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Original Article

Tectonic evolution of a sequence of related late Permian transtensive coal-bearing sub-basins, Mongolia: A global wrench tectonics portrait

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ABSTRACT

During the late Permian in Mongolia, inertia-driven transtensive reactivation of primordial fracture zones gave rise to the development of a sequence of related, but isolated, fault-bounded sub-basins; some of these became the locus of substantial peat accumulation that evolved into economically important coal deposits. The present study focuses on late Permian coal measures in two widely separated areas: Area 1: located in central Mongolia, developed along the southern margin of the Mongol-Transbaikalian Seaway. The late Permian coal sequence forms a c. 420 m thick middle part of a Permo-Triassic succession which spans c. 2,600 m. The V-shaped, fault-bounded NE oriented sub-basin evolved under transtensive conditions. The thick infill records a transition from shallow marine and humid coal forming depositional environments during the late Permian to relatively arid desolate terrestrial conditions during early Triassic times, considered here to mark the dramatic drainage of the Mongol-Transbaikalian Seaway across the Permo-Triassic boundary. Area 2: situated in southern Mongolia, is a NE oriented elongate sub-basin, bounded by two wrench faults, which formed under transtensive conditions. Thickness of the late Permian coal-bearing strata is c. 650 m. The sedimentary strata record a transition from a humid coal-bearing environment to predominantly marine conditions. Both study areas are located proximal to two controversial suture zones. However, the zones do not show the presumed shortening, major thrusting, regional metamorphism and given the complete absence of tuffs within the studied Permo-Triassic successions it could be argued that the sutures are not only cryptic but non-existent.

Keywords: Mongol-Transbaikalian Seaway, South Gobi Basin, Sulinkheer Suture Zone, Permian-Triassic boundary, tectonic superimposition, depositional dynamics.

INTRODUCTION TO WRENCH TECTONICS

To understand the Permian of Mongolia, and the rest of the country's geological history, we not only need essential field and laboratory observations but even more important is the availability of a functional global theory that establishes a natural interlinking of all “first order” phenomena - in time, space and scientific content. In the late 1960s it was hoped that plate tectonics would be able to fill this role, but apart from its rapid popularity it soon turned out that the model lacked the necessary explanatory and predictive capacity. Despite its inability to unify the Earth sciences, plate tectonics has nevertheless remained immune to rejection-even after negative critical tests and a never-ending flow of ad hoc repairs and special pleading.

The principal purpose of this paper is therefore to discuss the tectonic origin of Mongolia's Permian coal-bearing sub-basins within the framework of an alternative theory - Global Wrench Tectonics (Storetvedt, 2003; 2022). However, applying a new paradigmatic platform, unknown to most readers, requires a proper introductory overview - for which basic principles are outlined in the following together with a general wrench tectonic framework for Mongolia, before considering the evolutionary aspects of two late Permian coal-bearing sub-basins in central and southern Mongolia.

In a wider perspective, Mongolia's tectonic history constitutes a series of inertia-driven transpressive - transtensive reactivations of the global-extent orthogonal and steeply dipping fracture/fault system - building up superimposed tectono-magmatic successions in situ. In southwestern Mongolia, the cutting-across of the late Ordovician palaeoequator led to substantial reactivation of the steeply dipping orthogonal fracture/fault system, as well as paving the way for the overall geological history of the country.

We find reasons to maintain the traditional subdivision of Mongolia into two general provinces - "Caledonian" and "Hercynian", and the curved large-scale E-W oriented tectonic line is interpreted as an essentially middle-upper Palaeozoic inertia-produced structure. As the lower Palaeozoic equator passed through south-western Mongolia, this also led to reactivation of the deep-seated fault system in other parts of the country. Thereby, the foundation was laid for effective upper crustal pathways which completed the upward degassing flow from the deep Earth - predominantly consisting of hydrous and hydrocarbon rich fluids with leached metals from the mantle. This is probably the reason for Mongolia's unusual wealth of mineral deposits (Michaelsen and Storetvedt, in prep).

The core of the Earth is likely to be dominated by iron, but importantly seismic tomography conveys that both the inner and outer regions contain a substantial number of lighter elements - such as carbon, sulphur, silicon, oxygen, and hydrogen (Poirier, 2000 and references therein). Furthermore, Turekian (1976) argued that if the average carbonaceous chondrites resemble the original material of the mantle, as commonly believed, degassing of its internal water content would have produced a significantly larger volume than that presently covering the Earth's surface. In the same vein, experiments by Okuchi (1997) led to the conclusion that hydrogen could be the most prevalent light element in the core. The core is seemingly not in equilibrium with the mantle (e.g., Stevenson 1981), and the irregular core-mantle transition zone (CMTZ) draws in the same direction. An inferred connection between the irregular CMTZ "topography", in combination with the Earth's main surface features (Morelli and Dziewonski, 1987), is shown in Fig. 1. When projected to the Earth's surface, the illustration suggests that elevated regions of the core-mantle interface correspond to the world's deep-sea basins.

Based on Fig. 1, it seems likely that buoyant core masses have a close vertical link to the formation of the world's deep sea basins - and to the additive supply of surface water. Therefore, there ought to be a relatively clear seismic difference between continental and oceanic mantles - notably in the outer few hundred km, giving rise to continental roots and oceanic anti-roots. This dissimilarity in Earth's outer layering, originally described by MacDonald (1964) and Jordan (1975, 1979), has later been substantiated by three-dimensional global - scale

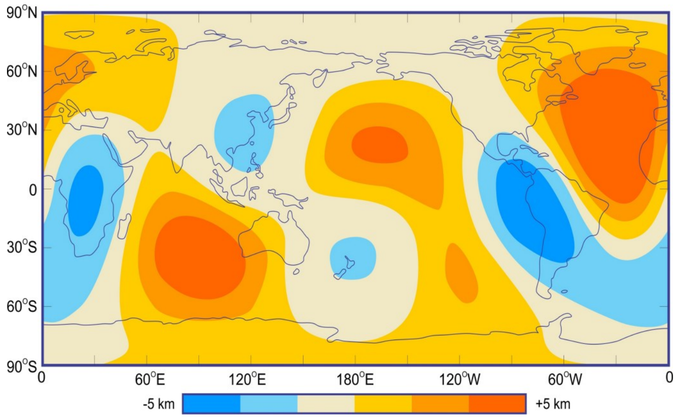

Fig. 1. The diagram depicts the 'topography' of the core-mantle boundary obtained by inversion of combined PcP and PKP residuals, corrected for lowermost mantle heterogeneity. The seismological results are seen in conjunction with the Earth's main surface topography. After Morelli and Dziewonski (1987). Note the correspondence of the elevated regions of the core-mantle interface with the world's deep-sea basins.

images of the interior (e.g., Dziewonski, 1984; Dziewonski and Woodhouse, 1987; Forte et al., 1995). In accordance with Fig. 1, the mantle below oceans and continents ought to display differences in composition, outward - directed hydrostatic pressure, fracture volume, chemical composition, and hence seismic velocities. These vertical differences, demonstrated in Fig. 2, negate the possibility of lateral continental drift. However, in current plate tectonics literature postulated continental blocks are wandering about without noticeable restrictions - as if the root problem does not exist.

During degassing, the upper mantle and lower crust would experience the build-up of high confining pressures caused by buoyant volatiles - a situation that have important geological consequences. For example, natural occurrences of granulite to eclogite transition demonstrate that the process is strongly impeded when hydrous fluids are absent (Austrheim, 1987, 1990; Walther, 1994; Leech, 2001), and Austrheim (1998) argued that for these metamorphic reactions to go forward, hydrous fluids are much more important than either temperature or pressure. Thus, Leech (2001) submits that the availability of hydrous fluids drives eclogitization, resulting crustal delamination, and progressive gravity thinning of the continental crust - from the bottom upwards. We are led to conclude that the slow degassing of the Earth's interior is the principal agent behind development of the planet's "first order" surface topography. However, this crustal "oceanization" process is often far from complete. Thus, the Atlantic and Indian oceans contain a series of partially assimilated continental ridges and plateaus, and the marine geological literature is full of examples that also the crust along mid-ocean ridges consist of old metamorphic and plutonic rocks (Cann and Vine, 1966; Chernysheva and Murdmaa, 1971; Hall and Robinson, 1979; Cannat et al., 1995; Pilot et al., 1998) - in addition to serpentinized and tectonized upper mantle peridotites. Fresh basalts that the plate tectonic model predicts are a rarity (Storetvedt, 1997).

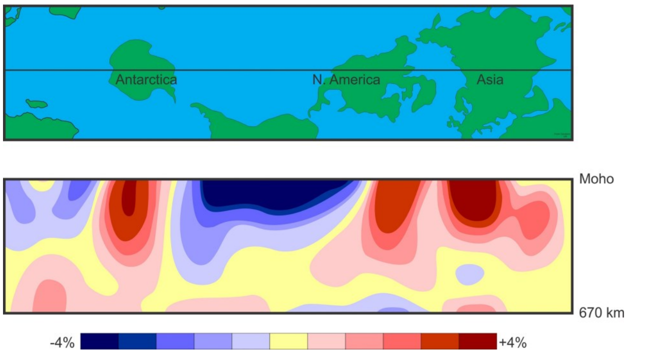

Fig. 2. Variations in upper mantle S-wave velocities (lower panel) along the 110° W meridian - displayed by the central line of the upper panel - from Moho to a depth of 670 km. The continents (Eurasia, North America and Antarctica) reveal relatively fast upper mantle velocities, while the mantle sections below the ocean basins show comparatively slow velocities. Vertical exaggeration is 20:1. Simplified after Dziewonski and Woodhouse (1987).

Changes in Earth rotation; tectonic and environmental implications

The internal mass reorganization anticipated from Fig. 1 would have affected Earth's rotation in two ways - a) changing its spatial orientation (True Polar Wander) and b) its rotation rate. A net outward mass transport (degassing) will decrease the moment of inertia and thereby the planet's spin rate, while an inward motion of

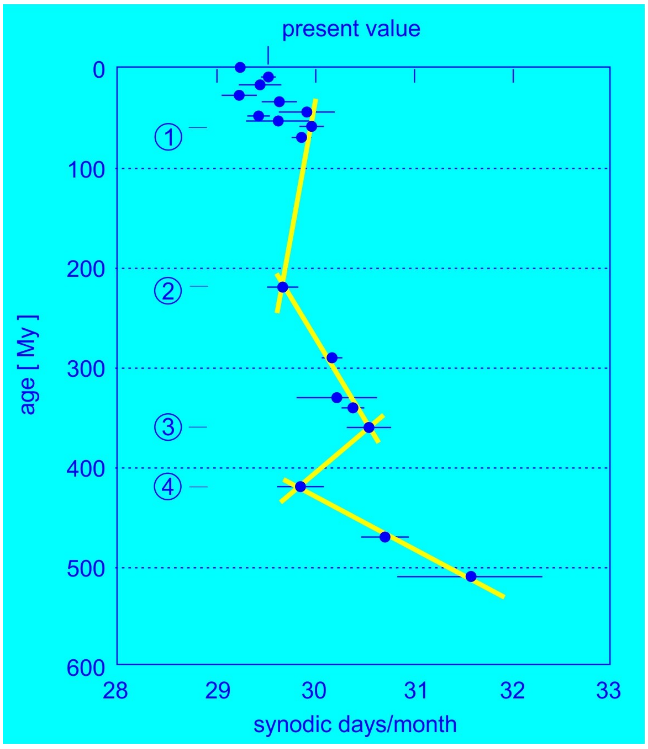

Fig. 3. Compilation of presumed days per month, based on growth rings in fossil shells - based on data compilation by Creer (1975). The breakpoints (1-4) in the graph correspond to predominant global tectonic events which also represent main geological time boundaries.

mass (loss of densified crustal material to the upper mantle) increases the moment of inertia and hence the spin rate. With this reasoning, it follows that the Earth's rotation history ought to define a zig-zag pattern - which indeed has been demonstrated by palaeontological "clock" data as well as by the episodic pattern of the polar wander path. It is remarkable how closely the established breakpoints (Fig. 3) - separating periods of deceleration from periods of acceleration - correspond to principal geological time boundaries which represent major global tectonic events. These are: Taconian (late Ordovician), Acadian (Devonian), Appalachian-Palatinian (at the Permian-Triassic boundary), and the Alpine climax (the Cretaceous-Tertiary boundary), respectively (Fig. 4). This indicate that global tectonics is closely tied to degassing related changes of Earth's spin, but also the generalized sea-level changes and Earth's spatial reorientation (i.e., shifting of the equatorial bulge) fall in the same category. A plot of compiled palaeontological annual spin rate data of the Earth is shown in Fig. 3.

Fossil evidence demonstrate that Antarctica had tropical to warm intermediate latitude conditions for at least 400 million years, until spatial reorientation of 35^{o} of of the Earth, at around the Eocene-Oligocene boundary, instigated the present polar condition (Elderfield, 2000). After this major spatial flip of the Earth, the long-lasting warm prehistory of both the Arctic region and Antarctica came to an end, after which the two antipodal regions became polar, probably for the first time since the Precambrian. In addition to the enormous amount of fossil evidence now available, independent verification of a former tropical status of Antarctica has come from palaeomagnetism and deep-sea drilling data. For example, ODP Leg 119, drilling into the Antarctic margin at Pryds Bay, encountered red sandstone equivalent to Devonian Old Red sediments in Europe and along the eastern seaboard of North America. Such observations stood in striking contrast to plate tectonics' expectations about polar conditions in the geological past. Furthermore, the characteristic flat-lying paleomagnetic inclinations in these undisturbed sediments confirmed their paleo-equatorial origin (Keating and Sakai, 1988). However, regardless of the severity of the anti-plate tectonic observations from Antarctica, the disturbing information has so far not had consequences for the dominant status of that model. But ignoring or explaining away troublesome data doesn't make them disappear - they are just hidden away for a while, until a scientific revolution brings them into focus. Thus, paradigm-based research can be described as a group commitment for which ingrained habitual thinking is the only condition that makes it meaningful to talk about a common paradigm (Kuhn, 1970; Margolis, 1993).

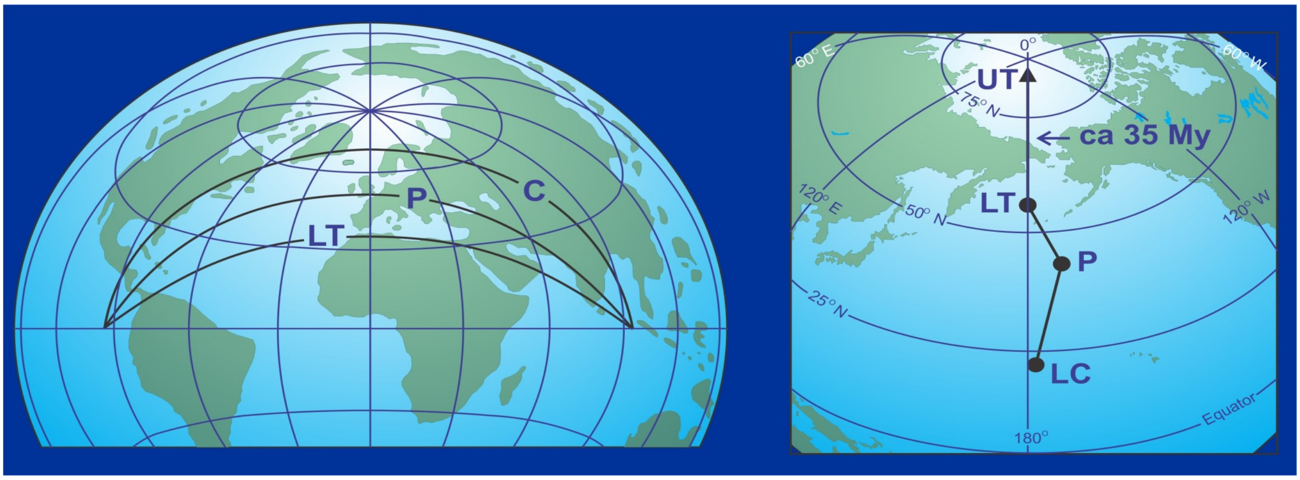

Fig. 4. Illustration to the left depicts Wegener's palaeoequator system representing Devonian-Carboniferous (C), lower Carboniferous (LC), Permian (P) and lower Tertiary (LT) and upper Tertiary (UT), respectively - intersecting at around 90^{o}W and 90^{o}E. The picture to the right shows the corresponding palaeomagnetic polar curve (Storetvedt, 1990). Note the marked polar and climatic shift in the middle Tertiary, during which both the Arctic and the Antarctic regions attained polar locations for the first time in post-Precambrian history.

In addition to largely ignoring the fossil evidence from Antarctica, Wegener also disregarded the many reports of glacial deposits in the northern hemisphere during the late Carboniferous-early Permian period - notably in North America, in particular the major Squantum tillite near Boston. He held that the reported North American cases probably were misunderstandings, but if at least some of these occurrences were correctly interpreted, he admitted they would undermine his crown (glacial) argument and be a blatant blow to his drift hypothesis (Wegener, 1928). It appears strange indeed that Wegener, who primarily was a meteorologist and palaeoclimatologist, disregarded the possibility that the many glacial occurrences from around the world, including his own selected data from Australia, India and South America, simply could be products of one or more short-lived events of global cooling – adding to the truly palaeo-polar ice cover in southern Africa. If so, the climatic situation in the late Carboniferous or early Permian would be just like that during late Neogene-Quaternary glacial period. In the early stages of plate tectonics, Lowenstam (1964) carried out oxygen -isotope temperature measurements of fossils from glacial and post-glacial lower Permian sediments from West-Australia. The reported temperatures were 8^{o}C and 24^{o}C respectively, suggesting that as soon as the “Permian” ice age was over, the temperature condition in Australia was back to normal. Nor did such clarifying observations receive significant attention; at a time when moving continents and crustal plates were about to take the lead in discussions of global tectonics; disturbing observations were only received with shrugs of the shoulders.

In the light of Darwin’s theory, the fauna and flora similarities between continents required that, formerly, there must have been land connections between land masses now separated by deep oceans. It was envisaged, therefore, that during the upper Cretaceous or lower Tertiary these intercontinental connections had broken up and subsided. By the early 20th Century several isthmian links had been proposed (e.g., Willis, 1932). To Wegener, these “land bridge” proposals contradicted the well-established principle of isostasy, a problem his continental drift hypothesis avoided. On the other hand, Barrell (1927) proposed a crustal oceanization model in which sub-crustal basification by magma injection had led to gradual subsidence, eventually forming deep-sea basins, though uneven crustal transformation and subsidence had left behind continental ridges and plateaus, providing necessary biological migration routes between remaining continents. Even Wegener, based on available continental rock material from the Azores region, considered this mid-oceanic plateau to be built on submerged continental crust; he also suggested that the South Atlantic Ridge could be a fragment of a sunken continental crust (Wegener, 1929/66). Wegener’s opinion that the indisputable notion of isostasy was contradictory to the “land bridge” concept, received constant setbacks.

Wegener referred frequently to the geological arguments of Du Toit (1927) who had written extensively on the geological similarities of South Africa and South America. In du Toit’s view, particular formations along the opposed margins tended to resemble one another more closely than their extensions within the respective continents. This contention was, however, markedly weakened by an intervening between-continental gap, of at least 400-800 km (Wegener, 1966), which du Toit regarded necessary to allow for differences in the observed rock facies. This meant that the geological resemblance, allegedly arguing in favour of continental unification, was not that clear-cut after all. In fact, if du Toit had to allow for a separation of 400-800 km or more to obtain a sensible geological pattern matching, how could he really set an upper limit to the initial separation of the two continents? Wegener accepted du Toit’s geological arguments, implying that a relatively broad continental belt between Africa and South America had foundered to oceanic depths. Again, Wegener's isostacy argument against the “land bridge” hypothesis was steadily losing potency.

For both Wegener and du Toit, the orthogonal configuration of the equatorial African margin and the matching shape of the opposite NE Brazil - fitting into each other, was a decisive factor behind the continental drift hypothesis. However, Wegener who in various situations had accepted that the continental crust could undergo major subsidence, wondered about the significance of the large-scale orthogonal fault system that follows the continental margins of NE Brazil extending far inland (Wegener, 1966). He had accepted that continental crust could be "oceanized", including a several hundred kilometres broad between-continental section. Therefore, it should have been a short leap for him to see that the equatorial South Atlantic "fitting" was nothing but a product of crustal subsidence and oceanization where the resulting adjacent margins were controlled by the ubiquitous orthogonal fault system. If so, he would have undermined his own theory - so he didn't see this possibility. Even more series was that, to a large extent, the drift hypothesis was without clear scientific rules. Besides, his continental reconfiguration had some grave palaeoclimatic self-contradictions.

