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Review paper

Worldwide distribution of the Glossopteris lineage - The significance of crustal and seawater events

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ABSTRACT

In support of the continental drift hypothesis, Alfred Wegener considered Glossopteris to be the dominating vegetation of his Gondwana continental merger near the Permian South Pole. But the plant's supposed ability to thrive in polar conditions has remained an enigma that has sparked a flood of ad hoc ecological mechanisms. Also, the glossopteris group of terrestrial vegetation has remained highly controversial, not least with regard to its distribution to all continents. In an attempt to find a reasonable explanation for the seemingly endless riddle, this article addresses two critical questions: the evolution of seawater and that of the deep-sea crust. The evaluation is based entirely on observational rock facts from the geoscientific literature - not from modelling, including inverted satellite gravity-derived seafloor topography. The analysis brings us back to the palaeontologists' classical land bridges. The Indian Ocean is given special attention. At the end of the Palaeozoic, the original continental crust was still in an early stage of "oceanization", and the generally shallow ocean basins at that time were divided by a network of intercontinental ridges and plateaus. Thus, terrestrial flora and fauna had open migration routes between India, Eurasia, Africa, Australia, Antarctica and the Americas. In the new paleogeographic development scheme, the overwhelming part of the Glossopteris habitat and dispersal routes occurred in tropical to warm mid-latitudes. There are no reasons to believe that glossopteris grew under polar conditions.

Keywords: glossopteris, flora migration, Permian, crustal development, seawater history

Introduction

Since the first description of Glossopteris leaves from India and Australia (Brongniart, 1828), fossils of this dominant late Palaeozoic vegetation have later been discovered in all continents. After Wegener's merger of the southern continents plus India, in association with his late Carboniferous-early Permian South Pole near South Africa, the Glossopteris flora is considered one of the most important pieces of evidence for his Gondwana unification (Wegener, 1929/66). He argued that the Glossopteris flora was confined to high southern latitudes while the northern continents experienced tropical to subtropical climates. However, it has become overwhelmingly clear that the alleged Gondwana flora regime has no northern limits (Krassilov, 2000; McLoughlin, 2011). And more, the northern population is divided into Angaran, Euramerican and Cathaysian flora provinces, yet there are no clear boundaries between them nor with the Gondwanan representatives to the south (McLoughlin, 2011). Hemispherical mixing of Glossopteris flora is an ongoing issue, and the ingrained belief that this forest vegetation grew under polar conditions has triggered a number of biological ad hoc mechanisms.

Against the longstanding biological-climatic controversy, fossil evidence from Antarctica demonstrates that the continent has had a several hundred million years long history in (sub)equatorial setting. Also, deep-sea drilling on the Antarctic margin (Pryds Bay, Ocean Drilling Program (ODP) Leg 119) found flat paleomagnetic inclinations in red sediments consistent with (sub)tropical Devonian palaeolatitudes (Keating and Sakai, 1988). Only in the mid-Tertiary did the Earth acquire its present spatial orientation; after a 35° event of spatial re-orientation, in approximately the Greenwich meridian plane (Storetvedt, 1990), Antarctica gained a corresponding fossil-based climatic shift from sub-tropical to polar conditions - and eventually an alleged ice sheet (cf. Elderfield, 2000). The post-Lower Palaeozoic polar wander path was established by Wegener, but in the south, he compromised his global climate system - which he had based on evidence from the northern continents plus Africa. The presently assumed global Ice Age during late Carboniferous to early Permian, Wegener did not consider the possibility of a global cold spell, like that during the Pleistocene, as an alternative to his reconfiguration of the southern continents (Gondwana). However, geological evidence supporting pre-Pleistocene glaciation may be ambiguous (Molén, 2023), so his diamictite grouping in the Southern Hemisphere may be incorrect and thus undermine his Gondwana concept. Nevertheless, Wegener's continental drift hypothesis created paleoclimatic-biological contradictions, primarily by placing the (sub) tropical Antarctica adjacent to the Permian South Pole. There are reasons to believe that Glossopteris originated in India and from there spread to all continents. But during the more than half century long reign of plate tectonics, observations have multiplied but a coherent paleogeographic explanation is apparently more distant than ever. There must be something fundamentally wrong with how scientists have interpreted the observational basis for Earth's surface evolution, crustal history, and water discharge from the interior (cf. Turekian, 1977; Hunt et al., 1992; Okuchi, 1997; Gold, 1999; Poirier, 2000), and migration of land biota. This article addresses the unresolved problem of Glossopteris dispersal, and in doing so, draws attention to an old but unconventional model of seafloor formation - the oceanization model, which implies that the continental crust has been densified and progressively delaminated from the bottom upwards (Barrell, 1927; Beloussov, 1962, 1990; Anderson, 2012). Specific examples are demonstrated below.

Glossopteris vegetation -a global perspective

The recent discoveries of Glossopteris in Mongolia (Naugolnykh and Uranbileg, 2018) and NE China (Zhang et al., 2004) may be the latest in a long line of observations of this vegetation in Central and North Asia (cf. Sahni, 1936; Zalessky, 1944; Meyen, 1977). This classical India Gondwana flora, first described by Brongniart (1828), from Indian and Australian fossils, probably has its origin from the Damodar, Son-Mahanadi, and Pranhita-Godavari graben system of India. Basin sediments and suggested glacier-interpreted boulder beds are followed by coal measures within which the bulk of the Glossopteris flora occur - known as the Gondwana Supergroup. Goswami (2014) writes: "Glossopteris itself and most of the other members of this flora is believed to be of post glacial origin (…). The flora soon reached its climax under a damp and wet temperature climate in marshy environment. This is evident by its association with huge number of coal bed seams and the general absence of growth rings in petrified stem fossils within Lower Gondwana rocks." Moreover, Maheshwari (1972), referring to Glossopteris leaves from the Permian of Siberia, notifies: "I have examined these specimens, and had I not known from where these specimens had come, I would have unhesitatingly accepted their placement under the Gondwanan Gangamopteris and Glossopteris. However, hardly any paleobiogeographer accepts that these leaves are same as the Gondwanan ones, probably because such an acceptance would not fit in with the concept of Continental Drift." Anyway, the lack of growth rings reported by Goswami (2014) is consistent with Wegener's

(1929/66) original Permian palaeoequator that passed across India, with the corresponding South Pole a little southwest of South Africa - a simple palaeogeographic system based on climate evidence from Eurasia, North America and Africa. That is, in the Permian the Earth had a different spatial orientation than today, with the North Pole in the North Pacific (~50°N). In the same climate frame, the recent observations from Mongolia and NE China would have grown in subtropical to warm mid-latitudes.

It is generally accepted that the late Palaeozoic (centred around 300 Ma) was the most intense and prolonged glacial interval in Earth history - consisting of a series of glacial periods lasting a few million years each, separated by warmer interglacials (Fielding et al., 2008, and references therein). On land, however, it is impossible to find clear evidence for polar ice caps for this period. Based on Wegener's paleoclimate system - supported by palaeomagnetism (Storetvedt, 1990), the paleogeographic poles were located in the southeastern South Atlantic - at ~0°E, 40°S - and in the northernmost Pacific - in ocean areas where direct information is not available. However, it was in this context that Wegener made his series misjudgement - by amalgamating the southern continents plus India. Wegener (1929/66) considered the Glossopteris flora as a characteristic vegetation of the southern continents which, according to his hypothesis, had been clustered around the late Carboniferous-early Permian South Pole adjacent to South Africa. However, from rock and fossil evidence, it was known already in Wegener's time that at least since Devonian, climate in Antarctica had been markedly different for that expected in polar environments - a climate situation confirmed by later studies. For example, Schopf (1973) stated that the growth rate in Permian woods in Antarctica was so large to suggest that the plant life did not experience polar conditions. And according to Barrett (1991), "climate on land was warm and semi-arid in south Victoria Land at least, judging from the soils and red beds", and he further noted that "red beds have also been described from dated or possible Devonian strata in the Ellsworth and Pensacola Mountains and in Dronning Maud Land".

In the Permo-Carboniferous, "growth was vigorous and annual increments were high (…) in sharp contrast to the narrow rings shown by trees growing today in high northern latitudes" (Thuswell, 1991) - that is, the climate situation was like that described for Glossopteris wood in India. Thus, in the Permian Coal Measures of East Antarctica, McLoughlin and Drinnan (1997) described abundant Glossopteris fossils associated with 2-10 m thick coal beds containing remains of up to 60 cm thick logs. However, the relatively high growth rate in the Glossopteris Gully Member sequence, indicating at least warm temperate mire facies conditions, is, according to the same authors, extensively covered by diamictite, which commonly is interpreted to be tillite, which according to Molén (2023) may be wrong. Also, within the Boston Bay Group, an extremely heterogeneous, unstratified, conglomerate sequence with striated rocks - regarded as the best example of late Palaeozoic glaciation in North America (Schwartzback, 1963) - includes two poorly preserved tree trunks which constrains the age to the boulder bed and its associated Ice Age (within an otherwise (sub)tropical North America) between upper Devonian and early Permian (Rehmer and Hepburn, 1974; Rehmer and Roy, 1976).

