First online volume
Jour. Indian Association of Sedimentologists, Vol. 35, No. 1 (2018), pp.5-22
ISSN 0970-3268

Late Paleozoic-Early Triassic Mega Sequences of Southern Pangea Supercontinent: Their Climate and Tectonic Regime between Panthalassa and Tethys: an overview

S. M. Casshyap and Helmut Wopfner*
Department of Geology, Aligarh Muslim University, Aligarh (Retd.)
*Geological Institute, University of Cologne, Germany (Retd.)
smcasshyap@gmail.com

Abstract: The contiguous assembly of continental plates in southern Pangea, comprising South America, Afro-Arabia, India, Antarctica and Australia constituted original "Gondwana", bounded by Panthalassa in the south and Tethys to the north. The sedimentary sequences overlying the super continental crust at Pangean stage have been referred to as Pangea Mega Sequence (PMS), the term is synonymous with the term "Lower Gondwana" of Indian stratigraphy ranging in age from Permo-Carboniferous to Early Triassic, exhibiting similar characters across the whole of Gondwana . During the Permo-Triassic extreme climatic variations across Gondwana were experienced beginning with Gondwana glaciation in the Late Carboniferous to Early Permian, followed by warm to semi-humid, and arid to hot conditions by the Late Permian-Early Triassic. The depositional period of PMS was equally governed by three contrasting tectonic regimes: i) compressive conditions on the Panthalassan edge of Gondwana plates along the southern margin; ii) corresponding trans-pressional sags forming interior cratonic basins of southern Africa, and iii) transtension and rifting experienced in the north along the Tethys margin and adjoining intracratonic basins. The resultant glacial and non-glacial facies developed are exemplified in the corresponding Gondwana sediment assemblage of peri/intracratonic tectonic basins of southern Pangean supercontinent. Stratigraphic setting, lithofacies, depositional environments and climatic history of the aforesaid sequences are reviewed in selective basins of Afro-Arabia, India, Antarctica, Australia, and detached blocks of East and Southeast Asia. The striking similarities between the lithofacies indicate matching climate/depositional conditions and similar timing of tectonic pulses. A synthesis of records on the direction of Permian glacial transport and paleocurrents of succeeding fluvial system in different basins of southern Pangea reveals a radial paleodrainage pattern in central-eastern Gondwanaland as in Antarctic highland, directed towards SW in South Africa, N in India, NW in West Australia, and SE in Eastern Australia. The paper explains the causes of climatic changes, the influence of pole drifting and arrangement of seas and continent.

Introduction

Pangea which was the latest supercontinent to form during 450-320 Ma and existed from Late Paleozoic to Early-Middle Mesozoic era, assembled, existing micro-continents affected by Early Paleozoic orogeny and fold belts. In contrast, to present earth and distribution of continental mass, much of Pangea was in southern hemisphere with contiguous assembly of continental plates comprising South America, Africa, India, Antarctica and Australia, which constituted original "Gondwana" bounded by a super ocean Panthalassa in the south and Tethys to the north. The sedimentary sequences overlying the super continental crust at the Pangea stage have been referred to as Pangea Mega Sequence (PMS). The term is synonymous with the term Lower Gondwana of Indian stratigraphy which embraces rock sequences ranging in age from Permo-Carboniferous to Early Triassic exhibiting similar facies and sedimentary characters across the whole of southern Pangea. Figure 1 represents the reconstruction of Gondwana display the major occurrences of Late Paleozoic-Early Triassic depositional basins including localized depocentres of Arabia, as detached Gondwana derived blocks (Wopfner,2012).The review treaties with climatic developments and tectonic regimes as recorded in the sedimentary sequences of the aforesaid depositional basins from Africa south of equator, through India, Antarctica and Australia.

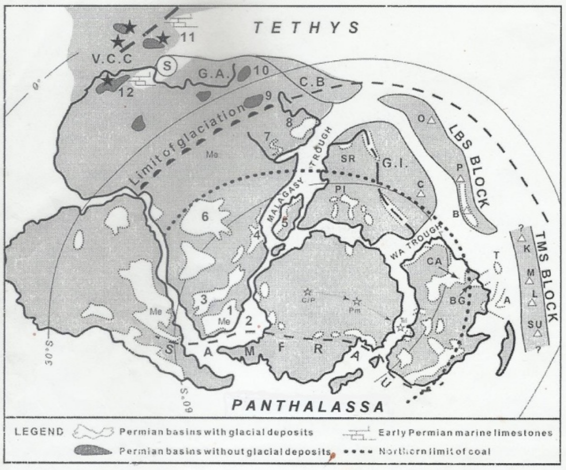


Figure: 1. Reconstruction of of southeren Pangean supercontinent / Gondwana in Early Permian time depicting distribution of with Late Carboniferous –Early Triassic sediments (=Pangean Mega Seqence /PMS), distinguishing between basins with or without glacigene deposits. Dashed curve shows the approximate northern limit of glaciation; dotted curve shows limit of coal formation. Numerals identify the following basins; 1. Karoo; 2.Falkland ; 3. Kalhari; 4. Ruhuhu (Southern Tanzania); 5. Morondava (Medagascar); 6. Congo; 7. Yemen; 8. South Oman; 9. Saudi Arabia; 10. Levante; 11.South Alpine Terrine (Collio-Etsch- Carni); 12. Morocco (after Wopfner, 2012). Gondwana derived Blocks including LBS: Lhasa-Baoshan-Shan; TMS: Tengchong-Malay-Sumatra. Open stars refer to position of Permian South Pole.

Evolutionary factors: climatic variations and tectonic regimes

During the end of Paleozoic/ beginning of Mesozoic extreme climatic variations across Gondwana were experienced, from great Gondwana glaciation when, glaciers flourished at places upon Gondwana in the Late Carboniferous–Early Permian, to warm to semi humid, and arid to hot climate by the Late Permian–Early Triassic. In Afro-Arabia, India, and Australia glaciers advanced to 40° paleo-latitude creating a steep gradient between them and hot– humid environment in the vicinity of equator. Synchronous deglaciation associated with a eustatic rise of sea level in the Early Sakmarian was followed by warm climate and increased humidity resulting in the formation of the large coal swamps/coal deposits between the South Pole and about 50° paleo-latitude succeeded by increasing aridity and hot climate towards equator in the north (Fig. 1), as exemplified by the Gondwana sediments in the various cratonic basins across southern supercontinent. The depositional period of PMS was equally influenced by three contrasting tectonic regimes: (i) the compressive system of the Samfrau Geosyncline dominated the Panthalassan margin of Gondwana in the south, resulting in the linear fold system extending from South America and Africa via Antarctica to eastern Australia (Veevers and Powell, 1994); (ii) corresponding trans-pressional sags controlling the adjoining interior cratonic basins of southern Africa; and, iii) the compressive conditions along the Panthalassan edge contrasted with the northern margin of Gondwana where extension and transtension prevailed and rifting was experienced along the Tethys margin (Sengor, 1998), which is in the adjoining intracratonic basins. The resultant glacial and non-glacial facies realms developed in the corresponding depositional sequences are reviewed from Karoo Super group and equivalents of South Africa, Tanzania, Madagascar, Arabia, southern Alpine terrine, Lower Gondwana and equivalents of India, Antarctica, Australia, and detached Gondwana derived blocks of East and Southeast Asia.

Karoo super group: Stratigraphy, lithofacies and depositional environment South Africa

The post-Numarian PMS in African continent south of Paleozoic equator is referred to as the Karoo Super group and its coeval equivalents (Fig. 2). The stratigraphic sequence of the Karoo Super group is demonstrated in figure 3. In the southern part of South Africa, Karoo sedimentation took place in the subsiding fore-deep of the Samfrau convergence (Catuneanu et al., 2005), but northern part extended onto the cratonic basins due to trans-pressional sags and rifting. A complex system of N-NE trending rift basins extended from Namibia/Botswana towards eastern parts of Africa, whereas large sag basins developed in the Congo, in Angola and in Gabon. These two settings were separated by an N-NE trending structural highs (Stratten, 1970; Wopfner, 1994). Much of this undulating terrain in south and central Africa was a focus of Permo-Carboniferous glaciation (Rust, 1975 & Visser,1997), with glacial movement and periglacial melt water streams directed from NE to SW towards fore-deep (Fig. 4). The Gondwana glaciation has left indubitable traces over parts of southern Africa and Arabia.

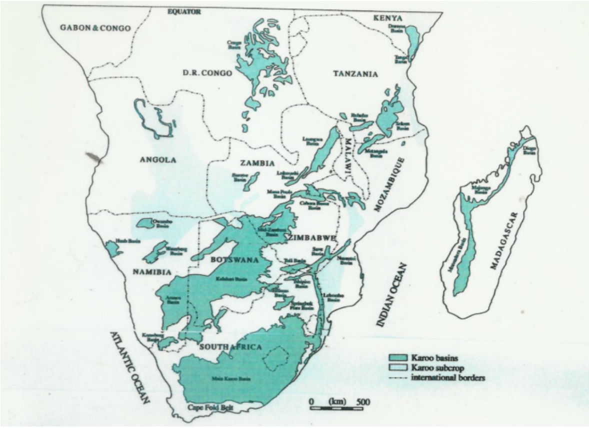


Figure: 2. Distribution of Karoo Basin in south-central Africa (after Wopfner, 2002).

