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Depositional model and tectonic evolution of Gondwana basins

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The paper analyses sedimentary evolution of Gondwana basins of Indian peninsula based on lithofacies, their association, dispersal and sedimentary characters from lowermost glacial Talchir (basal Permian) through Karharbari, Barakar, Barren Measure, Raniganj to Mahadeva (Middle Triassic). Particular attention is focussed on the role of formative processes and interaction of tectonism and climate on sedimentary evolution and basin configuration.

Key-words—Tectonic evolution, Gondwana, Depositional model, Indian Peninsula.

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साराँश

गोंडवाना द्रोणीयों का निक्षेपणीय प्रतिरूप एवं विवर्तनिक विकास

एस० एम० कश्यप एवं आर० सी० तिवारी

इस शोध-पत्र में करहरबारी, बराकार, बैरन मेज़र्स व रानीगंज नामक चरणों से गुजरते हुए अधरितम् हिमानी तालचिर (आधारी परमी) से महादेवा (मध्य त्रिसंघी) तक शैल-फ़ेसीज़, इनका साहचर्य, विकीरण एवं अवसादीय लक्षणों के आधार पर भारतीय प्रायद्वीप की गोंडवाना द्रोणीयों के अवसादीय विकास का विश्लेषण किया गया है। अवसादीय विकास एवं द्रोणी संरचना पर रचनात्मक प्रक्रियाओं तथा विवर्तनिकता एवं जलवायु की अन्तःक्रिया की भूमिका पर विशेष ध्यान दिया गया है।

PAST fifty years have seen rapid growth of literature on sedimentology of Gondwana Sequence of peninsular India. Depositional facies models have been developed for various formations of peninsular Gondwana basins. Even so our understanding of Gondwana basins is limited with respect to the framework of Gondwana basins, their depositional limits, and geomorphic, tectonic and climatic control on lithofacies dispersal and evolution of Gondwana lithic-fill through time and space.

The paper summarises sedimentary characters and lithofacies dispersal in Gondwana basins of the Peninsula. An attempt is made to analyse sedimentary evolution of Gondwana basins based on lithofacies dispersal from Talchir (basal Permian) to Mahadeva (Middle Triassic), with particular reference to geomorphic, tectonic and climatic setting.

LITHOFACIES DISPERSAL AND DEPOSITIONAL MODELS

Glacigene sedimentation

Gondwana sedimentation in peninsular India was initiated by deposition of glacigene Talchir sediments on uneven Precambrian basement, as

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preserved and available in three major basins of Koel-Damodar, Son-Mahanadi, Pranhita-Godavari and Satpura, and in small isolated basins. Several attempts have been made to interpret depositional environments and palaeogeography of Talchir sediments locally and regionally (Banerjee, 1966; Casshyap & Qidwai, 1974; Casshyap & Tewari, 1982; Casshyap & Srivastava, 1987; Frakes *et al.*, 1975; Ghosh & Mitra, 1975; Dickins & Shah, 1979; Datta *et al.*, 1979).

