedings Volume, International Seminar, Precambrian Crust in Eastern and Central India*. Geological Survey of India, Special Publications, **57**, 1–8.

Allen, J.R.L. 1980. Sandwaves: a model of origin and internal structure. *Sedimentary Geology*, **26**, 281–328.

Allen, J.R.L. 1981. Lower Cretaceous tides revealed by cross-bedding with mud drapes. *Nature*, **289**, 579–581.

Archer, A.W. 1995. Reliability of lunar orbital periods extracted from ancient cyclic tidal rhythmites. *Earth and Planetary Science Letters*, **141**, 1–10.

Archer, A.W. & Johnson, T.W. 1997. Modeling of cyclic tidal rhythmites (Carboniferous of Indiana and Kansas, Precambrian of Utah, U.S.A.) as a basis for reconstruction of intertidal positioning and palaeotidal regimes. *Sedimentology*, **44**, 991–1010.

Archer, A.W., Feldman, H.R., Kvale, E.P. & Lanier, W.P. 1994. Comparison of drier-to-wetter-interval estuarine roof facies in the Eastern and Western Interior coal basin, USA. *Palaeogeography, Palaeoclimatology, Palaeoecology*, **106**, 171–185.

Archer, A.W., Kuecher, G.J. & Kvale, E.P. 1995. The role of tidal-velocity asymmetries in the deposition of silty tidal rhythmites (Carboniferous, Eastern Interior Coal Basin, U.S.A.). *Journal of Sedimentary Research*, **A65**, 408–416.

Arnott, R.W.C. 1993. Quasi-planar-laminated beds in the Lower Cretaceous Bootlegger Member, north–central Montana: evidence of combined-flow sedimentation. *Journal of Sedimentary Petrology*, **63**, 488–494.

Arnott, R.W.C. & Southard, J.B. 1990. Exploratory flow-duct experiments on combined-flow bed configurations, and some implications for interpreting storm-event stratification. *Journal of Sedimentary Petrology*, **60**, 211–219.

Bandyopadhyay, S. 1999. Gondwana vertebrate faunas of India. *In:* Sahni, A. & Loyal, R.S. (eds) *Gondwana Assembly: New Issues and Perspectives*.

Proceedings Indian National Science Academy, Special Issues, **65**, 285–313.

Banks, N.L. 1973. The origin and significance of the some downcurrent dipping cross-stratification sets. *Journal of Sedimentology Petrology*, **43**, 423–427.

Biswas, S.K. 1999. A review on the evolution of rift basins in India during Gondwana with special reference to western Indian basins and their hydrocarbon prospects. *In:* Sahni, A. & Loyal, R.S. (eds) *Gondwana Assembly: New Issues and Perspectives*. Proceedings Indian National Science Academy, Special Issues, **65**, 261–283.

Biswas, S.K. 2003. Regional tectonic framework of the Pranhita–Godavari basin, India. *Journal of Asian Earth Sciences*, **21**, 543–551.

Boyd, R., Dalrymple, R.W. & Zaitlin, B. (eds) 1994. *Incised-valley Systems: Origin and Sedimentary Sequences*. Society for Economic Paleontologists and Mineralogists, Special Publications, **51**.

Brettle, M.J., McIlaroy, D., Elliott, T., Davies, S.J. & Waters, C.N. 2002. Identifying cryptic tidal influences within deltaic succession: an example from the Marsdenian (Namurian) interval of the Pennine Basin UK. *Journal of the Geological Society, London*, **159**, 379–391.

Breyer, A.J. & McCabe, J.P. 1986. Coal associated with tidal sediments in the Wilcox Group (Palaeogene), South Texas. *Journal of Sedimentary Petrology*, **56**, 510–519.

Bristow, C.S. & Best, J.L. 1993. Braided rivers: perspectives and problems. *In:* Best, J.L. & Bristow, C.S. (eds) *Braided Rivers*. Geological Society, London, Special Publications, **75**, 291–304.

Casshyap, S.M. 1970. Sedimentary cycles and environment of the deposition of the Barakar coal masures of Lower Gondwana, India. *Journal of Sedimentary Petrology*, **40**, 1302–1317.

Casshyap, S.M. 1973. Palaeocurrent and palaeogeographic reconstruction of Barakar sandstone of peninsular India. *Sedimentary Geology*, **9**, 383–404.

Casshyap, S.M. 1979. Patterns of sedimentation in Gondwana Basins. *In:* Laskar, B. & Raja Rao, C.S. (eds) *IV International Gondwana Symposium, Delhi, India*. Hindustan Publishing, New Delhi, 525–551.

