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Indian Gondwanas and their global analogues

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Abstract

Presence of hydrocarbons has been established in Gondwana sediments in various parts of India and also the world which were once the parts of the Gondwanaland. In the present study an endeavour has been made to gather and synthesize data indicating their tectono-stratigraphic set up vis a vis hydrocarbon potential. Parana Basin of Brazil, Karoo of South Africa, Cooper and Carnavoron Basin of Australia, Mandapeta Field of Indian Krishna Godavari Basin etc. have been part of this study with a humble attempt to envisage hydrocarbon potential of Indian Gondwana in light of their global analogues.

Introduction

Gondwana basins, representing about 200 Million years of geological record, with large repository of coal, carbonaceous shale and sandstone are capable of generating, migrating and entrapping conventional hydrocarbon in addition to their promising potential for CBM. Basins in the Indian peninsula, their equivalents in extra-peninsular region and globally in different continents (Fig.1) which once formed the Gondwanaland, can prove to be encouragingly prospective, if extensively explored. In spite of challenges in terms of lack of quality reservoirs and regional caps, basaltic cover, criss-cross network of basic sills and dykes, some of these are already producing hydrocarbons both in India and other parts of the world. Mukhopadhyay et. al., 2010 have attempted correlation of Indian Gondwana basins. Initial sedimentation (Talchirs) in Indian Gondwana basins during latest Carboniferous in sag type basins over the Precambrian basement through multiple deglaciation, coal bearing fluvial Karharbari Formation in small subsidiary basins, near Marine conditions in Lower barakar deposition in deeper basinal part, subsequent regressive phase with deposition of coal bearing part of Barakar Formation in a tectonically active environment, clay dominated upper part of Barakar Formation and overlying Barren Measures, succeeding regressive phase with deposition of Raniganj, large scale extinction occurred across the plant and animal kingdom all over the earth during latest Permian with temporary cessation of sedimentation in most of the Gondwana Basins of India, renewed sedimentation under an arid environment with advent of Triassic, followed by a period of nondeposition, basinal tilting, erosion and major faulting and a distinctly different depositional milieu with changed nature of sediments during Early Jurassic, opening of new basins during Middle Jurassic along the western margin of Peninsular India, separation of eastern Gondwana from western Gondwana, last phase of sedimentation during Early Cretaceous (Aptian-Albian), opening up of Pericratonic basins along the eastern coast, extrusion of tholeiitic lava in the form of Rajmahal Trap and Lamprophyre dykes/sills and searation of India from Antarctica and Australia marking the end of the history of Indian Gondwana basins.

Indian Gondwana basins

Gondwana sediments have been preserved in basins like Damodar-Koel, Satpura, South Rewa, Pranhita-Godavari, Wardha-Kamptee, Hasdo-Mahanadi and Rajmahal–Malda–Purnea-Galsi in linear rift related half grabens in peninsular India (Fig.2). Some of these have shown thermogenic gas both as seepages and in drilled wells reinforceing their generation potential (Pradhan et. al., 2012). Besides, factors like favourable source rock prospects in Lower Gondwana, potential sandstones reservoirs with moderate to good porosity and permeability within Lower and Upper Gondwana, operative sealing system in a number of local and intermediate fairly continuous argillaceous intervals in the fining upward cycles, effective entrapments in Late Permian fault closures and anticlines as well as gas migration during Mid Triassic onwards, offer enough encouragement for pursuing exploration with renewed vigour. Gas proved in Mandapeta Field, KG Basin, indications in other Indian Gondwanas including CBM and shale gas from Damodar Basin and evidences from NonIndian analogues provide further justification of the view. Current level of knowledge on possible Gondwana basins concealed beneath extensive basic extrusive cover in central and western India leave aside their hydrocarbon potential, is far from satisfactory.

Global Analogues

Gondwana sediments present now in different continents of the globe were once upon a time in geological past part of a major landmass called Gondwanaland (Fig.1). Parana, Reconcavo in South America, Karroo in Africa including Lamu Basin of Kenya, Cooper, Canning, Carnavoron, Browse, Arafura etc. in Australia to name a few, have been briefly discussed in the paper.Kraus et. al., 1996 investigated the evolution of Australia's rifted northwestern margin including the Permo- Cretaceous stratigraphy of the five major basins, the Bonaparte, Browse, Canning, Carnarvon, and Perth and prepared paleogeographic maps as a prerequisite for studying petroleum systems. The palynological work on the Carboniferous–Permian strata of presently scattered Gondwanan continents (Irfan U Jan, 2014) is mostly related to coal (in India, Australia and South America) and oil exploration (in Arabia and South America).