Thus, the surprising discoveries from Antarctica were clearly devastating to Wegener's unification of the southern land masses, but the seriousness of these facts was largely ignored. Wegener's wishful thinking won the race. Unfortunately, this neglect, ignorance or alienation has been inherited by plate tectonics, and consequently the airy Gondwana concept lives on as if everything were in perfect order.

A major outburst of juvenile surface water took place in the lower Palaeozoic. This discharge culminated in the late Ordovician during which 70-80% of the present land surface was covered by shallow seas (Vail et al., 1977; Hallam, 1992 and references therein).

From the cosmopolitan character of the shelf faunas, Boucot and Johnson (1973) inferred that in general the Palaeozoic Earth had a flat surface - without mountains and deep ocean barriers. The lower Palaeozoic inundation was superseded by gradual draining brought about by events of degassing-related sub-crustal thinning and isostatic basin growth. Associated Earth acceleration triggered periods of upper crustal wrenching (see below) and increased gas/fluid pressure, processes that released pulses of toxic gas with resulting biological crises. The progressive withdrawal of shallow seas culminated in a marked regression at around the Permian-Triassic boundary. A new wave of pristine water characterized the Mesozoic, reaching its peak in the upper Cretaceous (the Cenomanian transgression). Fig. 5 marks the 6 major periods of marine mass extinction in Earth history, all accompanied by relatively distinct regressive events - caused by episodic crustal loss to the upper mantle.

Traditionally, it is assumed that the Earth began as a hot molten mass which gradually became fully differentiated. On this background It has been acknowledged that, except for a very shallow outer layer, gravity would close all fractures, making degassing from the interior quite impossible. However, for an originally cold Earth, starting with a mix of gas and particulate matter - the likely starting point for a degassing Earth, the situation would be quite different (Hoyle, 1955; Gold, 1999). Thus, at each depth level rocks and fluids would be subject to a common pressure - a kind of pressure bath situation in which fractures are kept open just as in near-surface rocks at low pressures. If a buoyant fluid, occupying an existing fracture network, exerts an outward hydrostatic pressure as great as the opposing gravity pressure of the surrounding rocks, any existing fluid flow will be maintained. This principle has been well demonstrated by deep continental drilling - in the 12,262 m deep Kola Superdeep Borehole in far NW Russia (e.g., Kozlovsky, 1984) and in the KTB site of SE

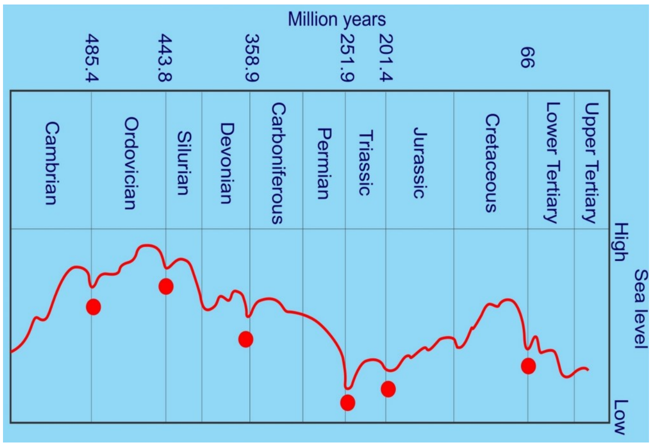

Fig. 5. Generalized sea-level curve for the Phanerozoic. The six principal events of marine mass extinction are marked by red symbols. After Hallam (1992). Note that the biotic catastrophes occur at times of distinct sea-level minima (regressions) which also correspond to main geological time boundaries, and changes in Earth rotation.

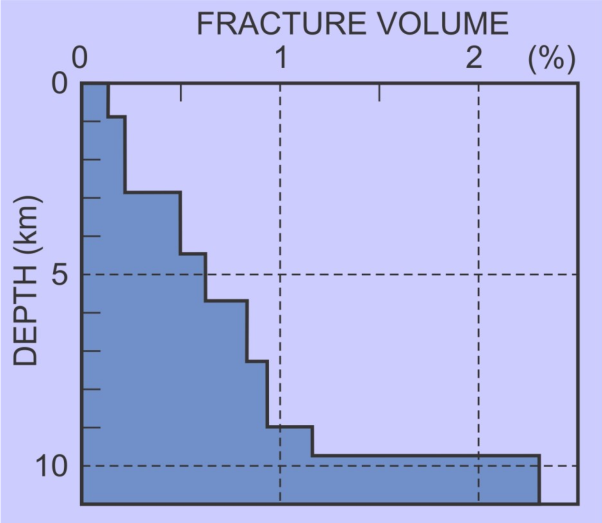

Fig. 6. The average fracture coefficient (%) in the Kola Superdeep Borehole, after Hunt (2001). Note the exponential increase of fracture volume with depth.

Fig. 7. The relative inertia-driven wrench rotations of Africa and Eurasia (black arrows) for upper Cretaceous-Eocene - a segment of the latitude-dependent westward torsion of the global (upper) crust at that time. The marked intermediate zone outlines the resulting Alpine fold belt. The relative continental rotation amounts to c. 50° (25° for each of the continents' upper crust), and the same between-continent motion is also demonstrated by the corresponding Permian palaeomagnetic field discordance (white arrows). Grey colour denotes fault reactivation and related basin formation in Africa.

Germany (e.g., Ito and Zoback, 2000). Fig. 6 demonstrates the exponential increase in fracture volume versus depth in the Kola drill hole. In the latter location, it was found that the fracture network - reaching a maximum volume of 4.3% and showing an exponential increase with depth, contained a free flow of hydrous fluids with dissolved hydrogen, carbon dioxide, nitrogen, methane and helium (Pavlenkova, 1991; Hunt et al., 1992). Traditional assumptions about the internal state of the Earth therefore stand to fall. But the far-reaching geological and geophysical consequences of deep-continental drilling results have so far attracted little attention.

Inertia-driven tectonic wrenching of the upper continental and deep-sea crust.

Kreichgauer (1902) was the first who associated formation of large-scale tectonic belts with Earth 's rotation; he submitted that the equatorward force of crustal motion had produced fold belts along time-equivalent equatorial regions along with palaeo-longitudinal rift zones. These weak forces have traditionally been considered inadequate for tectonic processes. However, evidence from continental drilling indicates that mechanically the crust becomes increasingly weakened with depth - indicating that in terms of inertia-driven mobility, a continent being subjected to even weak horizontal forces is likely to behave like a deck of cards; that is, the upper crust can potentially be variably affected by wrench rotation/deformation without losing physical contact with its underlying crust and mantle root. Re-evaluation of palaeomagnetic data (Storetvedt, 1990, 1997, 2003; Storetvedt and Longhinos, 2011, 2012) attest to the validity of this principle. The latitude-dependent wrenching has maximum westward drag in palaeo-equatorial belts: the northern palaeo-cap become twisted clockwise and the southern anti-clockwise. These motions turned the palaeo-equatorial region into a globe-encircling shear belt, though not easily recognized in the much more deformable deep-sea crust - where a wrenching event is liable to have had much more widespread effect. The continental crust will generally be exposed to transpressive conditions, though naturally interrupted by transtensive conditions in places. Fig. 7 demonstrates the relative upper crustal wrench rotation of Eurasia-Africa during the Alpine tectonic calamity. At that time the present surface configuration, with its thin-crusted deep-sea basins and remaining continental masses, was largely in place. This was apparently also the first time in Earth history that thin continental top layers underwent relative inertia-driven wrench rotations in situ - for which individual motions were primarily dependent on size and geographical location. In the early days of palaeomagnetism, between - continent palaeomagnetic discrepancies became misconceived in favour of Wegener's drift hypothesis (Storetvedt, 1990) - an error that has never been corrected.

Earth’s surface is extensively fractured, and based on experience from deep continental drillings it is likely that a dense system of open fluid-filled cracks increases exponentially with depth. Therefore, events of global torsion may readily have caused fault reactivation and reshaping of both continental and oceanic regions. It should come as no surprise therefore that the linear basins of late Mesozoic and Tertiary ages in Central Africa, associated with recurrent magmatic and tectonic activity, have developed along major Precambrian rift systems. Intracontinental shearing of Central Africa (e.g., Benkhelil et al., 1988; Binks and Fairhead, 1992 and references therein) have utilized weakened crust in Precambrian mobile belts - and given rise to superposed tectono-magmatic activities. Tectonic fault reactivation, with variegated tectono - magmatic consequences, is a central theme in the wrench tectonic theory.

The observed time-dependent high pressure/low temperature mineralogical variations (Ernst, 1972; Droop et al., 1990) suggest that the tectonic pressure in metamorphic belts has increased with time; owing to markedly increased mobility, tectonic pressures during the Alpine event were much stronger than during preceding epochs. Furthermore, local transtensive regimes with associated basin formation, basically reactivating elements of the ubiquitous orthogonal fracture network, would inevitably develop in places. Hence, ductile upper mantle material would easily be subject to upward tectonic squeezing through deep fractures. This ultrabasic material, generally altered to buoyant rocks rich in serpentine, chlorite, epidote and albite - often occur in association with volcanics and geosynclinal sediments. The general shearing tectonics along the Alpine-Himalaya tectonic axis readily accounts for the disconnected nature of these “exotic” rock bodies. In the same context, Brookfield (1977) concluded that ophiolitic material was found in narrow belts of vertical instability, between more rigid platforms and emplaced during high-angle wrench faulting. Similar arguments may readily apply to other regions and other times - such as to the Palaeozoic structural discontinuities in Mongolia.

From the above it follows that the oceanic crust is likely to have a larger fracture volume than the continental carapace, and hence a greater capacity for fault reactivation and structural deformability. As the deep-sea basins primarily developed in the upper Cretaceous, the deformed oceanic crust might be regarded as a new type of fold belts (Storetvedt, 1990). A prominent example is the mega-scale, broad, and slightly curved (NNE-SSW striking) tectonic belt of the western Indian Ocean, and which also matches the southern hemisphere’s anti-clockwise torsion in upper Cretaceous-Eocene. Moreover, physiographic images (NOAA Satellites and information, National Geophysical Data Centre, Boulder) convey that the southern mid-ocean ridge system is tectonically exceptionally sheared and very unlike that expected for a hypothesized spreading centre. Furthermore, numerous aseismic, shallow, and flat-topped continental ridges and plateaus are spread across the Indian Ocean. The most likely explanation of the extreme complexity is that an original continental crust has been progressively, but unevenly, thinned and chemically modified in situ, before being overprinted by widespread tectonic deformation during Alpine events. The idea of a former Gondwana configuration carries no weight.

Fig. 8 illustrates the pre-Alpine arrangement of the Atlantic continents, based on matching paleomagnetic polar paths (Storetvedt, 1990, 1992, 1997), seen in conjunction with the upper Cretaceous palaeoequator. For South America, the palaeomagnetic data suggest a moderate clockwise rotation, instead of the anti-clockwise Alpine torsion expected for the southern

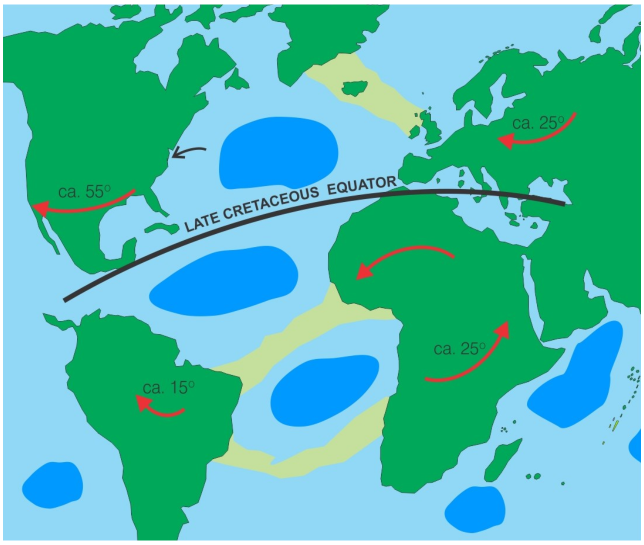

Fig. 8. Configuration of the Atlantic prior to the late Cretaceous-lower Tertiary tectonic climax - based on palaeomagnetic data. Thin and mechanically weak oceanic crust was now in accelerating development (medium blue), causing the continental blocks to undergo relative inertia-driven wrenching (red arrows).

hemisphere crust. This discrepancy is linked to the relatively narrow width and orthogonal shape of the equatorial Atlantic. Thus, the westward-directed pressure by NW Africa exerted tectonic forces across the relatively narrow equatorial ocean, generating transpressive forces along the margin of NE Brazil. This tectonic pressure was obviously stronger than the predicted inertial effect (anti-clockwise) because the resulting motion of South America was a moderate 15° clockwise. Adding to the South America-Africa interaction, the oceanic crust between the Gulf of Guinea and NE Brazil has an unusually dense system of transoceanic shear zones, in part cutting into the adjacent continents, and ODP Leg 159 uncovered intense folding, faulting, and shearing in Cretaceous strata. The equatorial Atlantic has also been affected by strong vertical movements on scales far beyond that expected by thermal models related to the seafloor spreading hypothesis (Bonatti et al., 1977; Bonatti and Chermak, 1981; Timofeev et al. 1990). During initial stages of the Alpine tectonic revolution, a few land "bridges" and island continents still existed, but in the lower Tertiary only the W Europe-Faeroes-Iceland-Greenland connection seems to have been intact.

In conclusion: The modern Atlantic continents have never been united. The present Atlantic basins have southward-fanning configurations, but after correction for Alpine wrench rotations of opposite continents, both the North and South Atlantic become elongated in NNE/SSW direction (Fig. 8). This pre-Alpine orientation of the oceanic basins matches one of the orthogonal sets of fault-fracture-joint systems that apparently characterize the entire crust - both continental and oceanic.

In the equatorial Atlantic, the tectonic interaction between NW Africa and South America reactivated and enlarged the other set of orthogonal crustal ruptures - giving rise to several mega-scale WNW/ESE oriented fault zones; these discontinuities run parallel to the northern margin of Brazil, in addition to being parallel with prominent fault zones inland (N Brazil). These equatorial faults correspond to preeminent fracture zones in the Central Atlantic (Vema, Kane, Atlantis, and more). We begin to see that the original stretched-out S-shape of the Atlantic has formed in situ, from a thinned and isostatically submerged continental crust that took its prevalent (pre-tectonic) shape from the old orthogonal fracture network - with NNE/SSW and WNW/ESE orientations, respec-tively. It follows that the widespread opinion that Africa and South America once were united, allegedly because the coastlines of Bay of Guinea and NE Brazil can be fitted, is a naïve approach carrying no weight. By accepting the oceanization model and the pre-upper Mesozoic configuration of the originally thick Atlantic crust (Fig. 8), the many perpetual problems facing plate tectonics - including the lack of confirmation of the model´s basic mechanisms, the classical continental fitting problems, the confusion surrounding the numerous continental ridges and plateaus in deep sea basins, as well as some severe paleoclimatic inconsistencies - will become non-relevant.

Critical tests of the Vine and Matthews (1963) model of seafloor spreading have become complete failures. From the most detailed of these tests - DSDP Leg 37 drilling, in a transect on the western flank of the mid-Atlantic ridge just south of the Azores - every basic geophysical and geological element were markedly at variance with expectations, including an extremely low heat flow (Aumento et al., 1977; Hall and Robinson, 1979). On the contrary, sheared and mylonitic serpentinites have been reported from many sites within fracture zones transverse to the Mid-Atlantic Ridge (e.g., Melson et al., 1972; Rona et al. 1992; Cannat, 1993; Rouméjon and Cannat, 2014). Instead of being regions characterized by sheeted dykes and fresh basalts (fundamental prerequisites of plate tectonics), mid-ocean ridges and deep-sea basins are dominated by altered, metamorphic, plutonic and old continental rocks. Furthermore, along mid-ocean ridges hydrothermal venting with relatively low temperatures have commonly been observed (e.g., Kelley et al., 2001) - results that are problematic for plate tectonics but readily fall in place in a degassing-driven Earth system.

An alternative interpretation of marine magnetic field “lineations” is the magnetic susceptibility-contrast model (Luyendyk and Melson, 1967; Opdyke and Hekinian, 1967) - producing contrasts in induced magnetic fields. Along fault zones, shear reactivation has led to partial or complete removal of iron-titanium oxides (and replaced them by non-magnetic silicates), hence lowering magnetic susceptibility and related induced magnetic field anomalies. Between fault zones, however, mineralogical alteration is expectedly lower and therefore the magnetic susceptibility would be higher. Thus, bands of stronger and weaker induced magnetization (varying perpendicular to the tectonic grain) would occur. During the Alpine climax, the palaeo-equator crossed the Central Atlantic (Fig. 8), a region where the westward inertia torsion would be at its maximum. North America’s relatively large clockwise swing (55^{o}), which expectedly caused an extra transtensive effect in the western part of Central Atlantic, is consistent with this prediction. For this part of the ocean, both sets of the orthogonal fractures seem to have taken part in the wrenching process - providing a proper test of the susceptibility-contrast model. Fig. 9 depicts a modern compilation of marine magnetic field anomalies for the western Central Atlantic - taken from World Digital Magnetic Anomaly

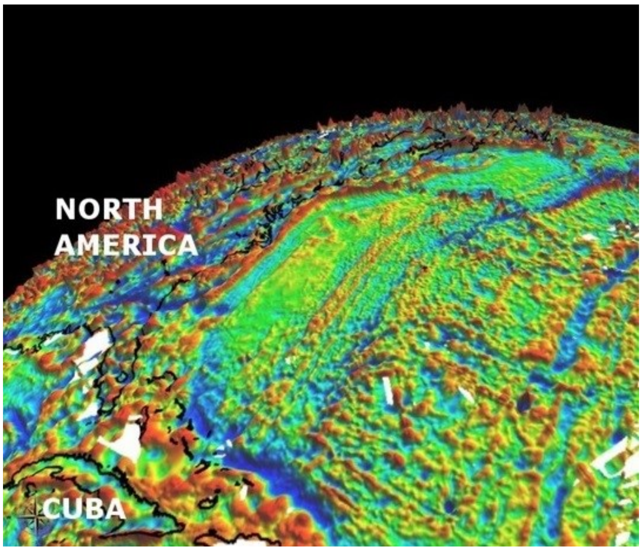

Fig. 9. Modern presentation of the marine magnetic anomaly structure for the western Central Atlantic - a cut from World Digital Magnetic Anomaly Map (EMAG 3). To a considerable extent, the anomalies display an orthogonal network for which the individual branches correspond to the orientation of the Atlantic fracture system - oriented NNE/SSW and WNW/ESE, respectively.

Map (EMAG 3), showing results that largely comply with the susceptibility-contrast model. The marine magnetic anomalies tend to form an orthogonal network in tandem with the underlying fracture-fault system. Once again, a fundamental assumption of plate tectonics has been put to question.

Mongolia seen from the perspective of a degassing Earth

Guided by unconfirmed plate tectonic processes, it is repeatedly claimed that the high plateau of Central Asia has been built by a multiplicity of amalgamated crustal blocks with speculative origins. In attempts to explain the complex concoction of colliding blocks, terranes and allegedly closed palaeo-oceans, a flora of auxiliary mechanisms and technical terms have been proposed. A series of inventive ad hoc operations - such as accretionary wedges, suture zones, subduction roll-back, one-sided or double -sided subduction, obduction, back-arc spreading, etc., have impaired the geoscientific literature. Adding to the multitude of riddles surrounding the lower Palaeozoic-Mesozoic geological history of Mongolia, the occurrence of the centrally located Khangai Dome, having originated along with the topographically uplifted Central Asia in the late Neogene, is a particularly hard nut to crack. Moreover, despite being located far from asserted plate boundaries, Central Mongolia has numerous small Neogene to Quaternary volcanic cones and lava fields. Also, the western half of Mongolia has historically been unexpectedly prone to seismic activity, up to Magnitude 8 or more on the Richter scale (Sodnomsambuu and Klyuchevskii, 2017) - again a puzzling problem for plate tectonics. Hence, a new theoretical platform, to guide future research, is clearly needed.

In the Introduction we considered some geodynamic consequences of the observed irregular outflow of mass from the core-mantle boundary (Fig. 1) - with resulting surface topographic repercussions, beside bolstering the largely ignored continental root problem. In this process, the original thick continental crust was subjected to progressive sub-crustal eclogitization with resulting gravity-driven delamination to the upper mantle, primarily in the upper Cretaceous. This thin deep-sea crust is mechanically weak and therefore particularly prone to tectonic deformation. Storetvedt (1990) therefore considered the often tectonically deformed deep-sea crust as a new type of Alpine fold belts. In this process, the primordial orthogonal fracture sets were reactivated, with a series of tectono-magmatic consequences, of which the results of DSDP Leg 37 in the Atlantic (Aumento et al., 1977) gave a representative demonstration. But even in continental crust, there are cases for which long-lasting tectonic history represents superimposed events - triggered by planetary outgassing and related dynamical changes. Mongolia is a star example in that context.