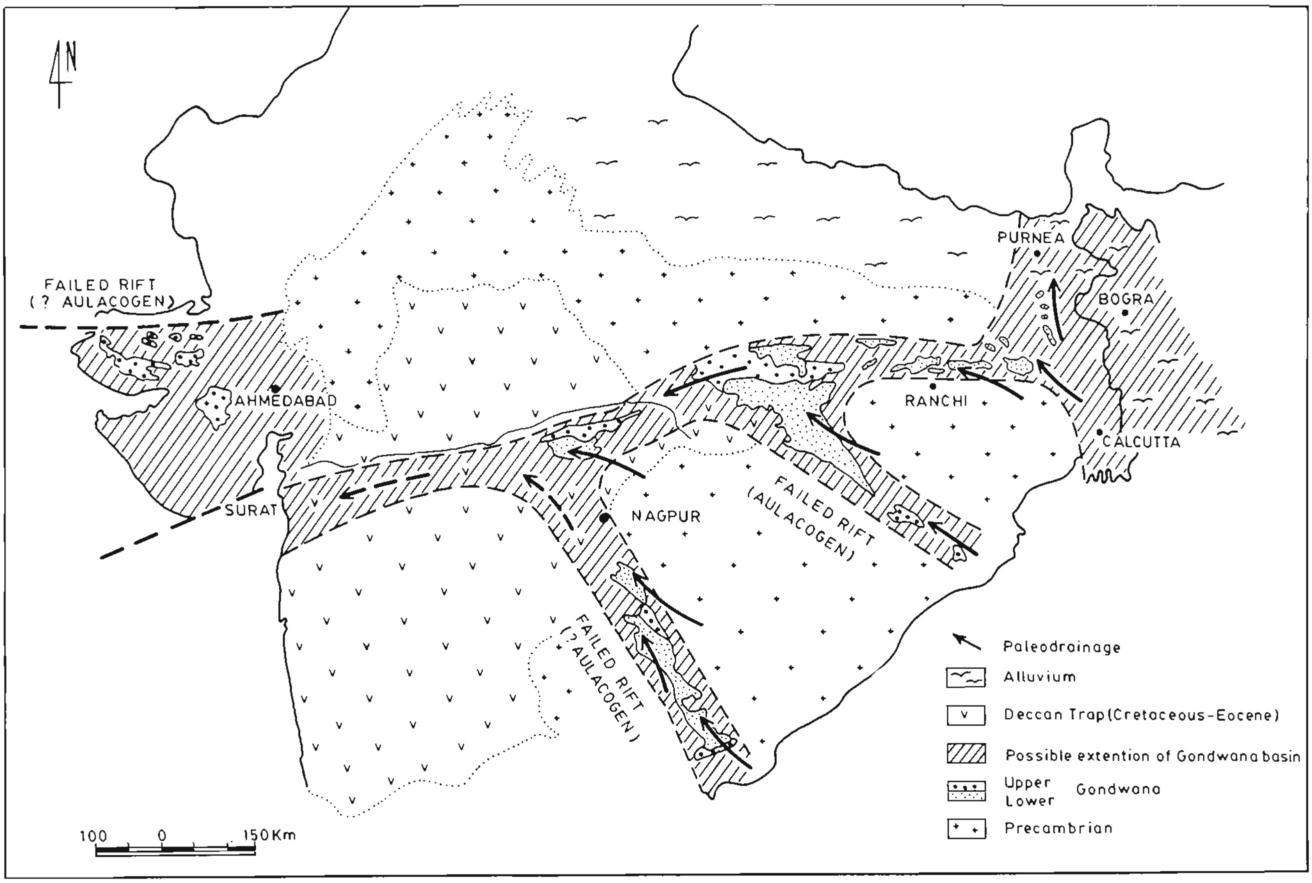
The Talchir sediments lying unconformably on Precambrian basement are marked by uniformly green colour and are composed of typical glacigene facies including tillite, conglomerate, sandstone, rhythmite and laminated shale. The tillite is locally massive but generally stratified, and occurs as thin beds in association with conglomerate, sandstone or shale. The conglomerate facies, as and where developed, commonly in upper part, occurs in channel-like elongate bodies and may be massive, stratified to cross-bedded. Majority of embedded lithoclasts in tillite and conglomerate are derived locally from bordering Precambrian highlands. Some lithoclasts of massive basal tillite are pentagonal in shape and may exhibit striations. Indeed, there is distinct increase in roundness and homogeneity of lithoclasts from tillite up to conglomerate (Tewari, in Press). The coarse clastic facies, by and large, occur in proximal parts near basin margins (Casshyap & Tewari, 1982; Casshyap & Srivastava, 1987). The sandstone facies occurring throughout the sequence in varying abundance is massive to thinly bedded, whereas those of upper part are profusely cross-bedded. The interbedded sequence of fine sandstone/siltstone and shale (rhythmite) is characterised by occasional sole structures, dropstones, ripple marks, and ripple- and flaser bedding. The interbedded facies occurs as thick units associated with channel-fill sandstone both laterally alongside and in downslope direction. Thin limestone beds are also associated with interbedded facies in some places. The laminated shale is the dominant facies of Talchir sediments in the areas away from the basin margin and in downslope direction.