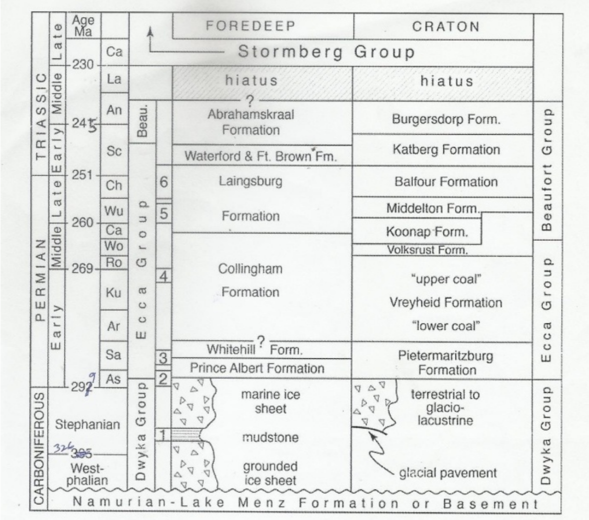


Figure: 3. Simplified stratigraphic columns of the Karoo Basin in South Africa, demonstrating marked facies change between the fore deep in the SW and terrestrial environment in the NE and N of the basin (Wopfner, 2012).

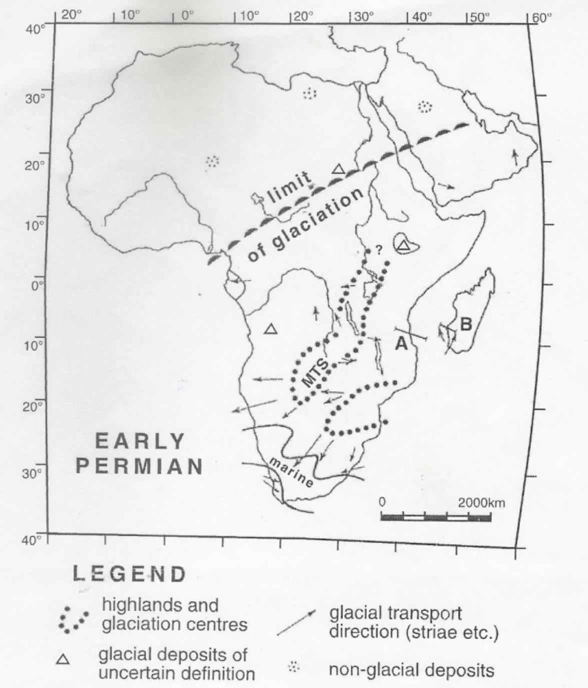


Figure: 4. Map of Afro-Arabia showing northern limit of glacial and MTS (Median Thermal Swell). The ridge separated rift basins in the east and sag basins in the west and supported the regional center of glaciation. Arrows indicate the direction of ice movement from local highlands (after Rust, 1874; Wopfner, 1994).

The field evidence for the lower limit is provided in the southern Karoo Basin, where tillites of the Dwyka Group rest uncomfortably on the Lower to Middle Carboniferous Namurian strata (Fig. 4) which, display of no evidence of glacial activity. The post-glacial Ecca Group contain the terminal deposits of the glacigene succession and comprises clastic sequences of the fore-deep including turbidites and banded siliciclastics, organic-rich mudstones and cherts of a deep marine environment represented by Prince Albert, White Hall, Collingham and Lainsburg Formations. The shallow marine Waterford and Fort Brown Formations conclude the Ecca succession in the southern Karoo Basin. However, on the cratonic shelf situated northeast and north of the fore-deep, the Ecca Group consists of terrestrial deposits beginning with the Petermartizburg Formation in the lower part comprising dark grey, carbonaceous siltstones and shale of fresh water origin. It is succeeded by the Vryheid Formation which harbors the coal deposits of southern Africa.

East Africa

The Permian sag and rift basins of south-central Africa representing Karoo sequence extend SW-NE from Namibia/Botswana, Zambia, Mozambique and Tanzania in the east (Fig. 2) (Wopfner & Kreuser, 1986). These basins were part of the complex rift system of the Malagasy (Madagascar).

Tanzania

One of the most complete sequences of the Karoo super group is that of Ruhuhu basin in SW Tanzania (Figs. 2, 7). The classical sequence is referred to as the Songea Group, with lithological subdivisions as shown in Figure 5 (Wopfner & Jin, 2009). Deposition was controlled by climatic and tectonic events resulting in five distinctive coal-bearing depositional cycles, (Casshyap et al., 1987; Wopfner and Casshyap, 1997). The sedimentary succession begins with the deposition of the Permo-Carboniferous glacigene Idusi Formation, comprising basal tillites, overlain by reworked glacial debris, slumped diamictites. The succeeding coal-bearing Mchuchuma Formation with thin coal seams initiated with medium to coarse cross-bedded sandstone (Mpera Sandstone Member) representing the humid phase of deglaciation. The overlying Mbuyura Formation embarks with red beds and cross-bedded scrap Sandstone Member representing floodplain and channel deposits of braided rivers in response to rising rift shoulders. It is succeeded by an assemblage comprising coal measures of the Mhukura Formation, overlain by the Ruhuhu and Usili Formations, consisting of calc marls, dolomites with stromatolitic limestone representing deposition in alkaline lakes (Fig.5). The Pangean sequence of Tanzania was concluded by Early Triassic fluviatile Kingori Sandstone, with a short evaporative event developed due to hot and semi-arid conditions represented by the Manda Beds.

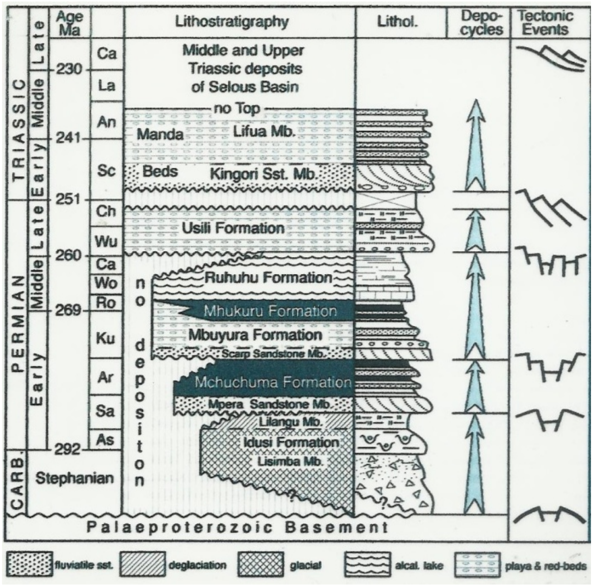


Figure: 5. Simplified stratigraphy, depositional cycles and tectonic phases of the Songea Group (PMS) of Ruhuhu basin, Southern Tanzania. Solid black colured beds depict coal measure formations (after Wopfner and Jin, 2009).

Madagascar

During the Pangean stage, Madagascar was situated opposite Eastern Africa including Tanzania (Fig 2,). Structurally, western Madagascar represents a mirror image of Permian rift system of eastern Africa

(Wopfner, 1994; Catuneanu et al., 2005). Thus, it is not the Permian – Early Triassic PMS sequences of the Island resemble those of the Karoo super group of eastern Africa.

In the Morondava Basin of western Madagascar, the succession is subdivided into three major lithology units consisting of Sakola, Sakamena and Isalo Groups, in ascending order. The Sakola Group comprises the glacigene deposits identical to that of the Idusi Formation of Tanzania, succeeded by coal measures, cross-bedded red beds, and marine limestone at the top. These correspond to Mchuchuma, Mbuyura, Mhukura, and Ruhuhu Formations of the Songea Group of Tanzania (Catuneanu et al., 2005). A tectonic event near the Middle–Late Permian boundary separates the Sakola from the overlying Sakamena Formation with an unconformity (Wopfner and Jin, 2009).

The Majunga Basin in the NW of Madagascar contains similar rock assemblage as the Morondava Basin but towards the top occur intercalated marine limestones (Lower Sakamena). Their fauna includes the similar cephalopod as that of the Salt Range of Pakistan suggesting southward extension of Tethys forming the Malagasy (Madagascar) Trough.

Arabian Peninsula

Isolated outcrops of PMS as time-equivalent to Karoo deposits occur in Yemen and Oman in southern Arabian Peninsula (Figs. 2, 7). Polished and striated pavements overlain by boulder tillites with faceted clasts have been observed in South Yemen (Kruck and Thiele, 1983) and in the South Oman (Braakman et al., 1982), indicating flawless evidence of continental glaciers in southern part of Arabian peninsula in Late Paleozoic time. The Oman succession of glacigene deposits is similar to the Idusi Formation of Tanzania and is termed the Alkhalata Formation of the Haushi Group (Fig. 6). It is topped by the black bituminous mudstones of the Rahab Shale. The latter has characteristic oil-bearing signatures (Levell et al., (1986). The Rahab Shale is followed by shallow marine deposits of Lower Gharif Formation. The succeeding sequence of Khuff Formation consisting of evaporates was deposited in shallow shelf sea which transgressed most of the Arabian Peninsula (Alsharan, 2006).