Canning Basin, Australia: The pericratonic Early Ordovician to Early Cretaceous Canning Basin with more than 10 km thick sediment fill in Fitzroy Trough-Gregory Sub-basin complex in north and the Willara Sub-basin-Kidson Sub-basin complex in south. In offshore the basin is divided into Oobagooma Sub-basin/Fitzroy Trough, Broome Platform, Willara Sub-basin, Samphire Embayment, Wallal Platform and Wallal Embayment.Different phases of basin evolution have been reported: 1.Early Ordovician extension and rapid subsidence and deposition and Late Ordovician and Silurian sag stage(evaporitic and playa), 2. Earliest Devonian minor folding, regional uplift and erosion with laterally extensive, aeolian and terrestrial deposits, 3.Mid-Devonian extension, rifting and rapid subsidence interrupted by tectonic pulses (conglomerate influx) along the northern margins, 4. Mid-Carboniferous compression and inversion of Devonian normal faults marked by syntectonic fluvial deposits, 5. Early Permian extension and rapid subsidence, widespread transgression following the glaciation and 6.Late Triassic - Early Jurassic regional dextral wrench movements, uplift and erosion, extensive molasse deposition followed by deposition of fluvio-deltaic and marine sediments. Hydrocarbon production is currently from Permo-Carboniferous sandstones (Lloyd, Sundown, etc) and Devonian carbonates (Blina) with many shows from Ordovician to Permian rocks. Proven plays include draped bioherms, anticlinal closures and tilted fault blocks. Untested plays include unconformities, fault rollovers, diapirs and stratigraphic traps.

Cooper Basin, Australia: Late Carboniferous to Middle Triassic Cooper Basin, a NE-SW trending intracratonic basin in nonmarine depositional setting in South Australia and Queensland, lies unconformably over early Palaeozoic Warburton Basin due to Devonian–Carboniferous Alice Springs Orogeny and is overlain disconformably by the central Eromanga Basin. Gidgealpa – Merrimelia – Innamincka ridge and Murteree ridge separate the basin into three troughs, viz., Patchawarra, Nappamerri and Tenappera with 2.5 km thick PermoCarboniferous to Mid Triassic sediments overlain by as much as 1.3 km of Jurassic-Tertiary cover Late Carboniferous to Late Permian Gidgealpa Group and Late Permian to Middle Triassic Nappamerri Group have non-marine sequences. The Late Carboniferous to Early Permian Merrimelia Formation and Tirrawarra Sandstone are deposited unconformably on a glacially scoured landscape. The Tirrawarra Sandstone (braided fluvial to fan-delta deposits) is overlain by peat swamp and floodplain facies of the Patchawarra Formation. Locally (e.g. Pondrinie Field), Merrimelia aeolianite forms a major gas reservoir. Murteree and Roseneath lacustrine shales with intervening Epsilon and Daralingie fluviodeltaic formations are overlain by Early Permian uplift and erosion, Late Permian Toolachee Formation and Late Permian to Middle Triassic Arrabury Formation and the Middle to early Late Triassic Tinchoo Formation. Thick Permian carbonaceous shale as source with type III kerogens, fluviodeltaic and shoreface sandstone as reservoir, lacustrine shales as seals, and faulted anticlines as major entrapments in this has been tested by a large number of wells. The oil window is as shallow as 1250m. Oils and condensates are typically medium to light and paraffinic. Most Permian oils contain significant dissolved gas and show no evidence of water washing. Local source rocks being in the 'oil window', the Patchawarra Trough contains the bulk of the oil and wet gas reserves. Hot Nappamerri Trough, underlain in part by granite, is over mature and contains mainly dry gas. Source and reservoir are in Toolachee and Patchawarra formations and reservoirs also in the Epsilon and Daralingie shoreface and delta distributary sands and low-sinuosity fluvial sands within the Tirrawarra. Towards basin margin, oil is also produced from the Patchawarra Formation and from fluvial channel sands in the Merrimelia Formation in Malgoona Field. Paning and Wimma Sandstone members form economic oil and gas reservoirs, and high-sinuosity fluvial sandstone of the Tinchoo Formation reservoirs oil. Early Permian Roseneath and Murteree shales and Triassic Arrabury Formation provide regional seals. Anticlinal and faulted anticlinal traps and stratigraphic and sub-unconformity traps are important exploration targets.