Casshyap, S.M. & Khan, A. 2000. Tectono-sedimentary evolution of the Gondwanan Satpura basin of central India: evidence of pre-Trap doming, rifting and palaeoslope reversal. *Journal of South African Earth Sciences*, **31**, 65–76.

Casshyap, S.M. & Qidwai, H.A. 1971. Palaeocurrent analysis of Lower Gondwana sedimentary rocks, Pench valley coalfield, Madhya Pradesh (India). *Sedimentary Geology*, **5**, 135–145.

Casshyap, S.M. & Qidwai, H.A. 1974. Glacial sedimentation of late Palaeozoic Talchir diamictitie, Pench valley coalfield, central India. *Geological Society of American Bulletin*, **85**, 749–760.

Casshyap, S.M. & Tewari, R.C. 1991. Depositional model and tectonic evolution of Gondwana basins. *In:* Venkatachala, B.S. & Maheswari, H.K. (eds) *Indian Gondwana*. Memoir Geological Society of India, **21**, 95–206.

Chatterjee, G.C. & Ghosh, P.K. 1970. Tectonic framework of peninsular Gondwanas of India. *Records Geological Survey of India*, **98**, 1–15.

Choi, S.K., Kim, O.B. & Park, A.Y. 2001. Late Pleistocene tidal rhythmites in Kyunggi Bay, West Coast of Korea: a comparison with simulated rhythmites based on the modern tides and implications for intertidal positioning. *Journal of Sedimentary Research*, **71**, 680–691.

Collinson, J.D. 1996. Alluvial sediments. *In:* Reading, H.G. (ed.) *Sedimentary Environments: Process, Facies and Stratigraphy.* Blackwell, Cambridge, MA, 37–82.

Dalrymple, R.W., Makino, Y. & Zaitlin, B.A. 1991. Temporal and spatial pattern of a rhythmite deposition on mudflat in the macrotidal Cobequid–Salmon River Estuary, Bay of Fundy, Canada. *In:* Smith, D.G., Reinson, G.F., Zaitlin, B.A. & Rahmani, R.A. (eds) *Clastic Tidal Sedimentology.* Canadian Society of Petroleum Geologists, Memoirs, **16**, 137–160.

Dalrymple, R.W., Zaitlin, B.A. & Boyd, R. 1992. Estuarine facies models: conceptual basis and stratigraphic implications. *Journal of Sedimentary Research*, **62**, 1130–1146.

De Boer, P.L., Oost, A.P. & Visser, M.J. 1989. The diurnal inequality of the tide as a parameter for recognizing tidal influences. *Journal of Sedimentary Petrology*, **59**, 912–921.

De Raaf, J.F.M., Boersma, J.R. & Van Gelder, A. 1977. Wave-generated structures and sequences from a shallow marine succession, Lower Carboniferous County Cork, Ireland. *Sedimentology*, **24**, 451–483.

Eriksson, K.A. & Simpson, E.L. 2000. Quantifying the oldest tidal record: the 3.2 Ga Moodies Group, Barberton Greenstone Belt, South Africa. *Geology*, **28**, 831–834.

Fox, C.S. 1931. *The Gondwana System and Related Formations*. Memoir Geological Survey of India, **58**.

Ghosh, S.K. 2003. First record of marine bivalves from the Talchir Formation of the Satpura Gondwana basin, India: palaeobiogeographic implications. *Gondwana Research (Gondwana Newsletter Section)*, **6**(2), 312–320.

Greb, S.F. & Archer, A.W. 1995. Rhythmic sedimentation in a mixed tide and wave deposit, Hazel Patch Sandstone (Pennsylvanian), Eastern Kentucky coalfield. *Journal of Sedimentary Research*, **B65**, 96–106.

Gupta, A. 1999. Early Permian palaeoenvironment in Damodar valley coalfields, India: an overview. *Gondwana Research*, **2**, 149–165.

Gupta, A. 2000. Role of storm in Ramgarh and West Bokaro coalfields and its implication in adjacent peninsular coalfields, India. *Gondwana Research*, **3**, 529–544.

Harms, J.C., Southard, J.B. & Walker, R.G. 1982. *Structures and Sequences in Clastic Rocks*. Society of Economic Paleontologists and Mineralogists, Short Courses, **9**.

Haszeldine, R.S. 1983. Fluvial bars reconstructed from deep straight channel, Upper Carboniferous coalfield of northeast England. *Journal of Sedimentary Petrology*, **53**, 1223–1247.