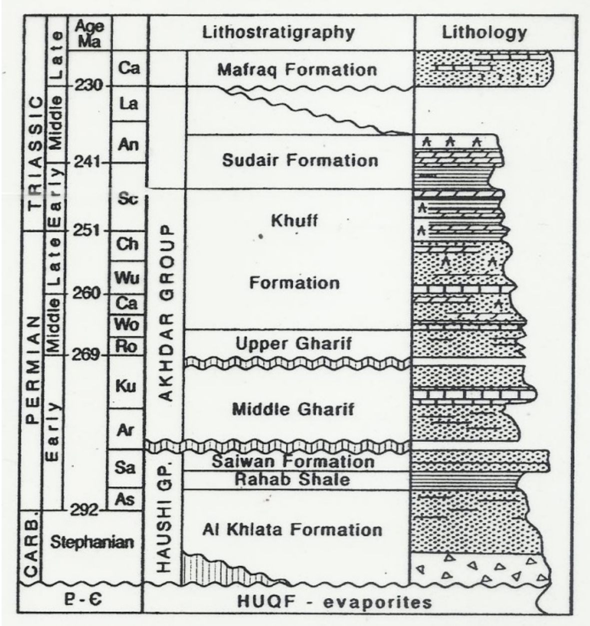


Figure: 6. Generalized stratigraphic columns of PMS of Southern Oman (after Alsharan, 2006; Wopfner and Jin, 2009).

Africa north of the glacial front

Based on the dispersal of northernmost exposures of glacigene sediments, Wopfner and Casshyap (1997) identified the northern limit of Late Paleozoic glaciation as a convex line extending from west-central Africa through Arabian Peninsula towards east-southeast (Figs. 2, 3). The non-glacial rock assemblage equivalent to PMS occur as isolated outcrops between glacial front and equator across the northern Africa as outlined below.

Central Saudi Arabia outcrops

Lying at the northern periphery of the line of glacial front (Fig. 2), isolated outcrops of

PMS in Central Saudi Arabia spectacle terminal facies of non-glacial/proglacial assemblage (Al-Laboun, 1987). The Permian succession is established by the dolomite-anhydrite beds of the Khuff Formation. This sequence is present in the subsurface of the Central Arabia Basin. Similar isolated outcrops of non-glacial sediments occur north of Saudi Arabia near Gulf of Suez and Sinai, Nagev, in Libiya, Tunisia, and Morocco in the NW near equator (Fig. 1). These sediments developed in localized sags and/or rifted basins consist of occasional conglomerate, sandstone, red beds, and evaporates suggestive of warm, hot to arid climate, which is not unlikely due to their proximity to equator.

Lower Gondwana and equivalents

Peninsular India

The Gondwana basins of Peninsular India, confined to three major linear elongated tracts, developed on the Archaean basement along a northerly paleoslope from the highlands to the south and southeast including the uplands of Eastern Ghats and ancestral mountains of Eastern Antarctica (Casshyap, 1973; 1976). Besides exposed rocks in the linear belts (Fig.7), the Gondwana sediments in Rajmahal Basin, Eastern Raniganj Basin, Upper Assam and western Satpura Basin, occur in subsurface under the Rajmahal Traps/Deccan Traps and below the recent alluvium cover. Occurrence of isolated outliers of Talchir glacial deposits and Karharbari/Barakar coal measures in the proximity of basins are, suggestive of wider extent of original exposures beyond the existing margins of the basins (Casshyap et al., 1993; Mitra, 1993). It is quite obvious, that the original Gondwana basins were extensive than exposed within the three major basins of Peninsular India.

Tectonic Setting

The Gondwana strata is low-dipping (5-10º), though steep dip occur in places and near boundary faults where rocks are locally folded. The Gondwana sediments were deposited in half-graben/failed rift structures and preserved in subsiding rifted basins bounded on their southern or northern margins by high-angle normal faults (Casshyap, 1979; Casshyap and Tewari, 2001; Verma and Singh, 1979).

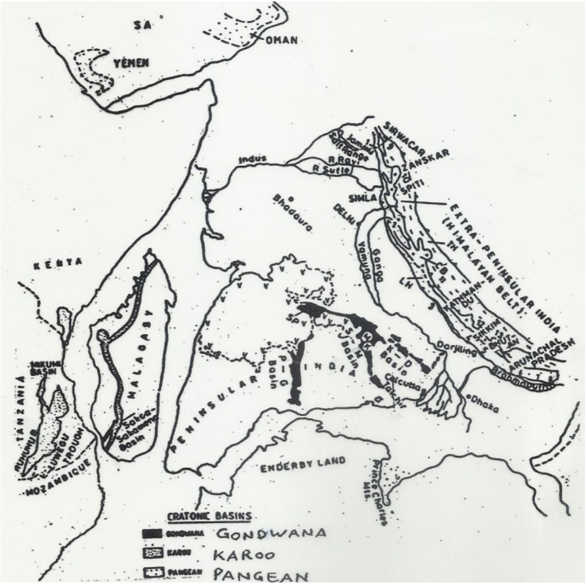


Figure: 7. Assembly of India in the Early Permian, showing exposures of Gondwana rocks in three major Linear belts in Peninsular India and in Lesser and Tethys Himalaya of Extra-Peninsular region. Also shown are areas of exposures of Karoo and equivalent rocks in Madagascar, Tanzania, Yemen, and Oman of South Arabia . Alphabets in Extra-Peninsular India refer to TH, Tethys Himalaya; CB, Crystalline Belt; LS, Lesser Himalaya.

Some of these faults truncated the exposed coal measures abruptly along the boundary, as perceived in Jharia (Mahuda sub-basin) and Singrauli Basins (Casshyap, 1979, 1981a; Casshyap et al., 1993).

Stratigraphic setting

The cratonic Gondwana basins are developed in the Damodar and Son-Mahanadi Valleys, including 1-30 coalfields (Fig 8). Besides, coalfields of less productive deposits occur in Pranhita – Godavri, and Satpura Basins in west-central India. These basins (coalfields), representing a thick pile (average thickness 2200 m) of the Permo-Triassic Lower Gondwana sequence (Fig. 9), provide a prolonged history of sedimentation (Casshyap,1977; 1981b). The stratigraphic and lithofacies sections of Permian Gondwana (Damuda Group) are displayed in figure 9.

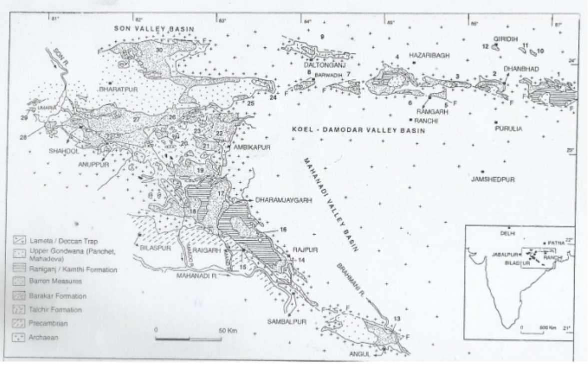


Figure: 8. Geological map showing the distribution of Gondwana rocks in the Koel-Damodar and Son -Mahanadi basins. Inset shows location of the basins. Numbers 1-30 refer to coalfields: (after Casshyap and Tewari, 1984; Ramakrishnan and Vaidyanadhan, 2008, fig. 7.2).

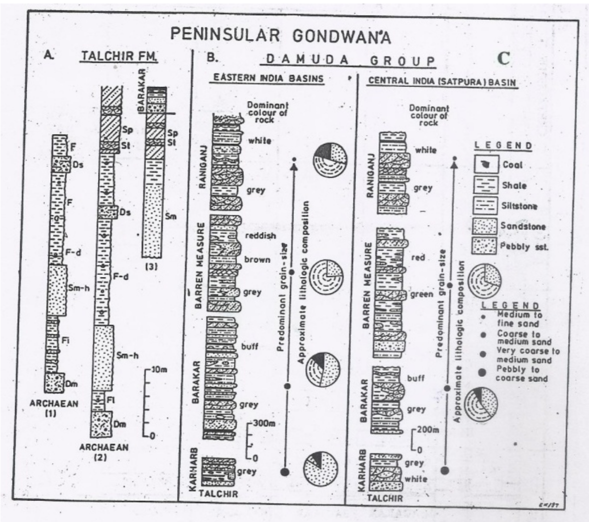


Figure: 9. Generalized stratigraphic sections of Permian Gondwana showing lithofacies, grain size and sedimentary structures : A. Glacial and glacigene sequence in Talchir Formation, measured at different locations between Korba and Ambikapur in Son-Mahanadi basin; B. Generalised sections of fluvial deposits of the damuda group in Koel-Damodar and Son-Mahanadi basins (C. Similar sections from Central India, Satpura basin (after Casshyap and Srivastava, 1988; Casshyap, 1999).