Palaeoice transport based on striated pavement, till fabric and matching of lithoclasts composition reveals inward ice movement from basin margins locally and from south-east to north-west regionally in various Gondwana basins (Casshyap & Qidwai, 1974; Casshyap & Srivastava, 1987; Ahmad *et al.*, 1976). Similar northwesterly palaeo-drainage is deduced from associated outwash conglomerate and sandstone (Casshyap & Tewari, 1982).

The varying facies assemblage of Talchir sequence in different basins does not favour a uniform regional depositional facies model. Besides the limited basal tillite of glacial origin, the Talchir sediments generally favour mixed facies of glacio-fluvial, glacio-lacustrine and/or shallow marine to tidal flat environments. The occurrence of marine invertebrate fauna near Umaria and Manendragarh in central India (*see* Sastri & Shah, 1964) is the only direct evidence of marine influence, but lack of fauna elsewhere is no justification to rule out marine environment altogether. Recently Casshyap and Srivastava (1987) demonstrated that Talchir sedimentation took place in glacial valleys in southern upland terrain and broad open shelf (delta plain?), influenced by tidal channels, in the low lying northern terrain in Son-Mahanadi Basin, and thus raised the possibility of marine influence in several other low lying areas of central and eastern India depending upon the basement configuration of the basin and its location (Srivastava *et al.*, 1988).

Fluvial sedimentation

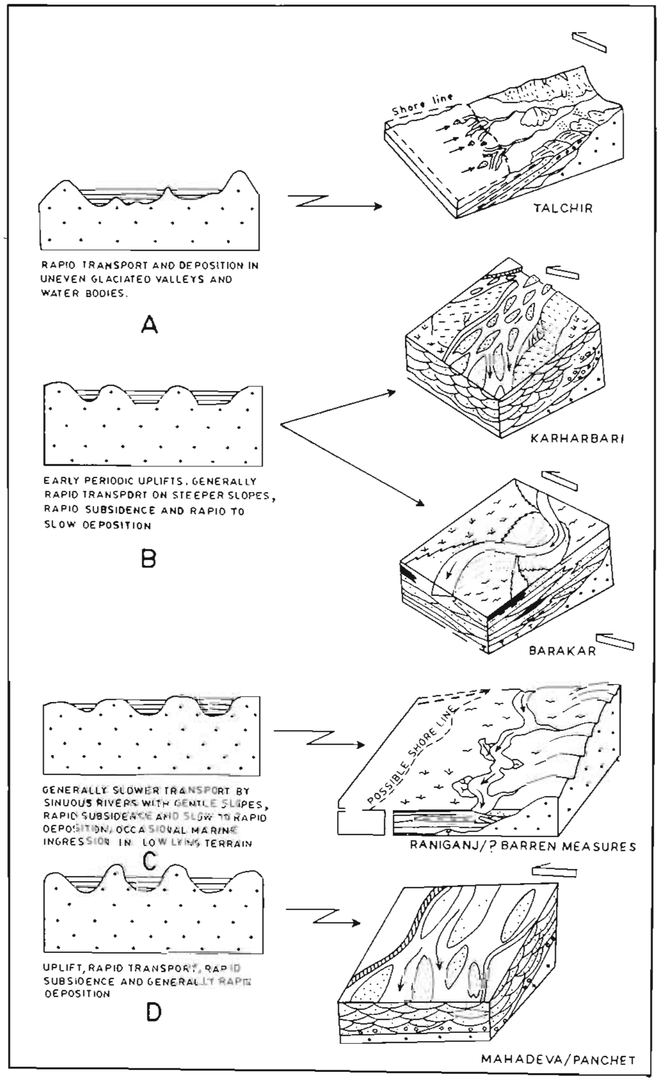
Karharbari Formation—The first phase of fluvial sedimentation is recorded by Karharbari sediments lying gradationally on the glacial outwash deposits. These fluvial sediments, occurring in discontinuous patches with a maximum thickness of about 300 m overlap, lie unconformably on the Precambrian basement, and cite evidence of expansion of the basin at this stage. Palaeohydrological studies from several basins suggest that Karharbari streams were low sinuous (1.12-1.25) with high width/depth ratio (53-68), flowed relatively down the steeper palaeoslope (65 cm/km) from south-east to north-west in most basins (Casshyap & Khan, 1982a; Casshyap & Tewari, 1984). The basal Karharbari is characterised by conglomerate bodies particularly in proximal parts, as in the southern part of Talcher Coalfield of Mahanadi Basin and East Bokaro Coalfield of Damodar Basin. The conglomerates are clast supported, elongate channel like, and massive to cross-bedded resembling longitudinal braid bars of medial alluvial fans. The recurrence of conglomerate in the upper Karharbari in southern part of Talcher Coalfield may be attributed to a minor tectonic uplift in the source land to the south-east. The conglomerate facies rapidly merge into multistorey and multilateral coalescing channel bodies of pebbly and gritty to coarse and medium sandstone, similar to the facies characterising distal alluvial fans. The bulk of the succeeding Karharbari consists of fining upward asymmetrical cycles in which the lower sandstone member exceeds the upper shale and coal (Casshyap & Khan, 1982b; Tewari & Casshyap, 1983). The sandstone facies characterised by cosets