Economic oil and gas are reservoired in the Nappamerri Group, paradoxically regarded as a regional seal to the Cooper Basin .

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Carnarvon Basin, Australia: The Carnarvon Basin in Western Australia extends both in onshore and offshore, has not been extensively explored and without any commercial Paleozoic petroleum. The Northern Carnarvon Basin includes the Exmouth Plateau, Wombat Plateau, I Sub-basin, Rankin Platform, Dampier, Exmouth, Barrow, Investigator and Beagle sub-basins, Enderby Terrace, Peedamullah Shelf and the Lambert Shelf. The Southern Carnarvon Basin consists of the Gascoyne, Merlinleigh, Bidgemia and Byro Sub-basins and Bernier Platform and is flanked to the east by the Archaean Pilbara Block. Four Paleozoic petroleum systems have been reported charged by source rocks in the oil-prone Silurian Coburn Formation, Devonian Gneudna Formation on the Gascoyne Platform peaked during the Carboniferous–Permian, Lower Permian gas-prone Wooramel Group of the Merlinleigh Subbasin peaked during the Late Permian and Upper Permian Kennedy Group peaked during the Cretaceous in the Peedamullah Shelf. Five discrete regional thermal maximum episodes within the Tertiary, Cretaceous, Jurassic, Permian, and Carboniferous have earlier been recognized (Ameed K et. al., 2005). Envisaged entrapment conditions due to MidCarboniferous – Lower Permian rifting precede possible hydrocarbon generation and migration from Silurian–Devonian and Lower Permian source rocks during the Early Permian and Permian–Triassic, respectively. The complex and varied depositional and erosional history of the basin, however, implies preservation is a major exploration risk. In addition, imaging of likely traps in the Southern Carnarvon Basin remains problematic with the existing seismic data, especially in the onshore part of the Gascoyne Platform where the seismic data are too sparse to map horizons, and data quality below the Cretaceous is usually extremely poor (Mory, A. J. et. al., 2003).

Browse Basin, Australia: The Late Carboniferous-Cainozoic Browse Basin in NW Australian offshore with established oil, condensate and gas reserves is reported to have been developed during six major tectonic phases: Late Carboniferous to Early Permian extension (Caswell and Barcoo Sub-basins with 15 km sed fill); Late Permian to Triassic thermal subsidence; Late Triassic to Early Jurassic inversion; Early to Middle Jurassic extension; Late Jurassic to Early Tertiary thermal subsidence; and Late Miocene inversion. The fluvio-deltaic Carboniferous, marine Permian-Early Triassic, fluvial and shallow marine Middle-Late Triassic, deltaic and coastal-plain Early-Middle Jurassic syn-rift sediments, occurred in the Callovian erosion and Upper Jurassic regional seal, Valanginian-Turonian transgressive open marine claystones and Turonian-Tertiary progradational clastic-to-carbonate cycle, Early Cretaceous claystones as regional seal and oil-prone source rocks. Potential source rocks also occur in the Late Jurassic, Middle-Early Jurassic, Triassic and syn-rift Palaeozoic sections. Reservoir facies are best developed within the fluvio-deltaic Middle-Early Jurassic section and submarine fans of Berriasian, Barremian, Campanian and Maastrichtian age. Four hydrocarbon families are present (Kennard *et al*. 2004) viz. from Jurassic dry gas-prone mixed terrestrial and marine source,Middle-Lower Jurassic wet gas/condensate-prone mixed terrestrial and marine source, Early Cretaceous oil and gas-prone marine algal and bacterial source and Permian or Jurassic high maturity dry gas-prone source.