Lithofacies and Depositional Environments

Glacial Facies

Glacigene facies of the Talchir Formation comprising boulder tillite and diamictite in the lower part were laid down by grounded ice in glacially scoured depressions and striated pavements on the Archaean basement (Smith, 1967). Subsequent melt waters deposited reworked stratified tills with thin inter-beds of cross-bedded sandstone, shale, with or without dripstones. The glacigene facies of the Talchir Formation comprising boulder tillite and diamictite in the lower part is grounded ice in glacially scoured depressions and striated pavements on the Archaean basement (Smith, 1967ltstone, with or without drop stones in the overlying assemblage (Fig. 9). Unlike the Dwyka tillites, the Talchir tillites/diamictites seldom exceed 2m in thickness. Lithofacies characters of Talchir Formation, depositional environments, paleoice and paleoflow transport have been studied (Casshyap, 1970, 1981b; Casshyap and Qidwai, 1971; Casshyap and Tewari, 1982; Casshyap and Srivastava, 1988; Casshyap et al., 1993; Frakes et al., 1975).

Post-glacial Fluviatile facies

The succeeding post-glacial sediments of coal-bearing Karharbari, Barakar and Raniganj Formations of Damuda Group, are products of extensive fluviatile system intercepted by swamps and lakes, deposited as channel sand bars and overbank fine clastics, resulting in the development of repeated sequences of cross-bedded sandstones, shale/siltstones carbonaceous shale, and coal (Casshyap, 1977, 1981a; Casshyap & Tewari, 1984, 1988). These coal measures are intervened by mid - Permian Barren Measures/Motur Formation exhibiting similar lithofacies and depositional environments (Casshyap & Tewari, 2001). Unlike other PMS basins of Pangean supercontinent, the Damuda Group is conspicuous by the recurring fining upward cycles/cyclothems terminated by coal of varying magnitude (Casshyap, 1970; Casshyap and Kumar, 1987; Casshyap et al., 1993). The cyclical characters of the Barakar coal measures have been established statistically by applying Entropy in Markov chain analysis based on measured sections and available borehole data (Casshyap and Khan, 1981).

The succeeding Early Triassic Panchet Formation is separated from the underlying Damuda Group by an unconformity (Casshyap, 1999; Casshyap and Tewari, 2001). Its variants are the Pachmarhi Sandstone in the Satpura Basin, Upper Pali Formation of Umaria, and middle and upper parts of the Kamthi Formation in the Kamptee and Pranhita-Godavari basins. Occurrence of coarse clastics, including pebble beds and coarse arkosic sandstone in the basal part, suggest a new episode of tectonic upliftment and readjustment of paleoslope. The Panchet Formation accomplishes the Lower Gondwana (PMS). It is separated from younger Mesozoic rocks by the mid-Triassic hiatus.

The depositional environments of post-glacial Permo-Triassic Gondwana facies were alluvial plains drained by river systems which were braided during the early stages of Karharbari Formation. The system became progressively meandering through Barakar to Raniganj (Middle to Upper Permian), and later changed to braided pattern during deposition of the Lower Triassic Panchet/ Pachmarhi, as depicted in the depositional models (Fig. 10) (Casshyap and Khan, 1981; Casshyap and Tewari, 1984; 1988).Based on the striking similarities between the facies and the onset of the sequence boundaries of the PMS (Lower Gondwana) of Peninsular India and those of eastern Africa (Tanzania/Zambia) indicate an identical climatic/depositional conditions and analogous timing of tectonic pulses, although post-depositional rifting and/or boundary faults played a greater role in the control of peninsular basins (Casshyap, 1999; Wopfner and Jin, 2009).

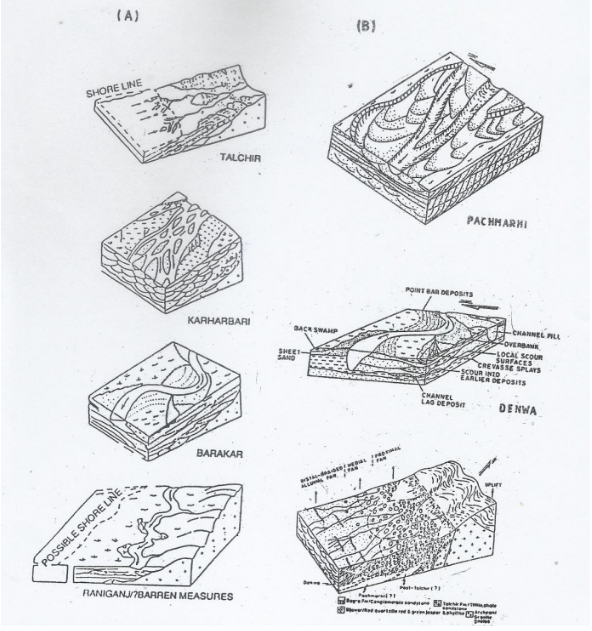


Figure: 10 Schematic depositional models of Gondwana sedimentation showing changing pattern of fluvio-glacial and fluvial system from Talchir, Karharbari to Pachmarhi (after Casshyap and Khan, 1981; Casshyap and Tewari, 1988).

Intermittent Marine Incursions

Following deglaciation of the Early Permian glacier, low lying areas of fluvial environments were locally intercepted by intermittent incursion of the Tethys sea from northeast into Peninsular Gondwana basins at/ or near the top of Talchir and other formations, along linear belt of the Lesser Himalaya.

Extra-Peninsular India

The Pangean successions of Extra-Peninsular India are, Lesser Himalaya and Tethyan Himalaya. The lesser Himalaya features is in conjoint with cratonic Gondwana facies, including a coal-bearing succession, whereas the Tethyan Himalaya demonstrate the stronger marine influence and, in places, are associated with acid volcanic rocks (Acharyya et al., 1979).

Lesser Himalaya

Isolated outcrops of Late Paleozoic succession in the Lesser Himalaya occur in continuous linear belt from Arunachal Pradesh to central Nepal via Bhutan and Darjeeling in the northeast (Fig. 7}. The Rangit tectonic window in Sikkim, comprising the succession correlated with the Gondwana super group of Peninsular India: the Rangit Pebble Slate is equivalent to the Talchir Formation, and the overlying assemblage is coeval to the formations of the Damuda Group.

Tethyan Himalaya

The bulk of the sediments of the Tethys Himalayan belt is marine and has been reliably correlated with the Peninsular India and Arunachal (Nakazava and Kapoor, 1979). The Tethyan zone extends from Kashmir to Spiti, into Lhasa block of Tibet and Baoshan and Tengchong blocks in Southwest China (Casshyap, 1999). These Gondwana succession dominated by thick continental basalt succeeding the glacigene succession (Gaetani and Garzanti, 1991; Wopfner and Casshyap, 1997).

Gondwana derived blocks

These are the Late Carboniferous to Early Permian glacigene marine deposits followed by the remarkable postglacial sequence (Fig.10), now organized in the form of a long belt (Fig.11), the western part of which is bounded between the former the Gondwana continent including India and northern continent, and includes Baoshan and Tengchong blocks of western Yunan bordering northern Myanmar, and Gangdise {Lhasa} and Qiangtang {Tibet} block. The eastern part constitutes the Sibumasu Block of Southeast Asis. The Baoshan and Tengchong blocks of western Yunan, separated by well-defined tectonic lineament, display well developed Late Paleozoic-Mesozoic sequence. The basal formation of Baoshan block comprises diamictite, tillite, and mudstone containing Brachiopods of Stephanian to Asselian age, overlain by thick basalt with intercalations of limestone. Similar sequence constitutes the Tengchong block. Both the blocks are deliberated to be of glaciomarine origin and, hence of Gondwana affinity. Besides, the sequences in Gangdise (Lhasa) and Qiangtang are of glaciomarine origin. Likewise, the presence of Gondwana affinity in parts of Southeast Asia has been remarked. The comprehensive term Sibumasu Block is considered to be composed of the Shan state of Mynamar, western and Northwestern Thailand and Western Malaysia and Sumatra (Metcalfe, 1988). It is believed that Sibumasu was adjacent to Gondwana through the Carboniferous and found striking similarities of the Paleozoic succession with that of Western Australia. Sibumasu was rifted off from the Gondwana in the earliest Permian to collide with south China in the Late Triassic.

