Tectonophysics - Elsevier Publishing Company, Amsterdam
Printed in The Netherlands

THE EVOLUTION OF THE INDIAN OCEAN MEGA-UNDATION

(CAUSING THE INDICO-FUGAL SPREADING OF GONDWANA FRAGMENTS)

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(Received April 1, 1965)

SUMMARY

In the first section the geomechanical model of mega-undations is elaborated:

(1) The lower mantle may have a Newtonian viscosity, but the upper mantle, which is largely in a crystalline state, shows an Andradean viscosity, with hot-creep phenomena and the formation of lamellae separated by zones or planes of high strain rate.

(2) Reliable solutions of the mechanics in the fault planes of earthquake foci indicate that the spreading of the mega-undations is characterized in the outer 400 km by the farther advance of the higher structural levels with respect to the underlying ones; whereas the movements in the foci of deep earthquakes underneath the Japan Sea and South America indicate a reverse process, the lower blocks moving faster towards the Pacific than the overlying ones. This is explained by the geomechanical model of the mega-undations.

(3) The crest of the mega-undations shifts in the course of time, either gradually or by steps. The effects of such shifts are discussed and illustrated.

(4) Four stages of evolution of mega-undations are distinguished: (a) young, (b) early mature or precocious, (c) late mature or ripe, and (d) fossil mega-undations. These stages are illustrated by type examples.

In the section on the development of the Indian Ocean Mega-Undation this geomechanical model is tested by an analysis of the geotectonic evolution of the Indian Ocean and the surrounding shields. It appears that there is a good correspondence between the expectations according to the hypothetical model (prognoses) and the geotectonic observations (diagnostic facts). This reinforces our confidence in the adequacy of the functioning of the model. The latter might be tested further by tectonic experiments, namely, by the centrifugation of models at a reduced scale.

ELABORATION OF THE GEOMECHANICAL MODEL

Newtonian and Andradean viscosity

Continental drift, nowadays a geonomically well established fact, is explained by the present author as a gravitational reaction to mega-upwarps and downwarps of the geoid, called "mega-undations" (Van Bemmelen, 1964a, b, c; 1965).

These mega-undations probably find their origin in turbulent and laminar flow systems in the lower mantle, where the matter may have a Newtonian viscosity. The physico-chemical differentiation of the original cosmic matter into various bonds and phases, and its distribution into specific layers, is thought to be the main source of endogenic energy.

These mass circuits cause a mega-undatory warping of the upper mantle and crust. These outer spheres are largely in a crystalline state and they react to the mega-warping by spreading of the rising areas and contraction of the subsiding ones. This occurs by means of rheid flow movements, which have the character of creep and hot-creep deformation (for rheidity see Carey, 1954; also Holmes, 1965, pp.202–206). Rheid flow movements under circumstances of Andradean viscosity differ from the Newtonian viscosity flow (Orowan, 1964). Instead of a spreading of the flow lines in a parabolic way (as was suggested, for instance, by Heiskanen and Vening Meinesz, 1958), the zones of deformation tend to concentrate in layers of a higher strain rate; the latter alternate with zones, in which little or no strain occurs. This gives a picture of "glide-lamellae" ("Gleitbretter", Schmidt, 1932), which are more or less competent and undeformed layers, separated by layers or zones of stronger deformations (higher strain rates) (see Fig.1).

In these layers of differential movement due to (hot-) creep phenomena, the internal cohesion is reduced and occasionally destroyed, giving rise to sudden stress drops (earthquakes).

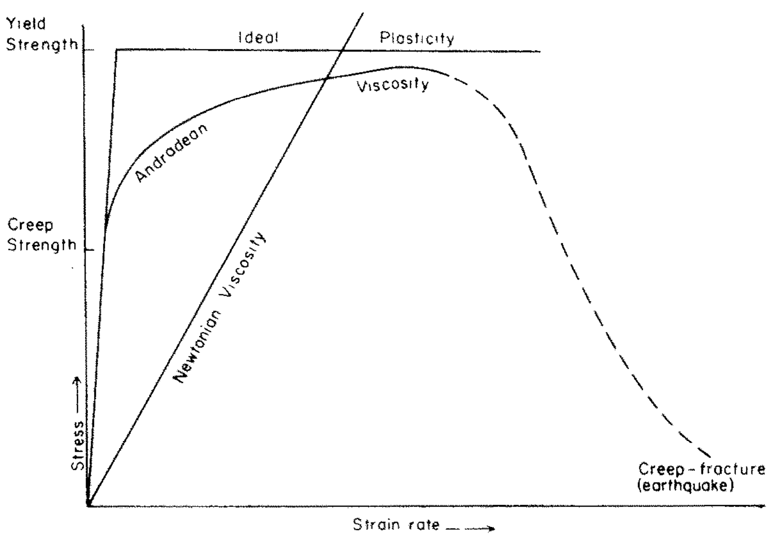


Fig.1. The relations between stress and strain rates according to the concept of Newtonian viscosity, ideal plasticity and Andradean viscosity.

Geomechanic facts provided by reliable fault-plane solutions

The author has compared the geodynamic processes in the outer mantle and crust with the spreading under gravity of a tilted stack of cards or pile of books, the higher units "gliding" or "flowing" farther forward than the deeper ones. This geomechanical model was the premise of fig.4 on p.400 of the preceding paper (Van Bemmelen, 1964b). Since then the author discussed this model with Ritsema whose recent paper on reliable fault plane solutions (1964) enables a further elaboration of the above model.

The normal and intermediate shocks have a hearth-mechanism, which is consistent with the expectations of this model. It appears for instance, from examples in Japan and South America, that during the shallow and intermediate shocks, which Ritsema (1964, p.71) defines as thrust or block-type hearth-mechanisms, the upper block is generally thrust farther forward towards the Pacific Ocean than the lower block.

But for the deeper shocks in these areas the direction of the thrust movements is reversed, namely the underlying unit moves oceanward with respect to the upper block. Evidently the picture of a tilted stack of layers spreading under gravity does not hold good for the lower part of the sclerosphere, situated underneath the Japan Sea and underneath the South American Shield. In these areas the lowermost part of the sclerosphere moves relatively faster oceanward than the overlying zone.

This diagnostic fact might be interpreted in the following way, according to the mechanical model for the evolution of mega-undations.

An upwarp of the boundary between the lower and upper mantle does not mean that the gravitational potential energy is restricted to the elevated and tilted outer layers. Also the upwarp of the outer mantle itself tends to spread under gravity towards the adjacent downwarp. Because the viscosity of the lower mantle matter is probably less than that of the overlying sclerosphere, the spreading of the upwelling of the lower mantle will occur with a relatively higher velocity. This sideward flow in the top of the lower mantle will have the character of an "under-current", which exerts a drag on the roof formed by the sclerosphere. This type of under-current would occur at a depth of many hundreds of kilometers instead of the common concept of shallow under-currents, at a depth of some dozens of kilometers immediately underneath the crust, as has been suggested by many contemporaneous geophysicists.