Understanding surface geology from the inside out

The 12 km deep Kola drill hole in NW Russia gave the surprising outcome that fracture spacing increases exponentially with depth (Fig. 6), and similar unexpected observations were obtained in the 9 km deep KTB drill hole in SE Germany. Another revealing discovery in the two continental sections was that the system of opening fractures was filled with hydrous fluids.

It was obvious that the crust is not the solid, impenetrable shield that often has been assumed, but instead a highly fractured and increasingly liquid/gas-filled layer. Such an open fracture system will occur when the outward directed hydrostatic pressure compensates the inward gravitational force. Even in the upper crust it is likely that the shear strength is likely to be much lower than what traditionally has been conjectured.

Moreover, the buoyant masses from the interior must have led to significant changes of the original anorthosite-diorite incrustation (e.g., Storetvedt, 2003, 2010) through mineral transformation in situ. Thus, Collins (1992) - discussing the longstanding granite problem relating to several case studies in North America, argues that "many…granites, including major batholites ones, contain myrmekite and have evolved from mafic rocks by replacement processes. These replacement processes are the result of hydrous fluids that move through fractured rocks in open systems". In the same context, Hunt et al. (1992) presents a series of arguments in favour of an endogenous origin of the enigmatic surface deposits of pure quarts deposits of sand and quartzites, underscoring the point that the mass of quartz is often too large and too pure to be the natural product of denudation and winnowing of local granites. Hunt further discusses how older rocks are transformed into granitoid masses through metasomatic and recrystallization processes. He proposes that monosilane (SiH_4) activity causes mafic cations to be replaced by silica and silicates, and diorites and gabbro to become felsic and silica rich.

With the availability of potassium and water (i.e., natural degassing products), granitization of the Precambrian crust may be a metasomatic transformation product - advanced from degassing of the deep interior. On this background, drilling into cratonic regions might encounter increasing granitization with depth. Consistent with this prediction, the more mafic top layer penetrated in the Kola drill site was followed by light-coloured granitic rocks at deeper levels, and "granitization also becomes more intense, ranging from slight biotization on the surface to migmatization at a depth of 6.8 km" (Russ. Acad. Sci., 1998). As they ascend buoyantly through the mantle, volatile carbides and hydrides in reaction with hydrogen/oxygen may produce other volatiles, such as monosilane (SiH_4) and methane (CH_4) - processes that are combustible and endowed with latent heat (Hunt et al., 1992). Here we most likely find the explanation of the widespread occurrence of post-Precambrian granitic plutons and other felsic rocks in Mongolia. With the likelihood that granitic melts have formed through metasomatic processes within the crust (producing heat), we have yet another physical factor (adding to the increasing fracture spacing with depth) that greatly reduces the mechanical strength of the upper continental crust - thereby increasing the tectonic deformability of a variable top layer.

The classical hydrothermal hypothesis of metal leaching, transport and deposition have been regarded quite unrealistic (Krauskopf, 1982). Interestingly, a new study of the giant Cu-Au Grasberg deposit in Indonesia by Henley et al. (2022) strongly indicates the deposit developed isochemically in a gas phase reactor where only sulphur and the economic metals (Cu, Mo, Au, etc.) were added by flux of reactive magmatic gas with repetitive fracturing generating high permeability flow paths for expansion of the magmatic gas. Nonetheless, considering the reactive state of supercritical hydrous fluids (see below), the role of water as an effective internal "conveyer belt", may change this view. Also, the degassing-related arguments of crustal granitization by Collins and Hunt, referred to above, may be central in this context. Thus, it appears likely that the widespread granitoid related gold mineralization in Mongolia is closely associated with the internal degassing system and its resulting crustal granitization. In a similar vein, Gold (1999) argues that rising hydrocarbon fluids surpass water in both the capacity to hold metals in solution and for the pumping power needed in the energy-intensive leaching process. Gold emphasized that many metals are carried in hydrocarbons that have entered molecular arrangements with metals to form complex compounds called organometallics; he finds it likely that organometallics are being produced by hydrocarbons leaching through the mantle. Then, when temperature, pressure or other solubility conditions reach a threshold at which a particular kind of organometallic can no longer stay in solution, a concentrated metal vein would form in that "spot". The fact that trails of soot are associated with a multitude of ore deposits (Gold, 1999; Hunt et al., 1992) may underscore the important role of both silane and hydrocarbon fluids for the leaching and solubility requirements for upward transport of metals - during which Earth's dynamic pulsation would provide the natural hydrostatic pumping device. Hence, "endogenic factors may be considered as the active prime-movers of global tectonics [and other surface products]. This hypothesis reflects a point of view in which the Earth is considered from its inner workings' outwards" (Wezel, 1992a, 1992b).

Mountains and plateau uplifts- newcomers in Earth history

Both Eurasia and other continents had a long history of shallow epicontinental seas and lowland topography (Boucot and Johnson, 1973; Hallam, 1992; Pomerol, 1982) - i.e., a relatively flat surface that ended with the uplift of highland plateaus and/or mountain ranges in the late Tertiary. Thus, according to Bond (1978), late Tertiary epeirogeny uplifted major parts of Africa, after which the continent was subjected to extensive denudation; the high plateau of Central Asia seems to have been generated in the same way, at the same time. In a survey of landscape elevation and development, recorded in adjacent sedimentary basins worldwide, Peizhen et al. (2001) concluded that "sediment deposited on several continental margins - such as on the Mississippi delta and its surroundings, the North Sea, several basins offshore southeast Asia, Nova Scotia, and the Vøring plateau off Norway - show abrupt several-fold increases in sediment deposition rates at 2-4 Ma". The authors further stated: "Deposition, especially of coarse material, increased abruptly in late Cenozoic times within and adjacent to much of high Asia. Rapid Pliocene-Quaternary deposition of conglomerate capping a sequence of finer, older Cenozoic sediment near the northern margin of Tibet has been used repeatedly to infer that the plateau rose abruptly in Quaternary times".

Many parts of the Altai Range consist of flat-topped mountains exposing uplifted erosion surfaces; the youthfulness of the topography may suggest that uplift has occurred during the last few million years (e.g., Cunningham, 1998). For more than a century, a strong body of evidence has accumulated to show that the formation of present-day continental mountain ranges and elevated plateaus are recent phenomena (for discussions and references, see Ollier, 1992, 2006; Ollier and Pain, 2000; Hay et al., 2002). In addition, Ewing and Ewing (1967) and Storetvedt (1997, 2003, 2015) have argued that uplift of mid-ocean ridges falls in the same category. The origin of both continental mountains and mid-ocean ridges can be regarded as a united global dynamo-tectonic expression and a provisional late stage in the episodic and perpetual alteration of the crust.

There is no "folding mountain", Ollier (2006) stated - implying that the term orogeny is a misnomer. Keller et al. (1998), who studied the crustal structure of the Rocky Mountains, did not find a connection between topography and predicted thickened crust - thus putting a big question mark on the conventional term of orogenesis. Instead, the latter authors reasoned that "the mantle is playing a major role in the attainment of isostatic balance in this area". Another much debated example is the Sierra Nevada of California where geophysical transects have observed an anomalously thin crust (e.g., Wernicke et al., 1996; Gilbert and Sheehan, 2004). Wernicke et al. concluded that at least the southern Sierra provides an example of a continental mountain chain supported mainly by lateral density variations in the upper mantle.

Furthermore, the Appalachian fold belt cutting across the Avalon Peninsula of Newfoundland has a ca. 5 km thinner crust than the adjacent Precambrian cratons (Hall et al., 1998), and nor do the Caledonian belt along coastal W. Norway show evidence of a thickened crust. The origin of the Norwegian mountain range has in fact long been regarded late Tertiary in age (Reusch, 1901), with a final uplift beginning at around 5 Ma (e.g., Japsen and Chalmers, 2022). The Ural belt is another striking example of the mismatch between tectonic deformation and anticipated topographic uplift. The Ural folding events date from the Palaeozoic, but even in the late Miocene the region still had shallow marine and littoral conditions (Pomerol, 1982) - 300 Ma after the main folding phase (i.e., Hercynian). Hence, today's standard terms orogeny and orogenic belts are clearly in dire straits.

The role of native water

Above, we have argued that Earth's slow internal degassing is likely to have been the driving force behind the planet's dynamo-tectonic, surface topographic, and geological development, for which water seems to be the crucial link. The first important part of surface water was degassed in the lower Palaeozoic, but the main amount of seawater was exhaled in the upper Cretaceous - in conjunction with formation of the deep-sea basins. For the first time in Earth history, thin-crusted deep oceans had been formed. The associated eclogitization and progressive gravitative delamination of the lower crust gave rise to planetary acceleration triggering the Alpine tectonic revolution. During this process, the orthogonal planar and steeply inclined rift/fault system became strongly reactivated. So, in the late Miocene, when Earth's slow degassing once again had reached a hydrostatic pressure level to instigate efficient metamorphic/metasomatic reactions, the Earth's crust was much more fractured than before - whereby more efficient pathways for chemical reactions had been formed. It can be envisaged that this was the situation in the upper Miocene when epeirogenic uplift took place and mountain ranges emerged - again for the first time in Earth history. In addition to water, carbon compounds are likely to have been an important factor for internal mass reorganization and concomitant building up of fluid/gas pressures in upper mantle and crust. There is also an increasing recognition that chloride brines are playing an important role in metamorphic and magmatic systems (e.g., Markl and Bucher, 1998; Newton and Manning, 2008, 2010).

Carbon is the fourth most abundant element in the solar system where it is found mostly in the form of hydrocarbons which, depending on temperature and pressure, may occur in either gaseous, liquid or solid states. Methane (CH_4) the simplest and most stable of the hydrocarbon molecules, occurs as a major component of the atmospheres of Jupiter, Saturn, Uranus, Neptune, the satellites Titan and Triton, and on asteroids and comets. On Earth, large quantities of methane hydrates occur along deep continental margins (e.g., Kenvolden, 1988; Milkov, 2000). Thus, Gold (1979, 1985, 1987, 1999) and Gold and Soter (1980, 1982) have repeatedly argued that during the Earth's consolidation, it acquired the carbon inventory predominantly in its unoxidized hydridic form - probably as solid hydrocarbons; they insist that if the Earth at some early stage had been a hot body, those primordial hydrocarbons would have been oxidized. The fact that large hydrocarbon fields occur in virtually all types of crystalline rocks (Gold, 1999; Koning, 2003; Petford and McCaffey, 2003) is prima facie evidence that the Earth's internal temperature has always been relatively low, albeit slowly increasing (Storetvedt, 2003, 2011). This represents the very foundation of a slowly degassing Earth, in its eternal struggle towards thermochemical equilibrium. The gradual accumulation of liquids and gases in the upper mantle and lower crust must have led to a significant increase in the hydrostatic pressure at these levels - to which hydrocarbons must have been a significant contributor.

At the pressures and temperatures of the lower crust, water will be in its supercritical reactive state (Belissent-Funel, 2001; Liebscher, 2010; Hirschman and Kohlstedt, 2012; Galli and Pan, 2013). Under such conditions fluids may behave quite differently compared to their operating mode under surface conditions, especially with respect to their ability to entrain solid matter and to precipitating substances from solutions (Pan et al., 2013). 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 combines low viscosity and high diffusivities with a high degree of solubility beside being very effective metasomatizing agents (Liebscher, 2010; Schienbein and Marx, 2020). For example, mud volcanoes are probably the product of rock disintegration and piercement structures at depth, under the action of supercritical hydrous fluids (Hovland et al., 2006). Nevertheless, the physical properties of supercritical water are far from satisfactorily known, and the "lack of water dielectric properties greatly limits our ability to model water-rock interactions and, in general, our understanding of aqueous fluids below the Earth's crust" (Pan et al., 2013).

Above, we have argued that the eclogitization-crustal delamination model seemingly is the most relevant degassing-related mechanism behind the upper Cretaceous development of the thin-crusted world oceans. The large increase in rock density upon eclogitization, in combination with the rheologically weak boundary layer between eclogite and the transition zone above, destabilizes the lower eclogitized granulitic crust and cause it to detach and gradually sink into the upper mantle (Leech, 2001). For the metamorphism-regulated density changes to be effective, subcrustal delamination in Leech's model is controlled by the amount of water available. But in the presence of abundant water, peridotites as well as eclogites would be prone to become serpentinized. In an oceanic setting, this type of tectonically-driven solid-state emplacement frequently occurs along mid-ocean ridges and prominent fracture zones - explaining the elevated topography of such structures. The abundant recovery of serpentinized peridotites from the Central Atlantic has been discussed by many authors (e.g., Christensen, 1972; Bonatti, 1976, 1978; Bonatti and Honnorez, 1976; Mart, 2022). Thus, Bonatti (1978), discussing mechanisms capable of causing the vertical transport of upper mantle ultramafic rocks to surface levels, emphasized the low strength and low density, and thereby the greater mobility, of serpentinites relative to other upper mantle and lower crustal rocks. Inertia-driven wrench tectonics may therefore be an important vertical driver of solid-state serpentinite emplacement through both oceanic and continental fault zones.

Owing to the significant uptake of water, increasing buoyancy but related volume expansion and clogging effect during serpentinization, conservation of fluid transport routes is crucial for sustaining hydration and metamorphic transformation en route. Thus, for understanding the fluid pathways during progressive serpentinization, authors like Tutolo et al. (2016, 2018) and Malvoisin et al. (2021) have studied the nanostructure and reactive transport processes in serpentinized ultrabasic rocks. As a rule of thumb, if the hydrostatic pressure of a hot fluid, occupying an existing fracture network or pore space, exerts an external pressure equal to the opposing gravity effect of the surrounding rocks, any existing fluid flow through the fracture network will be maintained - building up the pressure bath situation of Thomas Gold (Hoyle, 1955; Gold, 1999). In that context, we are led to believe that uplift of the Mongolian Plateau and associated rise of the Altai mountains have been a combined effect of strongly buoyant supercritical fluids and the dynamic potential of low density and ductile serpentinite - the latter brought into vertical motion by wrench tectonic forces. The metasomatic activity would naturally migrate upwards along the orthogonal fracture system - a claim which surface gravity measurements should be able to confirm (see below).

According to the degassing theory and results from deep continental drilling, the fracture system in the upper mantle and much of the crust would expectedly be filled with hydrous and hydrocarbon-rich fluids and gases. This means that large parts of the crust would experience high hydrostatic pressures, together with widespread metasomatically formed magma pockets. This should make the lower-middle crust more ductile and gas/fluid penetrating, and therefore less exposed to earthquake activity - violent breakthroughs of gas under high confining pressure. In this context, Chu et al. (2009), applying a new method to determine focal depths of central Asian earthquakes, found that the conventional Centroid Moment Tensor solutions systematically overestimated both source depths and durations - notably for shallow quakes. Chu et al. concluded that “most of the 606 earthquakes [investigated] occurred within the top 20 km of crust. This shallow distribution of earthquakes suggests a high geotherm and a weak ductile lower crust in the region” - an interpretation consistent with the elevated heat flow in central Mongolia (Hunt et al., 2012).

MONGOLIA - A CASE OF TECTONIC SUPERIMPOSITION

In a synthesis of fauna evidence for Ordovician global climatic zonation, Spjeldnæs (1961) claimed that the trend from warm (tropical) to cold (polar) conditions was obvious. Thus, he drew the upper Ordovician equator in NNE direction over eastern North America with Arctic Canada, Svalbard region, central Asia and Australia - forming an approximate great-circle girdle around the globe. Spjeldnæs’ Ordovician equator fitted well with Wegener’s palaeoclimatic trend, later supported by palaeomagnetic data (Fig. 4). In general agreement with the palaeogeographic system of Spjeldnæs, several later studies have substantiated late Ordovician polar glaciation in western Sahara (e.g., Tucker and Reid, 1973; Ghienne, 2003; Le Heron et al., 2007¸ Le Heron and Howard, 2010).

According to Spjeldnæs' spatial orientation of the Earth, the Ordovician equatorial belt apparently passed along the western Altai region where the cratonic crust was affected by inertia-driven wrench tectonics - giving rise to the deepest fault zones in Mongolia. In this process, the northern Ordovician crustal cap was twisted clockwise and the southern cap counter-clockwise - thus, turning the Ordovician equatorial crustal belt into an overall transpressive regime. The NW-SE orientation of this tectonic zone is consistent with one of the fundamental fracture sets. On the other hand, the orthogonal NE-SW oriented set of planar fabrics, turned eastern Mongolia into an overall transtensive region. With respect to the late Ordovician equator, Mongolia had NNE geographic orientation (Fig. 10), and located in tropical to sub-tropical palaeo-latitudes within the northern palaeo-hemisphere. Consequently, Mongolia was subject to relatively strong clockwise inertial forces. Fig. 10 outlines the latitude-dependent inertia pattern. With the passage of the upper Ordovician equator across

Central Asia, with wrench tectonic reactivation of the associated crustal belt, less affected regions remained as cratonic blocks.

With southward extension of the tectonic lineaments of western Altai and of the Zuunbayan Fault/Basin along the south-eastern margin, their intersection becomes right-angled. In present grids, these linear features have NW-SE and NE-SW orientations and are with post-Alpine orientation. But if we correct this orthogonal system with the estimated 25° of Alpine clockwise wrench rotation (Fig. 7), we are back to the pre-Alpine tectonic system for which the NNE-SSW set correspond to the original orientation of the Atlantic continents (Fig. 8). Thus, we begin to see the wide-reaching implications of the primordial fracture/fault network, in the episodic reorganization of Earth's tectonic system - including implantation of tectono-magmatic belts in colinear or orthogonal arrangements (e.g., the Grenville and Appalachian mega-belts along one of the basic crustal fracture sets of eastern North America). In Mongolia, the upper Ordovician tectonic event - governed by the latitude-dependent

Fig. 10. The illustration shows the late Ordovician and Devonian geographic orientation of Mongolia, together with the pattern of latitude-dependent inertial forces (curved arrow). Red lines denote the fundamental orthogonal fracture system for which the late Ordovician equator followed along the NW-SE set (A), while the right-angled planar fabric (B) basically follows Mongolia's longitudinal extent.

westward torsion of the combined tidal and Coriolis forces, repeatedly reactivated the orthogonal fracture/fault network. This wrench tectonic superimposition led to Mongolia's conspicuous south-facing structural arch as well as to its curved internal tectonic structure (see below).

The lower Palaeozoic experienced the first major supply of surface water. This influx of indigenous water, during which the generally flat planetary surface became extensively covered by epicontinental seas that in turn gave rise to marked tidal slowing. In the late Ordovician, retardation was superseded by planetary acceleration (Fig. 3), a distinct dynamic change which took place simultaneously as the global sea level reached its Palaeozoic maximum (Fig. 5). These changes occurred at the same time as the main Caledonian phase (Taconian) took place, during which the Earth's crust was tectonically deformed along an approximate palaeoequatorial belt. We begin to see how the various facets of a pulsating dynamic Earth are linked together.

With reference to the important facts obtained by deep continental drilling, the major influx of original water in the lower Palaeozoic must have led to considerable hydrostatic pressure increase in Earth's outer layering. Then, at the beginning of the late Ordovician Taconian event, the outward hydrostatic pressure (a counter force to gravity) was probably stronger than ever before in Earth's prior history. Thus, the fracture volume in the crust must have increased, upon which circulation of hydrous fluids became intensified. This made even the outer crust relatively deformable. Thus, the passage of the Caledonian equator across Central Asia, along with reactivation of the orthogonal fault system, probably had a major impact of the subsequent geological development of Mongolia. One can imagine that it is only an outer 10-20 km crust that has been subjected to repeated brittle deformation and fault reactivation (see also below). The deeper and increasingly laminated crust and upper mantle probably acted like a moderately twisted deck of cards. In this way, the crustal structure of Mongolia is regarded as having developed in situ; the top layer, which largely consists of deformed and metamorphosed Neoproterozoic and Phanerozoic rocks, are overlying a relatively stationary cratonic crust, albeit modified by penetrating degassing products. According to this view, the poorly exposed Precambrian metamorphic basement is covered by fault-bounded Palaeozoic and younger volcano-tectonic degassing products.

The late Ordovician inertia effect was probably quite effective, enabling the Altai region to become distinctly transpressive.