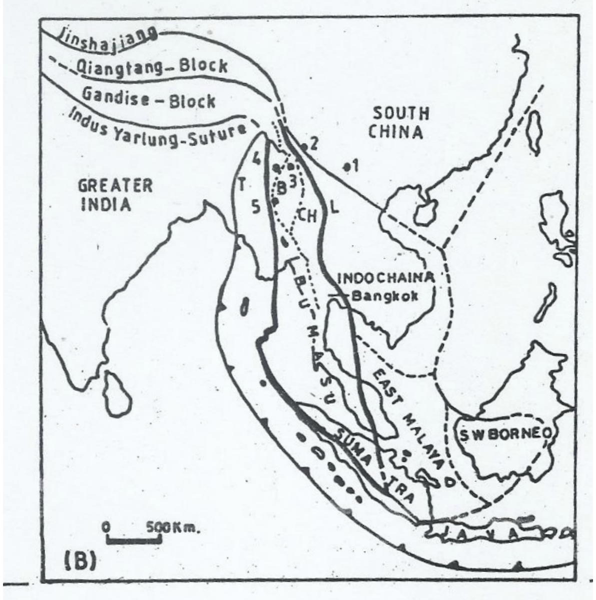


Figure: 11. Map showing Gondwana derived tectonic blocks characterized by glacigene and succeeding rocks showing Gondwana affinity in East and Southeast Asia. Alphabets refer to: B, Baoshan-Shan unit; T, Tengchong unit; CH, Chanling-Menglian unit. Numerals depict localities forming part of Sibumasu Block : 1. Kumming; 2, Dali; 3, Baoshan; 4, Tengchong (Yunan); 5, Mandlay (Myanmar) (after Wopfner and Jin, 2009).

Antarctica

The rifted/fault-bounded Permo-Triassic Gondwana sediments have been reported, in isolated outcrops, from Ellsworth Mountains, Pensacola Mountains, Ohio Range, Queen Maud Range, besides South Victoria Land (Fig. 12). These sediments were developed radially in (?) pericratonic basins on the coastal periphery around the East Antarctic Paleoupland (Trans Antarctic Mountains) in the proximity of East Coast of India, southern Africa, and southwest Australia. On the other side of the centrally located Paleoupland, close to the Ross Ice Shelf, occurred the Beardmore Glacier terrain (Fig. 12), displaying a well-developed Permo-Triassic glacigene and post-glacial succession of Antarctica (Barrett,1969). The 2600 m-thick Beacon sequence comprises eight formations: the Alexandria Formation (? Devonian), the Pagoda, Mackellar, Fairchild and Buckley Formations (Permian), the Fremouw and Falla Formations (Triassic), and the Triassic?-Jurassic Prebble Formation. The bulk of the sediment of Mackellar and Fairchild Formations are of terrestrial origin, consisting of interbedded current-bedded sandstones shale and siltstones, including arkosic sandstones, deposited by southeasterly flowing streams. The Buckley Formation is a crudely cyclic coal-bearing sequence embedded with fossil leaves and stems of *Glossopteris.* The Triassic Fremouw and Falla assemblages are sandstone-shale cyclic sequences. The depositional environments were generally fluviatile, lacustrine and paludal, with northwesterly paleoflow direction. Most other radial Glacier systems (basins) on either side of the East Antarctic Paleoupland, such as Beaver Lake, Shacklelton, Nimrod, Darwin, Victoria Land exhibit selective Gondwana facies.

Australia

In Australia, rock successions of PMS (Gondwana) have been deposited in three distinct tectonic settings: collision and fore deep environments of the Hunter-Bowen Fold Belt along the east coast, transcurrent sag basins in the central part, and rift and fault-bounded basins of West Australian Trough along the west coast of the continent, including Collie and Perth Basin in SW, Carnarvon, Canning, and Bonaparte Gulf Basins in NW. In Eastern Australian fold-belt setting, the basal Permian to Early Triassic PMS succession comprises in ascending order: Lower Marine, Greta Coal Measures, and Upper Marine Formations in Lower to Middle Permian, Singleton Formation in Late Permian, and Narrabeen and Hauksbury Formations in Early to Middle Triassic. However in Tasmania in the southeast, the bulk of the equivalent glacigene and periglacial sequence is dominated by marine sediment of Panthalassa margin (Wopfner, 2012). In West Australia, coal measures in Permian assemblage occur only in the south (Perth Basin) and carbonate formation was restricted to some thin bands of limestones, mainly in northern basins. Glacial deposits consisting of tillites, debris flows are known to occur in the Permian sequence of Bonaparte Gulf and Canning basins in the northwest (Wopfner, 1999, 2001).

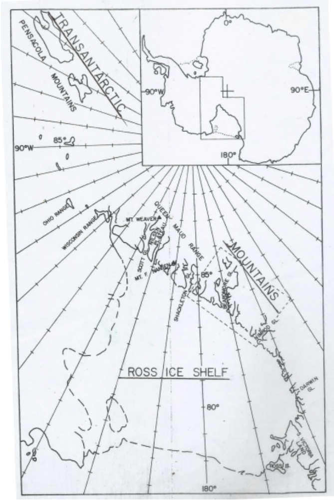


Figure: 12. Outline map of the central Trans Antarctic Mountains (East Antarctic Paleoupland) showing Beardmore Glacial Area. Inset shows entire map of Antarctica (after Barrett, 1969, fig. 1).

Paleodrainage and paleoslope

India

The glacial transport in the scoured depressions/valleys in the underlying Archaean terrain was directed from southeast to northwest, though locally intercepted by subsidiary lobes descending transversely or obliquely from adjoining highlands, as interpreted from the associated glacigene facies (Casshyap, 1973; Casshyap and Tewari, 1982; Casshyap and Srivastava, 1988). The succeeding paleodrainage pattern of postglacial fluvial system was, likewise, directed predominantly from southeast to northwest in practically all the major basins throughout the deposition of Permo-Triassic Gondwana sediments, as reconstructed by Casshyap (1973,1977, 1981b, and Mitra, 1991), and corroborated subsequently (Fig. 13) by Veevers and Tewari (1995, fig. 7.11). The consistent direction of glacial transport and paleocurrents imply that the paleoslopes in all the Gondwana basins were predominantly directed from southeast to northwest. However, during Upper Permian in the Damodar Valley, the paleocurrents were directed from east-southeast to west-northwest, possibly towards the Tethyan shoreline (Casshyap & Kumar, 1987).

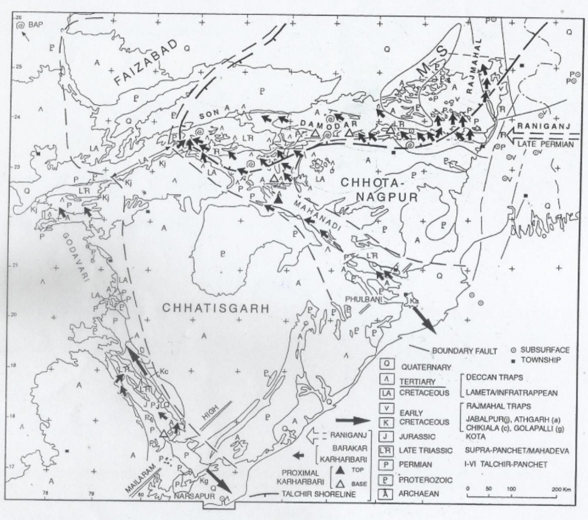


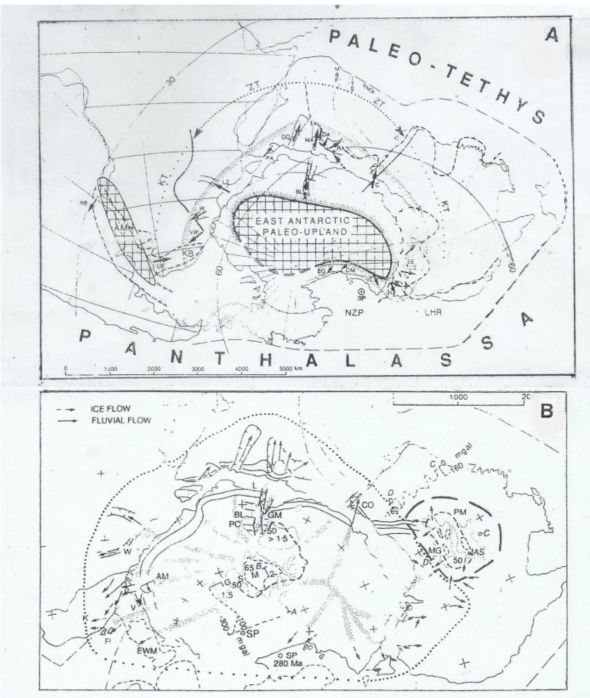
Figure: 13. Paleocurrent dispersal map of Permian Karharbari, Bokaro, and Raniganj Formations in the Gondwana basins of Peninsular India (Veevers and Tewari, 1995).

Local deviations/reversals in paleoflow directions in different formations and areas suggest contribution by local tributary channels from adjoining highlands. Significantly, the northwesterly directed Permo-Triassic Gondwana drainage was abruptly truncated along the faulted northern margins of the Singrauli and Satpura basins, which strongly questions their existing northern limits, apparently terminated by the Son-Narmada Lineament, and call for a critical review (Casshyap et al., 1993; Casshyap, 1999).

Radial Paleodrainage System in Gondwanaland

The figure 14A displays a comprehensive master map demonstrating, a radial paleodrainage system in Gondwanaland around the East Antarctic Paleoupland, as reconstructed by Tewari and Veevers (1993) and modified by Veevers and Tewari (1995, fig. 40). Among noteworthy features are, along the periphery of Antarctica inferring connections of paleo-ice and flow azimuths between Antarctica and bordering continents of South Africa, India, and Australia (Fig 14 B). The flow azimuths in the Permian Gondwana/Karoo sediments are radially directed southwest and west in the Karoo Basin of South Africa, northward in Mahanadi and Godavari Basins of east coast of India, northwest in West Australia, and southeast in Eastern Australia (Powell and Li, 1994; Veevers and Tewari, 1995, fig. 41). The perimeter of the radial drainage for fluvial deposition was at about 30^{o} paleolatitudes in India and adjoining continents as marked by dotted curve in Figure 14B.