This elaboration of the mechanical model for the spreading of a mega-undation is illustrated by Fig.2, 3 and 4. It bears some analogies with the mechanical model for the spreading of meso-undations, which the author has proposed for the Alps (Van Bemmelen, 1960a, b) (see Fig.5). When a geosynclinal area is pushed up due to the buoyancy of an orogenic asthenolithic root, the following mechanical reactions are to be expected: (1) the sedimentary strata glide from the emerging centre, forming nappes of the helvetic type; (2) the spreading of the crystalline basement complex with its sedimentary cover will cause nappes of the east-alpine type; (3) in still deeper levels in the asthenolith itself, where the lower part of the crust has been mobilized (migma, palingenetic and juvenile magmas), the stress-field is dominated by the downward pressure of the arched-up roof and the upward pressure caused by the byoyancy of the asthenolithic root. Here a sideward,

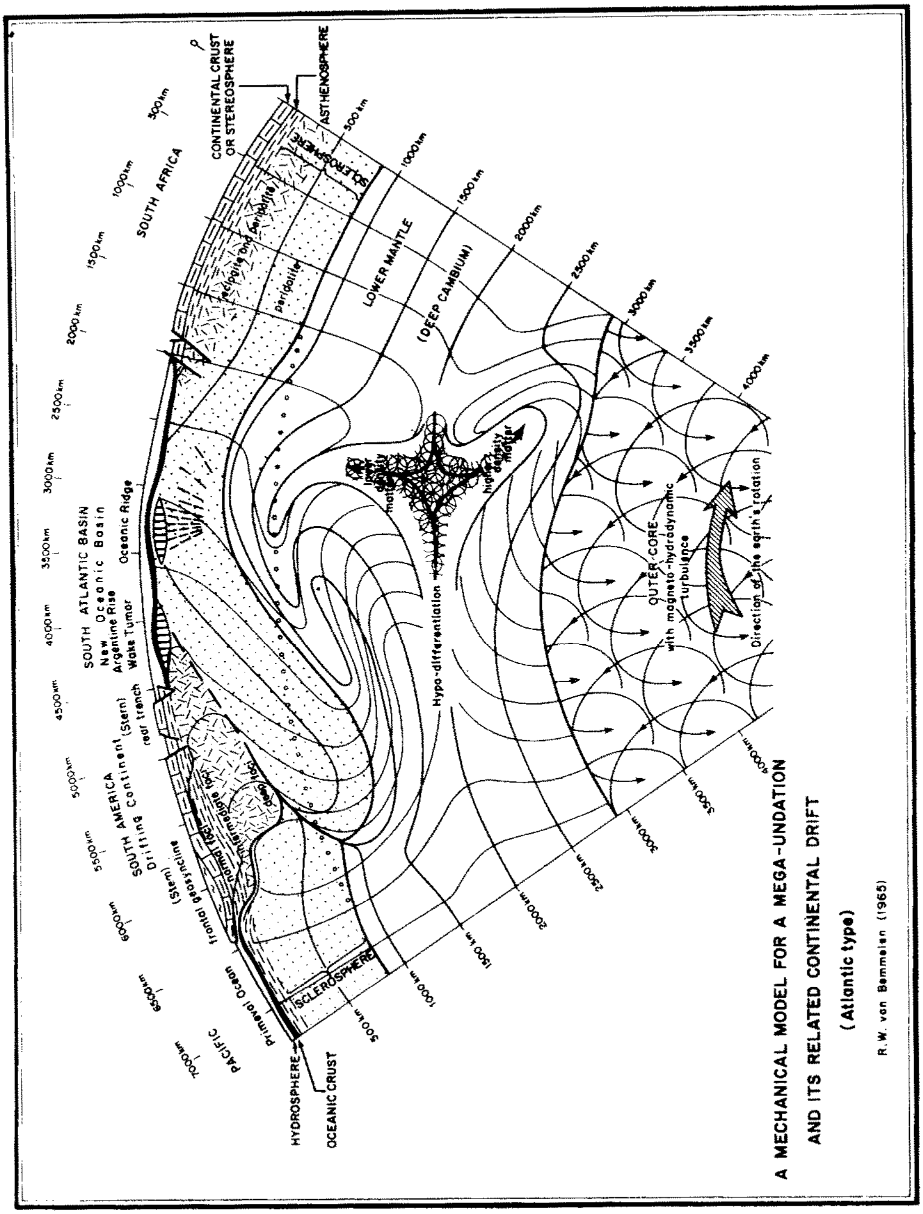
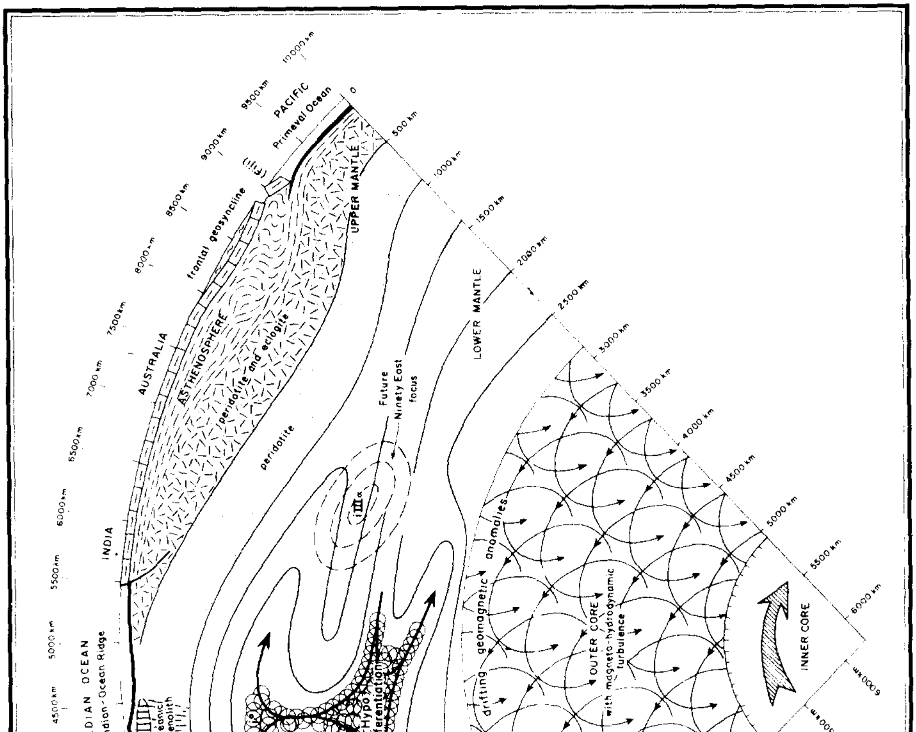


Fig. 2. Schematical section across the late mature Atlantic Mega-Undation.

Fig. 3. Schematical section across the Indian Ocean Mega-Undation during its Lower Mesozoic phase of evolution along 20°S. South America and Africa are not yet separated and India is still travelling together with Australia. The locations of the future foci of the South Atlantic and the 90°E mega-undatory upwelling are indicated. The first started in mid-Mesozoic time and the second in the Late Mesozoic.


A MECHANICAL MODEL FOR A MEGA-UNDATION
AND ITS RELATED CONTINENTAL DRIFT
(Indian-Ocean type)
LOWER MESOZOIC PHASE
SECTION ALONG 20° S
R.W. von Bemmelen (1965)
PACIFIC
Primeval Ocean
frontal geosyncline
AUSTRALIA
ASTHENOSPHERE
peridotite and eclogite
UPPER MANTLE
LOWER MANTLE
peridotite
Future Ninety East focus
INDIA
INDIAN OCEAN
Mid-Indian-Ocean Ridge
Oceanic asthenolith
Madagaskar
AFRICA
SOUTH AMERICA
STEREOSPHERE
SCLEROSPHERE
Hypo-differentiation
Westward drifting geomagnetic anomalies
OUTER CORE
with magneto-hydrodynamic turbulence
INNER CORE
Future focus of the South Atlantic Mega-Undation