Fig. 10 shows palaeoequator passed along western Altai, where the westward tectonic effect would be at its maximum. With Mongolia in the northern paleo-hemisphere, the inertial forces acquired a clockwise rotation, while they were counter-clockwise south of the equator. Hence, the late Ordovician equatorial belt obtained overall transpressive conditions. The insert map shows Mongolia within a broader Central Asian context. Red lines denote the fundamental orthogonal fracture system for which the late Ordovician equator followed along the NW-SE set (A), while the right-angled planar fabric (B) basically follows Mongolia's longitudinal extent. In this tectonic system the western half of the country became dominantly transpressive while the eastern half acquired overall transtensive conditions. Less affected regions remained cratonic blocks. The west-east dissimilarity in Mongolia's late Ordovician tectonic straining was crucial for the development of the country's tectono-physiographic curvature. Thus, the strongest clockwise bending was in the equatorial sector, visualized by the stepwise westward bend of the combined Altai ranges. In all, the overall curvature represents a kind of link chain between the NW-SE and NE-SW fracture sets in which the east-west running structural split-ups in the Gobi region form a constructional transition.

Since the late Ordovician, the structural bending has continued into modern times, building up an additive tectonic system - like the principle of superposition that apply for the rest of Mongolian geological history. Because of its proximity to the Ordovician equator, the mountainous western region achieved the deepest fault reactivations - here considered the ultimate cause of uplift of the late Neogene mountains, driven by the buoyancy of outgassing fluids and gases in their supercritical state. The hitherto unexplained concentration of seismic activity and the richness of metal deposits in Mongolia can similarly be explained as in situ ramifications of a degassing earth (Michaelsen and Storetvedt, in prep.). Fig. 10 shows the upper Ordovician geographical orientation together with marking of the changing inertial wrenching towards the paleo-equatorial tract. With this starting point, the combined Mongol and Gobi Altai region, along with major parts of western Mongolia, became an overall transpressive region with the deepest fault zones. On the other hand, eastern Mongolia - which was further from the paleo-equator and thus underwent more moderate tectonic reactivation, experienced inertial motion that produced general transtensive to strike-slip conditions. Also, in western Mongolia there might have been localized transtensive conditions, basin formation with magmatic activity, resulting in ophiolitic rock associations. Upon further shearing, ophiolitic complexes will become disconnected along strike. Ergo, in the wrench tectonic world view there is neither mountain building nor ocean closures.

Already in Taconian time, the fault zone underlying the combined Mongol and Gobi Altai structure began a counter clockwise wrenching away from their original rectilinear course - in particular by initiating a structural northward kink at ca. 95E/46N. This general counter-clockwise bending of the combined Altai structure has apparently been developed stepwise until modern time (see below) - in addition to forming the southward-bent, east-west running main tectonic line across Mongolia. In the clockwise inertial wrenching, the two basic orthogonal fracture sets in Mongolia (with NW and NE orientation) underwent a kind of links chain interaction. Thus, in the Gobi Desert region the southern Gobi Altai fault zone is apparently split into parallel segments - displaying a kind of cleaved west-east running crustal/structural arrangement. It seems that a similar structural divide has occurred between Tamsag and Zuunbayan basins (Fig. 10). It follows, therefore, that the large-scale tectonic line in Mongolia, which forms a conspicuous structural curvature, is an in-situ wrench tectonic product. The curvature began in Caledonian time and was further developed during the series of later wrench tectonic events.

In many ways, the late Ordovician tectonic upheaval laid the structural framework for the subsequent geological development of Mongolia. It is important to stress, however, that the mountain ranges in western Mongolia have no direct connection with crustal deformation; there is no crustal thickening and therefore no related buoyancy. As outlined above, mountain uplift is a Neogene event on Earth, probably mainly driven by low-density supercritical fluids. Hence, the traditional terms orogeny and mountain building - concepts that arose at the end of 19th century, are misnomers. Traditionally, the Altai region was called Caledonian, which is also an appropriate label within the new theory. The traditional term Hercynian is again relevant for central and eastern parts of Mongolia.

The Caledonian (Taconic) phase had an impact on all of Mongolia, but transpressive processes affected primarily the western region. In the Altai Terrane, for example, Badarch et al. (2002) submit that thick metamorphosed Cambrian (or Ordovician) successions of clastic and volcaniclastic rocks is intruded by plutons of late Ordovician ages upon which Silurian, Devonian and Mississippian volcanic and shallow-marine sedimentary rocks were laid down. Thus, the Caledonian phase was overprinted by both Acadian and Hercynian events. The Khovd Terrane, adjacent to western Altai, has a similar complex geological build-up - consisting of greenschist-amphibolite facies sediments, late Ordovician gabbro and granite plutons, Silurian volcaniclastic rocks, fault-bounded disrupted blocks, thrust sheets and tectonic slivers, besides having experienced Devonian and Mississippian volcanism and emplacement of Permian granite plutons (Badarch et al., 2002). Also, the Gobi Altai Terrane is described as consisting of greenschist facies basement rocks (Cambrian?), overlain by very disrupted and deformed Ordovician, Silurian, Devonian - Mississippian, Pennsylvanian sedimentary deposits, followed by Permian-Triassic volcanic and sedimentary rocks; the Gobi Altai succession is again intruded by Silurian-Permian granites.

The tectonic and magmatic superimposition does not stop with the Palaeozoic, and Cunningham (1998) points out that late Tertiary transpressive deformation also has taken place in western Altai. This tectonic phase is reported as continuous strike-slip faults, thrust-bounded areas associated with strike-slip faults, and possibly inverted Mesozoic graben - a widespread regional tectonic reactivation linked to the origin of the Khangai Dome (see below). Hence, the western Altai has seemingly been subjected to episodic shear reactivation throughout post-Precambrian time. Other regions of Mongolia demonstrate similar superimposed tectono-magmatic events governed by Earth's dynamic pulsation - a kind of hydraulic pumping device that has given rise to a series of interconnected surface geological processes. Mongolia is a fitting demonstration of the in-situ superimposition principle in global tectonics. Just as the geologic time table is episodic - consisting of long periods of quiescence punctuated by shorter intervals of revolutionary change, does the geological history of Mongolia apparently constitute a sequence of relatively short-lived tectono-magmatic events. In other words, we are back to a global geological modus operandi that Umbgrove (1942, 1947) called The Pulse of the Earth.

In terms of tectonics there is an overall difference between east and west in Mongolia: Transpressive conditions have prevailed in the west, transtensive in the east. This contrast is a consequence of the latitude-dependent clockwise wrenching in the northern hemisphere (Fig. 10). Another east-west difference is in topography. Western Mongolia, which was exposed to the regionally strongest Caledonian deformation, with formation of the deepest faults, is characterized by mountainous topography. This is primarily due to the presence of easier escape routes for the lifting power of supercritical gases and liquids in this part of Mongolia. The eastern half was further away from the upper Ordovician and later palaeoequators; therefore, that region was subjected to shallower tectonic disturbances and thus less deep faulting. This difference in depth of tectonization provides a reasonable explanation for why eastern Mongolia is basically flat.

Fig. 4 provides a sketch of the progressive palaeo-equatorial changes through the last 400 million years, during which Mongolia's latitudinal and azimuthal orientation changed stepwise, until its present E-W geographical orientation was completed at the Eocene-Oligocene boundary - some 34 Ma. Fig. 10 gives a sketch of the geographical situation during the Devonian for which present-day western Mongolia was sub-equatorial, while eastern Mongolia had present-day Mediterranean-like settings. With increasing distance from the equator, the inertia effects of a particular region a will normally be reduced. But in the case of Mongolia, the long-term development of intrusive magmatic activity in the region - primarily from extensive formation of metasomatic granite melts, the upper crust of the Mongolia region has retained its ductile and deformable state; this includes the late Neogene-Recent emergence of Lake Baikal. Due to progressive True Polar Wandering, during which the Earth's body moves undergo steps spatial rotations (in the Greenwich meridian plane) towards the Pacific, Mongolia gradually attained its present east-west orientation - in a final important step around the Eocene-Oligocene boundary (Fig. 4). With the stepwise increasing distance to the corresponding equator in post-Ordovician time, one would think that the inertia effects would be reduced correspondingly. However, the deformable state of the Mongolian upper crust was maintained by the long-lasting and unusually high production rate of metasomatic granitic melts.

Surface gravity anomalies, and the Khangai Dome

With reference to arguments above, we assert that inertia-driven wrench tectonics has primarily affected the upper ca. 10-20 km of Mongolian crust - or perhaps an even thinner surface layer. The reason for this is that the outward-directed hydrostatic pressure has kept the deep continental fracture system open and fluid-filled - which in turn has reduced the mechanical strength and led to the emergence of sub-horizontal layers with weakened mechanical strength. In addition, the prominent metasomatic melt production has clearly increased the possibility of mechanical detachment of the upper crust.

Thence, we may consider the crust as a deck of cards being subjected to skewed lateral pressure - decreasing downwards, because inertial forces will be strongest in the outermost part of the crust. It also follows that the upper crust, because of repeated wrench tectonic reactivation, will have a much denser fracture/ fault structure than deeper levels. The most effective solid-state "injection" of serpentinite has most likely occurred through the deepest fracture zones. In our case, the most prominent fault zones would have developed along the late Ordovician equator - simply because it is along palaeoequators that inertia-driven wrench forces would have been most effective. By this reasoning, the fault system associated with the Mongol-Gobi Altai would have been particularly susceptible to escalating, tectonically driven intrusion of low-density serpentinite. This should give rise to the regionally strongest negative gravity anomalies, also because the serpentinite effect comes in addition to negative gravity anomalies from any surface basins.

Fig. 11 shows an airborne free-air gravity anomaly map of Mongolia generated by a team from the Danish National Space Center (Forsberg et al., 2007). The prominent anomaly structure consists of a central topographic gravity core (positive), along the Altai ranges, flanked by relatively strong negative belts. The most prominent negative anomalies, along the Altai ranges, are interpreted as solid state intrusions of serpentinite along the deepest faults. These anomalies naturally become weaker eastward, away from the Ordovician palaeoequatorial region. But Central Mongolia displays the major part of a noticeable circular negative anomaly ring (outlined by white stippled line) which we relate to the origin of the Khangai Dome. In conformity with inertia strain/motion in the northern hemisphere, we infer that the stress situation provided by this moderately independent upper crustal unit is clockwise; this inference is consistent with regional GPS velocity vectors, including the stress pattern opening Lake Baikal.

At around the Caledonian maximum (late Ordovician-early Silurian), epicontinental seas covered major parts of a generally flat global continental surface, including Central Asia (Atlas of Paleobiogeography, Boucot and Johnson, 1973) when also sea-level reached its maximum (Fig. 5). “Fold mountains” did not exist. On the other hand, long before the late Neogene epeirogenic uplift of Central Asia, followed by uplift of the Mongolia mountains, the crust was permeated by hydrous and hydrocarbon-rich fluids, occasional streams of magma, and in-situ metasomatically formed acidic melts. Besides, the crust had been infiltrated by serpentinization along the ubiquitous orthogonal fracture network. In this slow transformation of the crust, the late Ordovician palaeoequator-connected shear zones had formed the deepest and thereby the most effective pathways for upward progressing hydration and metamorphic transformation. Therefore, during the hydrostatic pulse which led to epeirogenic continental uplift some 5 Ma ago, the deep Ordovician shear zone probably became subjected to differential tectonic reactivation. Strongly buoyant and pressurized supercritical fluids had always been around, as an active metamorphic and metasomatic agent, but during crustal uplift in the late Neogene, and due to volume expansion and the clogging effect of serpentinization, supercritical hydrous fluids found an easier escape route through the by now refreshed and widened deep fractures, along which serpentinization already long had been in action (exposed as pronounced negative gravity belts in Fig. 11). We therefore propose that differential reactivation of the primordial fracture network, during uplift of Central Asia, broke open the already serpentinized deep fracture zones, providing thereby more efficient access for buoyant supercritical fluids. Inferentially, this paved the way for topographic uplift of the Altai ranges within the wider serpentinized crustal segment.

At increasing distances north-eastward, the intensities of the NE-SW anomaly structure of Fig. 11 gradually wane. But in a wide region of central Mongolia, the subdued gravity arrangement is superimposed by a circular to oval-shaped, and regionally stronger, negative anomaly belt (contoured in Fig. 11). The circular shape of the anomaly belt, and the fact that it crosses the boundaries of tectonic terranes, excludes the possibility that it originates from a

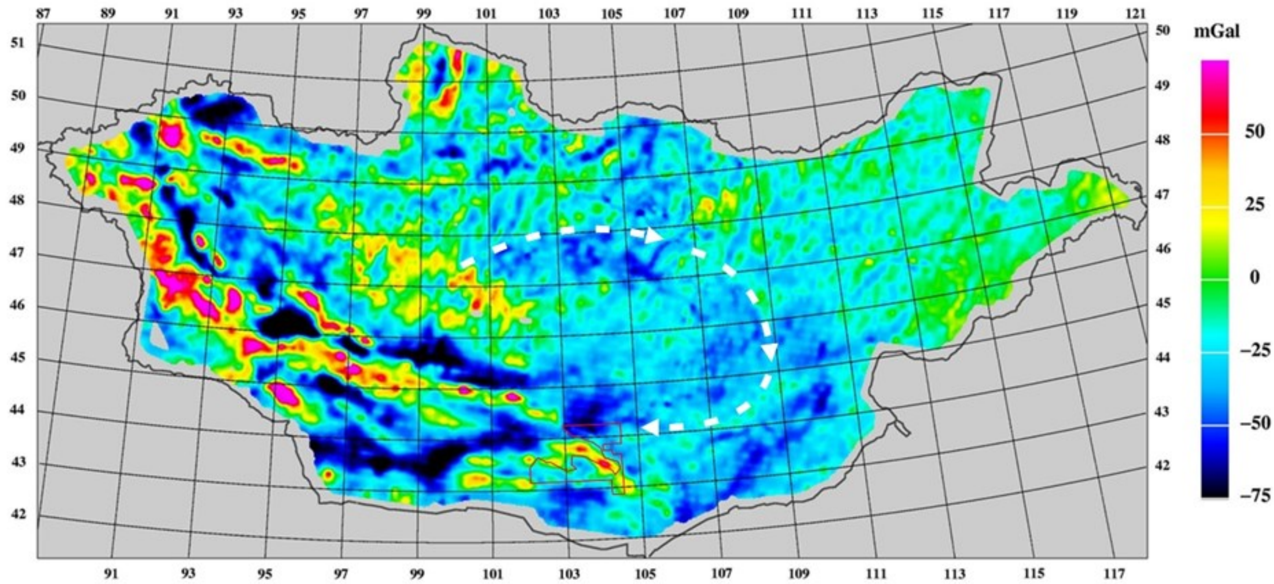

Fig. 11. Airborne free-air gravity anomaly map of Mongolia by the Danish National Space Center (modified from Forsberg et al., 2007). The prominent anomaly structure consists of a central topographic gravity core (positive), along the Altai ranges, flanked by relatively strong negative belts.

surface basin. Moreover, this apparently superimposed anomaly includes a major part of the Khangai Dome - a distinct topographic high in central western Mongolia within which numerous, but volumetrically small, late Miocene to Quaternary volcanic cones and lava flows are spread (Hunt et al., 2012; Ivanov et al., 2015; Khasmaral et al., 2019). The basement of the dome consists of Precambrian gneisses and schists overlain by thick middle Palaeozoic turbidite sequences which are intruded by Permian granitoids (Badarch et al., 2002).

In a seismic study of the Mongolian-Baikal Transect, Mordvinova et al. (2007, 2015) and Tiberi et al. (2008) found low-velocity upper mantle anomalies beneath Khangai Dome extending to mantle transition depths. Also Chen et al. (2015), employing an extended tomographic technique for entire Mongolia, again arrived at an upper mantle deep low shear wave speed beneath the dome - concluding that upwelling from the transition zone had affected a broader region of high elevation Central Asia. In these models, crustal uplift and the associated Khangai Dome have been powered by a mantle plume or an asthenosphere diapir. On the other hand, Feng (2021) found only scattered low-velocity anomalies in the uppermost mantle, along with relatively thick crust beneath both the Khangai Dome and the Gobi-Altai Mountains. Feng attributed the scattered low-velocity anomalies to small-scale asthenosphere upwelling with partial melting zones - presumably causing crustal buoyancy and uplift of Khangai Dome. Thus, the results from differing tomographic techniques, images of low -velocity anomalies, and conjectured upper mantle-crust interaction vary greatly. Thus, from geochemical evidence Barry et al. (2003) argued that thermal plume-like anomalies are not required, and that melting of metasomatized lower lithosphere might be a realistic alternative. In the same vein, Hunt et al. (2012) favoured small-scale lithospheric melt sources for Khangai Dome. However, a viable mechanism to account for the volumetrically small Neogene volcanic cones and lava flows in Central Mongolia is not currently available.

Moreover, the epeirogeny of Central Asia cannot be evaluated as a separate phenomenon, but as an integral part of Earth's slow degassing and related dynamic pulsation. However, for the origin of the Khangai Dome it would be natural to consider the possible role of the Earth's crust. Thus, Zhang et al. (2022), studying crustal Lg wave attenuation across the region, found widespread moderately low QLg values around the outer edge of the region suggesting a weakened margin; they also reported a minor high Qlg central part interpreted as a relatively unaffected Precambrian core. The negative gravity collar characterising Central Mongolia (Fig. 11), we therefore interpret as a ductile serpentinite ring, which may extend deep into the upper crust. The presence of an inner volcanic ring, elevated heat flow with a regional maximum in the Khangai Dome, low S-wave velocities, surface wave attenuation across the region, opening-up of fluid-filled fractures in deep continental drilling (Kola and KTB, SE Germany), and the apparent lack of earthquake focal depths below ca. 20 km (Chu et al., 2009) makes it likely that there may be a hot detachment/buoyant zone with magma pockets somewhere in the upper crust. The volumetrically small Neogene volcanic activity in Central Mongolia is consistent with this possibility. Considering a 600-800 km wide region with a depth of 10-20 km (or less), the suggested Central Mongolian tectonic unit consists of a relatively thin surface layer which undergoes moderate torsional stress, with both internal and external tectonic effects.

The circular to oval-shaped gravity anomaly, along with the ring of minor Neogene volcanic centres, hint to the possibility that Earth rotation is involved - powered by the northern hemisphere clockwise inertial rotation, albeit with modest motion. The clockwise wrenching stress is supported by the southward bending (or fault offset) of the easternmost Gobi Altai chain - a motion that would cause transtensive conditions along the Khangai Fault Zone and paving the way for supercritical water to lift the range. As indicated in Fig. 11, the Khangai Range is apparently without strong negative gravity anomalies - like those associated with the Altai ranges. This indicates that the underlying fault zone is without the clogging effect resulting from the serpentinization process, thereby providing an easier escape route for buoyant supercritical fluids.

The gravity map indicates that the circular gravity anomaly overprints and disturbs the basic NW-SE and NE-SW oriented anomaly sets - notably in north Mongolia. However, the left-lateral slip along the Bolnay Fault would be consistent with the suggested moderate clockwise wrenching of extended Central Mongolia block. In south-eastern Mongolia, the Zuunbayan Basin is characterized by a pronounced negative gravity anomaly, and the structural discordance between the southern Tamsag and the Zuunbayan basins (discussion above and Fig. 10) is also indicated. Moreover, in the eastern Gobi Altai, the anomaly ring seems to offset the mountain range at around 44°N, 103°E, and possibly also adding to the structural kink at 46°N, 95°E (discussed above), beside squeezing the more pronounced negative anomalies along the range into a bundle. Thus, the Neogene tectonic component is apparently adding to the longstanding progressive development of the southward tectonic curvature of Mongolia - as well as being in conformity with the split-up structure of the easternmost South Gobi region. It seems that the misalignment of the Altai ranges - by a certain counter clockwise tectonic swing of Gobi Altai, may have had a stepwise development ever since the Caledonian climax. Furthermore, the tectonic drag effect caused by the late Neogene to Quaternary clockwise wrenching is consistent with the prevailing left-lateral strike-slip on fault zones in eastern Mongolia. All in all, repeated fault reactivation along old basement trends and related tectono-magmatic processes, form important components of the superimposition principle that apparently have governed the geological evolution of Mongolia.

The inferred late Neogene-Quaternary clockwise wrenching and associated strain regime would expectedly produce northward transpressive stress in the westernmost region and transtensive stress states in central and eastern areas. This kinematic prediction gains support from two GPS studies in the region (Calais et al., 2003; Radziminovich et al., 2016). The studies found N-S compression, eastward extension, and NW-SE extension in western, central, and eastern Mongolia, respectively. Also, the measured NW-SE extension across the Baikal rift zone falls well into this tectonic stress system - reactivating one of the orthogonal fracture sets. These results are concordant with the strain situation arising from the moderate clockwise wrench tectonic regime. Thus, we seem to be faced with moderate internal late Neogene clockwise wrenching of the upper crust of Mongolia - post-dating the larger scale epeirogenic uplift.