Ever since the early part of the 20th century, fossil evidence from Antarctica has been consistent with tropical to warm temperate conditions throughout most of post-Precambrian time; it was only Wegener's hypothetical reconstruction, which placed Antarctica adjacent to the true relative South Pole located at ~0°E, 40°S, which required polar latitudes. Again, we are left with the same explanation as for India, and probably for North America - that the late Carboniferous-early Permian diamictites reflect a transient colder period during which observed well-defined growth rings (Maheshwari, 1972) would be as expected. Furthermore, if Wegener had extended his established northern hemisphere Permian equator around the globe, it would have passed both Australia and Antarctica thus forming a consistent global palaeoclimate system - with palaeopole and -equator 90 degrees of latitude apart. Nevertheless, current discussions about the growth conditions of

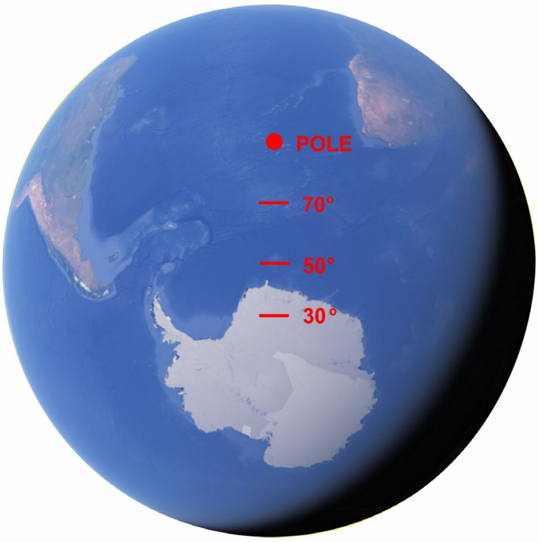

Fig. 1. Starting from Wegener's Permian pole (at c. 0°E, 40°S) and with Antarctica in its current relative geographical location, it is seen that the continent had (sub)tropical palaeolatitudes - consistent with the fossil record.

Glossopteris vegetation in Antarctica continue as if they were taking place at high latitudes (Gulbranson et al., 2014). In Wegener's global palaeoclimate evaluation, the possibility of a late Carboniferous-early Permian Ice Age apparently was not seriously considered. By the way, pre-Pleistocene glaciations may be difficult to assess on geological evidence alone (cf. Molén, 2023 and references therein).

Fig. 1 shows what the latitudinal situation for Antarctica would have been without Wegener's "forced" placement of Antarctica near his Permian South Pole. The same low palaeolatitudes for Antarctica would have been revealed if Schwartzbach's Devonian equator (Schwartzbach, 1963) and Spjeldnæs' Ordovician equator (Spjeldnæs, 1961) had been extended past Australia; these great circle belts would have passed Antarctica and thus been consistent with the fossil record. According to Wegener, the Lower Tertiary equator passed along the southern edge of the present Mediterranean, after which the Earth made a marked 35° spatial turn in the approximate Greenwich plane (Wegener's "Spitsbergen-Cape Town Line") at the Eocene-Oligocene boundary giving rise to a marked temperature drop in Europe (Buchardt, 1978; Pomerol, 1982). With this true polar wander event, the Earth had acquired its present spatial orientation with Antarctica in its present polar setting - probably for the first time since the Precambrian. Fig. 2 illustrates the dramatic climate shift in Antarctica ~34 Ma ago (Elderfield, 2000) - based on fossil evidence propped up by palaeomagnetic data, at least in terms of latitude (Storetvedt, 1990). However, even after this marked relative shift of the polar axis, giving rise to polar latitudes in Antarctica, the continent was not persistently covered by ice. Thus, fossil-bearing deposits in the Transantarctic Mountains testify to a variable

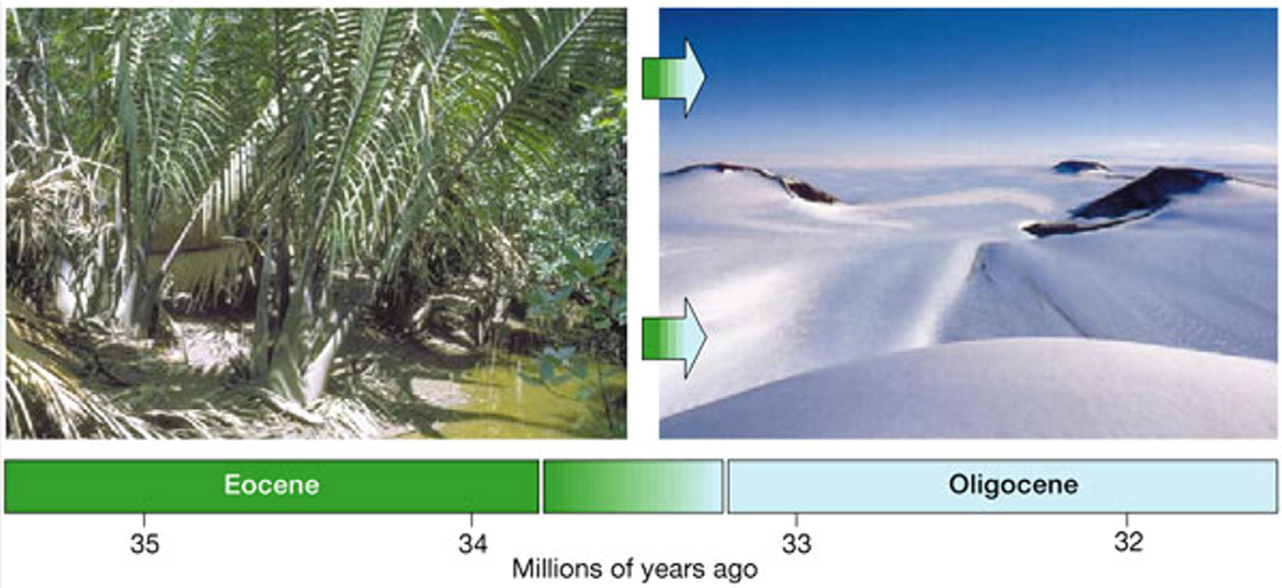

Fig. 2. Tropical to warm mid-latitude conditions had characterized Antarctica throughout most of the Phanerozoic - until the Eocene-Oligocene boundary. At that time, the Earth acquired its present spatial orientation and Antarctica its polar setting. After Elderfield (2000)

cool climate that in the Neogene allowed sparse coniferous vegetation to survive (Rees-Owen et al., 2018).

The Glossopteris flora has achieved near-iconic status through its alleged strong link-up to Wegener's polar Gondwana. However, the widespread occurrence of this group of humid forest vegetation, also on the northern continents, remains neither constrained nor understood (see debated issues in McLoughlin, 2011). Despite there is no indication that the long-standing and unresolved Glossopteris debate is concluding, hardly anyone seems ready to question Wegener's Gondwana. Though the Glossopteris flora is considered a key evidence for his hypothetical configuration, various Glossopteris assemblages are widespread in the Northern Hemisphere - described as Angaran, Euramerican and Cathaysian provinces, though without sharp boundaries (McLoughlin, 2011), and Srivastava (1992) discussed alien glossopteris elements in the Gondwana beds of India. Also, in the alleged (constructed) Gondwana continents, "one distribution pattern shows mixed floras along the marginal basins of the hypothesized oceanic Tethyan region during the middle and late Permian. Another pattern is evident in the Gondwana floras where Glossopteris contain several extra-Gondwanic elements" (Srivastava and Agnihotri, 2010). This indicates an intermixing of the various flora elements between the hemispheres. A critical question is therefore how the global distribution of this forest vegetation came about. Deep-sea drilling has disclosed that the principal sedimentation in the world oceans is late Mesozoic - primarily Upper Cretaceous. This may imply that formation of the oceanic crust and its break-up of former land connections, is a geologically recent phenomenon. Thus, we probably have found the real icing on the cake regarding the global migration of the Glossopteris flora.