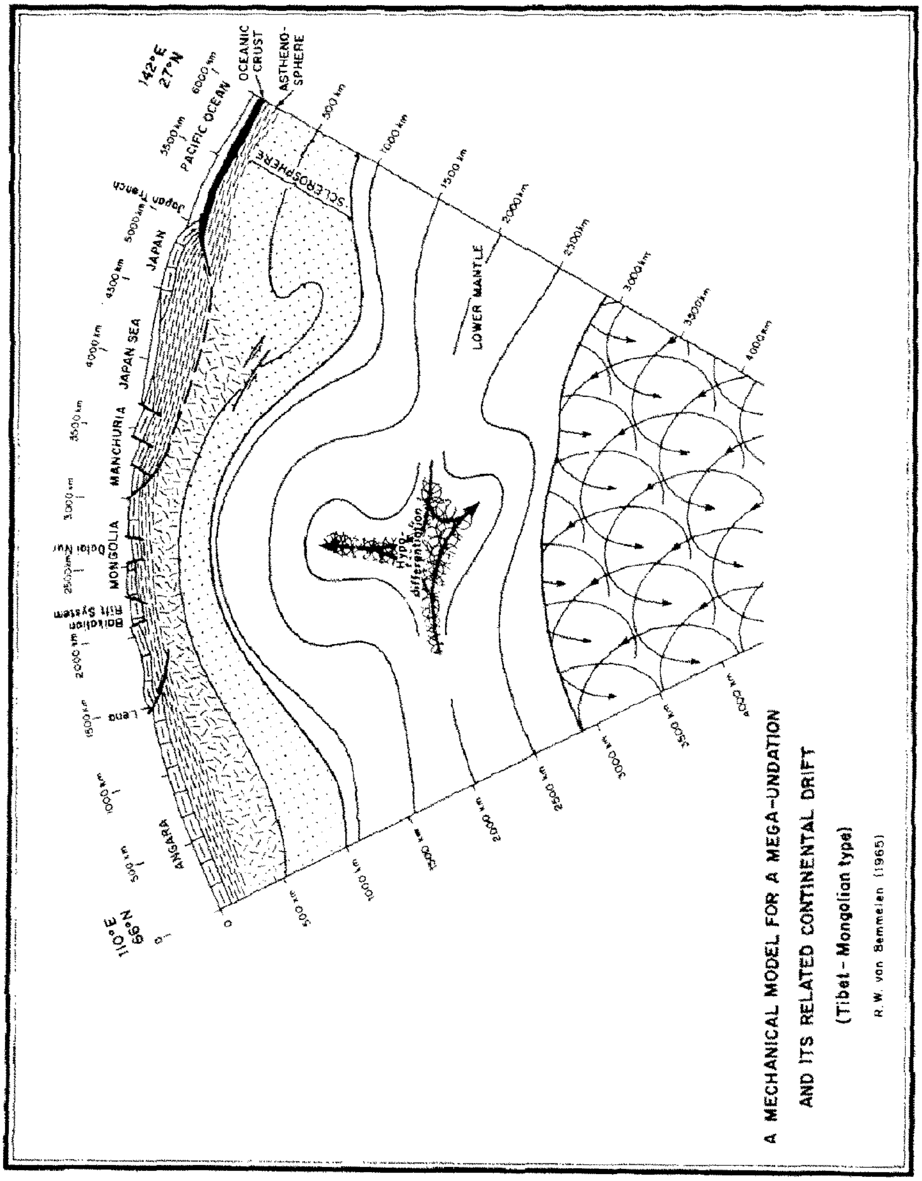
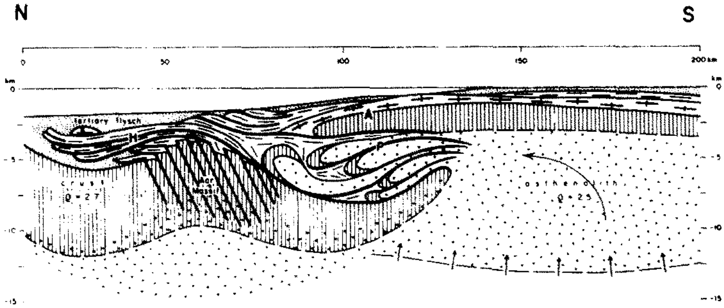


Fig.4. Schematical section across the early mature Tibet-Mongolian Mega-Undation.



	Involved levels (Stockwerk)		
Types of nappes	Sedimentary cover	Crystalline basement	Rheomorphic migma
H = Helvetides (a = austride Klippe)	Epidermal	——	——
A = Austrides	Epidermal and dermal		——
P = Pennides (diapiric injections)	Epidermal, dermal and bathydermal		

Fig.5. Structural scheme of the Western Alps at Lower–Mid Tertiary time, before their uplift. (After Van Bemmelen, 1960a, fig.4.)

mushroom-like spreading has to be expected, which is accompanied by lateral diapiric nappes with cores of injected asthenolithic matter: these are the pennine type of nappes of the Alps.

Similar geomechanic reactions are to be expected in the case of mega-undations, though at a hundred-fold enlarged magnitude.

The sideward flow of the crust (or "stereosphere", as it has been called by Bucher, 1955), the asthenosphere and the upper part of the sclerosphere can be compared with the mechanism of the formation of Helvetic and East Alpine nappes. These movements are accompanied by earthquakes at a normal and intermediate depth, down to about 400 km.

The reliable fault-plane solutions presented by Ritsema (1964) indicate that indeed these composite glide- or flow-movements occur, conforming to the principle of the spreading under gravity of a tilted stack of more competent layers (glide-lamellae).

But at still greater depths, underneath the seismologically well studied regions of Japan and South America, the lower part of the sclerosphere moves faster towards the Pacific than the overlying part. This might be interpreted as a sideward diapiric injection, moving away from the causative top part of the upwelling of lower mantle material in the rear. This mechanism conforms to the formation of pennine nappes. The sideward current in the top of the lower mantle may cover thousands of kilometers, whereas the Pennine nappes have a structural overlap of some tens of kilometers.

Thus the lateral displacement of the front of a drifting continent would be the cumulative effect of two types of movements: (1) gliding movements in the outer layers, down to a depth of about 400 km, and (2) a passive transport or an active drag by an under-current, occurring at a depth of between 500 and 1,000 km.

In Indonesia and the Fiji Islands a different situation is found. In these regions Ritsema's study of reliable fault-plane solutions indicates that not only in the levels of the normal and intermediate depth of earthquake foci, but also in the deepest levels of about 600 km the upper block moves relatively outward, away from the causative mega-undation. In Indonesia the movements are radial, eastward underneath Mindanao and Banda, southward under the eastern Java Sea and southwestward under the western Java Sea. In Fiji, (in the case of one earthquake only) the deep movement is northwestward, at an obtuse angle to the eastward movements of foci at intermediate depth. But the movements accompanying the intermediate and deep shocks are all radially arranged with respect to the strongly curved Fiji arc (see Fig.6).

The geotectonic situation in Indonesia and Fiji is similar, in so far that both regions are farthest away from the mega-undation which is thought to be responsible for their lateral displacements. Presumably the movements, according to the principle of the gravitational spreading of a tilted stack of layers, could penetrate in these areas to the greatest depths at which creep fractures can occur. Indonesia and Fiji are situated beyond the influence of the lower mantle under-current and they move autonomously, by means of their own gravitational potential energy. This is comparable with the East Alpine nappes, which could glide farther forward than the Pennine nappes.

The shifting crests of mega-undations

As the mega-undations are probably caused by geodynamic processes in the lower mantle, their crests will occur completely independent from the crustal configurations at the surface. They may occur entirely within the boundaries of primeval oceans (Darwin Rise in the Pacific Ocean), or underneath primeval continents (Atlantic and Indian Ocean Mega-Undations underneath Gondwanaland), or their crestline may pass from an ocean basin underneath a continent (East Pacific Rise, Afro–Arabian Rise).

The independence of the crestlines of the mega-undations from surface structures appears also from the haphazard manner in which the rifting of the overlying crust occurs with respect to its geotectonic trendlines. In Europe the trendlines of the Caledonian and Hercynian Mountain ranges are cut off, India and Australia are severed at right angles to the Permian basins (Ahmad, 1961), etc.

The parallelism between the American westcoast ranges and the crest of the East Pacific Rise is explained by the fact that the latter acted as a barrier to the westdrift of South and North America (Van Bemmelen, 1964b, p.416).

The crestlines of mega-undations coincide with the tops of active up wellings of lower mantle material which form the oceanic asthenoliths at the base of the mid-oceanic geo-undations. However, the position of these highest parts of lower mantle bulges can shift in the course of time.

In a former paper the author treated the Atlantic Mega-Undation s.l. as an example of a mega-undation with a crestline which extended in a longitudinal direction (see Van Bemmelen, 1964b). In four gigantic steps, each thousands of kilometers long (about 6,000, 5,000, 4,000, and 3,000 km respectively), the top part of the Atlantic Mega-Undation spread from the Southern Hemisphere to the North Pole.

In the case of the young Hawaii Mega-Undation the crest shifted east-southeastward over a distance of 3,000 km. At present coral-reefs and subsiding seamounts occur at the western end. These are the remnants of volcanoes which are about 100 million years old. Eastward along the Hawaii Ridge, the character of the islands ranges from basaltic relics, via deeply dissected volcanoes and well preserved extinct volcanoes, to the active volcanoes at its eastern end (see Holmes, 1965, fig.742).