At that time Mongolia had got its present geographic location (Fig. 4), and with its presently higher latitudes the inertia effects would normally have been much reduced compared to what they were in Palaeozoic-Mesozoic times. However, with the late Neogene uplift, Central Mongolia was affected by a thermal pulse which made the upper crust weaker and therefore more susceptible to being affected by inertial forces - a situation which led most of Mongolia into moderate wrench tectonic reactivation. Within a degassing Earth model, the classical assumption that increase in regional tectonic stress cause sudden mechanical rupture is not relevant. Rather, the dominant trigger of such events is a rapid yielding of rock strength after a build-up of high hydrostatic pressures in the crust. In this context, areas undergoing long lasting tectonic extension, such as eastern Mongolia, will release internal hydrostatic pressures gradually - and thereby diminishing the possibilities for strong earthquakes. On the other hand, areas that are subjected to compressive convergence as well as being associated with deep faults - such as western Mongolia, will basically have a different seismicity pattern. Firstly, deep faults provide more ready degassing routes which in turn lay the foundation for increased earthquake activity. Secondly, locally the compressive tectonic situation will make the crust able to withstand higher hydrostatic pressure - until the 'roof' eventually gives way and a resulting powerful earthquake occurs. In correspondence with this line of thought, western Mongolia has both the strongest earthquakes and by far the most frequent seismic activity (Bayasgalan et al., 1999, Gregory et al., 2018). Further, the seismicity map unveils that western Mongolia has several earthquake "spots" - relatively concentrated areas particularly exposed to seismic activity, which again underscore the relevance of the degassing theory.

Palaeomagnetic and environmental aspects

Due to Mongolia's complex geological history, in which all post-Precambrian periods and prominent tectonic events are represented, the region's paleomagnetic record will also be multiplex and experimentally challenging. Published paleomagnetic studies from Central and East Asia are often weakened by inherent remagnetization problems, so that standardized estimates of mean directions and related polar positions have highly variable quality. In consequence, the literature on crustal evolution of Central Asia has been riddled with conflicting ideas, with continental terranes and micro-blocks having shifted position as if restrictive physical bounds do not exist. As a countermeasure against this entrenched development, we will here critically discuss two recently published paleomagnetic studies, from western and northeastern Mongolia respectively. The purpose of this re-assessment is to exemplify why many published palaeomagnetic data, with associated and apparently never-ending flow of incoherent crustal reconfigurations, ought to be looked at with fresh eyes and given new meanings.

Zavkhan terrane, southwestern Mongolia

The Teel basalt formation (U-Pb zircon age of c. 446 Ma) in the Zavkhan terrane (Kilian et al., 2016) falls within a transtensive section along the overall transpressive late Ordovician palaeoequatorial tract of this paper. In this setting, the Teel Formation is described as a more than 1.8 km thick sequence of basalt, rhyolite and intercalated red sediments. In adjacent regions, granites of Carboniferous or older Palaeozoic ages occur abundantly, and according to Cunningham (1998) the nearby western Altai has been subjected to significant Neogene shear tectonics - which, according to evidence discussed above, seems to be a pan-Mongolian occurrence. In such a tectonic environment, the Teel Formation would naturally have been exposed to a long history of magneto-mineralogical alteration and related events of partial or complete remagnetization. But if the palaeomagnetic field acquired during the Caledonian (Taconian) upheaval have survived later overprinting events, we would expect to find a characteristic magnetization with near-horizontal inclination and a palaeo-azimuth directed due N-S. In other words, the paleomagnetic record of the Teel lavas would then be a positive test of the wrench tectonic theory.

In this tectonic setting, the original iron-titanium mineralogy of the Keel lavas would naturally have undergone a high degree of oxidative disintegration. In that context, Kilian et al. confirm that in many of the investigated flows the remanence unblock at temperatures characteristic of haematite (c. 610-680°C). On the other hand, in some sites they claim that there was no remanence left after removal of the magnetite component. That is an overstatement, because according to equal area plots of the two examples referred to (their Figs. 5A and 5B), the remaining remanence at higher temperatures swing, in both cases, into the characteristic direction of their haematite component – which is directed approximately due south and with sub-horizontal inclination. In evaluating orthogonal vector plots containing both magnetite and haematite, and to avoid a marked underestimation of the latter, it is an important fact that the intrinsic magnetization of magnetite is a factor 200 higher than that of haematite. As of today, the degree of alteration of the iron oxide mineralogy in the Teel basalts is largely unknown, and the few images that the authors present only give a superficial utterance of the situation. To gain a reasonable insight into the magneto-mineralogical situation, polished sections under high magnification and with oil immersion are usually what is needed - as a basis for realistic palaeomagnetic assessments.

For example, Storetvedt and Petersen (1970) and Rother and Storetvedt (1991) performed magneto-mineralogical studies of basalts from tectono-magmatically much quieter areas than the transpressive-transtensive conditions under which the Teel basalts were formed. Thus, in Permian lavas of the tectonically quiet northernmost Oslo graben, pseudo-morphism of rutile and haematite after ilmenite and exsolved titanomagnetite was a dominating feature. Other lava samples displayed an irregular and extremely fine intergrowth of rutile and haematite, forming a kind of "pockmark" structure. In his study of Tertiary lavas from Scotland, Ade-Hall (1969) called this phenomenon "granulation" and regarded it as a low-temperature alteration feature. Due to the nearly complete oxidation of titanomagnetite to haematite, the investigated lavas from the northern Oslo Graben had consequently been nearly completely remagnetised; the original reverse magnetization (belonging to the Kiaman superchron) had been replaced by a dual-polarity late Permian-early Triassic magnetization. In a study of lower Carboniferous volcanics of S. Scotland, the association of polyphase magnetization with significant low-temperature alteration was again demonstrated. The magneto-mineralogical changes along with remagnetization processes had clearly continued beyond the deuteric stage, covering at least the time span of geomagnetic field inversions. This study included also a site with a "brecciated" amorphous matrix - interpreted as stress-induced remelting, with a ring of small grains of exsolved secondary haematite. These examples are not exotic cases but shots from the real world of palaeomagnetism. Low temperature alteration, with precipitation of secondary magnetic oxides, is indeed the most common. Thus, an original cooling magnetization (TRM) can be partly or fully replaced by chemical magnetization (CRM) during later geological events. The most common situation is partial remagnetization building up a system of superimposed palaeomagnetic components - of variable ages and/or geomagnetic polarity. Separation of the individual field constituents, which may have closely overlapping stability spectra, represents the overall challenge in palaeomagnetic research.

Kilian et al. (2016) define two palaeomagnetic populations for which both, in geographical coordinates, have nearly due south declinations - a "haematite" component with near-horizontal inclination and a more poorly defined "magnetite" remanence with overall relatively steep inclinations but with clear spread-outs towards the "haematite" group. In their estimated "magnetite" component, they excluded the southward directed spread-out of site mean directions. However, excluding data for the commonly hidden intent of establishing a more satisfactory grouping (in this case for the "magnetite" population) is a dubious practice. From experience we know that "deviating" results represent resultant vectors often having "windows" in the stability spectra making it possible to split-up existing multi-component magnetizations.

The authors accept that their "haematite" group include sites with unblocking temperatures characteristic of both magnetite and haematite, and from their Figs. 5A and B also the 'magnetite' group too has a minor shallow south ("haematite") component. Tilt-correction of the latter group does not significantly change its average direction, but, instead, it gets a noticeable spread in declination. Regarding segments of smeared-out distribution in inclination, neither the "magnetite" group has a reasonable base for a realistic tilt-test. Further discussion of the palaeomagnetic build-up in the Teel lavas will therefore be with the remanence directions in their geographical coordinates.

In their interpretation, Kilian et al. (2016) take the oversimplified approach that (titano)-magnetite carries an original cooling magnetization (TRM), while haematite is a secondary chemical component (CRM) acquired by fluid flow during some later Palaeozoic event. This is an unrealistic portrayal of the palaeomagnetic reality. Thus, the due south-facing and flat-lying magnetite-bearing site means, which the authors, without scientific justification, reject, clearly belong to their "haematite" population. This implies that their best-defined paleomagnetic group is carried by both magnetite and hematite. This shallow down magnetization most likely represents the original deuteric remanent magnetization acquired by the Teel lavas - for which its low temperature phases may have been added during subsequent Taconic events. Being located within the Caledonian shear belt of SW Mongolia, it is likely that the Teel lavas underwent a lengthy post-tectonic magnetization history - deuteric to post-deuteric, during which haematite formed as the most stable and resistant remanence carrier. Therefore, subsequent remagnetization events primarily affected the remaining magnetite fraction - giving rise to the observed "remagnetization circles" (in geographic coordinates).

According to considerations above, it follows that the shallow south-facing group, loosely estimated with Declination 185° and Inclination 10° down, represent the lower Palaeozoic magnetization. This paleomagnetic direction is in good agreement with the paleogeographic situation depicted in Fig. 10 - with the Zavkhan terrane (and Teel Formation) located immediately north of the Ordovician equator. From the available data base, the potential remagnetization from the widespread regional Hercynian granite plutons (with an age of c. 286 Ma) is not evident. But the less oxidized magnetite fraction has clearly been strongly influenced by a relatively steeply inclined magnetic field for which the authors give the polar location at c. 86°N, 162°E. This is very close to the present North Pole, but that estimate probably would have been even closer to the North Pole had the underlying palaeomagnetic field direction been cleanly separated. Anyway, the "magnetite" pole apparently relates to remagnetization triggered by the marked throughgoing shear stress that affected western Mongolia in Neogene-Quaternary time - possibly including precipitation of small magnetite grains from patchy stress-induced remelting of the groundmass. In conclusion, the two characteristic magnetizations of the Teel lavas fit well into the Eurasian polar wander curve, and there is no need to relate the Teel palaeomagnetic results to fanciful tectonic interpretations.

Early Permian volcanic rocks, northeastern Mongolia

In the wake of the plate tectonics, and supported by many questionable paleomagnetic results, the tectonic history of Central Asia has been subject to a series of contradictory reconfigurations, surrounded by fictitious palaeo-oceans and subduction zones. One of the latest propositions is by (Zhao et al., 2020). From measurements of magnetic susceptibility versus temperature, the authors accept that the investigated lavas contain a substantial amount of haematite thus demonstrating that the magnetic minerals have been subjected to extensive oxidation with associated low temperature chemical remagnetization. Despite this fact, orthogonal vector plots with hematite as remanence carrier are not shown; that is, critical paleomagnetic information, likely present in the extended central part of the vector diagrams, is not uncovered. Due to the weak specific magnetization of haematite, even an extremely small amount of the magnetically much stronger magnetite can completely dominate the remanence build-up thus giving misleading impressions of both magnetic mineralogy, state of oxidation, and magnetization history. Despite this fact, and based on intensity decay curves vs. thermal demagnetization, the authors' claim that "magnetite and Ti-magnetite can be considered as the main magnetic carriers in the studied volcanic samples" is superficial and deceptive. Judging from the mixed message conveyed by the majority of the nine demagnetization examples shown, the paper is a typical example of unclarified remagnetization issues. Only half a page of executive summary is dedicated to describing the directional pattern vs. progressive demagnetization - while background information, details of secondary importance, and speculative tectonic implications get a disproportionate amount of article space.

According to their Fig. 6, the established magnetization directions are divided in two groups: a low temperature/coercivity component at specimen level and a high temperature/ coercivity component at site level. But why are the higher stability magnetizations, referred to as characteristic, shown by site means? The experienced reader will feel that the authors are not playing with open cards. It is a fact that by presenting statistical averages (in the form of site means), without showing the distribution of the underlying measurements (which would be very easy in this case), important information can be lost alongside providing a beautified picture of the paleomagnetic reality. The situation would have been significantly more enlightening if equal area plots, in combination with vector subtracted directions over actual stability sectors, had supplemented the orthogonal vector diagrams. The soft magnetization has a markedly extended directional distribution, primarily in declination, which suggests that it is in variable interaction with the higher coercivity/temperature component. However, since the soft magnetization could not be interpreted as a viscous process by the ambient geomagnetic field, it remained unexplained. On this background, it is reasonable to assume that the softer remanence has also been acquired by a natural magnetization mechanism and thus can contain relevant palaeomagnetic information. In geographic coordinates, most of the low temperature/coercivity directions are normally magnetized and 10 of them form an acceptable group which is closely antiparallel to the more resistant reversed magnetization group shown by 5 clustered site means (cf. their Fig. 6). It would have been illuminating and highly relevant information if the two magnetization groups could have been compared at the same level of observation (sample directions). Since magnetite, despite its volume inferiority to the weakly magnetic haematite, apparently carries both normal and reversed magnetizations, it is likely to be secondary (low temperature) and of post-Kiaman age. That is, the current magnetization probably formed in the late Permian or early Triassic - in conjunction with the degassing-related tectono-magmatic and biological mass extinction that occurred at that time. Thus, the magnetization problem basically boils down to being able to split the resultant magnetization consisting of two anti-parallel field components of post-Kiaman age.

Two sites (Nos. 14 and 16), also accepted in the group of high temperature/coercivity results, have normal polarity, but they have much lower credibility than the reversed sites. The problem is already exposed in the relation between measured and accepted samples. Thus, the normally magnetized group had an acceptance rate of less than 44%, while the acceptance rate for the reversed group was 86%. This more than indicates that there is something unexplained about the magnetization structure of these two sites. There is every reason to consider all specimen directions departing from the reversely magnetized group as belonging to the same class. Although only three vector plots are shown for sites 14 and 16, the high coercivity sections for two of them clearly bypass the origin - suggesting that the measured magnetizations represent unresolved interactions between the proposed normal and reverse sub-components. For proper evaluation of the remanence structure, expanding the central portion of the vector plots, in combination with equal area presentation of directional changes, for the purpose for better exposing of remagnetization circles, would again be needed. In geographic coordinates, the reported characteristic magnetizations of sites 14 and 16 have also remanence directions close to the normally magnetized group of softer magnetizations. In a remagnetization context, it is quite common that various stability ranges co-exist or overlap within individual samples. In the analysis of Zhao et al. (2020) their two normal polarity sites were critical for a positive fold (tilt) test. However, the underlying data are questionable - probably representing superimposed and unresolved low temperature normal and reverse magnetizations. The notion of a positive fold test rests on failing ground.

The investigated region has a near-vertical tectonic setting, but regarding the age of folding the authors refer it to a speculative collision of the Mongolia block with Siberia in the middle Mesozoic - a proposal that is little more than a blow to thin air. These early Permian rocks had existed for tens of millions of years within the reversed Kiaman field, which presumably gave rise to a well-defined deuteric to post-deuteric paleomagnetic field. But as the observed magnetization is dual polarity and magnetic mineralogy being in an advanced state of oxidation, it is more likely that the rocks were completely remagnetized in late Permian-early Triassic time. This may link the late Permian tectonics to the largest ever degassing-triggered upheaval in Earth history - setting off oxidizing fluids and stress-related remagnetization agents, among several other phenomena. This revolution included tectono-magmatic events such as the Appalachian-Palatinian and Siberian Traps events, during which also Mongolia underwent significant in situ tectono-magmatic reactivation - probably involving the near-vertical tilting of the investigated region.

With the inferred abundance of haematite in these rocks, it is likely that all opaque particles (including ilmenite) have undergone oxidative low temperature changes through fine-grained intergrowth of minerals such as haematite and rutile. It is conceivable that the considered magnetization history may resemble that of the early Permian lavas in the northern Oslo Graben (discussed above). In this process, a tiny fraction of magnetite (of late Permian-early Triassic age) seems to have formed - and which serves as the dominant magnetic constituent recorded in current thermal demagnetization experiments. From the consideration above we conclude that the early Permian magnetization was reset during the multi-phenomenological upheaval that swept the Earth in late Permian-early Triassic - and that the protracted palaeomagnetic resetting most likely cut across the tectono-stratigraphic system. Thus, in a remagnetizing setting like this one, escalating implantation of the late Permian palaeomagnetic field would have continued through the probably multi-phase dynamo-tectonic pulsation - before gradually fading off in the early Triassic. This means that nearby parts of a rock body, even different samples in the same site, not necessarily has the same remagnetization history. Thus, different samples may have had their paleomagnetic resetting at different stages of the tectonic process, or later, if degassing-conveyed remagnetizing fluids were still in action. This is the reason why the main material in the Zhao et al. investigation - the 5 sites with reversed palaeomagnetic polarity - need deeper analytical treatment than what so far has been published.

Despite the lack of needed experimental and analytical details, the subsequent tentative evaluation of remanence directions will be with the data in geographic (in situ) coordinates. Even with the lack of characteristic directions at sample level for the 5 reversed sites - for direct comparison with the directions of normal polarity, it is difficult to get past the impression that there is an approximately E-W oriented magnetization; its inclination is uncertain, but the axis orientation points towards a pole position in the northernmost Pacific Ocean. We need the help from other studies in Eurasia, with less complex palaeomagnetic build-ups, to establish a reasonable position of the late Permian-early Triassic palaeopole. At a first approximation, based on palaeoclimatic data from Wegener (1929) which indicated that the palaeoequator of the time passed over central India in a NW-SE direction, northeastern Mongolia will have a palaeo-latitude of approx. 50^{o}N, with the corresponding polar location around the western Aleutian arc. However, modern palaeomagnetic studies, from various regions of western and northern Eurasia (e.g., Torsvik et al., 1998; Van der Voo and Torsvik, 2004; Veselovskiy and Pavlov, 2006; Fetisova et al., 2023), have established assumed dipole field directions with associated palaeopoles forming a relatively well-grouped assemblage just south of Kamchatka. Although the paleomagnetic record from the Permian volcanic rocks of NE Mongolia is far from satisfactorily established, the published results nevertheless suggest a late Permian remagnetization history that is in line with much better defined late Permian results from western and northern Eurasia. A unified late Permian Eurasia at that time also gains support from a palaeomagnetic study in E Kazakhstan (Levashova et al., 2003). So, was this the end of a protracted continental welding history, or has the Eurasian crust always been united? The fact that the characteristic magnetization in the late Ordovician Teel Complex of SW Mongolia corresponds so well to the globe-enclosing late Ordovician palaeoequator (with the continents in their present relative positions) is prima facie evidence in favour of the latter alternative. This conclusion is also compatible with the continental mantle root problem (Fig. 2) - which since the mid-1960s has been a disregarded basic problem in global tectonics.

Change of scene

In a survey of 402 deep-sea borehole sections in the Atlantic, Indian and Pacific oceans, Ruditch (1990) submitted that the deep-sea basins are a relatively young feature on Earth - formed as an irregular mosaic of circular-oval depressions which attained their present depths primarily in the late Mesozoic. The wrench tectonic theory, which is consistent with the deep-sea drilling data, explains the oceanic crust is a thinned and chemically altered continental layer, driven by degassing - triggered eclogitization and progressive gravity-driven sub-crustal delamination into the upper mantle. The Pacific Ocean is the oldest, and its isostatic subsidence probably began already in the Palaeozoic. In other words, the modern deep-sea basins have developed in situ, but incomplete oceanization of the crust has left many remnants in the form of plateaus and trans-oceanic continental ridges - especially in the Atlantic and Indian Oceans, making Wegener-type relative continental drift an impossibility. Even in the Pacific, the ocean with the longest history of crustal oceanization, continental remnants are relatively widespread. Thus, different lines of evidence - including seismic profiling, sedimentological observations, dredging and drilling, led Choi (1987) and Choi et al. (1990, 1992) to conclude that during the Palaeozoic and Mesozoic, larger paleo-lands existed in the northwestern Pacific - in present-day deep-sea regions. Along the Obrechev Rise, for example, rock sampling at Detroit Seamount collected a wide variety of banded biotite and amphibole-bearing gneisses and other high-grade metamorphics. On Detroit Seamount, the collected rock material suggested that the Precambrian metamorphic basement had been intruded by granites and diorites, covered by lower-upper Tertiary sediments, and finally topped by late Neogene basalt and tuff - a geological succession not unlike that in Mongolia.

With the late Permian paleomagnetic North Pole located just south of Kamchatka, together with marine geological observations suggesting that the adjacent northwest Pacific was palaeo-land, it is possible that the Kamchatka region had a polar ice cap at the time. If so, the latitude-related climate in northeastern Mongolia would have been that of cool mid-latitudes. In addition, the upper Permian was evidently preceded by a major build-up of significant upper mantle volatile pressures that sat in motion a major upheaval in Earth history; an initial crustal uplift, which probably affected both continental and oceanic areas, was followed by a series of tectono-magmatic, climatic and aggravating environmental pulses, together with the most severe crisis in the history of life. An accidental weakening of the crust beneath Siberia led to the formation of a gas-driven outlet channel for magma and magmatic processes. This initiated a most prominent beginning of the degassing-driven surface revolution: The Siberian Traps. This extensive and mega-volume magmatic province, occurred within less than one million years at c. 251 Ma (e.g., Augland et al., 2019). In this process, the mantle exhaled significant pulses of climate-driven gases and toxic components, triggering the biotic revolution beside giving rise to an overall warm and locally dry environment.

