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ON MEGA-UNDATIONS: A NEW MODEL FOR THE EARTH'S EVOLUTION

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SUMMARY

Two fundamentally different views on the origin of the sialic crust of the earth are possible. According to one view the sialic crust has been produced from the inside by progressive physico-chemical differentiation of the earth's material into concentric spheres. Such an *endogenic origin of the crust* is supported by most contemporaneous geological theories. According to the other view the crust has been acquired from the outside, shortly after the earth's agglomeration, as an outer layer of more acid satellitic material. This *exogenic origin of the crust* is suggested by Berlage's theory on the origin of the planetary system.

In this paper it is attempted to test Berlage's astronomical theory by means of geonomical facts. It appears that the postulate of the acquisition of the crustal matter from the outside leads to a satisfactory theoretical model of the earth's evolution.

Three major phases can be distinguished:

(I) The *acquisition* of an acid layer from without.

(II) Its *transformation*.

(III) Its *incorporation* (see Fig.1).

An important aspect of this model is that it provides a synthesis of the two main trends in the geological thought of our time, the fixistic concepts (recently represented, for example, by Subbotin et al., 1965a,b,c), and the mobilistic concepts (recently represented, for example, by Blackett et al., 1965).

This synthesis is obtained by means of the *relativistic principle* in the analysis of the crustal movements and deformations. The effects of the causative mass displacements at various depths, and occurring at various times, are superimposed on each other. The processes in depth produce in combination the structural phenomena observable at the surface.

The Alpine cycle of orogeny is analysed according to this relativistic principle (Fig.3). The influence of mega-, geo- and meso-undations can be distinguished. The mega-undations are generated in the lower mantle. They cause the "Tethys-Twist" and the continental drift, which is accompanied by mega-shears and the formation of new ocean basins (Atlantic type of oceanization). The geo-undations are related to physico-chemical processes, which occur in the upper part of the upper mantle (the asthenosphere). They

result in the formation of eugeosynclines, accompanied by ophiolitic magmatism (the eugeosynclinal phase).

Thereafter, centres of orogeny are formed in the geosynclinal area by subcrustal mass circuits, which corrode the crust from beneath (Mediterranean type of oceanization). By this penetrative type of convection, the overlying crustal matter (covered by geosynclinal sediments) is rafted outward from these centres. Meanwhile migmatized sialic matter is injected sidewards into the flysch foredeeps. This tectogenesis produces nappe structures of East Alpine and Pennine character (flysch phase).

Finally, an isostatic equilibration of the matter that accumulated in the foredeeps produced meso-undations, namely the uplift of the Alpine mountain ranges and the subsidence of sidedeeps (molasse phase, see Fig.4 and 5).

An analysis of the present picture of the structural features of the earth (Fig.6) confirms the concept that the seemingly opposed mobilistic and fixistic mechanical models should be combined into a synthesis of relativistic character.

During the third phase of the earth's geological evolution (the last half billion years of its history), the sialic crust is progressively incorporated into the upper mantle by means of the Mediterranean type of oceanization. The crustal fragments thereby acquired a greater freedom of movement and they started drifting towards the Pacific area (Pacifico-petal drift), opening new oceanic basins in their wake (the Atlantic type of oceanization).

The expectation of this relativistic model of the earth's evolution appears to conform to the diagnostic data of the post-war geonomic researches, so that this hypothesis deserves further elaboration and testing.

INTRODUCTION

The concept of mega-undations has been introduced by the author (Van Bemmelen, 1964a). It has been elaborated in two papers, the first of which (Van Bemmelen, 1964b) analysed in more detail the evolution of the Atlantic Mega-Undation, and the second one (Van Bemmelen, 1965a) treated the Indian Ocean Mega-Undation. The present paper is the third part of this series. It is attempted in this paper to give a synthetic view of the structural features of the entire surface of the earth, and to discuss the evolution, which led to the present state of our planet. In this new model of the earth's evolution three general concepts are applied, which, up to now, were not or insufficiently taken into account:

(1) *The external origin of the sialic (or continental) crust.*

In a series of papers Berlage (1932, 1948, 1951, 1953, 1954, 1957, 1959, 1962) elaborated a theory on the origin of planets and satellites from discs of nebulous matter. The original disc around the sun evolved into concentric rings, which gave birth to planets. These planets obtained planetary discs of solid particles, which generated satellite rings. This uniform picture of cosmogenesis leads Berlage to the conclusion that the moon was not captured by the earth, but that it belonged to the earth's system from the beginning. However, it appears to be very improbable that a planetary disc is transformed into only one satellite. The earth probably created two moons. One satellite originated just outside Roche's limit and acquired 1/80 of the mass of the earth. This satellite - our present moon - has since increased its orbit to the present distance by means of the tidal forces mechanism, proposed by G.H. Darwin.

The material of a second satellitic ring, with about 1/60 of the earth's mass, formed a dust ring inside Roche's limit. The matter from this potential second moon fell on the earth, giving our planet its angular momentum, and probably also the inclination of its axis of rotation with respect to the ecliptic (Safranov, 1964). The average increase of the earth's radius by this layer of satellitic matter amounts to ca.65 km. The further history of our planet is characterized by the progressive transformation, and incorporation of this layer of satellitic (meteoritic) matter, as will be exposed in this paper.

(2) *The post-Cambrian formation of the simatic (or oceanic) terrestrial surface.*

Modern geonomic researches have led to the conclusion that at present the earth's surface is partly underlain by a continental crust, partly by an oceanic crust. It seems that this has not always been so. De Booy (1966a,b,c,d) stresses the fact, by means of his method of petrographic analyses of the detritus in sediments, that formerly (in pre-Alpine time) the sediments of the earliest stage of geosynclinal subsidence have always been deposited on a sialic basement. Only quite recently in geologic history can we observe the deposition of sediments on a simatic (at least "oceanic") crust, such as the sedimentary fans of Himalayan detritus in the Gulf of Bengal and the Arabian Sea (Heezen and Tharp, 1964).

The present author has discussed some examples of transformation of continental crust into the oceanic or intermediary type, i.e., the Caribbean area in Late Mesozoic time (Van Bemmelen, 1958) and the Gulf of Mexico in Cenozoic time (Van Bemmelen, 1964b, pp.422–423). The concept of "oceanization", introduced by the author (Van Bemmelen, 1958, 1964), will be elaborated in this paper.

(3) *The relativistic analysis of geodynamic processes.*

In the past the various concepts on the structural evolution of the earth were either "fixistic" or "mobilistic". The author (Van Bemmelen, 1962) pointed out that the migrations of mass in the various structural levels of the earth ("Stockwerke", "étages structuraux") add at the surface to a combined pattern of tectogenesis, which can only be mechanically interpreted if analysed according to the principle of relativism.

All migrations of matter by flow or creep occur due to the force of gravity. The generalized concept of gravity tectonics involves the idea that the disturbances of gravitational equilibrium are situated at various depths (see Van Bemmelen, 1964b, fig.2, p.390). Therefore the geodynamic processes, observable at the earth's surface, should be analyzed according to the causative mass displacements at various depths and rates.

This relativistic principle will be applied to the analysis of the geodynamic processes, during the Alpine orogeny and to the analysis of the present structural features of the earth.

THE THREE MAIN PHASES OF THE EARTH'S EVOLUTION

The earth's evolution comprises more than $4.5 \cdot 10^9$ years. In this immensely long time span three major phases can be distinguished (Fig.1).