Such a mechanism of an eastward shifting of the centre of volcanism as a reaction to an eastward shift of the deep-seated top of an upwelling of the lower mantle is just the reverse of Tuzo Wilson's concept (1963). Wilson supposes that the source of magma has a fixed position and that the volcanoes are passively carried off by convection currents at the base of the crust, acting as conveyor belts. However, instead of a drift of the extinct volcanoes in a longitudinal westward direction, the top of the mega-upwellings and the related rise of basalt magma may shift eastwards. This can be an active shift of the upwelling itself, but it can also be the effect of an asymmetric spreading of the upwelling. For instance, in the mechanical model of Fig.3 it is assumed that the top of the lower mantle bulge, which caused the South Atlantic Mega-Undation, after having had its summit underneath the Mid-Atlantic Ridge in mid-Mesozoic time, has spread later on westward in such a way that its crestline migrated eastward.

Nowadays the South Atlantic Ridge is still a geo-undatory upwarp with an oceanic asthenolith as buoyant root, but it is no longer very active volcanically. It is an almost extinct geo-undation. On the other hand, the shift of the highest part of the lower mantle upwelling towards the west coast of South Africa has not (yet) caused new segregations of basaltic magma and oceanic volcanism east of the Mid-Oceanic Ridge.

This eastward shift of the crest of the mega-undation had, however, a geotectonic effect. The section of the South Atlantic Ridge between Ascension and Bouvet, being situated in Cenozoic time on the west flank of the late mature mega-undation, took part also in the general westward drift. It was off-set by a dextral transcurrent fault along starboard (Ascension) and a sinistral strike-slip movement along port (Bouvet). Also the aseismic lateral Walvis Ridge was cut by later dextral transcurrent faults.

In the preceding paper (Van Bemmelen, 1964b), the author used the off-setting of the oceanic ridges by transcurrent faults as a means to determine the relative age of the various sections of the Atlantic Mega-Undation. In the light of the above-said this is no longer a valid method. The general succession of the main phases of the Atlantic Mega-Undations s.l. (I–IV) is still true, because it is based on the age of other related geotectonic features, and the age of the Thulean Plateau Basalts which are much younger than the Karroo System. But the three sets of sinistral and dextral transcurrent faults, which bound the first, second and third phase of the Atlantic Mega-Undation, respectively at their port and starboard sides, may indicate that the top parts of these sections shifted eastward. But these transcurrent faults can no longer be considered to represent diagnostic facts on which the chronological succession of the sections of the Atlantic Mega-Undation s.l. can be based.

In Permo-Triassic time South America travelled westward still united with Africa. In Upper Triassic and Liassic time the Karroo Plateau Basalts poured out and the rifting between both continents began. But it was not before the Cretaceous that the South Atlantic Basin opened up (Beurlen, 1961).

Harrington (1963) supposes that the process of the South American west-drift occurred intermittantly and irregularly. This might be the result of various pulsations of the lower mantle upwellings or other relaxation phenomena.

Theoretically, there are two possible ways of development of the fields of gravitational potential energy; either the top part shifts gradually in time, or there is a jerky evolution:

(1) Gradual shift of the top part of an upwelling can occur in the direction of the related continental drift, away from it, or in the longitudinal direction of the crest line. Gradual shifts cause wave motions with rolling hingelines. The westward-spreading under gravity of the South and North Atlantic Mega-Undations probably caused a gradual eastward shift of the top part, that is, in a direction opposite to the westward American drift. The development of the Hawaii Rise is an example of a gradual longitudinal shift in the course of about one hundred million years.

A gradual shift in the direction of the related continental drift would steadily reinforce this drift. It is possible that the spectacular drift of India is an example of such a development. India moved northward during the Cenozoic with an average drift rate of 11–13 cm per year over a distance of about 6,000 km (Van Hilten, 1962, p.423). It left an almost straight trace of that length in its wake, the 90°E nematath. India might be an example of a crustal shield which has been "surf-riding" on the frontal slope of a gradually sideways shifting mega-undation. The gradually northward evolving Indian Ocean Mega-Undation was the mechanical cause of its drift, until its further northward displacement was opposed by the barrier formed by the Tibet–Mongolian Mega-Undation.

(2) Jerky shifts of the top part of a mega-undation can also theoretically occur in three directions with respect to the related continental drift, namely in the same direction, in an opposite direction, and at right angles to it.

Such jerky shifts differ from common wave motions with rolling hingelines in that a stepwise displacement of the top occurs.

The present author described such a development for the orogenic meso-undations of Indonesia (Van Bemmelen, 1949, 1954). In this case the displacement of the Djambi nappes in Sumatra over some hundreds of kilometers was not the result of a single slope from crest to trough continuously moving forward. But "each stage of the journey", as Holmes has formulated it (1965, p.1144), "is carried out, as it were, by an ascent in a lift followed by an escalator descent into the next "lift", which, however, may not start "going up" for many million years".

The intermittant shifts of the Andean Orogenesis mentioned by Harrington is according to the present author the effect of stepwise shifting "meso-undations". This orogenesis is an effect of the preceding geosynclinal phase of subsidence, which is a "geo-undation". The latter, in its turn, is a geotectonic effect of the continental drift caused by the Atlantic "Mega-Undation". Thus the orogenic meso-undations are merely links derived from the chain reactions of the geodynamic evolution. They have only an indirect relation to the primary cause, the Atlantic Mega-Undation. They occur much later in time, and they are not in a strict space-time relationship with this initial cause (see table in Van Bemmelen, 1964c). Therefore, no direct relation