Following the initial crustal buoyancy and related gas-driven crustal processes, the overall eustatic sea-level experienced a deep regression - probably the most distinct ever in Earth history (Fig. 5). Epicontinental seas, which since the Lower Palaeozoic had been a prominent surface feature, had episodically been drained into rudimentary basins. But after the deep late-Permian regression, most continental areas were left with narrow waterways. The Mongol-Transbaikalian seaway had its opening to the northeast, towards the polar region of the time (Biakov et al., 2013), and thus may reinforce the possibility of a relatively cool late Permian climate in northeastern Mongolia. However, prominent limestone beds within the narrow vertically dipping Binder horizon (48°35'N/ 110°33E) clearly argue for periods with warmer climate. On the other hand, the southern Mongolian seaway apparently had a southern outlet and closer contact with the world's water masses. This led to influx of warmer seawater in the South Mongolian Basin (Manankov, 1998). Moreover, in a degassing Earth, with its perpetual but episodic remoulding of the crust, a natural consequence was a transgressive-regressive cyclicity over lower lying continental surface. As the degassing effects are not evenly distributed across the globe, regional or smaller scale crustal oscillation will be superimposed on the eustatic sea-level curve. It appears likely that at times with high level of upper mantle volatile pressure and associated powerful crustal oscillations, the transgressive and regressive events would have relatively high frequencies and large amplitudes. Following this reasoning, powerful sea-level changes ought to be readily recorded in late Permian shallow epicontinental seaways.

SEQUENCE OF RELATED LATE PERMIAN COAL-BEARING SUB-BASINS

The widespread coal deposition during the Permian period is unique as it is not matched in any period before or since (Carey, 2000). In Mongolia, middle to late Permian coal measures are well developed, with most research focused on the South Gobi region near the Chinese border which contains the vast majority of Mongolia's coking coal reserves (Erdenetsogt et al., 2009). Numerous Permian coal-bearing sub-basins sporadically outcrop north of the Chinese border from c. 94°-109°E with the main concentration in the South Gobi "Basin", which was never a coherent sedimentary basin as such but rather a sequence of related but disconnected sub-basins. Significantly, similar concentrations of predominantly elongate northeast-trending fault-bounded Paleozoic and Mesozoic coal-bearing sub-basins are very well developed in China.

Above all, the Permian coal measures in Mongolia are contained within sporadic isolated fault-bounded sub-basins that were the locus for substantial accumulation of peat. Global wrench tectonics (e.g., Storetvedt, 2003) best explain the sub-basins scattered and isolated spatial distribution associated with wrench faults (i.e., with vertical dimensions). The Mongolian system of coal-bearing sub-basins probably originated within an inertia-triggered wrench tectonic regime with the reactivation of old Precambrian fault zones. Coal was deposited during the transtensive processes of sub-basin development. Low-density supercritical water might have infiltrated smaller-scale regions with deep faults, softening them and making them increasingly vulnerable to subsequent wrench tectonic processes.

The architecture of the sub-basins varies greatly but is generally elongate and oriented east-west to northeast-southwest and taper out in the direction of shearing. The thickness of the sedimentary fill varies from less than 100 m to over 1,000 m. In places such as Area 1, Navtgar Uul, Tsant Uul, Tsagaan Tolgoi, Khuts Uul, Erdenebulag, Baruun Noyon Uul, and the Noyon sub-basins, transtensional generated subsidence and sedimentation continued across the Permian-Triassic boundary. The coal-bearing sub-basins are commonly warped into steeply dipping asymmetrical synclines, the result of transpressive structural dynamics possibly during late Jurassic times. Wrenching reactivation along the old principle fault systems naturally also reactivated the ubiquitous near-orthogonal joint-fracture-fault sets, causing tilting but not significant thrusting.

Importantly, in terms of moisture sources, during middle and late Permian times Mongolia was characterized by two epicontinental seaways (Fig. 12); the boreal Mongol-Transbaikalian Seaway (MTS) located in central and northeast Mongolia, and the Southern Mongolian Seaway (SMS) situated along the Chinese border in south Mongolia. The MTS experienced several marked regressive events and climatic changes during the Permian as indicated by the work of Manankov et al., (2006) as well as data collected during recent field work around Adaatsag, Binder, Delgertsogt, Tsenkhermandal, Jargaltkhan, Bayan, Bayantsagaan and Bayanjargalant.

The south Mongolian coal-bearing sub-basins developed proximal north of the Southern Mongolian Seaway (Fig. 12). The SMS is characterized by predominantly Permian marine sediments, which reach up to 5 km in thickness locally (Manankov, 1998, 1999). Detailed studies of the Permo-Triassic sedimentary succession in outcrop and drill core as well as extensive seismic profiles by the senior author during the past 18 years within two large hydrocarbon blocks and +50 exploration and mining licenses, shows frequent inter-digitation of parallic-shallow marine and coal bearing strata along the coastal plain. As an example, in 2020 a trilobite was uncovered in late Permian sediments inter-bedded with coal seams in a sub-basin in the Nomgon region and limestone beds have also been documented in several sub-basins by the authors. A static coastline is indicated in Fig. 12 but in fact the shoreline

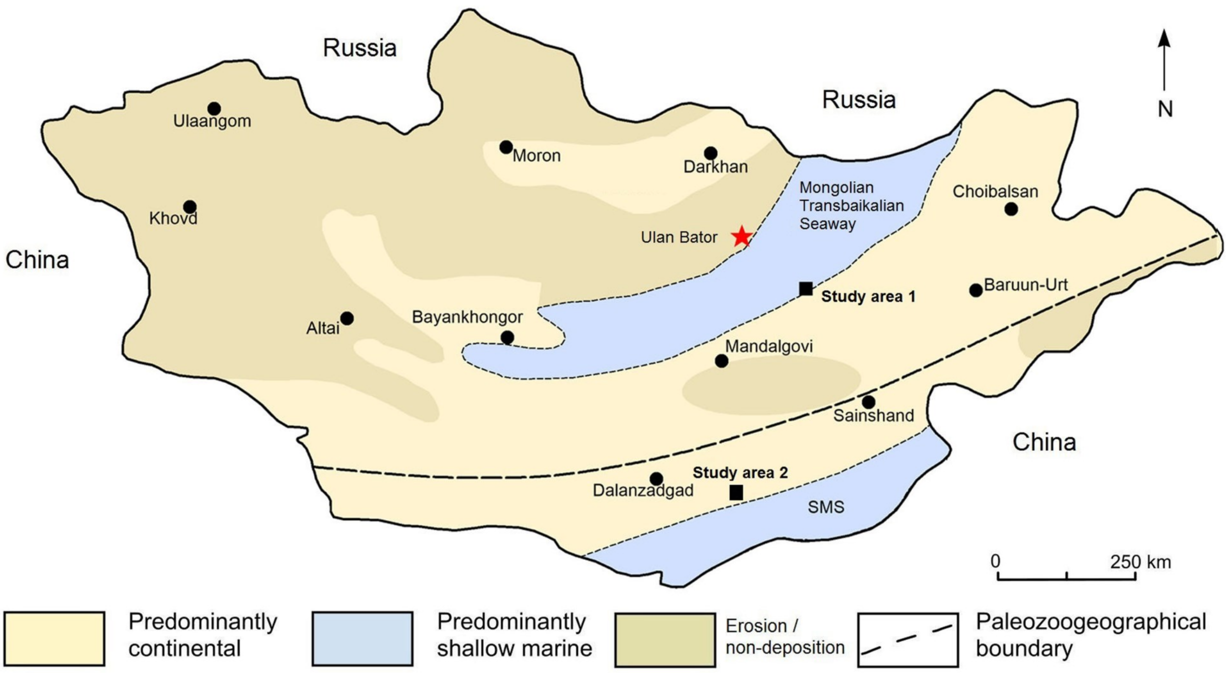

Fig. 12. Generalized spatial distribution map of Permian sedimentary strata in Mongolia showing location of the two study areas (modified from Manankov et al., 2006). Note that the Permian shoreline was not static as depicted here but moved dynamically in time and space.

moved dynamically along the coastal plain in time and space as indicated by results from study areas 1 and 2 and numerous other localities.

Palynology and macro flora data indicate coal deposition within the South Gobi sub-basins spanned from Roadian (c. 269 - 273 Ma) to Changhsingian times (c. 252 - 254 Ma), representing a significant timespan of c. 22 million years. While the world class coal-bearing Tavan Tolgoi sub-basin is middle Permian as based on macro flora (Durante, 1976), the vast majority of the sub-basins are considered to be of late Permian-early Triassic age. Palynological data from the Tsagaan Tolgoi sub-basin by Johnson et al. (2007) shows that the sub-basinal fill includes the Permo-Triassic boundary. Further, the coal measures are often comformably overlain by barren early Triassic fluvial and alluvial fan deposits. It is highlighted here that tuffs are absent or rare and thin within the Permo-Triassic sub-basins.

The northern epicontinental seaway is formerly known as the Khangai-Khentei Geosyncline (Durante, 1976) and is here termed the Mongol-Transbaikalian Seaway, as it is widely regarded as the southern extension of the Permian Mongol - Transbaikalian biogeographical province of the Boreal zoogeographical realm (see Manankov, 1999, 2012). The Permian succession is sporadically exposed over c. 900 km x 150 km (Fig. 12), with the most extensive outcrops west of Delgertsogt in the western part of the MTS. Outcrops are strongly dominated by sandstone beds characterized by very dense epeirogenic jointing considered here to be caused by rapid Neogene uplift. Sandstone framework grains are predominantly made up of angular to sub-angular quartz and feldspar showing low to moderate sphericity, indicating relatively limited transport from source to sink. Boreal-type brachiopods, bivalves and bryozoans appears to be relatively rare and concentrated in certain horizons (i.e., including shell beds). A relatively low energy environment is indicated by the often well-preserved nature of brachiopod and molluscan fossils. In contrast to the SMS, only one significant coal deposit is known to be developed along the shores of the MTS (i.e., Area 1 of this contribution). This late Permian coal deposit was situated along the southern shoreline. However, it is noted that

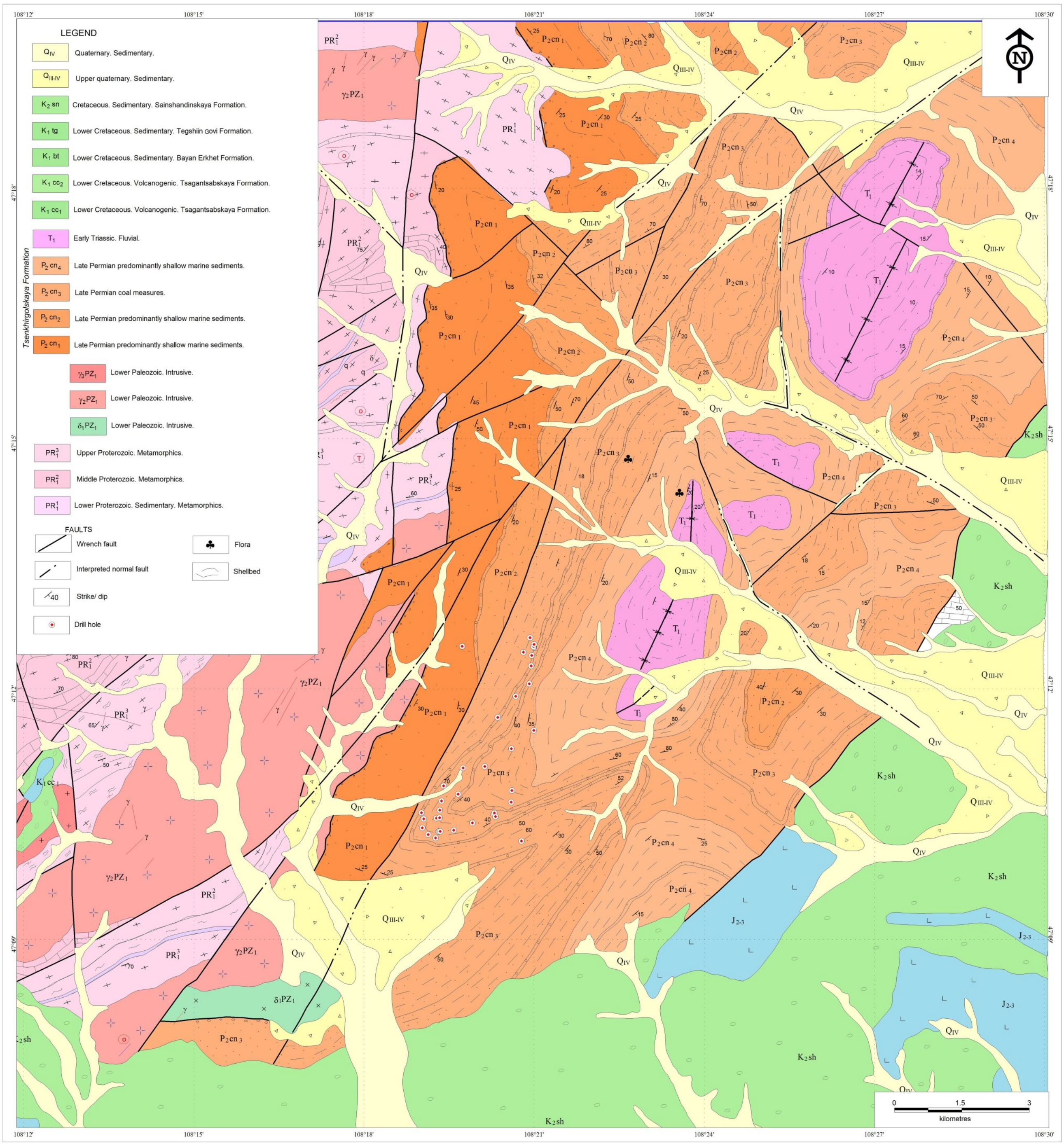

Fig. 13. Geology map of study Area 1 showing location of coal exploration drill holes, bedding, faults, stratigraphic units, shell bed and flora outcrops.

Permian organic debris was uncovered within sandstone outcrops 75 km to the ESE of Area 1 at Bayan South (47°6’20N/ 107°22’12E) as well as 220 km to the SE at Adaatsag (46°20’41N/ 105°4’3.14) which might indicate widespread vegetation along much of the seaway.

The MTS might represent an elongate fault-bounded depression which was gradually infilled by predominantly (but punctuated) clastic shallow marine sediments. The work by Manankov (2004) and Manankov et al. (2006) focused on brachiopod-bearing shallow marine sediments at various stratigraphic sections and indicated an early Sakmarian to middle Tatarian age for the studied marine deposits, representing a c. 30 million year long time span. It is noted that the work by Manankov (2004) focused on brachiopod fossils and did not include the late Permian coal measures and barren early Triassic sediments of this study. The results from this study suggest that in places the epicontinental basinal fill might span over a total of c. 50 million years from early Sakmarian to early Triassic times, and as such extends across the important Permo-Triassic boundary which records a marked upheaval of tectonics, magmatic and environmental processes (e.g., Erwin, 1993, 1994; Veevers et al., 1994; Tong and Yin, 1999; Michaelsen et al., 1999; Rampino et al., 2000; Hansen et al., 2000). This major prolonged degassing event, which included a range of toxic gasses, led to the most dramatic biological disaster in Earth history (Michaelsen, 2002).

Some climatic models suggest the Permian ice age terminated synchronously in the mid-Sakmarian (Isbell et al., 2003), however, this model does not account for the presence of cold climate indicators in late Permian strata in fx. eastern Australia (e.g., Michaelsen and Henderson, 2000a, 2000b; Michaelsen et al., 2000; Michaelsen, 2002) and Mongolia (Manankov et al., 2006; Michaelsen, 2016). Paleoclimatic indicators within study Area 1 include rare crystal clusters of glendolites (cf. Vickers et al., 2020; Pedersen et al., 2011), strongly developed annual growth rings observed in fragmented petrified tree trunks, and rare ice-rafted debris (IRD), indicating that boreal conditions persisted in central Mongolia to the Tatarian. Biakov et al. (2013) also noted that Northeast Asia was glaciated during the Capitanian Stage (Tatarian). Furthermore, cold-resistant faunas invaded the SMS during the Kungurian, reaching a climax during the Kazanian (Manankov et al., 2006).

Recently Glossopteris leaves (Rigby, 1969, 1972, 1978, 2001) were reported by Naugolnykh and Uranbileg (2018) from mid-Permian (Roadian-early Wordian) deposits in southern Mongolia, i.e., outside the Glosspterids boundary in the Southern Hemisphere (McLoughlin, 2011), and thus further challenging the geological integrity of plate tectonics (Pratt, 2000; James, 2018). However, as Rigby (pers, com.) noted, Glossopteris was a very successful leaf type, probably belonging to a number of separate families and therefore cannot be used as a generic name but part of indistinguishable families having different ecological requirements, thus allowing the possibility over a range of climates. More recently Cai et al. (2022) described a deciduous conifer from the Tsagaan Tolgoi sub-basin in South Gobi that lived in a seasonal, temperate, and wet climate. Notably, a growth interruption with inflated cells was present in the secondary xylem, indicating that the tree had survived climatic damage, probably an early spring cooling event. Cai et al. (2022) noted that growth ring analysis suggested relatively short growing seasons (i.e., similar to Area 1 which developed along the shores of the MTS).

METHODS

This study is based on 18 years of extensive field work on the Permian system throughout Mongolia. Significantly, the results from Area 1 draws on new database compiled in the context of district-scale exploration work targeting high energy Permian coal seams. The results of the exploration work for Area 1 (including all coal quality data) were continuously disclosed to the Australian Stock Exchange by Newera Resources, and as such in the public domain. The database consists of 38 drillholes and almost 3,000 m of shallow trenches. The present study is based extensive field work, detailed lithological logging, photo documentation, sampling and geophysical logging of 38 drill holes, totaling 2,703.2 m in composite length. The multiphase exploration drilling program mainly targeted the thick basal coal seam horizon along strike in the southeastern part of the study area. Event signatures, lithofacies contacts, sandstone attributes, biogenic features, sedimentary structures and coal characteristics were given special attention during the logging program. Subsequent mapping and sampling work was completed in the far southern part of the coal measures during 2016 and 2018 and in the central and northern part in 2023. Furthermore, a total of 82 coal core samples were analyzed for proximate, coking properties, relative density and CV. Petrological analysis of selected sandstone samples were conducted at Mongolian University of Science and Technology. This study has also drawn on previous work by Russian and Mongolian regional surveys (e.g., Erkhembaatar et al., 1995). Area 2 was investigated, mapped, sampled and photo-documented during field work from April - September, 2019.

Area 1: Shanagan

The Shanagan sub-basin is V-shaped and fault bounded (Fig. 13) and located c. 135 km southeast of Ulaanbaatar (Fig. 12). The sub-basin is interpreted as being generated by wrench tectonics during reactivation of an old Precambrian fault zone. The main NE-SW oriented wrench faults are in line with the pan global orthogonal fracture system (James, 2018). The thickness of the sedimentary fill is significant at c. 2,600 m. The sedimentary fill was warped into a NE-SW trending asymmetrical syncline with weak E-W shortening as a consequence of transpressive stress possibly during late Jurassic times where the primordial wrench faults were reactivated (Fig. 14). In general, the Permo-Triassic sediments strike northeast-southwest and dip towards the axis of the syncline (i.e., higher dips in places around faults and gradually lower towards the depocenter). A number of cross-cutting (ESE-WNW oriented) transfer faults upset the original basin length. Post depositional reactivation of the numerous wrench faults along the western flank of the sub-basin have somewhat deformed the original architecture of the sub-basin.

The study area is characterized by close spaced epeirogenic jointing, resulting in poor, very fragmented and sporadic outcrops. In this context this contribution is largely based on sub-surface data. Syn-depositional wrench faulting appears to have played an important role in peat mire development with localized thickening of peat proximal to these structures (i.e., on the downthrown side in a localized area characterized by accelerated subsidence). Wedge shaped coal beds with rapid thickening seams towards growth-faults were exposed in certain deep trenches within the study area. The basement in the region of the study area is structurally complex and comprised of a Neoproterozoic metamorphic suite, Paleozoic carbonates and volcanogenic rocks (Erdenetsogt et al., 2009). Part of the basement complex is well exposed in the western part of the study area (Fig. 13).

The late Permian Tsenkher Gol Formation is sporadically exposed within the study area and was estimated to be c. 2,600 m thick by a Mongolian mapping expedition (Erkhembaatar et al., 1995). Earlier Russian regional mapping work in 1947, which included the study area, established a late Permian age based on analysis of marine fossils at the base of the coal measures. Subsequently the Permian age was reconfirmed by another Russian mapping expedition in 1965, based on plant fossils in the lower-middle part of the succession.