Perth Basin, Australia: Perth Basin, a Permo-Cretaceous north-south trending elongate rift-trough system in west coast of Australia, with a number of Permian and Mesozoic petroleum systems proven by thirty significant discoveries. Petroleum system analysis indicates that mature source rocks are widespread, reservoirs are abundant, and structures are well-timed for hydrocarbon entrapment. The Darling Fault in the east with a cumulative throw of up to about 11 km has fundamentally controlled basin development and patterns of subsidence. The Dandaragan Trough is the main depocentre and kitchen with the Permian–Triassic section within the oil window. In the BunburyTrough the Early Cretaceous thermo-tectonic event resulted in widespread injection and flows of doleritic rocks. Petroleum-system analysis indicates that mature source rocks are widespread, reservoirs are abundant, and structures are well-timed for hydrocarbon entrapment. With Lower Permian Irwin River Coal Measures and Cattamarra Coal Measures as gas source, Lower Triassic basal Kockatea Shale as oil source, Lower Triassic and Permian sandstones (Dongara sst) as reservoir, intraformational shales as local seals and Kockatea Shale and Cadda Formation as regional seals, the identified prospective areas are Beagle-Dongara Ridge–Dandaragan Trough and fault traps in terraces along the basin's southern margin. In southern Perth there is no thick regional seal and the Cattamarra Coal Measures have been targeted on structural highs as in the case of the Mount Horner oilfield. (www.ga.gav.au)

Arafura Basin, Australia: The Neoproterozoic to Palaeozoic Arafura Basin on the northern Australian margin is underlain by the Proterozoic McArthur Basin and the Archean to Proterozoic Pine Creek Inlier and overlain by the Mesozoic to Recent Money Shoal Basin. The northwest trending asymmetric Goulburn Graben in the basin with 10 km thick sedimentary fill is in between the northern depocentre 15 km thick sediments and southern north-dipping relatively undeformed ramp with as much as 3 km thick sedimentary rocks. Major events in basin evolution include Neoproterozoic upper crustal extension (Wessel Group), Cambro-Ordovician subsidence, Late Devonian and Late Carboniferous to Early Permian were separated by long, tectonically quiescent periods of non-deposition and erosion. The predominantly marine carbonates of the Cambro-Ordovician Goulburn Group are overlain by shallow marine to non-marine clastics and carbonates of the Devonian Arafura Group and fluvio-deltaic clastics of the Late Carboniferous to Early Permian Kulshill Group equivalent. The Goulburn Graben formed in the Late Carboniferous to Early Permian in response to oblique extension associated with the break-up of Gondwana. Subsequent contraction in the Triassic resulted in oblique inversion of the Goulburn Graben, uplift and erosion of up to 3.5 km of sediment. The deformational event affected areas to the north and south of the Goulburn Graben to a lesser extent. Subsequent erosion resulted in formation of a peneplain across the basin upon which the sediments of the Money Shoal Basin were deposited. An oil and gas show in drilled well and presence of essential petroleum system elements including potential Palaeozoic and Mesozoic source and reservoir rocks and a thick regional seal in the overlying Money Shoal Basin sediments. The lack of commercial success has been attributed to a combination of poor quality reservoirs, restricted fluid movement, hydrocarbon charge, timing of events and breach of structure. However, despite the current lack of success, there are numerous indicators for untested petroleum potential, particularly in the undrilled northern region of the basin: The petroleum systems elements found in the Goulburn Graben are also likely to be present in the northern region. Many of the risks identified in the Goulburn Graben are reduced in the northern region (shallower reservoirs, reduced charge risk and reduced risk of breached structures). A wide range of play types are present, ranging from faulted anticlines and sub-unconformity plays in Palaeozoic strata to fault block plays and numerous stratigraphic plays in Mesozoic strata. Oil shows and gas indications in the majority of wells drilled, and the presence of interstitial solid bitumens in many samples are testimony for generation and migration of hydrocarbons in the basin.

Karoo Basins, South Africa: Covering two-thirds of Southern Africa, the retroarc foreland Karoo Basin was formed during the formation and breakup of Pangea. This basin was formed by the subduction and orogenesis along the boundary of Gondwana (the past African continent) and the Panthalassan Sea (paleo-Pacific). Its sediments as thick as 12 km are overlain by 1.4 km thick basaltic lavas (the Drakensberg Group). The Karoo Supergroup is divided into the following strata (from oldest to youngest): Dwyka Group (glacial marine), Ecca Group, Beaufort Group (terrestrial) and Stormberg Group (including basalts). The Palaeozoic part of the succession consists of glaciogenic deposits succeeded by mudrock-dominated marine and brackish to fresh water sediments deposited contemporaneously with sand-dominated fluvio-deltaic systems which prograded into the basin from the northeast and south (Johnson MR et. al., 2005). The non-marine Mesozoic succession is confined to the central part of the basin where it consists of the Katberg and Burgersdorp Formations, overlain by the Molteno, Elliot and Clarens Formations comprising fluvio-lacustrine deposits laid down under conditions of increasing aridification, culminating in the onset of desert conditions and deposition of the predominantly Aeolian Clarens Formation. The latter three formations are informally named the Stormberg group (Mid Triassic-Mid Jurassic) which forms a southeast thickening clastic wedge capped by the Drakensberg Volcanic Group (Mid Jurassic). The Molteno Formation at the base of the Stormberg group comprises three northerly thinning clastic wedges of vertically stacked coal-bearing cycles enclosed within a sequence of arid to semi-arid fluvio-lacustrine red beds capped by aeolian sandstones. As yet very little systematic modern exploration for petroleum has been done. The basin has promising potential for conventional and unconventional hydrocarbons. A fresh look is also being taken into the occurrences of oil in sandstones of the Ecca and Beaufort Group in a wide arc across the northern and north-eastern parts of the basin.