In the presently unclear situation, Krassilov (2000) has discussed the Permian Glossopteris geography and climate zonation in which the northern continents play a much more prominent role than one gets the impression of in the Wegenerian Gondwana-inspired literature. Krassilov (2000) depicts the mid-Permian plant geography for which Eurasia, southern North America and the Tethyan belt represents by far the largest number of reference sites. He writes: "The Tethyan phytogeographic realm is a continuous zone of mixed Cathaysian and Gondwana floras extending from southern Spain and Morocco over the Middle East, Anatolia and North Africa (….) to Tibet, Yunnan, Thailand (Phetchabun), Sumatra (Jambi) and West New Guinea (Irian Jaya). Ecological equivalents of the Southern Cathaysian vegetation might occur on the Gulf Coast and over Caribbean. Occasional reports of gigantopterids come from Mexico and Venezuela." Krassilov (2000) further argues that the Permian Euramerican-Cathamerican-Gondwana Glossopteris mixing is incompatible with the view of the Tethys as a wide oceanic indentation of the Pacific and with "a radical reassembly of the continents" Wegener's continental unification. The wide gap to the east of Wegener's oceanic Tethys, traditionally regarded a shallow epicontinental seaway along the southern borders of Eurasia, is a direct consequence of his closure of the South Atlantic.

However, if we consider Tethys in the traditional way - as a shallow and narrow epicontinental seaway along a deep, probably world-encircling, fracture zone (Wilson, 1954) on the southern rim of present-day Eurasia - it would be consistent with the Permian phytogeographic survey of Krassilov (2000). Also, Hughes (2016) found that tropical Cambrian marine fauna of northern India has a close link to those in parts of China. He further adds that "Links with Australia are suggested by non-cosmopolitan species, but Indian biotas share less in common with Australia than with parts of China" - suggesting a close Lower Palaeozoic shallow water fauna relationship between India and Asia and supporting again the traditional narrow and shallow Tethys.

If we take Wegener's global climate system as our starting point, disregarding the paleoclimatic contradictions that his continental drift hypothesis led to, the global distribution of Permian Glossopteris vegetation would have occurred within tropical to warm mid-latitudes. For example, the Shetland-Faeroes-Iceland-Greenland Ridge has traditionally been regarded a biogeographic land connection between Europe and North America (McKenna, 1975, 1983; Tiffney, 1985; Tiffney and Manchester, 2001). Following Wegener's palaeoclimatic system, Permian biotic migration across this land bridge would have taken place under subtropical conditions. This would imply that the Permian Angara flora in northern Greenland (Wagner et al., 2002) must have grown in warm mid-latitude habitats. An exception is southern Africa which apparently experienced boreal conditions.

The classic Dwyka Group of South Africa, with its striped pavements and boulder beds, has long been considered the centre of the late Paleozoic glaciation. However, Wegener (1929/66, p.128) - based on his description of the combined polar path and the global paleoclimate system - placed the Permian South Pole at ~0°E, 40°S. But to accommodate his Gondwana configuration, the South Pole was shifted to a little southeast of South Africa - but that manoeuvre had a much weaker scientific basis than his original polar estimate. In addition, his original polar estimate has been confirmed by paleomagnetic considerations (Storetvedt, 1990). On his original palaeogeographic basis, South Africa had a distance of 2000 km and more from the Permian South Pole, which in turn leads to the conclusion that the Dwyka Group probably formed in boreal latitudes. In this regard, Molén and Smit (2022) have re-evaluated key sites in the Dwyka Group used as evidence in favour of a glaciogenic origin. They argue that many field observations "warrant reinterpretation as non-glacial sediment gravity deposits."

Seawater and crustal histories

It seems likely that, on a flat or slightly undulating land surface, the first water pulse of any importance - a slow but accelerating supply of water to the surface associated with an explosion of higher marine life forms, was released from the Earth's interior in the Lower Palaeozoic, with maximum transgression in the Upper Ordovician (cf. first-order sea-level curves by Vail et al., 1977; Hallam, 1992). Assuming a weakly undulating Lower Palaeozoic surface is consistent with the global distribution of epicontinental seas in the Lower Silurian (Boucot and Johnson, 1973). In their study of Silurian brachiopods, which Boucot and Johnson described as cosmopolitan, the surface sea covered almost all of America and Eurasia, and parts of Africa and Australia. This probably means that in the Lower Palaeozoic the surface water was shallow and unevenly distributed. Consistent with this assumption, Suttner and Ernst (2007) found that the shallow water Upper Ordovician bryozoan communities of northern India have a close similarity to those of North America, the Baltic, Siberia and southern China. Under such circumstances, it would be natural to correlate the Cambrian shallow-water fauna of northern India (Lesser Himalaya) in a broader geographical context, as Hughes (2016) did. During the Middle and Upper Palaeozoic, however, the shallow epicontinental seas gradually, but episodically, retreated from an increasingly dry land surface - a development that culminated in a deep sea-level regression at the Permian-Triassic boundary. That is, the still limited amount of surface water had drained into rudimentary oceanic depressions – associated with regressive events and biological catastrophes at principal geological time boundaries (Newell, 1967; Vail et al. 1977; Hallam, 1992), but due to the lack of drilling information from deep-sea deposits older than upper Mesozoic we don't know where these early stages of basin formation began.

However, according to a compilation of deep-sea drilling data, the crustal thinning process must have accelerated in the Upper Cretaceous. In order to fill the extensive and rapidly growing basins of the world oceans with seawater, the amount drained from the continents were obviously insufficient. In this context, Ruditch (1990), who studied the sedimentary sections from 402 deep-sea drilling project (DSDP) sites, concluded that the world's oceans initially began as isolated basins with subsequent deepening and lateral expansion - caused by sub-crustal thinning and associated isostatic subsidence. Based on his DSDP survey, the Atlantic and Indian Oceans in particular had undergone accelerated crustal thinning in the late Cretaceous. According to DSDP drilling data, the deep-sea basins predominantly formed in the Cretaceous (see Ruditch, 1990, for data compilation), so to fill these major surface depressions it follows that the main volume of seawater must have been released from Earth's interior along with the crustal thinning process. There thus appears to be an intimate connection between crustal development and the history of seawater. Furthermore, water apparently is a critical element for sub-crustal eclogitization and associated gravity-driven delamination to the upper mantle (see below).

With the increasing land surface during the Permian, together with many unassimilated continental ridges and plateaus in the slowly evolving oceanic basins, the conditions were well suited for global spread of the glossopteris flora - from its possible origin in India. With the fluctuating development of the epicontinental Tethys, primarily caused by dynamo-tectonic sea-level variation and related vertical crustal oscillation, the shallow Tethys would time and again have formed migration corridors between India and Eurasia and beyond. Thus, the late Devonian-early Carboniferous palynoflora of the Tethyan Himalaya, India, is correlated with coeval records worldwide (Gupta et al., 2023). Another important observation is that the late Carboniferous flora of Kashmir Himalaya, India, is thought to have grown in warm climate and thus immediately before the suggested Carboniferous-Permian Ice Age (Singh et al., 2013). This observation further strengthens the view that the late Palaeozoic "Ice Age" was only a global cooling event - thus unrelated to Wegener's hypothetical Gondwana. In this context it is important to stress that Wegener's Permian poles were located in present oceanic regions (in northern Pacific and southwestern South Atlantic respectively) from which we lack relevant rock information. Nevertheless, in present plate tectonic considerations, Wegener's Permian North Pole has disappeared from the discussion, while his Permian South Pole is still the corner stone in the Gondwana concept. After the major regression around the P-T boundary, sea level remained relatively low for much of the Mesozoic. It is likely therefore that post-Permian biological migration routes between India and Asia were not significantly constrained by fluctuating sea level changes in an epicontinental Tethys.

Present-day tectonic assessments presume that India in the Mesozoic and early Tertiary drifted as an island continent before its alleged collision with Asia. However, the terrestrial vertebrates and dinosaurs seem to be cosmopolitan -having been reported from Europe (Le Loeuff, 1991), South America (Bonaparte et al., 2010), Madagascar (Sampson et al. 1998), and Wikipedia (2025) has a long list of references of late Triassic-late Cretaceous dinosaur fossils from all over Africa. According to recent studies (Bajpai et al., 2023; Khosla and Lucas, 2024), India was a main centre for neo-sauropod development - but this is probably a drift-inspired conclusion, because the diversity and widespread observations of dinosaur remain occur elsewhere, notably in Africa, cast doubt on this claim.