Text-figure 1—Map of peninsular India showing the distribution of Lower Gondwana basins and their possible original limits and areal extension underneath the younger traps along Narmada lineament in west and Ganga alluvium in northern Bihar and Bengal in the north.

of planar and trough cross beds has been attributed to longitudinal and transverse braid bars (Casshyap & Tewari, 1984). Thin bodies of shale capping channel sandstone represent vertical accretion during shifting and abandoning of channel. The Karharbari coals are evidently thin, laterally impersistent and show frequent splitting, typical of restricted peat swamps developed in the abondoned channels and distal crevasse splays of braid plain. A statistical analysis of lithologic variables reveals close association of channel sandstone and coal justifying the development of coal swamps in abandoned channels (Casshyap *et al.*, in Press).

Barakar Formation — Following the deposition of gravelly and sandy Karharbari, unified Gondwana basins further expanded areally to accommodate thick (880 m) and extensive Barakar sediments as is evident by overlapping of the Barakar sediments on to the underlying basement in several parts. The channel patterns of Gondwana streams demonstrate a progressive metamorphosis in their sinuosity from Karharbari through lower to upper Barakar. The Barakar streams were relatively sinuous (1.45-2.05) with low width/depth ratio (21-42). The palaeoslope remained unchanged during Barakar time trending more or less southeast-northwest and was more gentle (52 cm/km) than that of the underlying Karharbari. The resultant Barakar sediments, throughout, are made up of recurring fining upward symmetrical cycles of coarse to medium sandstone, interbedded fine sandstone/siltstone and shale, and coal (Casshyap, 1970; Casshyap & Khan, 1982b; Casshyap & Tewari, 1984; Tewari & Casshyap, 1983). The Barakar sandstone is commonly channel-shaped in lower part to tabular sheet-like in upper part showing abundant cosets of planar and trough cross beds; it has been attributed largely to channel shifting and lateral accretion of point bar. Associated thick persistent beds of thinly bedded fine sandstone/shale and carbonaceous shale correspond to levee deposits. Indeed, the fine clastic facies show a progressive increase in thickness and bulk volume from Karharbari through lower to upper Barakar. The Barakar coals are thick, laterally continuous and are associated with channel-fill sandstone and fine clastic levee deposits. Extensive