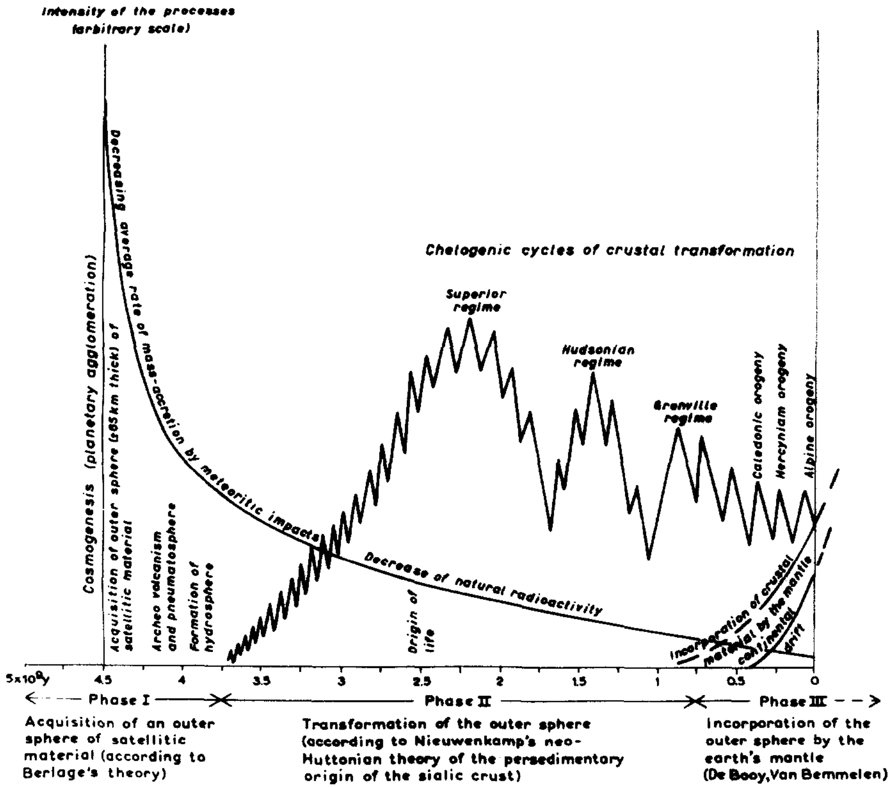

Fig.1. The three main phases of the earth's evolution.

Phase I

The age determinations of the continental shield by means of radioactive isotopes, indicate that a sialic basement complex of metamorphic sediments and granitic rocks already existed some $4 \cdot 10^9$ years ago (Donn et al., 1965). This means that the sialic crust was already present shortly after the formation of our planet, about $4.7 \cdot 10^9$ years ago. Because the chemical segregation of an acid crust from the more basic mantle of the earth would have to be a relatively slow process of magmatic differentiation, this new insight (that the crust is not much younger than the formation of our planet) disqualifies physico-chemical theories of the juvenile origin of the crust from within.

In a recent paper Rittmann (1964) stresses the fact that all magmas known cannot have been derived from one parent magma. Two independent sources have to be accepted: (a) basic (basaltic, simatic) magma suites, and (b) silicic (granitic, sialic) suites.

B.C. King (1965) published some reviews of recent investigations on the nature of basic igneous rocks and their relationship with associated acid rocks. He comes to the conclusion that there was and is simultaneous availability of basic and acid magmas. The coexistence of magmas of contrasting composition without appreciable mixing is not easily understood physicochemically; but it might indicate a different descendent, a contrasting origin of these two different suites.

If the crust were segregated from within by a causally coherent process of chemical differentiation, we should expect only one suite of magma. The presence of two suites might indicate that the simatic series has an internal origin, whereas the sialic suite is derived from extra-terrestrial material, which accumulated on the earth's surface from without.

This possibility has also been suggested by Donn et al. (1965), who consider continental origin by impact of extra-terrestrial material. Moreover, it is consistent with the theory of Berlage that during its evolution our planet had at least two satellitic dust rings.

The outer one, just outside Roche's limit, contracted into the body of our moon, which has a mass of about 1/80 that of the earth. The radius of the moon's orbit increased since its origin; it collected during this outward movement smaller and larger particles and bodies which belonged to the outer parts of the original planetary disc.

The inner satellitic dust ring was formed just inside Roche's limit, so that it could not contract by its own gravitational field into one satellitic body. The inner satellitic ring had about 1/60 of the earth's mass. Its further mechanical evolution caused the gradual decrease of the orbital radius, so that its matter fell on the earth's surface, forming a layer of ca.65 km average thickness.