Chatterjee (1992) may have hit the nail on the head when he wrote: "(…) the lack of endemism among Indian Cretaceous terrestrial biota is clearly inconsistent with the island continent hypothesis. On the contrary, these fossils show their closest affinity with those of Laurasia and Africa, indicating that India maintained overland connection with these landmasses during this period." Nevertheless, despite the long-known cosmopolitan nature of many dinosaur groups, Chatterjee and Scotese (1999) - in the wake of the drift motif for India, invented a new landmass allegedly having occupied the region between Somalia, eastern Arabia and northwestern India named "Greater Somalia". However, their proposed evolutionary pattern is complex and ad hoc, and what ultimately happened to their "Greater Somalia" is unclear. To account for the close biogeographic contact between India and the continents surrounding the Indian Ocean, it is of utmost importance to clarify the evolution of the tectono-topographic complexity of its seafloor. The strongly sheared 'mid-oceanic' ridges, the multitude of submerged continental plateaus and aseismic ridges with variable size and crustal thickness, as well as the scattered Neogene-Recent volcanic activity, sends a clear message that the development of the Indian Ocean needs reassessment.

Crustal Intricacies

In the Indian Ocean, late Neogene-Recent volcanism has taken place in diverse physiographic settings, without recourse to alleged seafloor spreading ridges. Thus, the Comores Islands and Reunion, both located remotely from the Central Indian Ridge (cf. Fig. 3), dominate the eruption record of the Indian Ocean by having 93% of dated events (see historical survey by Simkin and Siebert, 1994). At an even greater distance from the 'mid-ocean' ridge system, Heard Island (on the Kerguelen Plateau) has had historical eruptions, and the Kerguelen Islands to the north-west have been active in Holocene time. The occurrence of Holocene volcanic fields in Central and North Madagascar, displaying a linear distribution parallel with the island's fault-bounded west coast, has remained another puzzle. This indicates that volcanism in the Indian Ocean may be associated with the ubiquitous orthogonal fault system - that is, it can occur anywhere in an ocean basin without particular reference to the 'mid-ocean' ridge system. In this context, Baksi (1999) re-evaluated many published radiometric ages of rocks from the Mascarene Plateau, Laccadive-Chagos and Ninety-East ridges. He argued that most of the data were unreliable for assessment of proposed plate motion models and alleged hotspot tracks

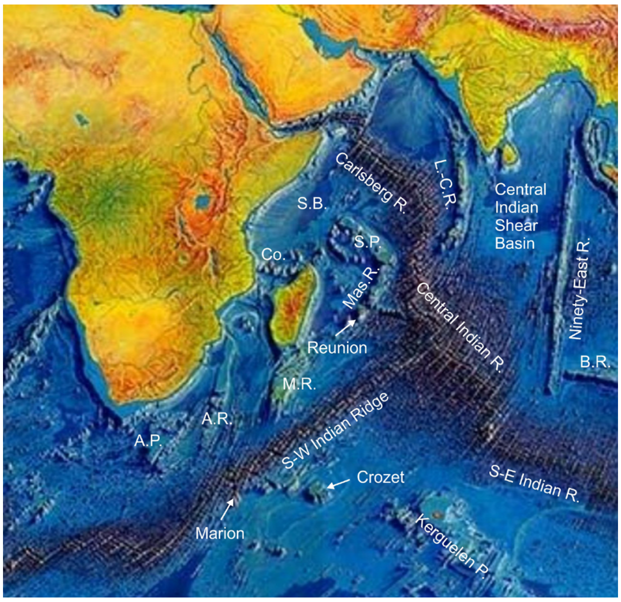

Fig. 3. Physiographic image of the main part of the Indian Ocean seafloor - based on NOAA Satellites and Information, National Geophysical Data Senter, Boulder. Abbreviations are: A.P., Agulhas Plateau; A.R., Agulhas Ridge; B.R., Broken Ridge; M.R, Madagascar Ridge; Mas.R., Mascarenes Ridge; S.B., Somali Basin; S.P., Seychelles Plateau; L.-C.R., Laccadive-Chagos Ridge

- age estimates that had previously been used for such purposes by Müller et al. (1993) and others.

Even on taking a less critical view of published radiometric ages than did Baksi (1999), there are many radiometric studies that give Lower Tertiary or Upper Cretaceous ages. Thus, Duncan (1991) reported Ar^{40}/Ar^{39} plateau and isochron ages from samples of the Ninety-East and Broken ridges that fall in two age categories: c. 85 Ma and c. 50 Ma. From whole rock Ar^{40}/Ar^{39} step heating studies, Storey et al. (1995) concluded that throughout Madagascar a relatively short-lived volcanic event swept the island in the late Cretaceous - ranging between 83.7±5 Ma and 88.5±0.9 Ma. They paid particular significance to the weighted mean of 87.6±0.6 Ma for nine samples from the island's eastern seaboard. Compared with the Madagascar dates, an Ar^{40}/Ar^{39} study of volcanic activity on St. Mary Island, southern India, gave a weighted average isochron age of 85.6±0.9 Ma (Pande et al., 2001). It seems pointless to argue, as Pande et al. (2001) did, because of the close correspondence in magmatic events, that Madagascar and South India lay side by side in the Upper Cretaceous. Instead, it is a fact that Upper Cretaceous volcanism is a global spot-like episode in the history of the Earth's oceanic crust, and it occurred simultaneously with the 'Cenomanian' sea-level rise. On this basis, it is likely that the irregular and limited deep-sea basins of the Indian Ocean also had scattered volcanic activity, especially in the late Mesozoic and early Tertiary. However, it is reasonable to believe that any volcanism in the presently deep basins was eliminated or minimized during a crustal oceanization process.

It has been repeatedly argued that the granulitic lower crust is readily becoming eclogitized and thus gravitationally unstable, but natural occurrences demonstrate that such metamorphism-regulated density changes are strongly impeded when hydrous fluids are absent (Austrheim, 1987, 1990; Walther, 1994; Leech, 2001; Anderson, 2012). Thus, Austrheim (1998) argued that, in order for the metamorphic reactions to go forward, water-rich fluids are much more important than temperature and pressure. In the same direction, Leech

(2001) stated that sub-crustal delamination is controlled by the amount of water available - implying that irregular regional concentration of water in the topmost mantle may lead to variable thinning of the lower crust and thereby to uneven, but fault-controlled, deep-sea basins and submerged continental crust. An inferred uneven oceanization of original continental crust, such as the patchwork of variably sized submerged aseismic plateaus and ridges, spread across Indian Ocean, is outlined in Fig. 3.

By Global Seafloor Topography from gravity data derived from satellite altimetry and ship depth soundings (Smith and Sandwell, 1997), the crystalline crust is laid bare. Thus, modern mapping of the Indian Ocean seafloor reveals a very composite tectono-topography, a complexity far exceeding that of the other world oceans. This may indicate that the oceans are at different stages of crustal development - implying that the crust of Indian Ocean is in the least advanced state of evolution. The model of variably oceanized continental crust was first proposed by Barrell (1927) and further developed by Beloussov (1962, 1990). However, as exemplified above, for the western Indian Ocean, the transition from thick continental to a progressively thinner (deep-sea) crust may be a common phenomenon.

Submerged land fragments crisscross the Indian Ocean

Dredging on the southern Agulhas Plateau (cf. Fig. 3), c. 500 km southeast of South Africa, has recovered a suite of granitic gneisses, in lower amphibole to granulite facies metamorphism, along with quartzose metasedimentary rocks, from which Tucholke et al. (1981) concluded that at least parts of the plateau is continental. K-Ar datings on fresh biotite yielded ages of 1,074±36 Ma and 478±17 Ma - referred to similar continental rocks in southern Africa, the Falkland Islands, Falkland Plateau, and Antarctica (Allen and Tucholke, 1981). Despite the evidence for a continental-type 20-25 km thick crust, Parsiegla et al. (2008) regard the Agulhas Plateau as a large igneous province (LIP) formed during the late Cretaceous during alleged reorganization of the southern landmasses - though they admitted that the suggested LIP concept is poorly understood. However, a crustal structure study in a transect from South Mozambique Margin to South Mozambique Ridge (cf. Fig. 3), Schnürle et al. (2023) found that the crustal thickness varies from 39 km to a gradually thinner crust of c. 27 km beneath the ridge. They concluded: "The results falsify the presence of an oceanic crust in that area and thus most of the plate reconstruction models." The gradual oceanward transition from thick to thin crust is demonstrated within Madagascar itself; the Moho depth which in the central-eastern cratonic part of the island is up to 46 km decreases gradually to c. 20 km in the coastal basins along the Mozambique Channel (Andriampenomanana et al., 2017) and an even thinner submerged continental crust, 10-12 km, is found in the Mozambique Channel (Vormann et al., 2020). The same seaward thinning (i.e. stepwise crustal oceanization) is demonstrated along the Madagascar Ridge - an elongated southern extension of the island, where the thick Malagasy cratonic crust is reduced to Moho depths varying from 25-18 km (Sinha et al., 1981).