Text-figure 2—Generalised schematic representation of palaeoprofile, topographic and tectonic setting, and patterns of Gondwana sedimentation from glacigene Talchir to fluviatile Mahadeva formations. Note the proximity of shore line to account for periodic ingression.

occurrence of coal seams in Barakar has been attributed to protected peat swamps developed in distal flood plains and protected lakes of meandering streams (Casshyap, 1970; Casshyap & Tewari, 1984). The progressive decline in channel sandstone and increase of fine clastics through time from Karharbari up to Barakar and down the palaeoslope in each basin is suggestive of progressive maturity of source land owing to prolonged erosion due to amelioration of climate and without pulses of uplift, and increase in channel sinuosity through space and time, as sedimentation progressed.

Barren Measure—Brown to reddish, dominantly clastic sequence of Barren Measure (800 m) which overlies the Barakar gradationally, but otherwise barren of coal, is more widespread in coalfields of Koel-Damodar Basin than in Son-Mahanadi and other basins. The Barren Measure is composed essentially of channel-like coarse to medium cross-bedded sandstone interbedded with siltstone, grey to red micaceous shale. The channel sandstone and fine clastic facies have been attributed to deposits of point bars and overbank levees of meandering streams which flowed dominantly upon pre-existing palaeoslope from southeast to northwest. Local discovery of phosphorite from Barren Measure of Ib-River Basin of southeastern Madhya Pradesh by the Geological Survey of India (communication by N. D. Mitra, 1987) is indeed interesting and calls for proper reconstruction and shifting of shore line during the course of fluviatile Gondwana sedimentation.

Raniganj Formation—As Gondwana basins grew in size through time, the Raniganj sediments were deposited gradationally above Barren Measure. These sediments are more widely developed in Koel-Damodar Basin with maximum thickness of 1,035 m than in other Gondwana basins. The Raniganj is likewise, represented by fining upward cycles of coarse to medium sandstone, interbedded fine sandstone/shale and coal (Casshyap & Kumar, 1987). Thin lenses of pebbly sandstone are locally recorded from the southern part of North Karanpura Basin. Raniganj sandstone is channel- to tabular-shaped, showing abundant planar and trough cross beds. Associated thinly interbedded fine sandstone/shale occur as thick and laterally persistent units exhibiting parallel lamination, ripple cross lamination, and rib-and-furrow structure. Coal occurs as thin to moderately thick seams, laterally persistent for several tens of kilometers interbedded with fine clastic facies. The reported occurrence of Jhingurdah coal seam as thick as 160 m from Raniganj sediments of Singrauli Coalfield of Son Basin is an exception. Facies models based on facies assemblage, sedimentary structures and their inter-relationship and consistency in palaeo-drainage directed toward northwest and west suggest unified nature of Damodar basins during Upper Permian Raniganj time (Casshyap & Kumar, 1987). Palaeohydrologic study reveals deposition of Raniganj sediments largely by meandering and locally by braided streams in the lower part. Indeed, the sinuous pattern of Raniganj streams shows a marginal increase in channel sinuosity in the downcurrent direction in Damodar Basin from east to west.

Triassic Gondwana—The Triassic Gondwana sediments collectively referred to as Mahadeva or classified as Panchet/Lugu/Kamtini/and Maleri in various basins, are markedly different from the underlying Raniganj sediments. These Upper Gondwana sediments with a maximum estimated thickness of 1,000 m constitute thickly forested high grounds as and where they occur in Raniganj, Bokaro, North Karanpura and adjoining coalfields of Koel-Damodar Basin, southern and northern parts of Son-Mahanadi Basin and Pranhita-Godavari and Satpura basins. Indeed, the Triassic sedimentation covered most of the peninsular basins, and their absence from certain critical areas such as the Jharia Coalfield of Damodar Basin and central part of Son-Mahanadi Basin can only be explained by post-Triassic tectonic uplift and subsequent erosion of Upper Gondwana sediments (Casshyap & Tewari, 1984, p. 122).