Erkhembaatar et al. (1995) mapped the entire c. 2,600 m thick Permo-Triassic sedimentary succession as late Permian. The sediment package was subdivided into five informal stratigraphic units. However, this study

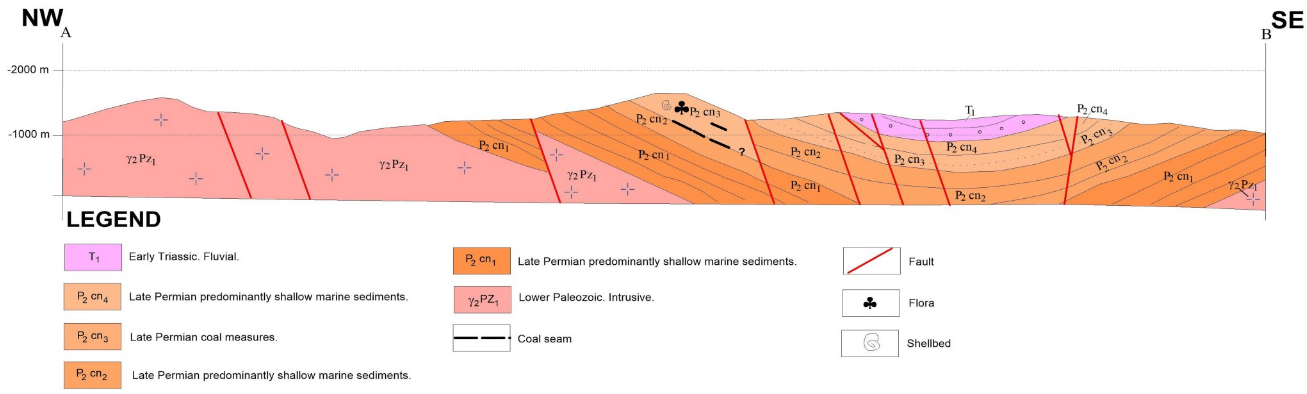

Fig. 14. Schematic northwest-southeast cross-section from Area 1 showing Permo-Triassic syncline characterized by limited structural deformation proximal to postulated suture zone.

Table 1. General overview of the five informal Permo-Triassic stratigraphic units and their main attributes from Area 1. While the original P2 cn stratigraphic nomenclature by Erkhembaatar et al. (1995) has been maintained (for now), they are considered here to be late Permian.

Chronology	Lithostratigraphy		Approximate Thickness (m)	Fossils	Paleoclimatic Indicators	Depositional Systems	Environmental Conditions
	Formation	Sub-Group					
Early Triassic		T^1	960	Barren	Barren greenish mudstones	Alluvial fan Fluvial	Relatively arid desolate conditions
Late Permian	Tsenkher Gol	P2 cn^4	180	Abundant *Thalassinoides*, *Skolithos* and *Planolites* ichno fossils in places. Shell fragments in siderite nodules	Siderite nodules	Predominantly shallow marine	Common base-level changes
		P2 cn^3	420	*Koretrophyllites* macroflora. Shellbed with cold resistant taxodont bivalves, archaeogastropods and Connulariid fragments. *Ophiomorpha cf. nodosa. Planolites.* Petrified wood. Oviposition lesions	Glendonites Petrified wood with strongly developed annual growth rings. Siderite horizons	Cold resistant peat mire ecosystem developed on coastal plain, inter-fingering with near shore depositional system	Cold climate with high-wind regime. High frequency base-level changes. Major sequence boundary developed at base
		P2 cn^2	360	*Taeniopteris* sp. macroflora Petrified wood wth oviposition lesions	Petrified wood with strongly developed annual growth rings	Predominantly shallow marine interrupted by noticiable regressive events	Boreal. Common base-level changes
		P2 cn^1	700	*Rufloria* macroflora. Abundant ichno fossils in places	Glacial erratics		

highlights that the upper unit is distinctly different from the lower predominantly shallow marine units; A) field work revealed the unit is barren of organic material, B) the siltstone beds are greenish, and C) the unit include up to 40 m thick alluvial fan deposits. Given the striking similarity with other early Triassic alluvial sediments in southern Mongolia and the Bowen Basin, Australia (e.g., Michaelsen et al., 2001; Michaelsen, 2002) the upper unit is classified as early Triassic in this study (Table 1).

The coal-bearing strata outcrop over a strike length of c. 26 km (generally with NNE-SSW strike). The outcrops of the Permo-Triassic package within the study area are characterized by a high sandstone/mudstone ratio. The four lower units contain a number of relatively thin felsic and greenish intrusive sills.

The five informal Permo-Triassic stratigraphic units are described briefly in descending stratigraphic order in the following (summarized in Table 1):

T1: This unit is estimated to be c. 960 m thick. The topmost part of the unit is c. 240 m thick and is dominated by sandstone and polymictic conglomerate with subordinate greenish siltstone. This unit contains a well exposed massive 40 m thick alluvial fan deposit in the northern part (Fig. 15), characterized by clast-supported conglomerate with individual clasts measuring up to 21 cm in size. The bedding dips are relatively gentle at c. 10-20° (Fig. 13 and 14). No organic material was observed during field work or reported from this unit. These deposits bear a striking similarity to early Triassic deposits in the South Gobi "Basin". The lower part of the T1 unit is predominantly a fine -grained unit estimated to be c. 720 m thick by Erkhembaatar et al. (1995). The unit is mainly composed of greenish siltstone, mudstone, sandstone and minor conglomerate.

P2 cn4: This unit is considered to be the topmost late Permian and is predominantly fine-grained. The unit is dominated by dark grey siltstone, carbonaceous mudstone, a thin calcareous mudstone bed and subordinate sandstone and conglomerate. This stratigraphic unit was intersected by one drill hole (DH01) in the far eastern part of study area, where the unit was c. 100 m thick. A 60 cm thick calcareous mudstone bed was intersected from 62.0 - 62.6 m in DH01. Previous workers (Erkhembaatar et al., 1995) estimated the thickness of this unit to c. 180 m. Some sections of this unit are highly bioturbated by an assemblage of Thalassinoides, Skolithos and Planolites ichno fossils.

Numerous shell fragments were recently recorded and sampled within siderite nodules. Recent field work during July, 2023, showed that these shallow marine deposits dip gently at c. 19-23° towards the depocenter. The unit is interpreted to represent a shallow marine inundation of the underlying coal measures.

P2 cn3: This stratigraphic unit was intersected by 35 drill holes and is characterized by coal-bearing strata. It is made up of a marine shell bed at the base, polymictic conglomerate, sandstone, siltstone, carbonaceous mudstone and eight high ash coal seams (Table 2). The thickness of this coal-bearing unit was estimated by Erkhembaatar et al. (1995) to be c. 420 m, which is in agreement with the results from this study. Core hole DH2 was the deepest hole at 300 m, intersected c. 250 m of the lower part of the coal- bearing strata. The topmost coal-bearing section was partly intersected by drillholes DH1, DH5 and DH7. Bedding dips of these deposits are generally around 30-50°. The late Permian peat mire ecosystem system is considered to have developed during boreal to temperate climatic conditions proximal to the shoreline of the Mongol - Transbaikalian Seaway. The seaway was likely frozen during the dark cold winter months. During the relatively short summer months the cold resistant peat forming plants probably benefited from moist air currents along the seaway with the short nights favoring steady plant growth. This is in agreement with recent work by Cai et al. (2022) proximal to Area 2 in southern Mongolia where growth ring analysis suggested relatively short growing seasons. Oviposition lesions (DT228 in particular) from plant-insect interaction were recently observed on leaves from this stratigraphic unit. The ash content within the coal seams is high with an average of 46.95% d.b. from 82 coal core samples and 43.45% a.d.b. from a 3t bulk sample. The very high ash content is considered to be a result of numerous active growth faults coupled with a high wind regime. A somewhat elevated sedimentary hinterland coupled with the smooth seaway surface (and limited friction) might have accelerated the flow of wind. The rapid

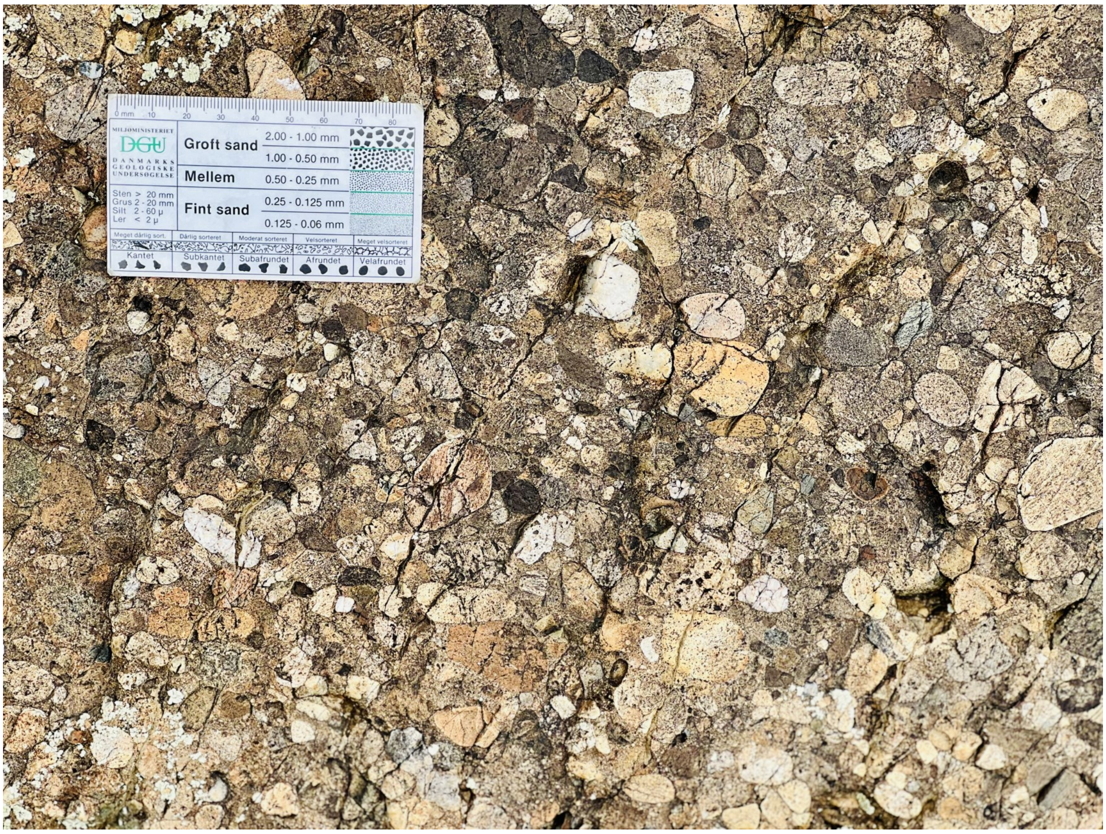

Fig. 15. Early Triassic polymictic pebble conglomerate from 40 m thick alluvial fan deposit from northern sector of Area 1.

Table 2. Summary of lithofacies characteristics from the late Permian coal measures (P2 cn3) from Area 1.

Facies Associatio	Lithology	Sedimentary Structures	Geometry	Fossils	Depositional System
1	Predominantly medium-grained sandstone (pebbly in places)	Trough-cross stratification and planar bedding	Ribbons up to 35.1m thick	Fragmented petrified wood with strongly developed annual growth rings	Fluvial channels
2	Siltstone, sandstone and carbonaceous mudstone	Planar bedding and ripple lamination	Wedges and lobes proximal-distal to FA1	*Koretrophyllites*	Levee / overbank to floodbasin
3	High ash coal	Planar lamination	Unstable sheets up to 12.8 m x +10 km		Peat mire
4	Predominantly elongate clast-supported, extra-formational conglomerate	Planar bedding	Extensive (c. 20 km) ribbons up to 3.1 m thick		Gravelly beachface
5	Interbedded sandstone and carbonaceous siltstone/ mudstone	Disturbed, planar, wavy and lensen bedding. Scour and fill structures	Thin sheets	Abundant ichno fossils *(Planolites, Thalassinoides and Skolithos*)	Tidal flat
6	Well sorted very fine-grained sandstone and siltstone. Crystal clusters of *Glendolites*	Horizontal bedding and lower flow regime symmetrical wave ripples	Extensive (+11 km) thin sheet	Shellbed with cold resistant taxodont bivalves, archaeogastropods and *Conulariida* fragments. *Ophiomorpha cf. nodosa.*	Sub-tidal shallow marine

thickness variations and unstable nature of the eight coal seams strongly suggest a syn-tectonic influence on their development which is very common within Permian coal measures in Mongolia. Interestingly, x-ray diffraction analysis results from a 3t bulk sample from the basal seam shows that the ash is strongly dominated by SiO_2 (77%). It is noted that the very high SiO_2 content is similar to the thick basal seam in the late Permian Tsagaan Tolgoi sub-basin in South Gobi c. 530 km to the southwest and c. 75 km southwest of Area 1. Here the SiO_2 content of the thick basal seam average 71%, decreasing upwards to 51% in the topmost Seam 8.

P2 cn2: This c. 360 m thick unit is dominated by well-sorted fine to medium-grained marine sandstone, subordinate mudstone, siltstone and conglomerate. A total of seven shallow trenches (generally with a depth of 0.5-1.5 m) were dug within this stratigraphic unit. Sporadic and very fragmented outcrops of sandstone strike ridges reveal rich organic material in places indicating common sea-level changes during emplacement of this unit. Oviposition lesions (DT246 in particular) were recently observed on a branch of a seed plant from this stratigraphic unit. A sample from one outcrop reveals a fertile spike of a taeniopterid, the morphology did not develop until earliest late Permian and continued into the Triassic (Rigby, pers. com.).

P2 cn1: This c. 700 m thick basal unit is dominated by sandstone with subordinate siltstone and conglomerate. The unit is only exposed along the western flank of the syncline (Fig. 13). The Permian flora Rufloria theodori was documented from this unit by a Russian mapping expedition in 1965 and by Erkhembaatar et al. (1995). A pebble to cobble size conglomerate bed is developed in the southeastern sector of the study area above the basement contact. The pebble clasts are elongate, well-rounded and up to 9.8 cm in length. Rare angular outsized clasts (up to 1.8 cm in length) observed in very well-sorted laminated siltstone in this unit was considered by Michaelsen (2016) to represent glacial derived drop stones. A 150 m deep hole (DH29) was drilled in this unit, intersecting a highly bioturbated fine-grained sandstone interval with abundant elongate mudstone pebbles (commonly 2-4 mm in length). Petrological analysis of sandstone from DH29 showed common elongate monocrystalline quartz slivers, indicating a volcanic source. DH3 was also drilled within this stratigraphic unit, intersecting a well sorted fine-medium grained sandstone sequence with three thin (15-40 cm) polymictic conglomerate beds, and nine relatively thin (3-55 cm) dark grey siltstone beds. Organic material is common in parts.

In summary, the significant 2,600 m thick sedimentary record at Area 1 shows that the shallow epicontinental seaway underwent several marked regressive events followed by a dramatic draining towards the end of the late Permian. The thick sub-basinal infill records a transition from shallow marine and humid coal forming depositional environments during late Permian times to relatively arid terrestrial conditions during early Triassic times, considered here to mark the dramatic drainage of the Mongol-Transbaikalian Seaway across the Permo-Triassic boundary, marking the most dramatic biological disaster in Earth history (e.g., Yin et al., 2001; Brand et al., 2012; Retallack, 2013; Li et al., 2016; Zhu et al., 2019).

The c. 1,060 m thick shallow marine basal part is characterized by glacial erratics as well as relatively thin terrestrial conglomerate and sandstone horizons rich in organic debris, the latter deposited during sea-level lowstands. These deposits are in turn conformable overlain by the c. 420 m thick coal measures which developed during a prolonged period of sealevel lowstand. Following deposition of the coal measures a marine incursion is recorded by a c. 180 m thick organic rich transitional unit with common ichno fossils as well as shell fragments (i.e., preserved within siderite nodules). Similar transitional units are developed above late Permian coal measures in Australia (Michaelsen et al., 2000) and within the South Gobi sub-basins (Johnson et al., 2007 with regards to the Tsagaan Tolgoi section). The shallow marine unit is conformable overlain by almost 1,000 m thick early Triassic alluvial fan and fluvial deposits barren of organic debris and containing greenish siltstone beds, marking dramatic environmental changes from the underlying Permian deposits. In this context Zhu et al. (2019) reported rapid climate change in north China across the Permo-Triassic boundary, and noted synchronous global expansion of alluvial fans in the early Triassic as a response to abrupt climate change associated with aridity, hypoxia, acid rain, and mass wasting.

Area 2: Luus Khudag

The Luus Khudag sub-basin is located c. 150 km ESE of Dalanzadgad (Fig. 12). Permian coal -bearing deposits, considered here to belong to the late Permian gas-bearing Yamaan-Us Formation (Orolmaa et al., 1999), are sporadically exposed over a strike length of c. 7.4 km with a width up to 1.3 km, covering an area of c. 9 km^2. The sub-basin is elongate in shape, trending northeast-southwest and fault-bounded towards Carboniferous basement to the north and south (Fig. 16). It is noted that a 100-200 m wide zone along the northern and southern fault lines are masked by Quaternary sediments and as such the Permian package might be somewhat thicker.

The two major faults are trending WSW-ENE and considered to represent two reactivated parallel wrench faults, with the Permian strata preserved within a down-dropped half graben block (i.e., a northward dipping monocline) sandwiched between late Carboniferous rocks to the north and more resistant early-late Carboniferous rocks to the south.

The primordial pan-global orthogonal wrench tectonic rupture system is expressed by linear northeast and northwest oriented ephemeral drainage systems within the wider South Gobi study area. This tectonic system is most likely of Precambrian origin but due to the long lasting wrench tectonic history, the old rupture system has been transferred into ever younger surface strata.

The late Permian coal measures are made up of sandstone, polymictic conglomerate, siltstone, carbonaceous mudstone, coal and limestone. A total of nine cyclothems are preserved within the study area, all containing limestone beds and with the basal two including coal seams. Heat affected sandstone beds are the most common lithology in the late Permian outcrops. The beds are generally thin (<1 m) and composed of well-sorted fine-medium grained sandstone. Horizontal bedding dominates with subordinate trough cross bedding generally with set height of <50 cm. Outcrops of Permian polymictic conglomerate beds are relatively rare, generally thin (<1 m) and contain predominantly well-rounded pebble size clasts. Some beds are matrix supported whereas others are clasts supported. Fine-grained felsic intrusive clasts are common within the conglomerate beds, arguing for a prolonged history of transtensional dynamics and felsic intrusive activity in the area.

No coal outcrops were observed within the study area. However, a shallow 210 m x 210 m wide box cut exposes a basal coal seam in the eastern "highwall" (Fig. 16). Here one highly intruded coal seam is exposed over a measured length of 116.3 m. Dip measurements show a range of northern dips from 40-47^o with an average of 44.75^o. The true gross thickness of the seam within the box cut was measured at 58.15 m. The thick coal seam contains numerous thin felsic sills measuring <1 cm to 42 cm, with one major thick sill in the lower part measuring 11.3 m (i.e., 5.65 m true thickness). The coal seam also contains numerous thin fine-grained organic rich clastic partings. The upper part of the seam is cut by a ramp, but digging with field shovels showed continuation of the seam across the ramp.

The thick nature of the coalescing coal seam within the box cut is in contrast to historical exploration drilling along strike, which intersected two seams, and is most likely a result of syn-tectonic deposition (i.e., northerly wrench fault with a vertical dimension), generating localized accelerated subsidence with consequential influx of clastic floodbasin fines into the peat mire. Subsequently the wrench fault was used as a conduit for emplacement of the felsic sills.