Though this layer of satellitic matter may originally have been thickest in the equatorial belt of the earth, the subsequent geodynamic evolution will have spread it more evenly over the entire surface of our planet.

Berlage's theory of the origin of our planetary system has a strictly logical mathematical character. It has the advantage that it does not involve hypotheses ad hoc, e.g., highly improbable catastrophic encounters with other celestial bodies, the capturing of the moon by our planet. Moreover, this concept leads to the prognosis, that the earth's hydrosphere probably was also an early product of cosmogenesis, resulting from the ice crystals present in the inner satellitic ring. This consequence is consistent with the geological observation, that the oldest sediments were laid down in water and that most probably the earth's surface was already covered by extensive seas at the end of the initial phase of its evolution.

The first phase of the earth's evolution may have lasted about $1/2–1 \cdot 10^9$ years after the agglomeration of our globe in the centre of a planetary dust disc. Isotopic analyses of xenon give indications that this agglomeration may have been completed in about $1/4 \cdot 10^9$ years (Pepin, 1963). Holmes (1964, p.157) remarks that there is an undated interval of about 1 billion years between the formation of the earth and the age of the oldest rocks known; it is to this time interval that we assign the first main phase of the earth's evolution.

The first phase of the earth's evolution might be characterized as follows: The surface of the central globe was "powdered" by the small particles and larger bodies of an inner satellitic dust ring; this gave the earth its angular momentum, and caused the inclination of its axis of rotation with respect to the ecliptic. Ice crystals occurring in this inner satellitic ring were first molten and evaporated; but the water vapour could not escape the earth's gravitational field, so that it finally rained down, forming a primeval hydrosphere.

Various sources of heat (such as the heat of impact, the liberation of heat by short-life radioactive isotopes, the heat of exothermal chemical reactions between the agglomerated particles, the heat liberated by compaction into high density phases of minerals) will have caused a rise of temperature in the cold primeval earth.

This will have led locally to zone-melting and the formation of magmas. The latter on reaching the surface caused volcanic activity. This archeo-volcanism will have been most intense in the beginning, because the endogenic sources of heat were greatest during this initial phase of the earth's evolution.

It is possible that the water at first formed a thick mantle of clouds, but soon afterwards the rains accumulated the water in the hydrosphere, forming primeval oceans. This hydrosphere covered the greatest part of the earth's surface; only the volcanoes formed by the archeo-volcanism emerged above its surface. Here the first major phase of the earth's evolution ended, and the stage had been set for the second phase.

The geological premise of uniformitarianism[1] of course cannot be applied to the geological processes, occurring during this first phase of the earth's evolution.

Phase II

Hutton (1795) remarked in his "Theory of the Earth" that however far we penetrate into the past, we still can find "no vestige of a beginning". There has been continuously a reworking of the crustal matter.

In our time Hutton's ideas have been revived by Nieuwenkamp (1948, 1949, 1956) in his neo-Huttonian theory on the persedimentary origin of the lithosphere. Nieuwenkamp remarked that the cyclic processes had started already before the "whirligig" was built. There were already oceans with sedimentation and orogenesis, while the rain of meteorites and cosmic dust still caused the accretion of the outer shell of the earth. This rain was almost over in Eo-Archaeic time, some $3 \cdot 10^9$ years ago. But there still is in the present time slow accretion of the earth by the cosmic dust it receives at the rate of ca.3,000 tons/day. However, this would amount to only ca. 1 m increase of radius in 10^9 years.

At the beginning of the second major phase of the earth's evolution the processes of erosion of the oldest volcanic islands (under the influence of solar radiation and rains) and sedimentation (in the surrounding primeval oceans) could start their work, partly dissolving the rock substances and partly accumulating them (as clay minerals enriched in silica and alumina) in the shelves around the islands (Gussow, 1963). The heat flow from within and the rising magmas transformed these sediments into granitic rocks.