Based on above perspective it is inferred that the Permian paleodrainage system, including glacial lobes and melt-water fluvio-glacial network, developed in elevated terrains of the East-Central Antarctica, descended downhill along valleys radially towards coastal periphery, connecting with respective paleodrainage of the aforesaid low-lying depositional basins of the bordering continents of South Africa, India, and Australia, resulting in the radial paleodrainage system of Gondwanaland.



eastern Gondwanaland around the East Antarctic Paleoupland (Trans Antarctic Mountains) . Full arrows indicate the azimuths of Permian and fluvial transport (after Tewari and Veevers, 1993; Veevers and Tewari, 1995, fig. 40). Alphabets refer to: **Antarctica**: BL, Beaver Lake; BG, Beardmore Glacial Area; DM, Darwin Mountain; VL, Victoria Land. **India:** M, Mahanadi; DA, Damodar; RA, Rajmahal; GO, Godavri; P, Palar; RNGI, restore northern edge of Greater India. **South Africa**: LZ, Lower Zambezi; W, Waterberg; VR, Vryheid; KB, Karoo Basin; UE Upper Ecca; Am. Atlanctic Mountain. **Australia**: C, collie; SEAUS, southeastern Australia. Curves indicate: ZT, Zambezian or fault-bounded terrain; KT, Basement of Karoo basin (Rust, 1975). B) Large radial drainage system . Generalised arrows showing fluvial flow azimuths, depicting connections with adjoining continents (Powell and Li, 1994; Veevers and Tewari, 1995, fig. 41).

Paleoclimate history

Afro-Arabia

During Permo-Triassic, Africa and Arabia extended from area proximal to the South Pole into lower latitudes so that the regions near the Tethyan margin remained free of ice cover during the Gondwana glaciation (Fig. 1). Drifting of Permian pole was an important factor, among others, for governing the Permo-Triassic climatic changes during Pangean/Gondwana sedimentation from Afro-Arabia through India to Antarctica/Australia.

Glacial Climate

The onset of the Pangean depositional succession was synonymous to the Late Paleozoic glaciation in the southern supercontinent of Gondwana. The question of whether the South African glacial deposits (Dwyka Group) resulted from a single sub-polar ice sheet emanating from Antarctic highlands and/or from individual glacial centers (Visser, 1997), or from a large ice sheet covering Antarctica and Samfrau, with coalescing centers in South Africa (Wopfner and Diekmann, 1996), is still a matter of debate. The basal boulder tillite facies of Karoo Basin developed extensively from fore deep in the south to cratonic shelf areas towards north and northeast (Fig. 2). In the neighboring areas of Mozambique, Zambia, Tanzania, and Madagascar in Central and East Africa which were not at much lower latitudes, the glacial deposits of the Idusi Formation of Ruhuhu basin of Southwest Tanzania resulted from plateau type glaciers, with lodgment tills and reworked glacial debris (Wopfner and Kreuser, 1986). Further north, Southern Arabia was situated at lower latitude; consequently, the glacial deposits in Oman formed as repeated intertounging flow tills, slurred debris and turbidities (Levell et al., 1988). The evidences presented in this paper indicate that the glacier front In Afro-Arabia extended to about 40° paleolatitudes (Figs. 1, 3). Synchronous deglaciation associated with a eustatic rise of sea level in the Early Sakmarian was followed by retreat of glaciers, and warm climate and increased humidity, which is a wide spread event across the southern Pangea.

Transition to Warmer Climate

In southern half of Africa, deglaciation and the retreat of glaciers is followed by the Ecca and Songea Groups respectively, comprising fluviatile sandstones, shale, and carbonaceous shale embedded with *Glossopteris* flora. This flora along with the overlying coal seams suggests high precipitation rate and prolific plant growth, providing the biomass for peat accumulation and coal formation. In Africa coal formation extended to about 55^o palaeolatitude which approximates the limit on other parts of Gondwana (Fig. 1). Coal formation ceased in South Africa when temperature increased in the Middle Permian, ushering in the deposition of the Beaufort Group. North of the 'coal-line', climate became rapidly dryer, warmer and semi-arid. In Arabia this trend is evidenced by the evaporate and anhydrite beds in the Middle Gharif and Lower and Middle Khuff Formations of Oman .

Warm to hot, semi-arid to arid climate

This phase, characterized by elevated temperatures, is exemplified by the Permo-Triassic Songea and Ruhuhu Groups of Tanzania, comprising repeated red bed facies of shale and sandstones, and stromatolitic limestones/dolomites which are interpreted as the product of hot, arid to semi-arid climate. There was a distinct gradient from the warm semi-arid climate dominating the environment of the Beaufort Group in southern Africa, to the arid to hotter conditions on the Arabian Peninsula, northern Africa, and terminating to the evaporate conditions in the South Alpine Terrine close to the northern margin of Tethys at the end of Permian.

India

The Gondwana Basins of Peninsular India were at same latitude as those of East Africa and Madagascar (Fig. 3). Consequently they experienced a similar climatic history.

Glacial and Transitional Phase

Climatic development during the depositional event of the Talchir Formation is exemplified by the glacigene successions in the Damodar, Son-Mahanadi, Pench Valley, and other basins as investigated by Casshyap and Qidwai (1971), Casshyap and Tewari (1982), and Casshyap and Srivastava (1988). Deglaciation phase and retreat of Talchir glaciers was followed by the development of periglacial melt water streams, lakes and ponds, comprising channel sandstones, eskers, and varvites with or without drop stones. The Extra-Peninsular glacial and proglacial successions were deposited at lower latitude close to Tethyan margin of Gondwana. The presence of Eurydesmas and Bryozoa/Mollusc fauna in several parts with occurrence of *Gangamopteris* flora suggestive of cool climate during the period of Talchir sedimentation up to the top layers, date to the Early Sakmarian.

Postglacial Phase

The postglacial phase was marked by a cool, temperate climate during deposition of alluvial fan and braided river facies of the Lower Permian Karaharbai and Barakar Formations, which abound in fresh to slightly weathered feldspar. The recurrence of fining upward cycles topped by coal seams with prolific *Glossopteris, Gangamopteris* and related flora indicate seasonal warming of climate. The red coloured Barren Measures provide the first signs of a hot/warm, humid climate during the Middle Permian throughout Peninsular India, followed by the Upper Permian Raniganj coal measures dominated by *Glossopteris*, suggestive of reversal to cooler, mild climate (Casshyap and Kumar, 1987).

The coastline facies of Lesser Himalaya and the shelf facies of Tethyan Himalaya which succeed the glacigene deposit abound in carbonate and fine clastics. They are indicative of warm temperate climate. The Triassic period represented by Panchet/Pachmarhi Formations comprises pebbly sandstone and red- and yellow shale, suggesting a seasonally warm, semi-arid and humid climate.

Antarctica, Australia

The retreat of glaciers was a synchronous Gondwana-wide event. The Early Permian Mackeller Formation of the Beardmore Glacier area, comprising black carbonaceous, interbedded with turbidities is suggestive of deglaciation phase in Antarctica. Simultaneous was the onset of the formation of coal beds in Gondwana, including the Buckley Coal Measures of Antarctica and the formation of red beds (Wopfner and Casshyap, 1997). Middle Permian fossil forests and plant assemblages demonstrate that the Late Artinskian onward, Antarctica was vegetated and free of glaciers as was Gondwana (Wopfner, 2012).

In Eastern Australia, the Permo-Carboniferous glaciomarine/glacigene deposits succeeded by a sequence including Permian Lower and Upper Gretra Coal Measures and Permo-Triassic Singleton Formation are associated with terrestrial deposits of Permo-Triassic Narabeen and Hauksbury Formations. Similar facies characterized the Permian Perth Basin in the south and other basins of northwest Australia. Of particular significance is the deglaciation facies in both the Canning and Bonaparte Gulf basins, consisting of thick black carbonaceous lutites (Wopfner, 1999). Above characteristics are suggestive of a climatic regime similar to that of East Africa, Extra-Peninsular India, and neighboring Antarctica.

DISCUSSION

Causes of Glaciation and Climatic Change

A northward drift of Afro-Arabia and/or of Gondwana as a whole towards the equator was assumed to explain the amelioration of post-Sakmarian climate (Scotese and Langford, 1995, and others), which was, however, a physical impossibility as the African continent was attached to Antarctica till Jurassic. In the Late Paleozoic/Early Permian, the paleo-south pole for Gondwana was placed on or near central Antarctica in the vicinity of present South Pole (Powell and Li, 1994). During the Permian, however, the pole moved towards Australia to reach a position in southeastern Australia in the Early Triassic (Powell and Li, 1994) (Fig 1). Thus, southerly pole shift towards southeast Australia resulted in pole-ward expansion of central latitudinal tropical belts to influence climatic change (Wopfner and Jin, 2009), as evidenced by the coal formation and paucity of red beds in the Permian basins of Australia, supporting its closer position to South pole (Fig. 1).