Generally speaking, the Triassic Gondwana sediments abound in pebbly coarse to medium sandstone. Sandstone bodies are thick (4-7 m), channel-like, showing abundant cosets of planar and trough cross-bedding. The associated interbeds of shale are grey, micaceous to red in colour; they are thin (2 m) in lower part of Mahadeva sequence of Rewa-Son Basin and thick (3-4 m) in upper part, and in westerly downcurrent direction. Overall lithofacies association and sedimentary characters of Mahadeva sediments are suggestive of their deposition by westerly and southwesterly flowing system of bed load braided streams; the channel pattern became moderately sinuous in the downcurrent direction in the west (Tewari, in preparation).

TECTONIC SETTING

The origin of intracratonic basins in the peninsular shield during Late Palaeozoic time and their prolonged subsidence to produce thick pile of classical Gondwana Sequence is a fundamental problem of global tectonics which is seriously engaging the attention of modern sedimentologists. Pranhita-Godavari-Satpura and Son-Mahanadi basins, oriented transversely to the present day east coast are, undoubtedly, linear basins elongating southeast-northwest in the direction of palaeoslope (Text-fig. 1). These basins may have coincided with ancient crustal lineaments and represent reactivated Permian grabens or, more precisely, failed rifts. Their lithofacies dispersal and palaeodrainage and subsequent reversal by and large demonstrate the character of aulacogens. The Koel-Damodar Basin now represented by a large number of disconnected coalfields of Bihar and Bengal, including those of Rajmahal to the north seems to have been considerably truncated and modified as a consequence of large scale post-Gondwana faulting and erosion (Casshyap, 1977). This basin was possibly areally much more extensive, interrupted locally by Precambrian highlands. Tectonically, this basin may represent a regional sag in the crust or half graben, but not a typical linear rift as visualised by Fox (1934) and others.

The problem of origin of Gondwana basins of the Peninsula remains an open question until sufficient surface and subsurface evidences are obtained in support of their tectonic setting.

BASIN EVOLUTION AND PALAEOGEOGRAPHY

Text-figure 2 a-d illustrates systematic evolution of peninsular Gondwana basins through time from Talchir up to Mahadeva.

Talchir glacial basins

Indeed, there is not enough evidence to support the early concept (Fox, 1934; Pascoe, 1959) that the Late Palaeozoic glaciers occurred as continental sheet in the Indian Peninsula, which occupied an estimated palaeolatitude of the order of about 50°S and 60°S during Late Palaeozoic (Runnegar, 1979). The available evidence, at most, favours mild glaciation in peninsular India similar to the temperate valley glaciers (Casshyap & Srivastava, 1987) (Text-fig. 2a).

It is more likely that Talchir glaciers were derived from ice-caps occupying the highlands in the proximity of various basins (Frakes *et al.*, 1975; Casshyap & Srivastava, 1987). The bulk of glacial sedimentation in each basin was brought about during the retreat of glacial lobes. Thin and impersistent massive tillite may correspond to deposits laid down directly on the basement. These basal tillites outcrop commonly in the proximity of highlands near the margin or within the basin wherever they occur. The stratified tillites are, however, more common; they are thin, laterally more persistent than massive basal tillite and occur at different horizons in the Talchir sequence. These tillites are evidently attributed to reworking by meltwater/subglacial water soon after they were deposited by glaciers or dropped as large chunks (icebergs) by floating ice in the underlying body of water in different parts of basin. Indeed, the stratified tillites are occasionally associated with stratified to cross-stratified channel-like bodies of conglomerate and coarse pebbly sandstone as reported from different basins (Casshyap & Tewari, 1982; Casshyap & Srivastava, 1987).