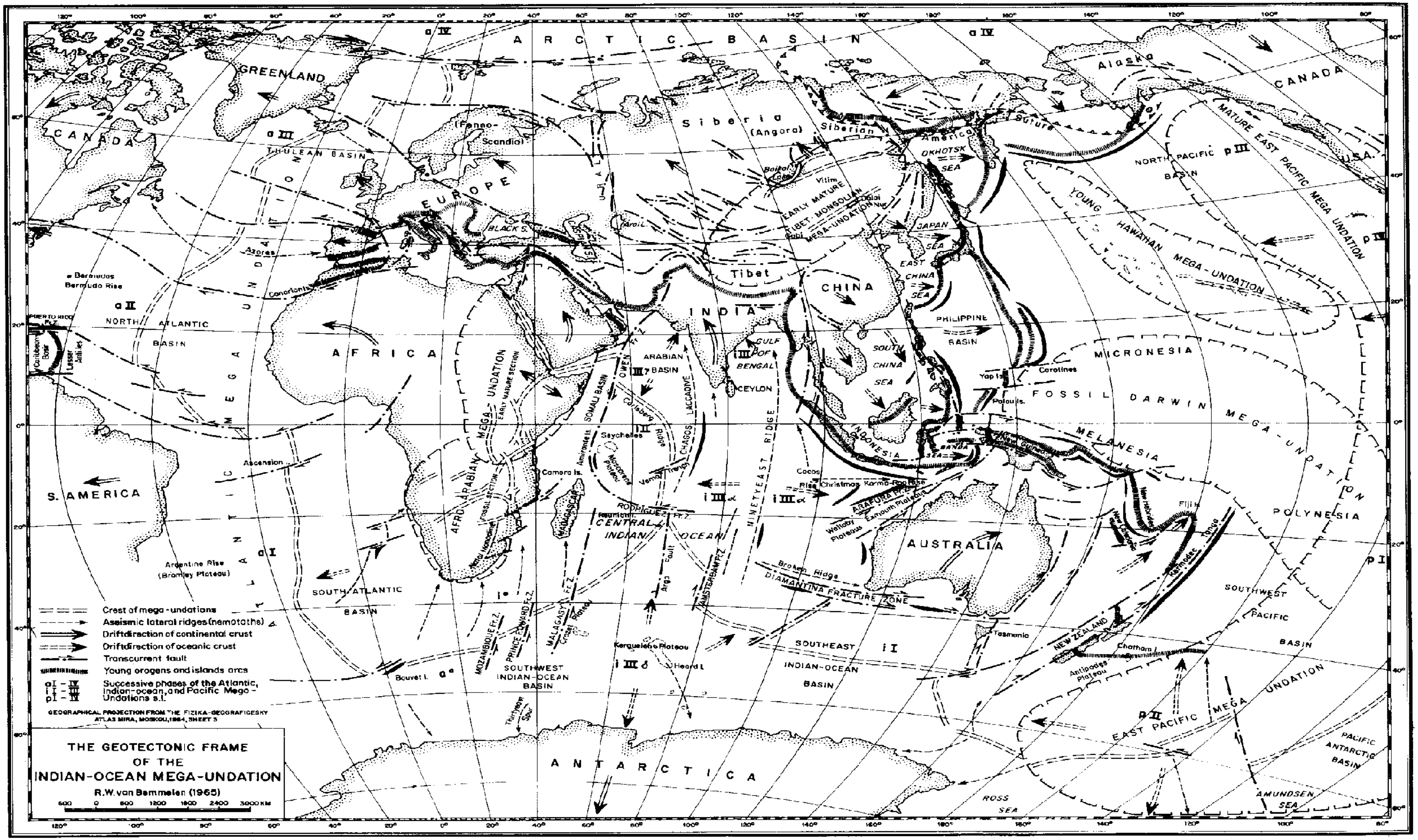


Fig.6. The geotectonic frame of the Indian Ocean Mega-Undation.

between the time of the Andean orogenesis and that of the westward drift of South America can be expected.

In the case of mega-undations a stepwise displacement of the top part of the lower mantle upwelling in the direction of the continental drift is illustrated by the shift from the original Indian Ocean centre (iO) to the South Atlantic centre (aI) (see Fig.3).

The iI phase of the Indian Ocean Mega-Undation s.l. caused the separation of Antarctica from the India–Australia fragment. This Mega-Undation represented a step, in mid-Mesozoic time, of some 6,000 km from the iO centre, whereas the South Atlantic Mega-Undation was a step in mid-Mesozoic time, also measuring about 6,000 km, from the initial focus of the Indian Ocean Mega-Undation s.l. in a westward direction (from iO + aO to aI).

The progressive evolution of the Atlantic Mega-Undation from the Antarctic region to the Arctic in four successive steps (aI–IV) is a good example of the intermittant displacement of the top of a mega-undation at right angles to the general direction of the related drift.

The "why" of these intermittant shifts over great distances is still unknown. It is suggested that, in the section across the Indian Ocean during its Lower Mesozoic phase of opening, the disturbances of the physico-chemical equilibrium of the matter in the lower mantle, caused by the changes of temperature and pressure during such mega-circuits, may initiate hypo-differentiation in other centres. These rearrangements of the chemical bonds will be exothermal, being the adaption of the original cosmic matter to the new planetary circumstances. Once started, a chain reaction will ensue of turbulent splitting-up of lower mantle material into products of lower and greater density. The buoyancy of the former will cause another mega-undatory upwarp and all its geotectonic consequences. It is of course possible that the hypo-differentiation of the lower mantle is - in its turn - a link in a chain-reaction, which starts still deeper in the earth. For instance, there are hypotheses suggesting that energy is liberated by phase changes in the core, so that material is added to the mantle. This material might cause a physico-chemical instability in the lower mantle (potential chemical energy), and then hypo-differentiation will transform this potential chemical energy into potential gravitational energy.

Holmes (1965, pp.991–993) distinguishes three possible sources of endogenic energy for maintaining the earth's magnetic field. He discards the first source (radioactivity) as being insufficient, and because - if it were the motor of the central dynamo - the mantle would have become too hot. The second source is differentiation of the mantle and migration of iron from the mantle to the core. This is also seriously questioned by Holmes, because - if happening at all - it should have come to an end long ago, or have now become too slow to supply any significant amount of heat. Holmes prefers the third possibility, the liberation of energy during phase changes as a result of decrease of pressure (Holmes, 1965, p.1031). This hypothesis is developed by Egyed's theory of the expansion of the earth (1957).

The present author agrees that this third source of endogenic energy indeed might be sufficiently strong and persistent to explain the geodynamic evolution. However, it will start chain reactions, which may cause hypo-differentiation in the mantle and the formation of mega-undations, as outlined above (see also Van Bemmelen, 1964c, table I).

Holmes' objections against the second possibility would have been countered, if we see the second and the third source of natural energy distinguished by Holmes as links in the great chain reaction of physico-chemical evolution of our planet.

In the final chapter of his magistral book, Holmes (1965, p.1244) remarks that "the earth is an extremely old rotating electro-magneting hydrodynamic machine with a geochemical structure of great complexity". The hypothesis of the physico-chemical chain reaction of the earth's evolution is one of the many possible models, the adequacy of which, according to Holmes, might be ultimately checked by high-speed electronic computing.

In a preceding paper (Van Bemmelen, 1964b) the evolution of the Atlantic Mega-Undation has been discussed as a test case. Later in this paper the very complex development of the Indian Ocean Mega-Undation and its structural frame will be analysed as another test case. Before doing so, there are still some additional general remarks on the stages of evolution of mega-undations to be made.

Stages of evolution of mega-undations

Four stages of evolution of a mega-undation might be distinguished by means of various diagnostic features:

(1) *Young mega-undations*. These are characterized by dike intrusions and effusions of plateau basalts, and the initiation of the spreading of the overlying structural strata. The eastern end of the Hawaii Rise is in this young stage of evolution. The eastern islands cause also giant submarine slides. Moore (1964) describes such a slide 150 km long and 50 km wide, departing from a niche at the northeastern side of Oahu which moved over an average slope of only 2°. This slide has the dimensions of the East Alpine nappes.

(2) *Early mature or precocious mega-undations*.These have a declining activity of the plateau-basalt effusions. When situated underneath continental realms the sideward spreading of the overlying continental crust has caused already great rift systems, which may become the site of new ocean basins. In the central part of these new ocean basins the rising basalt-magma starts to form mid-oceanic ridges, which mark the crest of the deep-seated upwellings.

The Afro–Arabian upwarp is a type example of such an early mature stage. The rifting on its top has led to flood-basalt outpourings, which nowadays are in a declining phase. The Red Sea and the Gulf of Aden are new ocean basins; dike intrusions in their axis (accompanied by large magnetic anomalies, high heat-flow, and seismicity) represent the initiation of a mid-oceanic ridge (Girdler, 1962; Laughton and Matthews, 1964a).

Another type example is the Tibet–Mongolian Mega-Undation. It has also typical rift systems on its crest (the Baikal Rift System and the Dalai Nur Depression, which is drained by the Amur River). The Baikal Rift System is the site of Pleistocene to Recent basaltic flows on the rifted belt and beyond it to north and south. Near the upper reaches of the Vitim River, midway between the Baikal Rifts and the Dalai Nur Depression, three barely extinct volcanoes have been discovered (Holmes, 1965, p.1103).

The Moho-discontinuity lies underneath this Tibet–Mongolian Mega-Undation at depths of 50–75 km; that is at twice the normal value (according to Dementzkaya, 1961, quoted in Smirnov, 1964, map 18). This indicates that a relatively high heat-flow tends to the transformation of high density (eclogitic) matter into basaltic or gabbroic matter, thus causing a downward migration of the Moho. In the case of the Tibet–Mongolian Mega-Undation the crustal spreading has not yet caused the opening of new ocean basins, though the deep Baikal Trench (with a maximum depth of water of 1,741 m) is comparable to the Red Sea.

Geotectonically there are indications that the overlying crust spreads northwestward in Siberia and southeastward and eastward in eastern Asia. The latter movement is not restricted to the mainland but it has given rise to a series of marginal new sea basins fringed at their eastern side by island arcs. The latter advance in places even thousands of km eastward into the Pacific Basin. In the case of the Mariana–Yap–Palan Arc dextral transcurrent faults are caused by the barrier of the fossil Darwin Rise.