Alternative perspectives have been proposed in the context of climatic variations. Crowell (1978) proposed that the southern supercontinent was oriented during this time that its north shore received onshore moist winds from the Tethys Sea and its southern shore on the edge of Panthalassa received precipitation originating from an ice-free sub-polar ocean (Fig. 15). The ice age apparently ended when strong circulation of air and ocean currents parallel to latitudes in the Early Mesozoic. Thus, besides pole drifting the arrangement of seas and continents with respect to the air circulation may be an important cause of ice sheet and glaciation.

Conclusion

- The contiguous assembly of continents from South America, Africa, via Antarctica, India to Australia, forming Late Paleozoic-Early Mesozoic Pangean supercontinent, named as Gondwana, bounded by Panthalassa in the south and Tethys in the north, developed

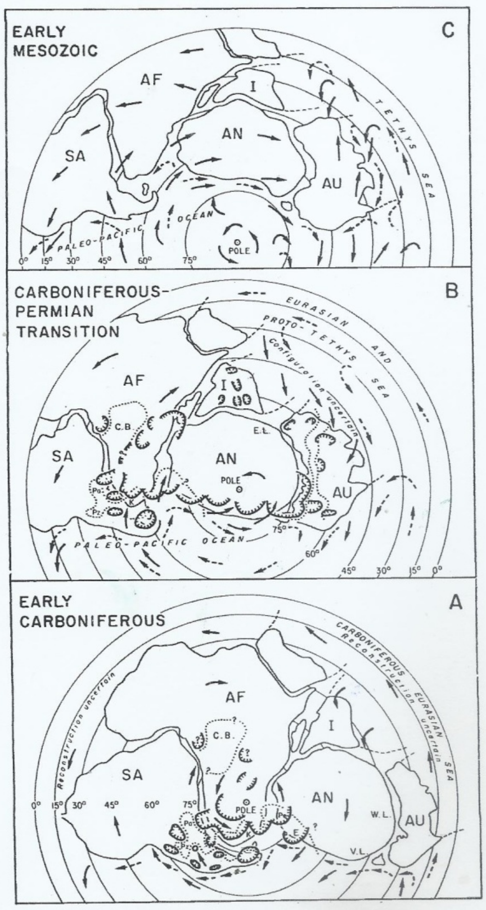


Figure: 15. Schematic diagrams showing the position of Gondwana: (A) during the Early Carboniferous;(B) near the time of the Carboniferous-Permian transition; and (C) Early Mesozoic. Ocean currents shown as dashed arrows, winds as soilid arrows, epeiric seas as bounded by dotted line, and ice centres with hatured lines Alphabets indicate: AF, Africa; AN, Antarctica; AU, Australia; CB, Congo Basin; E, Ellsworth Range; I, India; K, Karoo Basin; PA, Parana Basin; Pa, Pensacola Mt.; SA, South America; V.L., Victoria Land; W.L., Wilkes Land (after Crowell,1978, fig.5).

multiple depositional basins to provide a prolonged history of sedimentation. The Permo-Triassic mega-assemblage so developed and referred to as Pangean Mega Sequence (PMS), the term synonymous with the term Lower Gondwana of Indian stratigraphy, exhibits striking similarities of lithofacies in response to similar if not identical paleoclimate through space and time.

A micro shift of Afro-Arabia or of Gondwana as a whole towards the equator was assumed to explain the amelioration of the post-Sakmarian/postglacial climate. Northerly shift of Permian Africa, however, was a remote possibility as stated earlier. Besides, pole drifting the arrangement of Permian seas and continents with respect to the air-ocean circulation is probably an cause of glaciation.

References

Acharyya, S.K., Shah, S.C., Ghosh, S.C and Ghosh, R.N. (1979). Gondwana of Himalaya and its Stratigraphy. *Proc. IV Intern. Gondwana Symposium, 1977*, Geol. Surv. India, Calcutta, 2, 420-430.

Al-Laboun A.A. (1987). Unaytah Formation: a new Permian-Carboniferous Unit in Saudi Arabia. *Amer.Assoc. Petrol. Geol.,* Bull. 71, 29-38.

Alsharan, A.S. (2006). Sedimentological character and hydrocarbon parameters of the Middle Permian to Early Triassic Khuff Formatio*n. United Arab Emirates. GeoArabia*, 11, 121-158.

Archbold, N.W. (2001). Post-Gondwana, Early Permian (Asselan-Sakmarian-Artinskian) correlations. *In:* Weiss, R. H. (Ed.) *Contributions to Geology and Palaeontology of Gondwana in Honour of Helmut* Wopfner. Geological Institute, University of Cologne, 29-33.

Barrett, Peter (1969). Stratigraphy and Petrology of the mainly flluviatilePermian and Triassic Beardmore Glacier Area, Antarctica. *Institute of Polar Studies, The Ohio State University, Columbus Ohio, USA,* Report No. 34, August 1969, 1-132.

Braakman, J.H., Levell, B.K., Martin,T.H., Potter,T.L. and Van Vliet,A. (1982). Late Palaeozoic gondwana glaciation in Oman, *Nature*, 299, 48-50.

Casshyap, S.M. (1970). Sedimentary cycles and environments of deposition of the Barakar Coal Measures of Lower Gondwana, India. *Jour. Sedimet. Petrol.* 40, 1302-1317.

Casshyap, S.M. (1973). Paleocurrents and paleogeographic reconstruction of the Barakar (Lower Gondwana) sandstones of Peninsular India. *Sediment. Geol.,* 9, 283-303.

Casshyap, S.M. (1976). Paleocurrents and continent assembly: a compaarision from Permian coal Measures of South Africa, Antarctica, India, and

Australia. Abstract: *25th Intern Geol. Congr Sydney,* 238-239.

Casshyap, S.M. (1977). Sedimentation trends in Gondwana basins. Key Paper, *IV Intern. Gondw. Symp., Geol. Surv. India, Calcutta*, 1-34.

Casshyap, S.M. (1979). Paleocurrents and basin framework: an example from Jharia coalfield. *Proc. IV Intern. Gondw. Symp. India, 1977, Geol. Surv. India,* Calcutta, 2, 826-842.

Casshyap, S.M. (1981a). Lithofacies analysis of Late Permian Raniganj coal measures (Mahuda basin) and their paleogeographic implications. *In: Cresswell, M.M. & Vella, P. (Eds.) Gondwana Five,* A. Balkema, Rotterdam, 29-83.

Casshyap, S.M. (1981b). Paleogeography and paleodrainage of the Son Valley Gondwana basins, Madhya Pradesh. In: *Valdiya, K.S., Geology of Vindhyachal.* Hindustan Publ. Corp., Delhi, 132-142.

Casshyap, S.M. (1999). Southern Pangea Gondwana / Karoo super sequence of India and neighboring Cratonic platforms of Central Gondwanaland: Stratigraphy, sedimentation and paleogeograp*hy. Presidential Address, ESS Section, 86th Session of Ind. Sci. Congress, 1999, 1-51.*

Casshyap, S.M & Qidwai, H.A. (1971). Paleocurrent analysis of Lower Gondwana sedimentary rocks, Pench Valley coalfield, Madhya Pradesh (India). *Sediment. Geol*., 5, 135-145.

Casshyap, S.M. & Khan, Z.A. (981) Entropy in Markov chain analysis of Late Paleozoic cyclical coal measures of East Bokaro basin, Bihar, India. *Jour. Mathem. Geol.,* 13, 153-162.

Casshyap, S.M. and Khan, Z.A. (1982). Paleohydrology of Permian Gondwana streams in Bokaro basin, Bihar, India. *Jour. Geol. Soc. India,* 23, 419-430.

Casshyap, S.M &Tewari, R.C. (1982). Facies analysis and paleogeographic implications of a Late Paleozoic glacial outwash deposit, Bihar, India. *Jour. Sediment. Petrol.,* 52, 1243-1256.

Casshyap, S.M & Tewari, R.C. (1984). Fluvial models of the Lower Permian coal measures of Son-Mahanadi and Koel-Damodar Valley basins, India, *Spl. Publ. Intern Assoc. Sedimentology*, 7, 121-147.

Casshyap, S. M., Kreuser, T. & Wopfner, H. (1987). Analysis of cyclic sedimentation in the Lower Permian Mchuchuma coalfield (Southwest Tanzania). *Geol. Rundschau,* 76. 869-863.

Casshyap, S.M. and Kumar, Ajay. (1987). Fluvial architecture of the Upper Permian Raniganj coal measure in the Damodar basin, Eastern India. *Sediment. Geol.* 51, 181-213.

Casshyap, S.M & Srivastava, V.K. (1988). Glacial and postglacial Talchir sedimentation in Son-Mahanadi Gondwana basin: paleogeographical reconstruction. In: McKenzie, G.D. (Ed.) *Gondwana Six, Amer. Geophy. Union, Monograph*, 41, 167-182.