DSDP Leg 25 in the southern Indian Ocean, which included 3 drilling locations in the Mozambique Channell, found that the clay mineral palygorskite was prevalent in all sites. Palygorskite is generally considered to have formed under warm alkaline and evaporative conditions (Ryan et al., 2019). Nevertheless, Thiry and Pletch (2011) argued that in some marine cases "palygorskite clay was formed on adjacent continents and was subsequently transported to the deep-sea deposition site. However, microstructural and mineralogical evidence suggest that the purest deposits were formed in situ on the seafloor in the case of the Middle Cretaceous to Lower Eocene". That is, they speculate whether climatic conditions in the Upper Cretaceous were so extreme that palygorskite could form even in deep sea. However, during the Upper Cretaceous, the DSDP Leg 25 sites were in warm subtropical latitudes undergoing accelerating sub-crustal thinning and oceanic basin subsidence (Storetvedt, 1990). Therefore, the palygorskite deposits in Leg 25 sites are likely to have formed under warm littoral evaporative dolomite conditions (Ryan et al., 2019) - which makes the ad hoc assumption of extreme climate conditions non-pertinent.

In the northern end of the Mozambique Channel, in the WNW oriented Comores Archipelago, there are direct surface evidence of continental crust underlying a top sequence of basaltic lavas. A multitude of inclusions of continental rocks in the lavas - such as quartz sandstone, quartzite, orthogneiss, quartz monzonite, amphibole granite, granodiorite, anorthosite, lherzolitic and gabbroic nodules, etc., obviously torn off from lower crustal levels during volcanic eruptions - have been reported (Flower and Strong, 1969; Esson et al., 1970). Recently, Nature World News (Co, 2023) exposed more revealing news from the Comores - reporting on the occurrence of "half a mountain of quartzite" on the Island of Anjouan, situated in the middle of northern Mozambique Channel. That the archipelago lies on continental crust should be beyond doubt. For example, Francis et al. (1966) found a continuous thinning of continental crust eastward as far as the Seychelles and Darracott (1974) - based on geophysical and drilling data, concluded that Africa and Madagascar are connected by attenuated continental crust, implying that Madagascar has always been located where it is. More recently, Milsom et al. (2016) reported new evidence for continental crust in the Comoros region.

Seychelles, located in the northern end of the extensive bow-shaped Mascarene aseismic Ridge, consists of undeformed and unmetamorphosed monzogranites and granodiorites, spread over the archipelago. U-Pb zircon methods yield late Proterozoic ages around 750 Ma (Ashwal et al., 2002). The old Precambrian basement in the northern Mascarene Ridge, was, around the Cretaceous-Tertiary boundary, intruded by basic dykes and ring complexes (Baker and Miller, 1963; Macintyre et al., 1985; Shellnutt et al., 2017) - which is consistent with deep-sea drilling results indicating that ocean basins mainly developed at this time. In the southern Mascarenes Ridge, the subaerial volcanism of Mauritius has been isotopically dated between 7.8-6.8 Ma, but rock evidence and the anomalously thick crust of the Mascarene Ridge (Torsvik et al., 2013) suggest that the entire Ridge is thinned continental crust - only intersected locally my younger magmatic events. Thus, the discovery of Proterozoic zircons in basaltic beach sand from Mauritius (Torsvik et al., 2013), assimilated/torn off from the underlying crust, confirm the continental nature of the foundered Mascarene Ridge. Consistent with this conclusion, a subsequent study (Ashwal et al., 2017) found Archaean-aged zircons in a young Mauritian trachyte plug. Moho depths of 28-42 km were reported by Hammond et al. (2013), and a gravity inversion technique predicts that the entire Mascarenes, extending southwards to Mauritius, has a contiguous continental-type crust of c. 25 km (Trivedi et al., 2012; Torsvik et al., 2013). From the crustal thickness assessment of Trivedi et al. (2012), the Mascarene Basin, located between the Mascarene Ridge and Madagascar, has a highly irregular Moho with depths in the range of 10-14 km (Fig. 4). Again, the most likely basin interpretation would be in the form of an irregular attenuation of continental crust - such as for the Mozambique Channel and the Somali Basin discussed above. Furthermore, the results of the study by Trivedi et al. (2012) also show that the Laccadive-Chagos Ridge has a thick crust with Moho depths of >22 km, decreasing to c. 10 km in the basin to the west, before the Moho depth again increases to ~15 km beneath the Central Indian and Carlsberg ridges (see later). Consistent with the relatively thick Laccadive-Chagos Ridge, ODP site 715 (Backmann et al., 1988) found, in the northern sector, conclusive evidence of subaerial or shallow-water volcanism in Palaeocene-Eocene time. Furthermore, at DSDP site 219, Recent-Eocene deep-water pelagic oozes overlie shallow-water Palaeocene sediments (Whitmarsh et al., 1974), indicating that the ridge was subaerial or shallow-water in early Tertiary.

For the southern Madagascar Ridge and Crozet Plateau (cf. Fig. 3), Goslin et al. (1981) found crustal thicknesses of 15-17 km while, for the Crozet Bank, Recq et al. (1998) discovered a pronounced eastward Moho variation from 16.5 to 10 km - on the expense of the lower crust. At the Ninety-East Ridge, Grevemeyer et al. (2001) reported crustal thickness of up to 24 km. However, the estimated seismic velocities at the inferred crust/mantle boundary are only 7.3-7.4 km/s, while a normal Moho velocity of about 8.2 km/s was found at a depth of about 35 km. This may indicate that the true crustal thickness of the Ninety-East Ridge is in excess of 30 km - consistent with thickness estimates of 20-40 km for the Broken Ridge and Kerguelen Plateau (cf. Magri et al. 2024 - and references therein). Based on a combination of mineral sediments containing metamorphic shales and palynological evidence of land plant growth, Udintsev and Koroneva (1982) considered Broken Ridge and Ninety-East Ridge to have been parts of a more extensive ancient landmass. This landmass was probably considerably larger, as repeatedly demonstrated by submerged continental remnants in the eastern Indian Ocean (Gardner et al., 2015; Halpin et al., 2017), and Elan Bank of the Kerguelen Plateau is widely recognized as continental (Asimus et al., 2025 - and references therein). Thus, on the eastern flank of the Raggatt Basin, ODP site 750 (Leg 120) obtained clasts of conifer wood, partly in excellent structural preservation (Francis and Coffin, 1992), suggesting that Kerguelen Plateau was forested land in the Upper Cretaceous. Furthermore, ODP Leg 183 results (Coffin et al., 2000) concluded that the origin of the Kerguelen Plateau had been subaerial, with abundant evidence from wood fragments, charcoal, spores and pollen recovered in 90 Ma old sediments just southeast of Heard Island. In the summary of ODP Leg 183, the Shipboard Scientific Party (Frey et al., 2003) concludes: "Palynological studies will help date terrestrial and terrigenous sediment and determine vegetation types and paleoclimates when the Kerguelen Plateau and Broken Ridge were subaerial."

Operto and Charvis (1996), studying the crust/upper mantle structure of the southern Kerguelen Plateau, suggested a 22 km thick crust. However, the absence of high velocities at the base of crust, strong azimuthal anisotropy, and upper mantle velocities between 8.60 and 8.00 km/s, may be consistent with eclogitization and gravity-driven delamination of the lower crust (cf. Anderson, 2012). If so, the original continental crust beneath the Kerguelen Plateau may have been much thicker than the proposed 22 km, which is consistent with fossil evidence favouring forested land. Furthermore, the Plateau has a long history of magmatic activity, from late Cretaceous-Neogene (Duncan et al., 2016). Ar^{40}/Ar^{39} plateau ages of 122-90 Ma have been obtained from volcanic rocks, from both dredged and cored material, from Southern and Central Kerguelen, Elan Bank, and Broken Ridge (Asimus et al, 2025 - and references therein). In their summary of late Cretaceous volcanic events, Asimus et al. included also occurrences on the Ninety-East Ridge. The latter authors, using petrographic techniques and U-Pb zircon and apatite dating, described xenoliths of granitoids and felsic gneisses that yielded Archean, Proterozoic, and Cambrian ages. Asimus et al. (2025) concluded that the xenoliths must have been torn loose from a continental basement during late Cretaceous volcanic eruptions. According to deep-sea drilling data, this was also the main period for global deep-sea and seafloor tectono-topographic development (Ruditch, 1990). As a consequence of seafloor evolution discussed above, the oceanization process of original continental crust has naturally also led to the cessation of land-based migration routes between the continents around the Indian Ocean.