In how far the southeastward and eastward flow of the stereosphere (crust) and asthenosphere in the East Asiatic belt has caused frontal geosynclines with a rising Moho-discontinuity, and an enforcement of the east drift by Coriolis forces caused by subsiding columns, is a subject which needs closer investigation. It is remarkable that even beyond the Marianas Arc the depth of the Moho shows wave-like variations (Woollard and Strange, 1962).

(3) *The late mature or ripe mega-undations*. These are characterized by wide new ocean basins and well-developed mid-oceanic ridges. The latter are already disrupted by wrench faults due to later shifts of the crestline of the lower-mantle upwelling.

In the wake of drifting shields geotumors may have developed due to the pressure relief in the exposed eclogitic base of the continents (Bermuda Rise, east of North America; Argentine Rise or Bromley Plateau, east of South America).

The sections I and II of the Atlantic Mega-Undation s.l. are good type examples of this stage of evolution.

(4) *Fossil mega-undations*. These can also be distinguished; they are generally subsiding and no longer actively spreading at their top. Instead they are indented and cut by younger transcurrent faults, induced by the stress-fields emanating from other, younger mega-undations. The best example is the Darwin Rise in the Pacific (see Fig.6). Other examples might be South Africa, which forms the southern part of the Afro–Arabian upwarp, and Angara with its basalt effusions.

The effusion of the Siberian Plateau Basalts started in Late Carboniferous time and continued up to the Triassic. These Siberian traps are analogous to the basalts of the Karroo System, though they are somewhat older. In how far they were accompanied by (or followed by) crustal spreading needs closer investigation. At any rate this Siberian field of plateau basalts is now surrounded on all sides by younger geotectonic features, caused by surrounding mega-undatory centres.

The above-said is summarized in Table I.

A schematical section across the South Atlantic Mega-Undation illustrates the ripe phase of evolution (Fig.2), and another one across the

TABLE I

Stages of evolution of mega-undations

Diagnostic features	Stages of evolution			
	(a) young	(b) early mature (precocious)	(c) late mature (ripe)	(d) fossil
Basaltic volcanism	active	declining	almost extinct	-
If occurring underneath Continents: development of new basins	beginning of the formation of a rift system on the crest	well developed rift system and/ or narrow ocean basins	wide new ocean basins	-
Formation of "geo-undatory" mid-ocean ridges	-	active	declining	-
Deformation of the mid-ocean ridges by transcurrent faults inherent to the geotectonic pattern	-		active	-
Deformation of the margin of the mega-undation by transcurrent faults from the outside of its geotectonic pattern	-			active
Type examples	Hawaii Ridge	Afro–Arabian and Tibet–Mongolian Mega-Undation	South- and North-Atlantic Mega-Undation	Darwin Rise Angara

Tibet–Mongolian Mega-Undation the precocious phase (Fig.4). The section across the Indian Ocean (Fig.3) gives a tentative picture of the late-mature situation of the original Indian Ocean Mega-Undation at the end of the Lower Mesozoic.

These sections are all based on the geomechanical model of the undation theory, which has been elaborated in the preceding pages. One of the distinctive features of this model is the great amplitude of the mega-undatory deformations of the boundary between the lower and upper mantle. This boundary is probably a transition zone, in which gradual shifts occur in the grade of crystallinity and the physical parameters, such as density and viscosity. Therefore, it will be difficult to test this supposition by seismic methods.

It will perhaps be possible to check this model by centrifuged model experiments (Ramberg, 1963; Fultz, 1964). Of course such model experiments cannot prove that the geodynamic processes really occurred in "nature" in the way of the model. They will only be a help for our imaginative faculty of the spatial relations of the geodynamic processes. Thus, they might help us in the formulation of prognoses about the geotectonic and geophysical effects of these processes; the latter should be tested by further geotectonic and geophysical investigations which will provide us with additional diagnostic facts.

In the following section the geotectonic analysis of the evolution of the Indian Ocean Mega-Undation is given as another test.

THE DEVELOPMENT OF THE INDIAN OCEAN MEGA-UNDATION

International oceanographic cooperation in the past decade has greatly enlarged our knowledge about the Indian Ocean. This has been the subject of group discussions during the 22nd Session of the International Geological Congress in India, 1964, and the results have been incorporated in the admirable physiographic diagram of the Indian Ocean and the accompanying descriptive sheet by Heezen and Tharp (1965). These publications have been the basis for Fig.6; also use has been made of the excellent maps of the Russian Fiziko–Geograficesky Atlas Mira (1964) and some other sources (Krause, 1965; Smith, 1964, 1965).

Instead of repeating the physiographic and structural details of these newer data, here only a short survey will be given of their interpretation according to the mechanical model as elaborated in the preceding chapter.

The i0 phase

The disruption of the old Gondwanaland and the centrifugal spreading of its cratonic fragments started probably already in Permo–Triassic time. This is indicated, for instance, by the beginning of the dextral transcurrent movements in the Tethys Belt, as follows from paleomagnetic data and the ignimbritic eruptions along these transcurrent faults (de Boer, 1963, 1965; Guicherit, 1964; Van Bemmelen, 1964a).

The basaltic magma, segregated from the rising upwarps of the upper mantle, reached the surface in the Upper Triassic (the Karroo System).

The original centre of the Indian Ocean Mega-Undation s.l. (i0) was probably situated somewhere in the area where the three branches of the Indian Ocean ridges meet.

This initial phase drove South America together with Africa westward, India together with Australia eastward, and Antarctica southward[1]. These indico-fugal movements initiated frontal geosynclinal subsidences in the Tethys, the Andean belt, in New Zealand and in Antarctica between 60° and 120°W. All these "geo-undatory" geosynclines were, later on, the birth-place of mountain systems, which are characterized by cycles of "meso-undations". The latter are generally referred to as the Alpine Mountain System.

The i1 phase

The i0 centre then shifted eastward to the southeast Indian Ocean Basin; this part of the Indian Ocean was enlarged in Mid- and Upper-Mesozoic time, Australia moving northeastward, India northward, and Antarctica farther southward. The anti-clockwise rotation of India occurred between the Jurassic and Cretaceous according to Van Hilten (1964, plate I); by this rotation India was severed from Australia and thereafter it began its independent northward drift-journey.

The Australian drift was accompanied along its port side by the sinistral transcurrent fault zone of Arafura, and along its starboard side by the dextral transcurrent fault zone of New Zealand.

The Arafura Fault caused typical drag phenomena in the ridges extending northwestward from the northwestern Australian coast. The Van Diemen Rise, Londonderry Rise and Leveque Rise have a southeast–northwest trend, separating the Bonaparte Depression and the Browse Depression. At their northwestern end they all swing into a west-southwestern direction (Fairbridge, 1952).

The dextral transcurrent movements of the Alpine Fault in New Zealand produced a cumulative offset of 480 km (300 miles) according to Wellman (1950) and Grindley (1961). This fault displaced Lower Mesozoic strata and it was active since the Jurassic; the transcurrent movements came to a halt in the Tertiary.

The p11 phase

Toward the end of the Mesozoic the East Pacific Rise grew out into a south-westward direction. This development caused the centrifugal spreading of the overlying crustal elements (partly oceanic, partly continental in composition) towards the north, west and south.

This spreading disrupted the young geosynclinal and orogenic trend-lines along the frontal margins of Australia and Antarctica. The section

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[1] Of course these directions are given with respect to the present situation of the earth's axis of rotation. For the older positions Van Hilten's (1964) paper might be consulted.

between the Alpine Fault and the Chatham Islands rotated anticlockwise from a north–south into a west–east direction, thus forming the typically oroclinal bend in the South Island of New Zealand. It ends abruptly east of Chatham, but this end is united by a nematath with the crest of the East Pacific Mega-Undation. At the other side of this crest line another clear aseismic lateral ridge points to the Cenozoic orogen of western Antarctica. This young marginal orogen of Antarctica continues its course via Graham Land to the South Shetlands (see Adie, 1964).

Thus the original connection between the east Australian and the north Antarctican frontal geosynclines was disrupted by the pII phase at the southwestern end of the East Pacific Rise; but the aseismic lateral ridges, branching from the central ridge like a herring-bone, clearly indicate how the Alpine Mountain System of New Zealand originally extended into that of Antarctica. This method for the reconstruction of the former fit of drifting crustal shields has been devised by Tuzo Wilson (1963).