The rapid gradation of lithofacies from margin towards inner part of basin, particularly conspicuous in Son-Mahanadi Basin especially in Talcher, Korba and Manendragarh areas, is apparently not so remarkable in Koel-Damodar and other basins. Rapid dispersal of lithofacies in marginal parts is genetically significant and has been attributed primarily to the pre-existing basement profile of the basins (Casshyap & Srivastava, 1987). The pre-Talchir basement profile in Son-Mahanadi Basin was much too uneven owing to the occurrence of the older granitoid uplands, providing a net-work of interconnected valleys and sub-basins. Apparently, the basement profile was not so in the case of Koel-Damodar as is evident from lack of granitoid inliers through the Talchir terrain. It is therefore reiterated that basement profile was the dominant factor in controlling patterns of Talchir sedimentation in each basin.

The meltwater streams from receding ice-caps evidently brought down and deposited the bulk of Talchir sediments in the overlooking basin laterally and longitudinally down the slope. The evidence from lithofacies arrangement, texture and structure, by and large, favour intermixing of environments from time to time and at any given place including fluvial, lacustrine and shallow marine tidal to eustary. Of these, the lacustrine and/or shallow marine tidal flats/estuary seem to be more widespread than generally believed and reported. Surely, the marine Talchir can not remain restricted to a few outcrops where invertebrate fossils have been reported. The overall lithofacies association, general paucity of largescale trough cross stratification, occasional occurrence of flat bedding, wave ripples and wave ripple bedding, flaser bedding calcareous nodules and calcareous shale, and overall preponderance of green colour are some of the features indicating periodic intermixing of lacustrine and shallow marine tidal flats through most part of the Talchir sequence.

The fluvial influence became more prominent in upper part owing to amelioration of climate and increase in meltwater streams as indicated by interbedding of profusely cross-bedded channel sandstone locally associated with carbonaceous shale, and occurrence of dark grey rather than green shale. The palaeodrainage initiated by receding glaciers remained unchanged as the fluvial streams became dominant towards the end of Talchir sedimentation. It is here suggested that the marine influence and shore line receded locally and regionally gradually with the retreat and termination of Talchir ice lobes and consequent regional uplift.

Post-glacial fluviatile basins

At the end of glacigene sedimentation, and with the advent of well-defined fluvial system, the Gondwana basins expanded areally and became more or less unified into three linear basins of Koel-Damodar, Son-Mahanadi and Pranhita-Godavari and Satpura (Text-fig. 1). These linear basins became the site of fluvial sedimentation which continued more or less uninterruptedly for about 70 Ma to produce some 4,000 m thick pile of sediments represented by Karharbari, Barakar, Barren Measure, Raniganj and Mahadeva in different basins.

The fluvial system of streams transported and deposited essentially quartzose gravels and coarse sand. These basal clastics known as the Karharbari Formation abound in conglomerate/pebbly sandstone, and coarse to medium sandstone with thin interbeds of shale and coal. The mature, monomictic clast supported conglomerate may well be indicative of early periodic uplifts at the onset of Karharbari sedimentation. Steeper slopes on account of periodic uplifts became the site for braided and anastomosed Karharbari streams to transport abundant bed load. Associated distal fan facies represented by pebbly coarse arkose to subarkose is indicative of rapid deposition and rapid subsidence (Text-fig. 2b). Rapid subsidence and frequent shifting of braided channels should have prevented development of thick peat swamps to produce only thin, impersistent and splitted coal seams such as those which characterise the Karharbari Formation. The occurrence of a distinct and well-developed (~ 40 m) conglomeratic horizon in the uppermost Karharbari in Talcher and IB-River coalfields of Mahanadi Basin is suggestive of yet another episode of tectonic uplift at the end of Karharbari sedimentation.