Plutonic and old metamorphic rocks along 'mid-ocean' ridges

Serpentinization of mantle peridotites along the elevated mid-ocean ridges, is likely the cause of the artificially deep Moho (c. 16 km, Fig. 4) of the Carlsberg Ridge (northwestern Indian Ocean) estimated by Trivedi et al. (2012). Furthermore, in case the underlying crust of the ridges has a background in oceanized continental crust, one would expect to find a variety of dynamo-metamorphic rocks in surface exposures. Thus, Afanas'yev et al. (1966, in Russian, reported by Meyerhoff and Meyerhoff, 1974) described numerous igneous and metamorphic rocks dredged from the Carlsberg Ridge with late Precambrian and Palaeozoic K-Ar ages. The recovered rocks included granitic material, metadolerites, metagabbro, greenstone, and altered ultrabasics. The fact that the gabbro samples often are mylonitized and sometimes

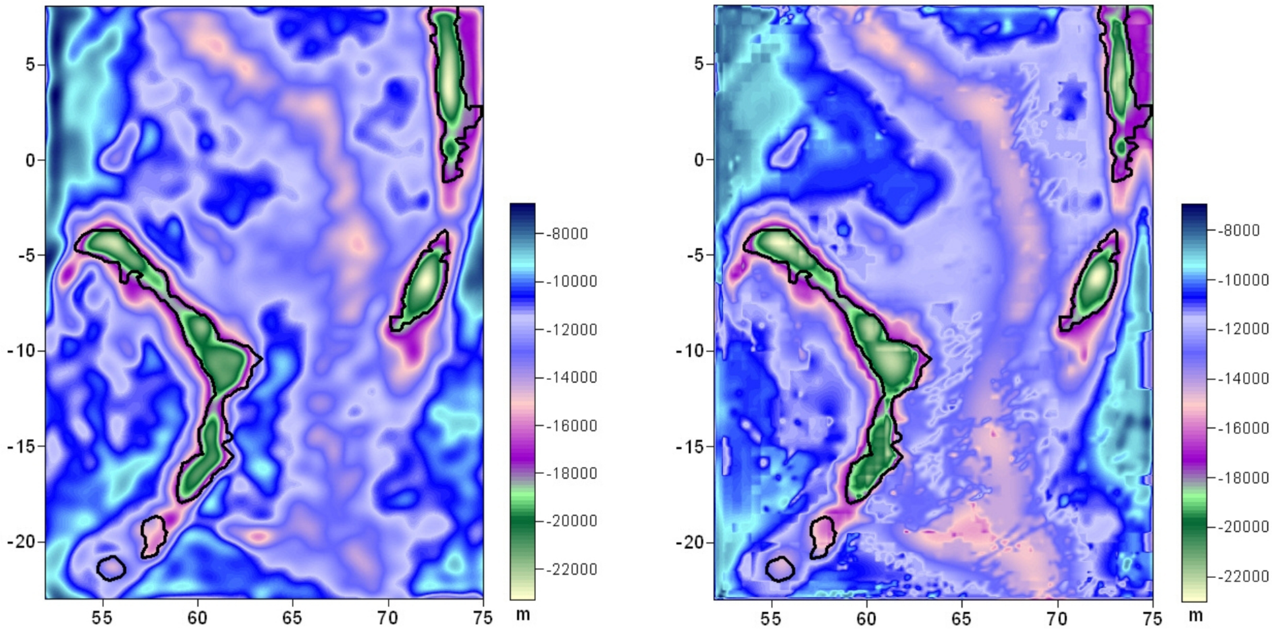

Fig. 4. Moho depth estimates from two gravity inversion techniques in the northern Indian Ocean encompassing the submerged Mascarene Ridge (left) and Laccadive-Chagos Ridge (right) - from Trivedi et al. (2012). The results from the two ridges are in general agreement with that of other studies, but the artificially thick Moho depth of the intervening Carlsberg Ridge is interpreted here as a tectonized and serpentinized belt of the topmost mantle.

metamorphosed to amphibolite facies, and that the ultrabasic material has undergone cataclasis and extensive serpentinization, suggest that the basement of Carlsberg Ridge has experienced dynamo-metamorphic processes. Despite the low potassium content of the metamorphic rocks, the reported K-Ar ages were consistently old. Young ages from the Carlsberg Ridge were obtained only from a minor fraction of fresh basalts - results that are consistent with the sporadic younger volcanic activity spread across the Indian Ocean, from widely different geographic settings.

Adding to the rock data from the Carlsberg Ridge, Engel and Fisher (1975) discussed petrological results from 56 dredge hauls from fracture zones of the Central Indian and its branching SW Indian and SE Indian ridges - sampling deep into the crust along prominent fracture zones. The recovered material varied in composition from granitic to ultrabasic but, apart from sporadic occurrence of a top layer of relatively fresh basalts, the bulk of the lower sections consists of altered gabbroic and ultramafic material. On the SW Indian Ridge, the rocks seem notably more altered, cataclastically sheared, albitized and amphibolized than elsewhere in the western Indian Ocean. Similar metamorphic complexes were obtained during ODP Leg 118 in the SW Indian Ridge (Robinson et al., 1989). Engel and Fisher (1975) concluded that beneath the sporadic occurrences of fresh basalts, the mid-ocean regions have coarse-grained stratiform rock associations which, in terms of their shape, dimension and diversity of rock types, can be equated with major Precambrian stratiform complexes - such as Stillwater and Bushveld Stillwater Complex (Montana, US) and Bushveld Complex (South Africa) are layered basic intrusions of Precambrian age. With this comparison, Engel and Fisher (1975) believed that the basement beneath the western Indian Ocean had strong petrological similarities to the Bushveld Complex of South Africa - that is, the deep-sea basin had developed from ancient continental crust.

Re-entry into drilling hole 735 B (extended to a depth of 1508 m sub-bottom), ODP Leg 176 (Dick et al., 1998) sampled a diversified plutonic complex. More than 250 felsic veins were encountered, spread over the c. 1 km of the deeper oceanic crust (exemplifying granitization of continental crust?), and a large number of both high- and low-angle shear zones were reported. According to Natland et al. (1998), the metasomatism and alteration occurred in two stages: the first produced a high-temperature sequence from granulite to amphibolite facies in a dynamic environment, while the second, related to a different set of fractures, involved lower temperature alteration products. It may be the second tectonic event that affected the thin oceanic crust in the Upper Cretaceous - an inertial related wrenching that, to a variable extent, affected the entire global crust (see below).

In a summary of results obtained from dredged rocks from six areas of the Central Indian Ridge, Chernysheva and Murdmaa (1971) concluded: "All stages of metamorphism are connected with multiple deformation of the rocks. Infiltration of volatile fluids (possibly of upper mantle origin) through deep fracture zones is considered to be an important factor in the metamorphism. The metamorphic greenstone association is distinctly separated from unaltered tholeiitic basalts by a period of tectonic deformation and metamorphism". This summary is in line with other observations (outlined above) that original Precambrian basement has been metasomatically affected by rising mantle fluids - which in the Upper Cretaceous gave rise to accelerated crustal thinning, related dynamo-tectonic wrench deformation, and 'eventually' also to sporadic younger basalt intrusions.

With this unexpected rock information in mind, it is not difficult to understand that linear marine magnetic anomalies along the SW Indian Ridge are extremely difficult to define (Cannat et al., 1999; Patriat et al., 2008; Bronner et al., 2014; Zhou and Dyment, 2022). In fact, the ability of the mid-oceanic crust to record geomagnetic polarity reversals thereby establishing linear age isochrons for lateral seafloor expansion has never been confirmed (see comprehensive evaluation and discussion in Storetvedt, 2003/23). The expected along-ridge sheeted dikes are absent, fresh basalts are scarce, the fossil magnetic remanence intensity in the upper crust is far too low to explain marine magnetic lineations (where they exist), the critical test of the seafloor spreading model - DSDP Leg 37, was completely negative, etc. Thus, in a review article on the drilling results along the Central Atlantic Ridge, two of the principal scientists on DSDP Leg 37, Hall and Robinson (1979), wrote: "Oceanic crustal drilling by R.V. Glomar Challenger at 15 sites in the North Atlantic has led to a complex picture of the upper half kilometre of the crust. Elements of the picture include the absence of the (remanence) source for linear magnetic anomalies, marked episodicity of volcanic activity, ubiquitous low temperature alteration, and evidence for large scale tectonic disturbance."