Parana Basin, South America: The Paraná Basin typical intra-cratonic elliptical flexural basin spread mainly in Brazil, eastern Paraguay, northeastern Argentina and northern Uruguay is related to the convergence between the Gondwanaland and Panthalassa.. The basin has 7 km thick Ordovician to the Cretaceous infill divided into the following six second order allostratigraphic supersequences bound by distinct depositional hiati, due to erosion. Rio Ivaí Supersequence of Late Ordovician to Early Silurian age consists of Alto Garças Sandstone Formation, glacial Rio Ivaí Formation and the fossil rich muddy Vila Maria Formation. Paraná Supersequence comprises of the basal Devonian sandstones of the Furnas Formation and on the top the Ponta Grossa Formation with muddy, macrofossils-rich potential petroleum source rock. The Carboniferous to Early Triassic Gondwana I Supersequence with Early Carboniferous major glaciation (Karoo Ice Age) forming huge glacial deposits composed mainly by sandstones, diamictites, conglomerates and muddy rocks (Itararé Group) followed by Late Carboníferous deglaciation and Middle Permian Rio Bonito sandstones Formation with Glossopteris flora and the huge coal deposits. Finally, the Late Permian Irati Formation is represented by bituminous shale, a potential petroleum source rock, with Mesosaurus fauna. The top of this supersequence defines the end of the marine phase. Gondwana II Supersequence consists of Triassic continental sedimentation with reptile and mammal fauna. The Late Jurassic to Early Cretaceous Gondwana III Supersequence is represented by the desertic Botucatu Formation of still united Gondwana and flood basalts of Serra Geral Formation associated with the rifting of Gondwana and the opening of the South Atlantic Ocean during 137 to 127 Ma. The Cretaceous Bauru Supersequence in the north-central part of the basin is composed mainly of sandy-conglomeratic deposits.The Barra Bonita field is one important gas field in the basin. Hydrocarbons are also being extracted from oil shales in the Irati Formation.

Reconcavo Basin, Brazil: The Recôncavo Basin covering an area of about 10,000 km^2 is the southernmost part of the Recôncavo-Tucano-JatobáBasin (NE Brazil) an elongated N-S rift with several half-grabens united by interaction during the Neocomian, Barremian and early Aptianas break of the Gondwana continent and consequent Africa and South America formation. The pre rift with continental sediments deposited during the Permian to Jurassic, containing the main reservoirs. This sequence represents the subsidence stage and consequent formation of an intracratonic basin in which the continental sediments of the Brotas Group accumulated. The Sergi Formation is part of the last sedimentation stage of the Brotas Group and represents a continental depositional system characterized by alternating fluvial-eolian sandstones and red lacustrine mudstones. The rift sequence composed by continental sediments from lacustrine origin at the base, changing laterally and vertically to deltaic and fluvial domains at the top, this section contains the main source rocks. The post-rift sequence with little thickness is Aptian to Recent in age. The Recôncavo Basin, basically a half-graben extending in a NE direction is subdivided into three main compartments by Mata Catu Fault – a released normal fault and Itanagra Araças, a transfer fault. An interesting feature is the Alagoinhas Low that formed mainly at the end of rift stage. The main source rock sequence is the lacustrine freshwater shale of the lowermost Cretaceous Gomo Member of the Candeias Formation. Reservoir rocks are found within the Late Jurassic pre-rift Aliana and Sergi Formations as well as in the syn-rift Candeiras and Marfim Formations (turbiditic sands). While the pre-rift reservoirs are predominantly structural traps formed during the rifting, the syn-rift reservoirs consist mainly of stratigraphic traps. Geochemical and basin modelling of the Reconcavo Basin (Rudkiewicz et al., 2000) indicates that petroleum generation and migration started during the Aptian and continue up to the present in certain parts of the system.