The second phase lasted from about $4 \cdot 10^9$ to ca.$0.5 \cdot 10^9$ years ago. During this great stretch of time the sediments were again and again metamorphosed and melted into granitic rocks and then subjected to renewed

[1] The concept of uniformitarianism is used here in its "substantive" sense, as a testable proposition asserting constancy of rates of change or material conditions through time; and not in its "methodological" sense, asserting the spatial and temporal invariance of laws describing the operation of natures processes, according to the immanent properties of the matter concerned. (See Gould, 1965).

erosion. These cycles of metamorphism and palingenesis were accompanied by geodynamic phenomena, such as the folding of sediments and diapirism of granitic magmas (Wegmann, 1930).

This reworking of rocks was largely restricted to the outer layer of satellitic matter. The neo-Huttonian cycles consolidated large parts of this layer into cratons or shields of sialic matter. Sutton (1963) proposed the name of "chelogenic" (shield-forming) cycles for the major phases of crustal consolidation. Dearnly (1965a) distinguishes three major groups: The Superior Regime (> 2750–1950 $\cdot 10^6$ years), the Hudsonian Regime (1950–1075 $\cdot 10^6$ years) and the Grenville Regime (1075 $\cdot 10^6$ years–Present). This author is of the opinion that the distribution and the truncations of the ancient fold-belts indicate that they were formed prior to continental drift; they provide strong evidence for the reconstructions of the continental positions at the beginning of the third phase (e.g., du Toit's, 1937, reconstruction in "Our Wandering Continents").

This neo-Huttonian type of evolution created continental (cratonic) areas, separated by still mobile geosynclinal belts. The extent of the continental shields increased, and that of the mobile belts decreased.

At the end of the Precambrian the continental nuclei were welded together, forming large primeval continents, such as Gondwana and Laurasia. These two super-continents may have been united into a still greater continental area, a kind of "Pangea". At the surface the continental areas were still largely flooded by seas.

At their base, beneath the Moho discontinuity, the sialic matter may have been present in the form of high-density phases, which may have reached depths of several hundreds of kilometers in the upper mantle because of their strive for isostatic equilibrium.

There is one main characteristic feature, which distinguishes the second phase of the evolution of the earth from the third one: The reworking and the recycling of the crustal matter in the outer layer was almost entirely restricted to the layer of more acid satellitic matter, acquired by the earth at the beginning of phase I. Additions of more basic (simatic) matter from the underlying mantle were only of minor importance. Initially, at the beginning of the accumulation of sequences of sedimentary strata, the floor of the seas of the mobile geosynclinal belts was always of the sialic type. No instances of the initial deposition of geosynclinal sediments on an oceanic ("or simatic") crustal floor are known from Precambrian times (De Booy, 1966(

Subsidence, the accumulation of thick piles of sediments, was not always followed by orogenesis, as is thought by theories on geosynclinal evolution. According to Furon (1964) many instances of non-metamorphic and non-folded accumulations of thick Precambrian sediments are known, for instance the 8,000–20,000 m thick Sinian deposits in the southern part of Manchuria, and the nearly 10,000 m thick Beltian deposits in North America (especially in Montana and Idaho). The occurrence of orogenesis accompanied by metamorphism, plutonism and volcanism evidently did not depend on the thickness of the sedimentary epiderm on top; but it was determined by the regional intensity of the heat flow from depth, which was accompanied by the intrusion of granitic magmas.

The crust was occasionally invaded by basaltic dike-swarms and basalt outflows (diabase formations), but it is questionable whether these are equivalent to the floodbasalts of post-Cambrian time of phase III. These manifestations of the basic (simatic) material underneath the sialic crust rarely or perhaps never reached the stage, that the overlying sialic crust was entirely destroyed and swallowed up, subsiding into the mantle under the weight of the intrusion and extrusion of juvenile basalt magma.

These Precambrian diabase formations were probably deposited on land or in shallow seas, so they cannot be compared with the basalt outflows and ultrabasic intrusions of the ophiolitic magmatism at the end of the Alpine geosynclinal subsidence, which occurred on the floor of deep-sea trenches.

Manifestations of basic to ultrabasic magmas rising from the upper mantle into the crust were in Precambrian time less frequent and less important than the granitic magmatic activity.