To better understand the unexpected geological and tectonic complexity of 'mid-ocean' ridges of the Indian Ocean, let us turn to the tectonic driving forces that were promulgated in the early 20th century. These were the classical inertial effects caused by the Earth's rotation, but which traditionally have been considered too weak to have any noticeable effects on tectonics. But today, with a broader insight into the physical constitution and mechanical properties of the crust - primarily from deep continental drilling, it has become urgent to reassess the significance of inertial effects.

Wrench tectonics along 'mid-ocean' ridges

In his book *Die Äquatorfrage in der Geologie*, physicist Damian Kreichgauer (1902) submitted that his equatorward force of crustal motion, directed away from the poles, would have produced fold belts aligned along time-equivalent equators, while a second set of tectonomagmatic belts would have evolved in meridional settings (orthogonal to corresponding palaeoequators) owing to the westward directed tidal drag from the Sun and Moon. According to Kreichgauer, interpretation of ancient climates derived from rocks and fossils, polar wander seemed a necessity. For dynamical reasons, the rotational axis had to be aligned along, or to remain in the vicinity of, Earth's axis of inertia. Therefore, it became an inevitable physical conclusion that axial shifts had intermittently occurred during Earth's history. Thus, the displacement of the poles over the surface was a result of the Earth's body periodically changing its orientation in space. Kreichgauer's contribution to tectonophysics, linking global tectonics to events in planetary rotation, was, 90 years later, affirmed by palaeomagnetic assessment (Storetvedt, 1990).

Wegener (1912, 1915, 1929) gave Kreichgauer the credit for having discovered the *pole-fleeing force*, i.e. the combined effect of the dynamics of Earth rotation and the principle of isostasy - later named *Eötvös force* (Eötvös, 1913). Also, Wegener adhered to the westward tidal drag as the driving force for his continental drift, but exactly how this splitting-apart had occurred - with lateral drift in many directions, he was unable to explain. He just believed that time would prove him right. The important period for Wegenerian drift was the Mesozoic, but deep-sea drilling in the latest half century has shown that the oceanic basins, and by inference also their thin crystalline crust, primarily dates from the Upper Cretaceous. This means that Wegener's postulated continental drift must have mainly occurred while the crust was thick (and continental). Moreover, modern mantle tomography has shown that the continents have mantle roots several hundred kilometres deep (Dziewonski and Woodhouse, 1987), which makes it virtually impossible to move continents laterally - the roots must follow.

More groundbreaking information (regarding crustal mobility and the role of interior water) has come from deep continental drilling on Kola and in the borehole in SE Germany (e.g. Kozlovsky, 1984; Pavlenkova, 1991; Ito and Zoback, 2000) – reaching depths of 12.2 and 9.1 km respectively, the recovered data suggest that critical aspects about Earth's interior need reconsideration. But so far, the outcome has attracted little attention. In the two drilling sites, hydrous fluids were abundantly present, and fracture volume increased with depth. Thus, in the Kola borehole the fracture expansion increased exponentially to a maximum of 4.3%, and the flow of hydrous fluids contained dissolved hydrogen, carbon dioxide, nitrogen, methane and helium. So, what kept the fracture system open - against the closing effect of gravity?

Astrophysicists Fred Hoyle (1955) and Thomas Gold (1999) have discussed this problem, under the plausible assumption that the Earth is unlikely to be completely outgassed. This belief is based on seismological evidence that the Earth's core has a density deficit - that is, it must have a selection of light elements (see review in Poirier, 2000) which show that thermo-chemical equilibrium has not yet been achieved. It may be precisely the Earth's lack of internal equilibrium that has maintained the planet's pulsating dynamo-tectonic history, including the tectono-biological upheavals that define the major geological time boundaries. Following the Hoyle-Gold assumption that all planets began as a mixture of cold gas and rock-forming elements (see also Cameron, 1962, 1985), the rocks and the outgassing aqueous fluids in the mantle and crust - except for a thin surface layer - would be subject to a common pressure. This condition has produced a kind of pressure bath situation in which fractures would be held open just as in rocks near the surface. Thus, if a fluid flow, occupying an existing fracture network, exerts an outward hydrostatic pressure as great as the opposing gravitational pressure of the surrounding rocks, any existing fluid flow would be maintained. It was evidently this physical principle that the Kola and South Germany boreholes experienced.

Above, it was argued that the main amount of seawater was exhaled in the upper Cretaceous - in conjunction with formation of the deep-sea basins. Thus, the build-up of high hydrous fluid pressure in the Cretaceous topmost mantle, instigating subcrustal eclogitization with associated progressive gravitative delamination to the upper mantle (cf. Leech, 2001; Anderson, 2012), may be a crucial factor for understanding the tectono-topographic state of the Indian Ocean. Furthermore, on the assumption of a pressure bath situation even in the upper crust, it is likely that aqueous fluids are in the reactive supercritical state (Belissent-Funel, 2001; Hirschman and Kohlstedt, 2012). Both as a free buoyant fluid or as a dissolved component in silicate minerals, supercritical water can be expected to greatly influence the structure and dynamics of the Earth; it is suggested that it combines low viscosity and high diffusivity with a high degree of solubility beside being very effective metasomatizing agents (Liebscher, 2010; Schienbein and Marx, 2020). For example, mud volcanoes can be regarded the product of rock disintegration and piercement structures at depth, under the action of supercritical hydrous fluids (Hovland et al., 2006; Zeng, 2010).

Based on the above considerations and the results from the two deep-continental boreholes, the westward-directed inertial forces - invoked by Damian Kreichgauer and Alfred Wegener, but for completely different dynamo-tectonic reasons, must now be re-evaluated. The continental crust can no longer be viewed as mechanically compact blocks, but rather like a 'deck of cards' subjected to skewed lateral pressure (Michaelsen and Storetvedt, 2023). Access of supercritical water in the crust has probably broken silicate minerals down to mud, and abundant water has, in addition, given rise to serpentinization. Thus, the continental crust easily acquires a layered structure where the combined inertial forces have given rise to internal slip surfaces, with the tectonic effect decreasing downwards. This is a reasonable explanation for the thrust sheet problem, as well as for today's GPS velocity measurements showing regional crustal rotations (see below) - and with rotational motions the continental root problem is avoided. Furthermore, it is probably only the upper half of the continental crust that is notably inertially affected. As the thin and mechanically weaker oceanic crust is an integral part of the global inertial system, adjacent ocean regions will inevitably be tectonically deformed - depending on the degree of crustal thinning and associated mechanical strength.

During the late Cretaceous, when the loss of the lower crust to the upper mantle was at its maximum, the corresponding equator ran along the present southern Mediterranean - a conclusion based on paleoclimatic (Wegener, 1929) and paleomagnetic (Storetvedt, 1990) evidence. In the general westward inertial drag, which increased towards the palaeoequator, the northern (upper) crustal cap was subjected to clockwise inertial torsion, while the southern cap (including Africa) was twisted counterclockwise. So, by extending Wegener's late Cretaceous-early Tertiary palaeoequator around the globe, this great circle belt would pass across India and Australia, as well as Antarctica (cf. Fig. 2). After the extensive crustal oceanization in the Upper Cretaceous, with its associated dynamo-tectonic repercussions, the Indian Ocean was surrounded by continental masses. India, Australia and Antarctica had palaeoequatorial locations where the inertial effect was/is at its maximum. Thus, according to paleomagnetic data, these three relatively small landmasses experienced rotational movements of >90°, movements that are consistent with respective regional tectonic patterns and qualitatively supported by GPS velocity structures (see below). Africa, on the other hand, which was entirely located south of the adjacent palaeoequator, underwent only ~25° counterclockwise motion (Storetvedt, 2003/23). In all, the continental masses surrounding the Indian Ocean will have been subject to inertial rotations with associated deformative effects, especially in the thinnest seafloor segments.