As sedimentation progressed, the topography of source land located to southeast of each basin, progressively became mature. The Gondwana streams, consequently, underwent progressive metamorphosis in channel from braided, moderately sinuous to meandering to deposit the lower, middle and upper Barakar sediments, respectively. At this stage the expanded basins areally became unified into longitudinal alluvial plains, apparently bigger in size than their present limits (Text-fig. 1). The sinuous to meandering Barakar rivers loaded with abundant mixed- and suspended load flowed on gentle palaeoslope from southeast to northwest. The resultant sediments are characterised by a progressive increase in the fine clastic facies through time from lower to upper Barakar and along the length of the basin in downcurrent direction. The lithofacies composition and their dispersal, abundance of fine clastics and absence of conglomerate horizons, and immature to submature sandstone are indicative of rapid to slow deposition and rapid subsidence of Lower Permian Barakar sediments (Text-fig. 2b). Overall, the Barakar sediments lack evidence of pronounced tectonic uplifts and are suggestive of continued amelioration of climate which matured the topography of source land more than the underlying Karharbari.

The bulk of overlying Barren Measure and Raniganj sediments were deposited largely by meandering streams flowing on a distinctly gentle palaeoslope directed towards northwest and west. These meandering streams deposited greater amount of suspended sediments than the underlying Barakar. Petrographically, the Raniganj sandstones are subarkosic to arkosic arenites and texturally immature to submature. It is suggested that the bulk of Upper Permian sediments may represent slow to rapid deposition and rapid subsidence. Owing to near flat topography and proximity of shore line in the north, it is possible there may have been marine ingressions in the low lying terrain during Barren Measure and Raniganj sedimentation, occasionally, in response to pulses of rapid subsidence (Text-fig. 2c).

Evidence from lithofacies of Triassic Gondwana rocks suggests a fresh episode of tectonic uplift and readjustment of palaeoslope at the onset of Upper Gondwana sedimentation. The Triassic Gondwana sediments record a sudden increase in coarse clastic including pebble beds (Text-fig. 2d) and decline in bulk fine clastics as compared to the underlying Permian sediments. Further, the northwesterly palaeodrainage so well established in the Upper Permian was slightly readjusted towards west and southwest, in response to tectonic uplift. The coarse clastic sediments of Pachmarhi, and Mahadeva resembling those of the Early Permian Karharbari were deposited largely by braided streams which became moderately sinuous in the downcurrent direction. The occurrence of red bed facies may call for semi-arid climate during Triassic times.

CONCLUDING REMARKS

About 140 Ma prior to the rifting of Indian Plate, the Gondwana sedimentation in the Peninsula was brought about in linear intracratonic basins during the retreat of ice lobes at the beginning of Permian Period (Asselian). The primitive Gondwana basins which were confined to narrow-to-broad glacial valleys grew in size with the onset of fluviatile sedimentation at the termination of Talchir ice age in Early Permian. The basins expanded areally through time as sedimentation progressed through Middle and Upper Permian up to Triassic. The northwesterly to northerly palaeodrainage established at the onset of glacial outwash remained more or less unchanged throughout the Permian, and shifted slightly towards west and west-southwest during Late Permian to Middle Triassic, respectively, particularly in the central tract along the Narmada lineament.

It is suggested that the progressive maturity of source land topography due to prolonged amelioration of climate from glacial, cold, warm to semi-arid exerted greater control on Gondwana sedimentation than basinal and extrabasinal tectonics. However, periodic tectonic uplifts were operative during crustal rebound in Early Permian following the retreat of Talchir ice lobes and again in Early Triassic as is evident by the occurrence of conglomeratic and pebble bed horizons, and the preponderance of coarse arkosic to subarkosic sandstones. Lack of corroborative rock records implies that end of Triassic witnessed a period of non-deposition in the intracratonic basins throughout the Peninsula, although transgressive Jurassic Sea had inundated parts of western margin of Indian Shield in Kutch and western Rajasthan, beyond realm of Gondwana basins. Deltaic to paralic and shallow marine sedimentation continued during the Cretaceous Period selectively in cratonic embayments along Narmada lineament in west and in localised coastal (?) troughs (basins) of Gujarat and along the east coast, as also in southern parts of the pre-existing Gondwana troughs, following the reversal of palaeoslope to the south and creation of the east coast and the sea after separation of India from Antarctica. The palaeoslope so established some 140 Ma ago in Early Cretaceous time has remained practically unchanged till present time.

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