Hobday, D.K. 1987. Gondwana coal basins of Australia and South Africa: tectonic setting, depositional systems and resources. *In:* Scott, A.C. (ed.) *Coal and Coal-bearing Strata: Recent Advances*. Geological Society, London, Special Publications, **32**, 219–233.

Homewood, P. & Allen, P.A. 1981. Wave-, tide- and current-controlled sandbodies of Miocene Molasse, western Switzerland. *AAPG Bulletin*, **65**, 2534–2545.

Kvale, E.P. & Archer, A.W. 1990. Tidal deposits associated with low-sulfur coals, Brazil Fm. (Lower Pennsylvanian), Indiana. *Journal of Sedimentary Research*, **60**, 563–574.

Kvale, E.P. & Barnhill, M.L. 1994. Evolution of Lower Pennsylvanian estuarine facies within two adjacent palaeovalleys, Illinois basin, Indiana. *In:* Boyd, R., Dalrymple, R.W. & Zaitlin, B. (eds) *Incised-valley Systems: Origin and Sedimentary Sequences*. Society for Economic Paleontologists and Mineralogists, Special Publications, **51**, 191–207.

Kvale, E.P. & Mastalerz, M. 1998. Evidence of ancient freshwater tidal deposits. *In:* Alexander, C.R., Davies, R.A. & Henry, V.J. (eds) *Tidalites: Processes and Products*. Society for Economic Paleontologists and Mineralogists, Special Publications, **61**, 95–107.

Kvale, E.P., Archer, A.W., Mastalerz, M., Feldman, H.R. & Hester, N.C. 1997. *Guidebook to: Tidal Rhythmites and their Applications*. Canadian Society of Petroleum Geologists–Society of Economic Paleontologists and Mineralogists Joint Convention, 1–101.

Maulik, P.K., Chakraborty, C., Ghosh, P. & Rudra, D. 2000. Meso- and macro-scale architecture of a Triassic fluvial succession: Denwa Formation, Satpura Gondwana Basin, Madhya Pradesh. *Journal of Geological Society of India*, **56**, 489–504.

Medlicott, H.B. 1873. *Notes on the Satpura coal basin*. Memoir Geological Survey of India, **10**, 133–188.

Mellere, D., Plink-Bjorklund, P. & Steel, R. 2002. Anatomy of shelf deltas at the edge of a prograding Eocene shelf margin, Spitsbergen. *Sedimentology*, **49**, 1181–1206.

Miall, A.D. 1988. Facies architectures in clastic sedimentary basins. *In:* Kleinspehn, K. & Paola, C. (eds) *New Perspective in Basin Analysis*. Springer, New York, 67–88.

Michaelsen, P. & Henderson, R.A. 2000. Facies relationships and cyclicity of high-latitude, Late Permian coal measures, Bowen Basin, Australia. *International Journal of Coal Geology*, **44**, 19–48.

Mitra, N.D. 1994. Tensile resurgence along fossil sutures: a hypothesis on the evolution of Gondwana basins of peninsular India. *In: Abstracts of Proceedings of 2nd Symposium on Petroliferous Basins of India*. KDMIPE, Dehradun, 55–62.

Myrow, P.M. & Southard, J.B. 1996. Tempestite deposition. *Journal of Sedimentary Research*, **A66**, 875–887.

Myrow, P.M., Fisher, W. & Goodge, J.W. 2002. Wave-modified turbidites: combined-flow shoreline and shelf deposits, Cambrian, Antarctica. *Journal of Sedimentary Research*, **72**, 641–656.

Naqvi, S.M., Rao, D. & Narain, H. 1974. The protocontinental growth of the Indian shield and the antiquity of its rift valleys. *Precambrian Research*, **1**, 345–398.

Nemec, W. 1995. The dynamics of deltaic suspension plumes. *In:* Oti, M.N. & Postama, G. (eds) *Geology of Deltas*. Balkema, Rotterdam, 31–93.

Nio, S.D. & Yang, C.H. 1991. Diagnostic attributes of clastic tidal deposits: a review. *In:* Smith, D.G., Reinson, G.F., Zaitlin, B.A. & Rahmani, R.A. (eds) *Clastic Tidal Sedimentology.* Canadian Society of Petroleum Geologists, Memoirs, **16**, 3–28.

Peters, J. & Singh, S.K. 2001. Satpura basin—an example of pre-rift, syn-rift and post-rift Gondwana sedimentation in India. *Journal of Geological Society of India*, **57**, 309–320.