Fig. 5 shows a section of the global Base Map from National Organization of Atmospheric Administration (NOAA) Satellite Radar Altimetry of the seafloor. To present an undisturbed image of the satellite information for the Indian Ocean, all names, abbreviations (except for a few) and structural details are itemized in Fig. 3. The thin oceanic crust of southwestern Indian Ocean is strongly cut by a dense shear grain that obliquely cuts the slightly elevated SW Indian Ridge - a tectonic feature that dominates all elevated parts of the western Indian Ocean and its ridge system, including Carlsberg Ridge and Gulf of Aden to the north. Thus, the prevailing tectonic grain, which is

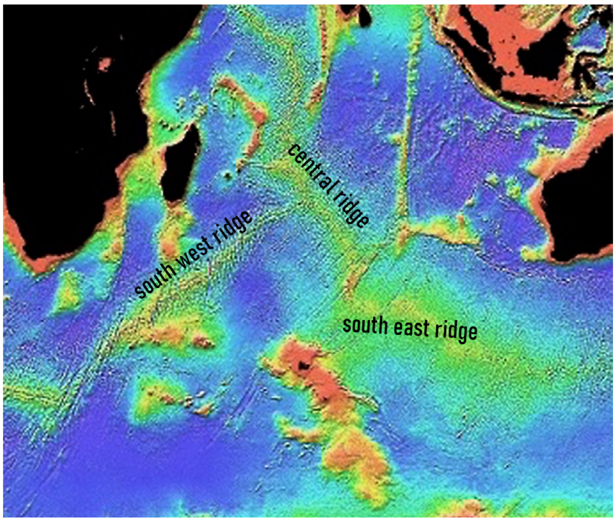

Fig. 5. Cut from NOAA Global Seafloor Topography map based on gravity data derived from satellite altimetry (Smith and Sandwell, 1997). Note how the tectonized mid-ocean ridges meander between submerged continental remnants. Another important feature is that the individual mid-ocean ridges do not have smooth transitions but instead show lateral displacements or marked discontinuities in direction.

consistent with the fault-bounded margin of eastern Madagascar, defines also the shape of the submerged Agulhas Plateau, Agulhas Ridge, Madagascar Ridge, as well as Madagascar itself. Furthermore, the shear grain cuts into the Mozambique Channel and is clearly related to Madagascar's gradual crustal thinning towards the Channel, discussed above. What we are seeing is not the breaking up of new tectonic structures, but the reactivation of one of the primordial sets of the ubiquitous orthogonal fracture network. This structural feature, which is dominant also at outcrop level (e.g. Scheidegger, 1980, 1985; Scheidegger and Schubert, 1989; Storetvedt and Scheidegger, 1992) has been elucidated on a global scale (Storetvedt, 2003/23, chap. 7) - resulting in characteristic pre-Upper Cretaceous jointing oriented NNE and WNW respectively. Further east, the arcuate and largely submerged Mascarene Ridge apparently has both structural trends. However, since the ridge is surrounded by thin and therefore deformable crust, the two characteristic fracture populations, in addition to the ridge's modest rotation, have apparently been subject to a certain 'links-chain' interaction (cf. Scheidegger, 1980, 1985) - which accounts for both the overall and individual component arc shape. A similar curvature, caused by inertial tectonics, is indicated in the moderate clockwise bending of Laccadive-Chagos Ridge (to the northeast).

India is positioned in the northern end of the Central Indian Shear Belt which in turn is bounded by the Laccadive-Chagos and Ninety-East ridges. The transpressional nature of the shear belt, which is manifested by seismic activity, undulations in topography and gravity, intense folding of the sedimentary succession, and high angle reverse faulting (e.g. Neprochnov et al., 1988; Curray and Munasinghe, 1989; Bull and Scrutton, 1992), has remained an unsolved puzzle within plate tectonics. Tectonically, India was located in an unpredictable wrench tectonic position - sandwiched between the Central Indian Shear Belt to the south and the clockwise rotation of the northern palaeo-hemispherical crustal cap. In a compilation study, Wezel (1988) concluded that the combined Central Indian Basin and Bay of Bengal have been subject to significant transpressive deformation. As a result of the complex tectonic situation, Greater India has apparently, based on palaeomagnetic data and related tectonic evidence, undergone significant in situ clockwise rotation (Storetvedt, 1990, 2003/23). At the end of the Cretaceous, this motion gave rise to the formation of the Deccan lava complex (Basu et al., 2020 and references therein), together with the westward bending/formation of the Carlsberg Ridge (Storetvedt, 2003/23). The clockwise rotation of Greater India is still in action, as demonstrated by the regional pattern of GPS velocity vectors (e.g. Zhang et al., 2004; Taylor and Yin, 2009; Bisht et al., 2020).

Furthermore, consistent GPS velocity vectors demonstrate counterclockwise rotation of Greater Australia (Puntodewo et al., 1994; Larson et al., 1997; Rangin et al., 1999 - an expected inertial rotation toward the present equator. Based on palaeomagnetic data, the original Australian Bight faced the Indian Ocean (Storetvedt, 1990, 2003/23). Subsequent counterclockwise rotation of Greater Australia has led to significant transpressive deformation of the knee-shaped margin of SW Pacific, while the trailing edge of the motion shows visible traces of transtension in the Wharton Basin. Thus, the orthogonal Ninety-East and Broken ridge system has apparently rotated about 20 degrees counterclockwise - away from their respective original NNE and WNW orientations - a feature consistent with the NOAA satellite-based physiography of the Wharton Basin. A similar inertial impact on the Indian Ocean seafloor, with its many submerged continental remains, has seemingly been caused by the major clockwise rotation of Antarctica (Storetvedt, 1990, 2003/23) - a motion which is still, but on a modest scale (Bouin and Vigny, 2000), still taking place. The Kerguelen Plateau appears to be rotated about 20 degrees clockwise (relative to the assumed fundamental WNW direction), but NOAA satellite imagery of the seafloor shows a relatively continuous tectonic shear structure to the junction of the Ninety-East and Broken ridges.

From Fig. 5 the mid-ocean ridges curve between what apparently are submerged continental remnants. Another characteristic is the lack of smooth transitions between the different ridge segments. Thus, the SW Ridge is perpendicular to the Central Ridge, the curved Carlsberg Ridge forms an oblique angle to the Central Ridge, while the Central Ridge shows an almost perpendicular offset to the SE Ridge. It is likely that this complex mid-ocean ridge system is a wrench tectonic product brought about by rotation of individual surrounding continents. Furthermore, the intensive shearing along the SW Ridge is absent as it approaches the Central Ridge. This probably means that with increasing distance from Africa, the continent's tectonic effect on the oceanic crust disappears. These conditions together with the observational basis discussed above provide strong evidence in support of the Indian Ocean being composed of thinned and assimilated continental crust - which in turn has been overprinted by wrench tectonic deformation mainly in the Upper Cretaceous. In the tectonic superposition, the main effect would naturally have occurred in the thinnest and mechanically weakest crust, which would suggest that this condition is localized to the mid-ocean ridges. Furthermore, since there is abundant water in the lithosphere, conditions would be favourable for serpentinization in the topmost ultrabasic mantle, along the tectonized mid-ocean ridges. This would in turn lead to crustal uplift along the ridge axes with exposure of the underlying continental basement - as repeatedly observed. Thus, Bonatti (1978) emphasized the low strength and low density, and thereby the greater mobility, of solid-state serpentinites to cause uplift along mid-ocean ridges and fault zones. Young volcanism along mid-ocean ridges in the Indian Ocean is apparently only an occasional phenomenon, which is also consistent with their exceptionally low heat flow along these ridges (cf. Geller et al., 1983).

Late Palaeozoic Land Bridges gains a foothold

During the Permian, the crust in the area covering the present-day Indian Ocean was in a very early stage of crustal thinning - an oceanization process that was not very effective until the Upper Cretaceous. That is, the surface situation in the Indian Ocean must have been roughly similar to that of the modern continents at that time: a network of dry land and shallow seaways. In other words, most mid-ocean ridges and submerged continental fragments in this vast region were probably land in the Permian, and according to recovered plant remains, at least parts were forested. According to Wegener's global climate system - with the Permian South Pole at ~0°E, 40°S (an approximate corner stone of present plate tectonics), with the associated palaeoequator across central Europe, further across India, Australia and Antarctica, etc., the area of the present Indian Ocean would have had very favourable latitude-related climate and migration route conditions. Thus, from east to west the environment would have changed from tropical to subtropical to warm mid-latitudes. In the Permian, we thus see a paleogeographic situation in which a network of land and shallow seaways, provided the basis for both favourable growth conditions and biological migration routes. Furthermore, on the basis of a Permian phytogeographical zonal and climate assessment, Krassilov (2000) found it necessary to support the traditional view of the Tethys as a narrow epicontinental seaway along the southern edge of present-day Eurasia. In that case, the dispersal routes for the Glossopteris vegetation from India to Eurasia were open, at least periodically - and then across the long-lasting North Atlantic land bridge to the Americas.

Once the late Carboniferous to early Permian cold period "Ice Age" vaned, the Permian of South Africa flourished with Glossopteris forests and herbivores. Special attention has been paid to Moschops - a robust reptile and herbivore that lived in Antarctica and southern Africa in the Middle to Upper Permian (Colbert, 1966). At that time, Earth's relatively moderate seawater volume was in a state of major regression (cf. Hallam, 1984, 1992) - draining surface water into developing semi-continental basins. In this situation, the migration of Moschops between Africa and Antarctica could easily take place via late Palaeozoic land bridges of the southwestern Indian Ocean.

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