The iII phase

Towards the end of the Mesozoic the top part of the original Indian Ocean Mega-Undation shifted northward, to the northwestern Indian Ocean. It was partly situated underneath the Indian Shield, where it caused the outpourings of the Deccan Traps. During the Lower Tertiary it contributed to the northward "surf riding" of India, and the northwestward drift of Arabia and North Africa. Perhaps it is also responsible for the dextral northeast–southwest transcurrent faults along the eastern margin of central and southern Africa.

The Carlsberg Ridge came into existence during this phase of evolution.

The iIII phase; α centre

It is not probable that the iII phase also initiated the eastward drift of Australia in Cenozoic time, because the remarkably straight course of 90°E nematath excludes the presence of a younger centre of crustal spreading at its western or eastern side.

On the other hand there are various grounds for the opinion, that India and Australia drifted together till the Upper Mesozoic; but since the Cretaceous India continued its drift in a northward direction and Australia started an eastward course.

A westward movement, away from the 90°E Ridge, is indicated between 10 and 20°S by the Vema and the Rodriguez Fracture zones, which displace the ocean ridge along the crest of the iII phase. Rodriguez Island is a small basaltic shield volcano at the eastern end of the undersea east–west ridge at 20°S (Upton and Wadsworth, 1964).

In the opposite direction, away from the 90°E Ridge, the Australian Shield drifted eastward in Cenozoic time. This indicates that the 90°E Ridge itself became a new centre of spreading, changing in character from an aseismic lateral ridge (nematath) into an active mid-ocean crest-line of a mega undation. The eastward drift of Australia is marked at its starboard by the dextral transcurrency of the Diamantina Fracture zone, which offsets between Tasmania and Australia the older dextral northwest–southeast starboard transcurrent fault. This was suggested already in 1962 by Carey in an address to the Australian and New Zealand Association for the Advancement of Science; the dextral west–east transcurrent fault in Bass Strait caused also the Cenozoic northwest–southeast rifts in Tasmania.

Along port the Cenozoic east-drift of the Australian Shield is accompanied by a system of sinistral west–east transcurrent faults. One of them offsets near Etna Bay the northern end of the northeast–southwest Arafura Fault in a sinistral way with respect to the southern end of the northeast–southwest fault along the southeastern margin of Geelvink Bay. This fault can be traced westward to the Flores Deep. It cuts off the southern and southeastern arms of the Celebes (Sulawesi) Orogene. Another sinistral strike-slip fault, the Sorong Fault described by Visser and Hermes (1963), offsets the northeast–southwest Geelvink Bay Fault with respect to the Mapia Fault. The Sorong Fault extends westward to the Sula Spur in Indonesia, and eastward along the southern margin of the Cyclops Mountains and the Markham Valley to the New Britain–New Ireland arc and its foredeep in Melanesia.

The Mapia Ridge is cut off at its northern end by still another important sinistral transcurrent fault with respect to the structural trends of Palau and The Philippines (Krause, 1965). The eastward extension of this transcurrent fault displaces also the outlines of the fossil Darwin Rise.

These sinistral transcurrent movements have been recognized in eastern New Guinea already in 1938 by Carey; recently Smith (1964 and 1965) has confirmed Carey's ideas on sinistral transcurrent faults and on the origin of the Purari orocline.

In the wake of the eastward drifting Australian Shield the stretching of the outer few hundreds of km of the earth caused deeply subsided parts of the sea floor. The northeastern Indian Ocean Basin is more than 6,000 m deep in extensive areas and in narrow rifts. The latter extend northwards, separating the plateaus of the Cocos–Christmas–Karma–Roo Rise (Kanaev, 1964). Furthermore, the Banda Deep and the Weber Deep in the southern Moluccas (eastern Indonesia) are probably related to this crustal stretching and rifting in the wake of the eastward drifting Australian Shield.

Thus the Mesozoic and Cenozoic drift movements of Australia are clearly reflected by geotectonic movements at all sides. Marginal geosynclinal subsidence (followed by orogenesis) occurred along the frontal side, whereas crustal stretching and rifting with nemataths took place in the wake; sinistral transcurrent movements developed along the port (first in the Mesozoic, southwest–northeast; thereafter, in the Cenozoic west–east) and dextral transcurrent movements along starboard (first, in the Mesozoic, southwest–northeast; thereafter, in the Cenozoic, west–east).

These geotectonic features represent strong converging evidence for the supposed drift of the Australian Shield, which was southwest–northeast in the Mesozoic and west–east in the Cenozoic. The Mesozoic drift severed the former connections with the African and Antarctic fragments of Gondwanaland. The post-Cretaceous drift moved Australia eastward, away from India which continued its northward course[1].

There is still another curious point in relation with the Australian drift, namely the displacement of New Caledonia, Fiji and New Zealand. According to Woollard and Strange (1962), the Moho-discontinuity is situated at depths of 20, 30 and 35 km respectively. This means that they probably are isolated fragments of continental (sialic) crust, amidst oceanic crustal conditions (Officer, 1955).

Fairbridge (1961) says that from Fiji no typical continental sediments or granite-type rocks are known. They are volcanic islands, the andesitic volcanicity of which began in the Cretaceous and continued in the Tertiary. The Moho at 30 km depth indicates, however, that this island group has a continental character of the crust.

The isolated position of these micro-continental fragments can be explained in two ways. According to fixistic concept the sialic crust between Australia and these islands suffered basification and thus it was transformed into an oceanic crust, so that the interjacent continental areas subsided to oceanic depths. According to the mobilistic concept these islands have the character of "Klippen". They moved autonomously away from Australia without being pushed eastward by the main shield. Their eastward drift is either the result of an eastward undercurrent which acted as a conveyor belt; or it is the result of an eastward coriolis push exerted by the subsiding column underneath the frontal geosyncline. The latter possibility has been suggested as a mechanical cause for the formation of the East Asiatic island arcs, the Lesser Antilles and the southern Antillean arc (see the section on Stages of evolution of mega-undations in this paper). The reliable solution of a deep focus earthquake in the Fiji Group, given by Ritsema (1964), indicates that, besides an eastward spreading due to coriolis forces, glide-lamellae in the direction of the Darwin Rise also might be active.

The initial stage of the formations of the Fiji Klippe and its autonomous forward movement at the end of the Lower Mesozoic has been depicted in Fig.3.

The IIII phase; β centre

The 90°E nematath ends in the Gulf of Bengal. North of it the east–west trending Dauki Fault occurs, along which the northeastern corner of the Indian Shield was displaced in a right lateral sense, about 250 km westward with respect to the Shillong Plateau (Evans, 1964). Movements along this fault continued until the end of the Cenozoic. Along the northeastern coast of Ceylon, Stewart, Dietz and Shepard (1964) mention a very steep oceanic slope, which might be related to a north-northwest–south-southeast trending fault.

[1] The rapid evolution of our knowledge on the former geotectonic relations of Australia with Gondwanaland is best illustrated by the fact that an expert like Teichert could write in 1958 (p.586): "Any ideas of a former westward extension of the Australian continent across the present Indian Ocean are thus disproved. If there was a restricted Gondwanaland further west, Australia never formed part of it." However, in 1961 Ahmad published a map of the palaeogeographical match between India and Western Australia, relating the trendlines of the Permian basins in a very convincing way (see also Holmes 1965, fig.871, p.1223).

The Ceylon Fault and the Dauki Fault might be a conjugated set of faults, related to a northwest directed stress field, emanating from the northern end of the 90°E Ridge. This northern end might represent another Cenozoic centre of mega-undatory upwarp and concomittant lateral spreading, which we call the iIIIβ centre.

The iIII phase; γ centre

In Cenozoic time another centre of upwelling and spreading developed underneath the Arabian Basin. This centre is characterized by an extensive field of negative gravity anomalies (Kaula, 1963), which indicate that it is in a young and active state of buoyancy.