Casshyap, S.M & Tewari, R.C. (1988). Depositional model and tectonic evolution of Gondwana basins. The *Paleobotanist,* 16, 59-66.

Casshyap, S.M. and Tewari, R.C. (2001). Lithofacies and sedimentation of Mid. Permian Lower Gondwana red beds of eastern Peninsular India. In; Weiss, R.H. (Ed.) *Contributions to Geology and Palaeontology of Gondwana in Honour of Helmut Wopfner*. Geological Institute, University of Cologne, 63-72.

Casshyap, S.M., Tewari, R.C. and Srivastava, V.K. (1993). Origin and evolution of intracratonic Gondwana basins and their depositional limits in relation to Narmada-Son Lineament. In: Casshyap, S.M., Valdiya, K.S., Khain, V.V., Milanovsky, E.E. and Raza, M. (Eds.), *Rifted Basins and Aulacogens: Geological and Geophysical Approach*. *Gyaanodaya Prakashan, Nainital, India*, 200-215.

Catuneanu, O, Wopfner, H., Cairncross, B., Rubidge,B.S., Smith, R.M.H. and Hancox, P.j. (2005). In:Catuneanu, O., Guirand, R., Eriksson, P. , Thomas, B., Shone, R., Key, R (Eds.) The Karoo basin of south-central Africa: Phanerozoic Evolution of Africa. *Jour. of African Earth Sciences,* 43, 211-253.

Crowell, J.C. (1978). Gondwana glaciation, cyclothems, continental positioning and climatic change. *American Jour. Sci.,* 278, 1345-1372.

Frakes, L.A., Kemp, E.M. and Crowell, J.C. (1975). Late Palaeozoic glaciation: Part VI, Asia. *Geol. Soc. America Bull.,* 86. 454-464.

Gaetani, M. and Garzanti, E. (1991). Multicyclic history of the Northern India continental margin (North-West Himalaya). Ameriican *Assoc. Petrol. Geol. Bull.* ica75, 1427-1446.

Kruck,W. and Thiel, J.C. (1983). Late Palaeozoic glacial deposits in the Yemen. *Geologisches Jharbuch (B),* 46, 3-29.

Levell, B.K., Braakman, J.H and Rutten, K.W. (1988). Oil-bearing sediments of Gondwana glaciation in Oman. *American Assoc. Petrol. Geol. Bull*., 72, 775-796.

Lopez- Gamundi (1997). Glacial-Post-glacial transition in the Late Palaeozoic basins of southern South America. *In: Martini, I.P. (Ed.) Deglaciation and global changes: Quaternary, Permo-Carboniferous and Proterozoic. Oxford University Press, Oxford*, 147-168. 2, 409-416.

Metcalfe, I. (1988). Origin and assembly of Southeast Asian continental terrannes. In: Audley-Charles, *M.G. and Hallam,A. (Eds.) Gondwana and Tethys.Geol. Soc., London*, Special Publ., 37, 101-118.

Mitra, N.D. (1991). The sedimentary history of Lower Gondwana coal basins of Peninsular India. In: Ulbrich, H. and Rocha Campus, A.C. (Eds.) *Gondwana Seven, Proc. Seventh Gondwana Symposium, Institute of Geosciences, Universidade de Sao Paulo*, 273-288.

Mitra, N.D. (1993). Tectonic history of Lower Gondwana basins of Peninsular India. In: *Casshyap, S.M.,Valdiya, K.S., Khain,V.K., Milanovsky, E.E. and Raza, M. (Eds.) Rifted basins and Aulacogens; Geological and Geophysical Approach.* Gyanodaya Prakasan, Nainital, 216-221.

Nakazava, K and Kapoor, H.M. (1979). Correlation of the marine Permian in the Tethys and Gondwana.*Proc. IV Intern Gondw. Symp., Calcutta*, 2 409-416.

Powell, C.M. and Li, Z.X. (1994) Reconstruction of the Panthalassan margin of Gondwanaland. In: Veevers J.J. and Powell, C.McA (Eds.) *Permian-Triassic Pangean Basins and Foldbelts along the Panthalassan Margin of Gondwanaland. Geol. Soc. of America, Boulder, Memoir* 184, 5-10.

Rust, L. C. (1975). Tectonic and sedimentary framework of Gondwana basins in southern Africa. In: Campbell, K.S.W. (Ed.) *Gondwana Geology. Australian National University Press, Canberra*, 537-564.

Scotese, P.Z. and Langford, R.P. (1995). Pangea and the Palaeogeography of the Permian. *In: Scholle, P.A., Peryt, T.M. and UlmerScholle, D.S. (Eds.) The Permian of Northern Pangea. Vol. I: Palaeogeography Palaeoclimatic Stratigraphy.* Spriger, Berlin, 3-19.

Sengor, A.M. (1998). Die Tethys: vor hundert jahren und heute. *Mitteilungen der Osterreichischen Geologischen Gesellschaft*, 89,5-177.

Smith, A.J. (1969). Evidence of a Talchir (Lower Gondwana) glaciation: striated pavement and boulder Bed at Irai, central India, *Jour. Sediment. Petrol*., 33, 739-750.

Smith, R.M.H., Eriksson, P.G. and Botha, W.J. (1993). A review of the stratigraphy and sedimentary environments of the Karoo-aged basins of Southern Africa. *Jour. African Earth Sci,* 16, 143-169.

Stratton, T. (1970). Tectonic framework of sedimentation during the Dwyka period in South Africa. *Second Gondwana Symp. Proceedings and Papers, Pretoria, South Africa*, 483-490.

Taveren-Smith, R. (1982). Prograding coastal facies associations in Vryheid Formation (Permian) at Effingham Quarries, near Durban, South Africa. *Sediment. Geol*., 32, 111-140.

Tewari, R.C. and Veevers, J.J. (1993). Gondwana basins of India occupy the middle of a 7500 km sector of Radial valleys and loibes in central-eastern Gondwana. *Gondwana Eight*, Balkema, Rotterdam, 507-512.

Veevers, J.J. and Powell, C.M. (Eds.) (1994). Permian-Triassic Pangean Basins and Foldbelts along the Panthalassan Margin of Gondwanaland. *Geol. Soc. America, Boulder*, Memoir 184.

Veevers, J.J. and Tewari, R.C. (1995). Gondwana Master Basin of Peninsular India. *Geol. Soc. America,* Memoir 187, 72p.

Verma, R.P. and Singh, V.K. (1979). A chronology of tectonics and igneous activity in Damodar Valley coalfields. *Proc. IV Intern. Gondw. Symp., 1977, Geol. Surv. India, Calcutta*, 2, 901-907.

Visser, J.N.J. (1989). The Perm-Carboniferous Dwyka Formation of Southern Africa: deposition by a predominantly sub-polar marine ice sheet. Palaogeog., Palaoclimat.,Palaoecol., 118, 213-243.

Visser, J.N.J. (1997). A review of the Permo-Carboniferous glaciation in Africa. In: *Martini, I.P. (Ed.) Deglaciaation and Global changes: Quaternary, Permo-Carboniferous and Proterozoic. Oxford University Press, Oxford*, 169-191.

Wopfner, H. (1991). Extent and timing of the Late Palaeozoic glaciation in Africa. *Festschrift Karl* Brunnacker*, University zu Koln,* 82, 447-453.

Wopfner, H. (1994). The Malagasy Rift, a chasm in the Tethyan margin of Gondwana. *Jour. Southeast* Asia *Earth Sci.,* 9, 456-461.

Wopfner, H. (1999). The Early Permian deglaciation event between East Africa and northwestern Australia. *Proc. of the Tenth Gondwana Symp., Cape Town. Jour. of African Earth Sci*, 29, 77-90.

Wopfner, H. (2002). Tectonic and climatic events controlling deposition in Tanzanian Karoo basins. *Jour. African Earth Sci.* 34, 167-17.

Wopfner, H. (2012). Late Palaeozoic-Early Triassic deposition and climates between Samfrau and Tethys: A review. *Geol. Soc., London Special Publication published online, Nov. 26, 2012*:10. 1144/SP, 376.4.

Wopfner, H. and Kreuser, T. (1986). Evidence for Late Palaeozoc in Southern Tanzania. *Palaeogeog., Palaeoclimat., Palaeoecol*., 56, 256-275.

Wopfner, H. and Diekmann, B. (1996). The Late Palaeozoic Idusi Formation of Southwest Tanzania: A Record of change from glacial to postglacial conditions. *Jour. African Earth Sci.*, 22, 575-595.

Wopfner, H. and Casshyap, S.M. (1997). Transition from freezing to subtropical climates in the Permo- Carboniferous of Afro-Arbia and India. In: Martini, I.P. (Ed.) *Deglaciation and Global changes: Quaternry, Permo-Carboniferous and Proterzoic. Oxford University Press, Oxford,* 192-212.

Wopfner, H. and Jin, X.C. (2009). Pangean Mega sequences of Tetyan Gondwana-margin reflect global changes of climate and tectonism in Late Paleozoic and Early Triassic times – a review. *Paleoworld,* 18, 169-192.