Lamu Basin, Kenya: This fault bounded basin in southeast Kenya onshore and offshore was formed due to Paleozoic-early Mesozoic rifting at the onset of Gondwana disintegration filled by Permian-Early Jurassic Karroo continental siliciclastic sediments and Middle to Late Jurassic Carbonate deposits associated with the Tethyan sea invasion. Cessation of the relative motion between Madagascar and Africa in the Early Cretaceous heralded passive margin development and deltaic sediment progradation until the Paleo-gene. Shallow seas transgressed the basin in the Miocene when another carbonate regime prevailed.The basin depositional history is characterized by pulses of transgressive and regressive cycles, bounded by tectonically enhanced unconformities dividing the total sedimentary succession into discrete megasequences. Paleogene source rock (within Megasequence III) matured in Miocene. A basement high on the continental shelf has potential for Karroo sandstone and Jurassic limestone reservoirs. Halokinesis of Middle Jurassic salt in Miocene provides additional prospects in the offshore area. Paleogene deltaic sands occur in rotated listric fault blocks (Nyagah, K. et. ai.,1996)

Conclusion and recommendation

- Gondwana sediments present in different continents of the world which were once part of the Gondwanaland contribute ingredients which constitute various elements of an effective petroleum system, in addition to their potential for coal and CBM and shale gas.
- A systematic study of the known and proved petroleum system provides impetus for venturing into basins with envisaged ones both in India and other countries.

- Augmenting knowledge base about the nature and hydrocarbon potential of gondwana sediments in frontier areas like extrapeninsular India and subbasalt concealed basins is necessary.

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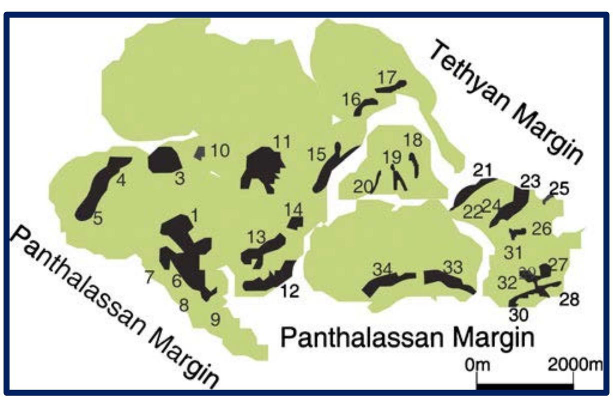
Image



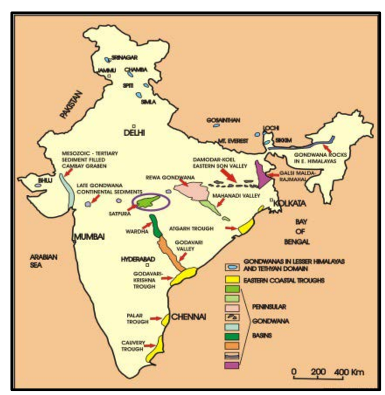


Figure 2. Indian Gondwana basins

Figure 1. Chief Carboniferous–Permian basins of Gondwana.

(1) Paran´a, (2) Chacoparan´a, (3) Parna´ıba, (4)Amazonas, (5) Solim˜oes, (6) Paganzo, (7) Calingasta-Uspallata, (8) San Rafael, (9) Tepuel, (10) Gabon, (11)Congo, (12) Karoo, (13) Kalahari, (14) Zambezi, (15)Tanzanian -Malagasy, (16) Yemen, (17) Oman, (18)Himalayan zone, (19) Satpura, Son-Mahanadi, Koel-Damodar, (20) Godavari, (21) Carnarvon, (22) Collie-Perth,(23) Canning, (24) Officer, (25) Bonaparte, (26) Pedirka,(27) Galilee, (28) Bowen-Gunnedah, (29) Cooper, (30) Sydney,(31) Arckaringa, (32) Murray, (33) Victoria Land, (34)central Transantarctic Mountains (after Stephenson 2008).