At its eastern side it is bounded by the Indian Shield and the Chagos–Laccadive nematath. At its western side the Owen Fracture zone occurs, which extends from the Amirantes Orogen, way up the Indus Valley according to Snelgrove (1964).

The Owen Fracture zone is a right lateral transcurrent fault which offsets the Carlsberg Ridge 320 km with respect to its extension into the Gulf of Aden (Laughton and Matthews, 1964b).

This dextral wrench faulting must have occurred later than the formation of the Carlsberg Ridge itself which belongs to the iII phase. Therefore, we assign it to an iIII phase, with a centre in the Arabian Basin. The dextral motion of the Owen Fracture zone is exactly opposite to the sinistral offset of the Malagasy Fracture zone which forms its southern extension. The latter apparently belongs to another centre of crustal spreading (the δ centre of the iIII phase, discussed hereafter).

The dextral Owen Fault and the sinistral Rodriguez Fault form a conjugated set of wrench faults which embraces in its apex the Mascarene Plateau.

This plateau bears the Seychelles Islands at its northern end, one of the many micro-continents, which occur out of place in their oceanic environment. The Moho lies underneath the Seychelles at a depth of 30 km (Laughton and Matthews, 1964c). The Seychelles have a Precambrian basement of granites and dolerites, which is cut by Early Tertiary igneous intrusions (a syenite ring complex and dolerites). These intrusions are of the same age as the Deccan traps and they are related to the iII phase of the Indian Ocean Mega-Undation.

At the frontal (west-southwestern-) side of this plateau the arc-shaped Amirantes Ridge and Trench occur, which form a young orogenic system of meso-undations (Beloussov, 1964). The Amirantes Trench extends from 4°S 53°30'E–9°S 54°E, and it shows negative gravity anomalies (Laughton and Matthews, 1964d).

The Owen and Rodriguez Faults and the Amirantes Orogen are probably caused by a southward crustal spreading away from the Young Cenozoic δ centre of the iIII phase, in combination with the westward spreading from the α centre of this youngest phase of evolution of the Indian Ocean Mega-Undation s.l.

The iIII phase; δ centre

A young centre of crustal spreading occurs also in the Kerguelen area, in the southern part of the Indian Ocean. This plateau is another micro-continent with sialic igneous rocks, paleogene limestones and Young Cenozoic volcanism. The Heard Volcano is still active (Neumann van Padang, 1963, pp. 52–88). The mid-ocean ridge between Africa and Antarctica is displaced by sinistral transcurrent faults (the fracture zones of Mozambique, Prince Edward, and Malagasy). The mid-ocean ridge between Australia and Antarctica has been subjected to dextral offsets in a northern direction (the Amsterdam Fracture Zone) and in a northeastern direction (at 96°E 45°S).

These transcurrent movements cut across the older mid-ocean ridges and therefore, they are younger structural elements. The southward movement of Antarctica (as indicated by the 30°E spur in the wake and the frontal orogenesis at the Pacific side) is, most probably, largely related with the i0 and iI phases of evolution. But it may have been reinforced by the δ centre of the Cenozoic iIII phase, which caused a centrifugal spreading of the oceanic and continental crustal elements.

Table II summarizes the various drift movements related to the successive stages of evolution of the Indian Ocean Mega-Undation s.l.

TABLE II

Phases of evolution of the Indian Ocean Mega-Undation s.l. and the related indicofugal directions of the Gondwana fragments

Gondwana fragments	Phases of evolution						
	i0	iI	iII	iIII			
				α	β	γ	δ
(South) Africa	←	-	↙	-	-	-	-
North Africa and Arabia	←	-	←	-	-	-	-
India	↗	↑	↑	-	↖	↑	-
Australia	→	↗	-	→	-	-	-
Antarctica	↓	↓	-	-	-	-	↓
Age	Lower	Middle	Upper	Cenozoic			
	Mesozoicum						

CONCLUSION

The foregoing analysis of the geotectonic features of the Indian Ocean and the surrounding parts of the old Gondwanaland shows that there is a good correspondence between the expectations (prognoses) based on the geomechanical model of the undation theory and the diagnostic observations.

The successive phases of evolution of the Indian Ocean Mega-Undation have caused an indico-fugal spreading of the Gondwana fragments. These drift directions are summarized in Table II.

Australia is a particularly clear test case. It drifted first eastward (i0 phase), then northeastward (iI phase), and finally again eastward (iIII phase, α centre).

The iI and iIII phases are accompanied by dextral transcurrent fault systems along starboard and sinistral fault systems along port.

The east- and northeastward Australian Drift caused a frontal geosynclinal subsidence, the Papuan Geosyncline, which can be traced southward to New Zealand.

At the rear side, along the western and northwestern coast, these drift movements caused extension phenomena and depressed crustal wedges, such as the submarine Wallaby and Exmouth Plateaus and the west-coast basins.

The subsiding columns underneath the eastern frontal geosyncline were subjected to Coriolis forces, which promoted the outward (eastward) drift of continental fragments as isolated Klippen (New Caledonia, Fiji, New Zealand).

At its southern end the orogenic trend lines swung anticlockwise around a hinge in the South Island of New Zealand, obtaining an east–west direction and ending abruptly east of Chatham Island. The latter movements can be explained by an interference of the indico-fugal drift movements with a younger phase of evolution of the East Pacific Rise (pII phase).

The northward drift of India was finally brought to a halt by a gravitational stress field radiating from the early-mature Tibet–Mongolian Mega-Undation.

The African continent moved westward, first in combination with South America (i0 phase). It got a renewed impulse in the Upper Mesozoic (iII phase), which had a southwestward direction in South Africa and a northwestward direction in North Africa. This northwestward drift movement of North Africa was hampered by the European Shield, so that it was turned off into a westward direction along the Tethys Belt. In Lower Cenozoic time, during the iIII phase, the northwestward drift direction could be effected, however, because the European foreland was pulled away by the opening up of the Thulean Ocean Basin (the aIII phase; see Van Bemmelen, 1964b, p.414).

Future research will certainly lead to further adjustments and elaborations of the above scheme of mega- and geotectonic evolution. But it can be concluded that the great wealth of geonomic data, a great part of which was obtained in the past decade, strongly supports the hypothesis that continental drift is the result of the gravitational spreading of mega-undations.

RÉSUMÉ

Dans le premier chapitre un modèle géomécanique des méga-ondations est mis au point.

(1) Le manteau inférieur a probablement une viscosité newtonienne, mais le manteau supérieur, qui est largement en état cristallin, présente une viscosité andradienne; les déformations s'y produisent par "hot-creep" et par formation de lamelles de mouvements différentiels.

(2) Les solutions sûres de la mécanique des mouvements dans les plans de rupture survenant aux centres des tremblements de terre indiquent, que jusqu'à une profondeur d'environ 400 km l'étalement des méga-ondations

montre un avancement des niveaux supérieurs par rapport aux blocs sous-jacents, tandis que les tremblements de terre à grandes profondeurs au-dessous de la mer du Japon et de l'Amérique du Sud présentent un processus inverse, les blocs inférieurs avançant plus vite vers l'Océan Pacifique que les blocs sus-jacents. Ces faits diagnostiques sont expliqués par le modèle géomécanique des méga-ondations.

(3) Les sites de culmination des méga-ondations se déplacent pendant l'évolution de manière graduelle ou pas à pas. Les effets de ces déplacements sont discutés et illustrés.

(4) On peut distinguer quatre phases d'évolution: méga-ondations en état (a) jeune, (b) précoce, (c) mûr, et (d) fossile. Ces phases d'évolution des méga-ondations sont illustrées par des exemples typiques.

Dans le second chapitre le modèle géomécanique des méga-ondations est éprouvé par l'analyse de l'évolution géotectonique de l'Océan Indien et des continents environnants. Il paraît qu'il y a une bonne correspondance entre les expectations à partir au modèle hypothétique (les prognoses) et les observations géotectoniques (les faits diagnostiques). Ceci vient renforcer notre confiance dans la capacité de fonctionnement du modèle.

On pourra aussi essayer d'éprouver le modèle géomécanique au moyen de la centrifugation de modèles à échelle réduite.

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