Above all, the Permian coal-bearing deposits within the sub-basin are characterized by an abundance of intrusive sills. The sills range in thickness from <1 cm to +60 m and often appear in swarms. The composition is generally fine-grained felsic with subordinate greenish intrusives in places. Emplacement is considered to have occurred during Eocene times, possibly during two phases, as a result of renewed

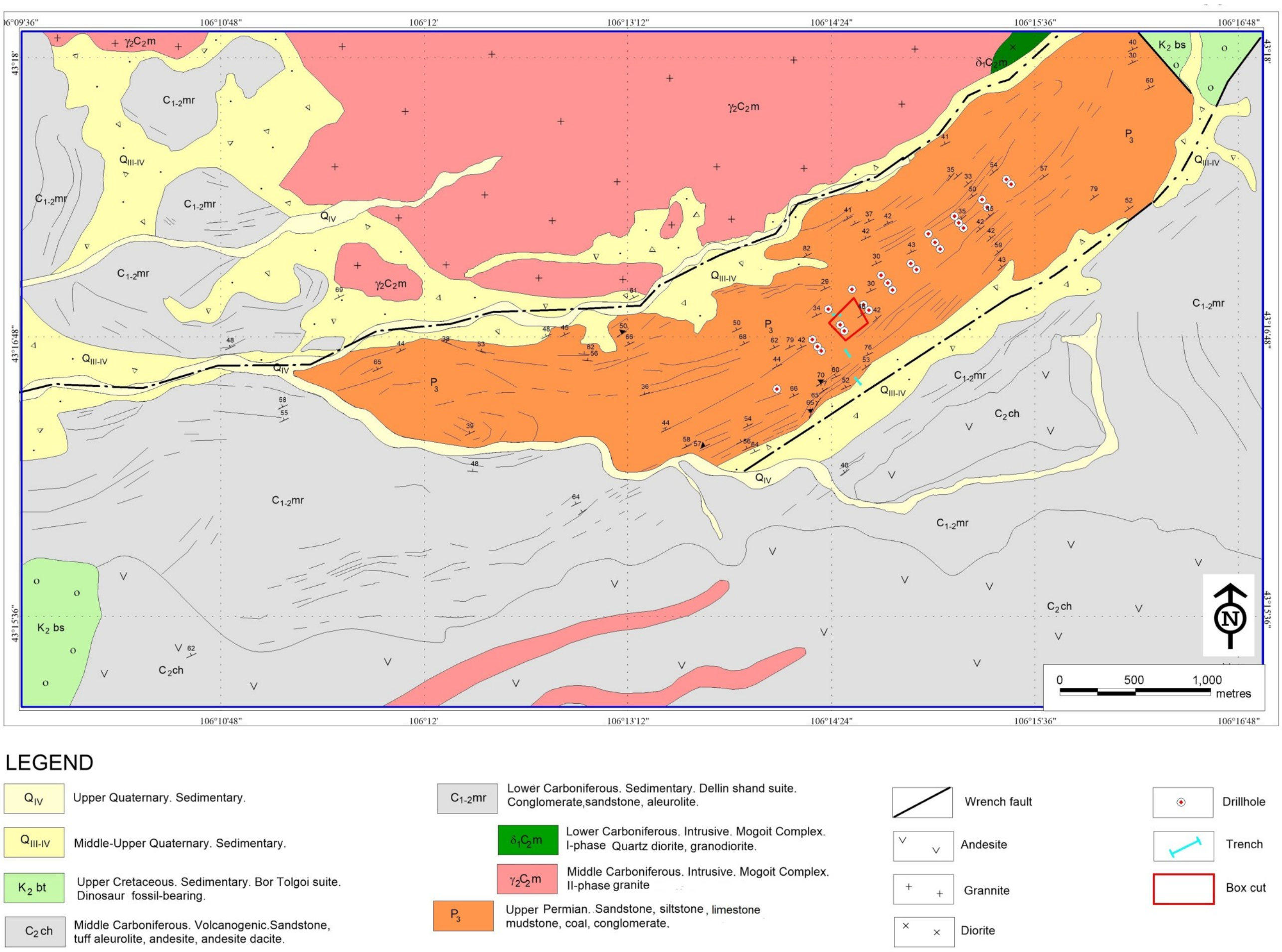

Fig. 16. Geology map of the Luus Khudag sub-basin (Area 2), showing location of coal exploration drill holes, trenches, initial box cut mining area, bedding, faults and stratigraphic units.

transtension along the primordial wrench fault lines.

Thickness of the Permian coal-bearing strata was quantified by a number of transects perpendicular to strike and indicate a maximum true thickness of 650 m, which is similar to the late Permian coal measures within the Bulag Suuj, Yangir and Tsagaan Tolgoi sub-basins in the eastern part of the South Gobi sub-basin cluster. Significantly, a total of nine late Permian limestone beds were documented and sampled. The limestone beds extend from the base of the coal measures to the very top, and varies in thickness from 20 cm to 20 m but are generally <1 m thick. The limestone beds can be traced for 4.5 km along strike (i.e., from the central to the far eastern part of the study area). The limestone beds are primarily characterized by massive bedding. However, some outcrops display bryozoan reef building structures up to 20 cm across (Fig. 17).

The late Permian coal measures at Luus Khudag record a transition from a humid coal-bearing environment influenced by sea-level changes in the lower part of the succession to dominantly marine conditions in the upper part. A similar transition is evident in Area 1 where a final marine incursion is recorded by the 180 m thick organic rich unit with common ichno fossils and shell fragments, conformably overlaying the 420 m thick coal measures. The Luus Khudag coal-bearing strata are considered to have developed basinwards of the Tsagaan Tolgoi sub-basin, located c. 75 km to the SW, where eight coal horizons are preserved (i.e., identical to Area 1) with a thick basal seam with similar very high concentration of SiO_2 within the ash. Substantial field work within the Tsagaan Tolgoi sub-basin shows a strong marine influence. Furthermore, spore-pollen analysis by Johnson et al. (2007) confirmed the Permo-Triassic boundary within the Tsagaan Tolgoi sub-basin. It is also noted that a similar facies transition is preserved in the western sector of the South Gobi Basin at the far eastern part of the Baruun Noyon Uul (BNU) sub-basin. Eight laterally continuous coal seams are preserved in the western part of the BNU area, however, only the basal seam is preserved in the far eastern part (on the eastern side of a NNW trending dextral wrench fault). Similar to Area 2, the middle and upper parts of the far eastern BNU succession are characterized by coal-barren cyclothems which include paralic calcareous beds.

Fig. 17. Permian limestone bed exposed down dip of Luus Khudag box cut in study area 2

In-situ stress measurements from the Area 2 sub-basin shows the direction of maximum compressive stress (SH Max) is NNE-SSW (Fig. 18). This is in agreement with data from Area 1 and extensive in-situ stress measurements by the authors within numerous South Gobi sub-basins and MTS localities. Slickenside structures are relatively rare within Area 2, however, field measurements of the striations were in line with the in-situ stress measurements obtained from joint surfaces.

Reflections

The history of science is full of examples where real progress depended on being freed from the shackles of conventional wisdom - beliefs implanted through continuous repetition and the need for tribal loyalty. Science analyst Howard

Margolis (1993), for example, points out that shared habits of mind are the only important condition that unites a research community in such a way that it is meaningful to talk about a common paradigm. The plate tectonic model has survived on inertia, endless repetition, and not least by the internet's colourful and indoctrinating "documentaries". Hence, it has become impolitically to question it. But for the sake of science, perhaps time has come to re-examine the Gondwana concept and interpretation of paleomagnetic data that decades ago triggered Asia's enigmatic plate tectonic history? Anyway, the archives of science tell us that conventional wisdom is difficult to overturn - even when strong facts contradict it. The inclination of human nature, to conceal problems that are potential threats to an individual's network of beliefs, naturally creates a mental block militating against alternative thinking (Kuhn, 1970). However, questioning an ingrained paradigm has arisen precisely because it has proven inept. But as Popper (1990) stated, breakthroughs in science are very rare and strongly opposed, simply because it means that the previous experts were wrong.

It is one of the rarities in the history of science that those who have been highly rewarded for their contributions no longer recognize the ideas they once led to victory. Even so, the two principal advocates and mainstays of plate tectonics in the 1960s - Stanley Keith Runcorn (Newcastle) and John Tuzo Wilson (Toronto) - must eventually have found the development completely untenable. For example, within geophysical circles in Europe it was widely known that, from the early 1980s onwards, Runcorn had left "the sinking ship" - an expression he sometimes used among intimate colleagues to describe the development of plate tectonics. At a memorial symposium for Runcorn, at the 1996 EGS Assembly in The Hague, his opinion that plate tectonics, and misinterpretation of palaeomagnetic data, had "completely muddled global tectonics" was made public - to the greatest dismay of many. At the same symposium, it was reported that also Tuzo Wilson, the once ardent proponent of seafloor spreading and the inventor of the transform fault concept and the Wilson cycle, had turned his back on plate tectonics. In a guest lecture (with written abstract) at Memorial University of Newfoundland in the fall of 1992, Wilson discussed some of the most pressing problems and mistakes that had been made in global geology and geophysics and argued that the geosciences needed an entirely new paradigm. Wilson's abstract was published at The Hague symposium - with reactions of disbelief, especially among North Americans (Storetvedt, 2022).

The complex and undecided constitution of the Earth's interior, revealed by modern seismic tomography, along with the range of lighter

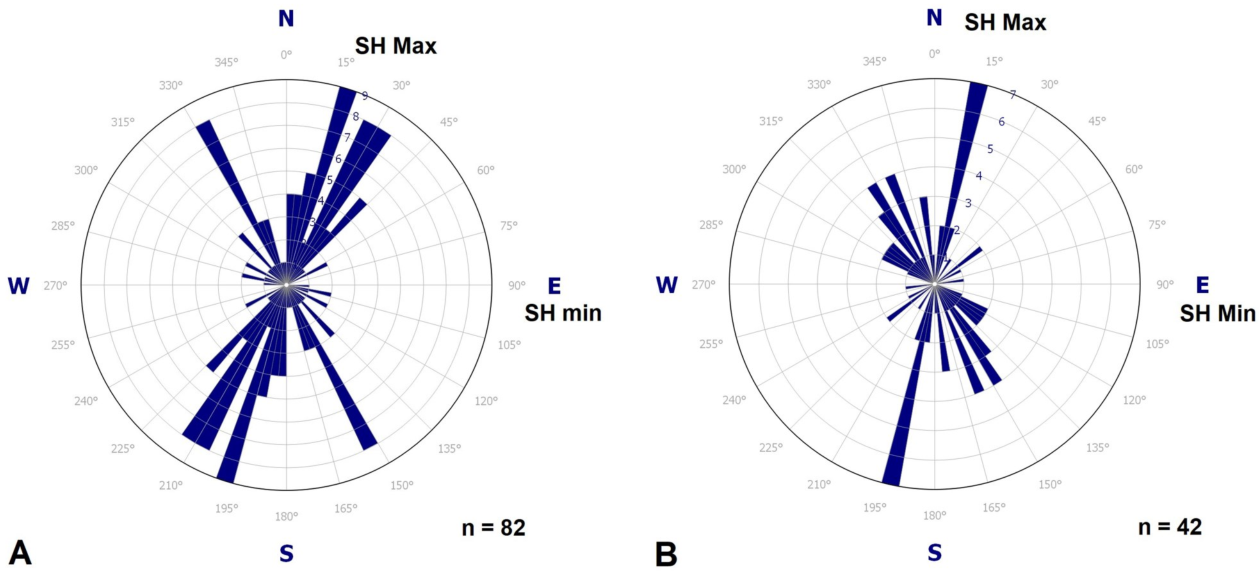

Fig. 18. Rose diagram of reconciled in-situ stress indicators obtained from study areas 1 (A) and 2 (B).

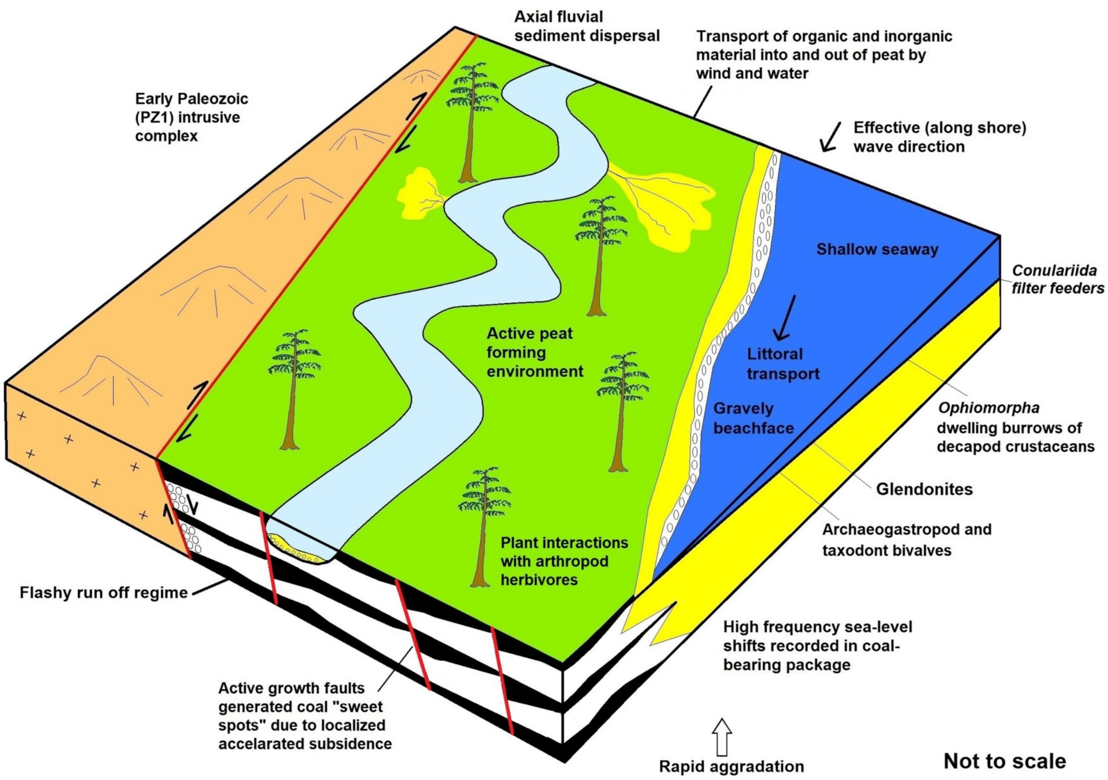

Fig. 19. Schematic depositional model for the emplacement of the late Permian coal measures at Area 1. Not to scale.

elements now regarded as necessary constituents of the deep Earth (Poirier, 2000), suggests that the planet is far from being fully outgassed. These observations are strongly supported by deep continental drilling (Kola and KTB Germany) which shows that fractures, filled with hydrous fluids, expand with increasing depth - suggesting that the Earth's interior has an outward-directed hydrostatic pressure that increasingly counteract the inward-directed gravitational force. These unexpected results ought to profoundly influence the way we think about the Earth - its origin, development pattern, internal constitution, crust-mantle formation and subsequent interaction, tectonic deformability, along with surface accumulation of water, metals and hydrocarbons. Hydrocarbons, in either gaseous, liquid or solid state, occur abundantly in the solar system, and liquid inclusions of methane (CH_4) and carbon dioxide have been found to occur frequently in natural diamonds from Africa and Brazil (Melton and Giardini, 1974). On the other hand, Hunt et al. (1992) - which presupposes an original hydridic proto-Earth - regard silicon as one of the important buoyant elements of the core's metal hydrides.

In the present wrench tectonic evaluation of Mongolia, it has appeared that there are good reasons for believing that the crust behaves like a deck of cards being subjected to oblique inertia-driven lateral pressure (decreasing downwards). In this way, the upper continental layer can undergo wrench deformation without losing physical contact with the rest of the crust and the continental mantle root. Thus, Mongolia did not form as a mixture of supposedly northward drifting and progressively amalgamating continental masses gradually building up the extended Central Asian crust; we are led to conclude that the region has always been a physically united crustal mass. Driven by palaeolatitude-dependent wrench forces, the ubiquitous orthogonal fracture system has, during global dynamo-tectonic events, been subjected to torsion - thus building up a progressive tectono-magmatic history. However, the overall upper crustal reshaping in Mongolia only amounts to a few tens of degrees.

As the accumulating fluid- and gas-pressure in upper mantle and crust somehow will find escape routes to the surface, it is natural to direct attention to the unusually high earthquake frequency in Mongolia; the western half has a most unusual concentration of seismic activity and occasionally very strong tremors (Sodnomsambuu and Klyuchevskii, 2017). This is also the region where the orthogonal fault system was most strongly reactivated by the passage of the late Ordovician equator, thus giving rise to the deepest fault zones. Therefore, in the degassing scenario, earthquakes are not caused by a sudden mechanical slippage within a fault zone. The role of deep faults is rather that of representing ready escape routes for rising pressurized volatiles. Thus, sudden breakthroughs of high-pressure gasses and fluids through mechanical barriers become the cause of seismic activity, during which also tectonic disruption around focal centres takes place. Hence, there are reasons to reassess the geophysical significance of focal mechanism studies - considering that crust may be dominated by the primeval network of orthogonal fractures. Moreover, mechanically weakened channels may repeatedly serve as a degassing escape route thereby explaining "earthquake spots" - places that in the recorded history are known for their persistent low-moderate level seismic activity (Gold and Soter, 1982; Gold, 1987). In closing, the degassing Earth theory also gives a new opening for evaluating leaching, transport and unloading of metal combinations in the upper crust when physical conditions dictate. Water in its reactive supercritical state undoubtedly plays an important role, but what about the contribution from buoyant hydrocarbon fluids which according to Gold (1999) has both the capacity for leaching and for holding metals in solution (Michaelsen and Storetvedt, in prep).

CONCLUSIONS

Wrench tectonics played a critical role during late Permian times in Mongolia, where a sequence of related transtensive sub-basins formed along reactivated primordial fault systems (Fig. 19). Some of the sub-basins became the locus for substantial tracts of peat accumulation. Global wrench tectonics best explains the sub-basins scattered and isolated spatial distribution associated with wrench faults (Fig. 20). It is highlighted here that similar concentrations of elongate predominantly NE trending transtensive coal-bearing sub-basins are also developed in China (Michaelsen and Storetvedt, in prep.).

The Mongol - Transbaikalian Seaway experienced several marked regressive events during the late Permian, and the thick sub-basinal infill from Area 1 records a history of inter-digitation of shallow marine and coal forming depositional environments. In contrast, the conformable overlaying early Triassic deposits record relatively arid terrestrial conditions, considered to mark the dramatic drainage of the Mongol - Transbaikalian Seaway across the Permo-Triassic boundary.

The location of Area 1 proximal to an assumed suture zone - a tectonic element that represents the minimal and complex surface remains of a fingered Mongol - Okhotsk Ocean. However, the tectonic belt does not show the presumed shortening, major thrusting, regional metamorphism and the complete absence of tuffs within the thick investigated sedimentary package is again inconsistent with plate tectonic expectations.

The late Permian sedimentary strata preserved in the Area 2 sub-basin record a transition from a humid coal-bearing environment influenced by sea-level changes in the lower part of the succession to dominantly marine conditions in the middle and upper parts. A similar facies transition is preserved in the far eastern part of the Baruun Noyon Uul sub-basin, in the western sector of the South Gobi Basin.

Significantly, Area 2 is located proximal north of the controversial Sulinkheer Suture Zone. In the absence of expected subduction related features, including significant regional metamorphism and large-scale thrusting, in addition to the absence of tuff beds in the studied coal measures, it could be argued that subduction has not taken place - i.e., the alleged Sulinkheer Suture is not only cryptic but non-existent.

Along any major shear zone, transtensive conditions will readily occur. This leads to the development of disconnected sedimentary

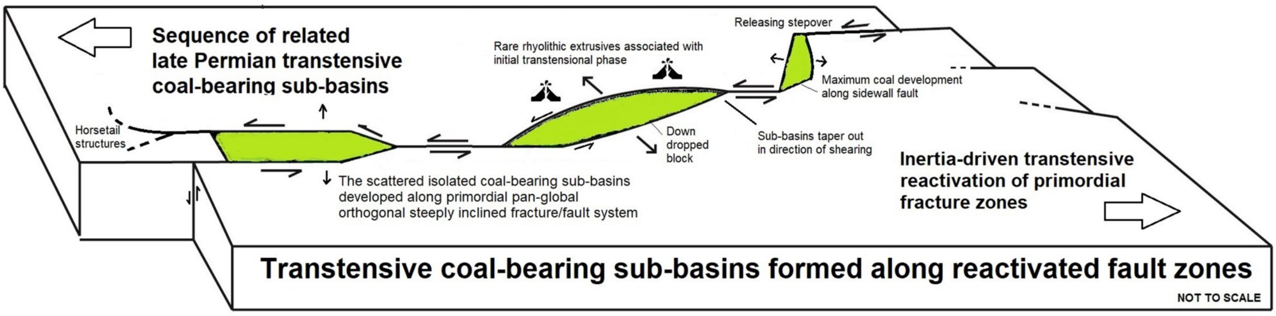

Fig. 20. Schematic illustration of the sequence of related transtensive Permian coal-bearing sub-basins formed along reactivated primordial fault zones in central and southern Mongolia. Not to scale.

basins which together with volcanic and intrusive material and blocks of upper mantle rocks (the latter tectonically forced to the surface in solid state) are termed ophiolites. In plate tectonic contexts, these complex rock associations are often wrongly interpreted as suture zones - random remainders of conjured up palaeo-oceans.

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