Rai, K.L. & Shukla, R.T. 1977. Depositional environment and the origin of coal in Pench Valley Coalfield, M.P. India. *In:* Laskar, B. & Raja Rao, C.S. (eds) *4th International Gondwana Symposium*. Geological Survey of India, Calcutta, 265–277.

Raja Rao, C.S. 1982. *Coalfields of India. Vol. II, Coal Resources of Tamil Nadu, Andhra Pradesh, Orissa and Maharashtra*. Bulletin Geological Survey of India, Series A, **45**.

Raja Rao, C.S. 1983. *Coalfields of India. Vol. III, Coal Resources of Madhya*

Pradesh and Jammu & Kashmir. Bulletin Geological Survey of India, Series A, **45**.

Raja Rao, C.S. 1987. *Coalfields of India. Vol. IV, Part I. Coal Resources of Bihar*. Bulletin Geological Survey of India, Series A, **45**.

Ray, S. & Chakraborty, T. 2002. Lower Gondwana fluvial succession of the Pench–Kanhan valley, India: stratigraphic architecture and depositional controls. *Sedimentary Geology*, **151**, 243–271.

Reineck, H.E. 1972. Tidal flats. *In:* Rigbay, J.K. & Hamblin, W.M.K. (eds) *Recognition of the Ancient Sedimentary Environments*. Society for Economic Paleontologists and Mineralogists, Special Publications, **16**, 146–159.

Reineck, H.E. & Wunderlich, F. 1968. Classification and origin of flaser and lenticular bedding. *Sedimentology*, **11**, 99–104.

Robinson, P.L. 1967. The Indian Gondwana Formations—a review. *In:* Amos, A.J. (ed.) *First Symposium on Gondwana Stratigraphy, Ar Del Plata, Argentina*. UNESCO, Paris, 201–268.

Shanley, K.W., McCabe, P.J. & Hettinger, R.D. 1992. Tidal influence in Cretaceous fluvial strata from Utah, USA: a key to sequence stratigraphic interpretation. *Sedimentology*, **39**, 905–930.

Shanmugam, G., Poffenberger, M. & Toro Alava, J. 2000. Tide-dominated estuarine facies in the Hollin and Napo ('T' and 'U') Formations (Cretaceous), Sacha field, Oriente basin, Ecuador. *AAPG Bulletin*, **84**, 652–682.

Suess, E. 1885. *Das Satilitz der Ende, Band 1*. Vienna.

Tessier, B. 1993. Upper intertidal rhythmites in the Mont-Saint-Michel Bay (NW France): perspectives for palaeoreconstruction. *Marine Geology*, **110**, 355–367.

Van de Meene, J.W.H., Boersma, J.R. & Terwindt, J.H.J. 1996. Sedimentary structures of combined flow deposits from the shoreface-connected ridges along the central Dutch coast. *Marine Geology*, **131**, 151–175.

Veevers, J.J. & Tewari, R.C. 1995. *Gondwana Master Basin of Peninsular India between Tethys and the Interior of the Gondwanaland Province of Pangea*. Geological Society of America, Memoirs, **187**, 1–73.

Visser, M.J. 1980. Neap–Spring cycles reflected in Holocene subtidal large-scale bedform deposits: a preliminary note. *Geology*, **8**, 543–546.

Williams, G.E. 1989. Late Precambrian tidal rhythmites in South Australia and the history of the Earth's rotation. *Journal of the Geological Society, London*, **146**, 97–111.

Willis, B.J. & Gabel, S.L. 2003. Formation of deep incisions into tide-dominated river deltas: implications for the stratigraphy of the Sego Sandstone, Book Cliffs, Utah, U.S.AÒ *Journal of Sedimentary Research*, **73**(2), 246–263.

Wiseman, W.J., Fan, Y.B. & Bornhold, B.D. *et al*. 1986. Suspended sediment advection by tidal currents off the Huanghe (Yellow River) Delta. *Geo-Marine Letters*, **6**, 115–120.

Wright, L.D. 1977. Sediment transport and deposition at river mouth: a synthesis. *Geological Society of America Bulletin*, **88**, 857–868.

Wright, L.D. & Coleman, J.M. 1974. Mississippi river mouth processes: effluent dynamics and morphological development. *Journal of Geology*, **82**, 751–778.

Yang, C.S. & Nio, S.D. 1985. The estimation of palaeohydrodynamic processes from subtidal deposits using time series analysis methods. *Sedimentology*, **32**, 41–57.

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