There are indeed some notorious exceptions to this rule; namely, there are places where the basic to ultrabasic mantle material has pierced the crust in great bulk, such as the Bushveld in South Africa (age about 1950 $\pm 150 \cdot 10^6$ years) and other great basic to ultrabasic plutonic bodies (like Duluth and Muskox in Canada, age about $1100 \cdot 10^6$ years). But these are rather exceptions. Perhaps Dietz (1963) is correct, interpreting them as "astroblemes", as huge scars in the sialic crust, caused by the impact of great bodies (e.g., asteroids).

The objection made by Bucher (1963) that there is a distinct relation between the location of the "astroblemes" and the regional geology might be countered by the remark, that the after-effects of such huge concentrations of impact energy will have influenced the following geological history of a region for many millions of years[1]. The subsequent structural and volcanic features of large areas will have been determined for the greater part by the after-effects of such impacts (Van Bemmelen, 1964a, pp.33–34). Why should only the moon have been hit occasionally by large fragments of celestial bodies, and not the earth also in the course of its 4 1/2 billion years of existence?

According to Faure et al. (1963) the age of the Great Dyke is comparable to that of Bushfeld, within the limit of error, i.e., $2110 \pm 350 \cdot 10^6$ years. This correspondence of age might indicate that the whole complex of major geological features in the oldest part of South Africa (Trompsberg–Vredefort–Bushveld–Great Dyke) is a genetically coherent geotectonic feature. In that case the whole complex is either the result of endogenic energy, which created at mutual distances of hundreds of kilometers interdependent rises of diapiric columns of juvenile magmas from depth; or the energy might have an extraterrestrial origin, the ascending magmas being the after-effects of the impact of a swarm of huge celestial bodies, planetoids (asteroids). According to the present author the hypothesis of external origin gives a more logical explanation for the above mentioned contemporaneity than the hypothesis that these geodynamic processes originated from within by means of some miraculously synchronous mechanism of physico-chemical processes in the (outer) mantle. Does not the Rand Basin with its central Vredefort Dome show a remarkable resemblance to a moon crater with a central uplift?

[1] Bucher's argument against the impact theory that the geological position is unique has been conclusively countered for by the Riescaldera, the meteoric origin of which has been proven by Hörz (1965) and others.

Phase III

In the course of the latest $0.5 \cdot 10^9$ years of the earth's evolution some important new features have come to the fore. This implies that the geological postulate of (substantive) uniformitarianism is applicable only to the last part of this third phase of geological evolution. De Booy (1966a,b,c,d) draws attention to the following facts:

(1) Before the Mesozoic no examples are known that sediments were deposited on an oceanic crust, like the Himalayan molasse, which now spreads into the Gulf of Bengal and the Arabian Sea.

(2) Before the Mesozoic no examples are known that basic and ultrabasic magma's poured out on the floor of deep sea trenches, like the ophiolites of the Alpine eugeosynclinal belts.

(3) Before the younger Paleozoic no typical flood basalts are known, like the Siberian traps, the South African Karroo Basalts and the Indian Deccan traps.

This indicates some fundamental changes in the sial–sima regime during the latest $3 \cdot 10^8$ years. First basaltic magma began to pierce the continental crust along dike-swarms (which indicate tension), and it poured out voluminously, flooding the sialic crust with plateau basalts. Then deep trenches were formed in the mobile belts of the Alpine system, where basic to ultra-basic magmas reached the sea-floor, forming pillow lavas and other outflows without pores (because of the high pressure of the overlying water columns). Finally parts of the continental crust are progressively transformed into areas with crusts of the oceanic type (Illies, 1965a). Such "oceanizations" have been described by the author from the Caribbean Sea (Van Bemmelen, 1958) and by Beloussov and Ruditch (1961) from the Japan Sea. The reality of the "en bloc" collapse of large formerly continental segments of the western Pacific marginal seas (from Okhotsk to the Coral Sea) was pointed out already by Fairbridge (1950, 1961). For the Indonesian area (Banda Sea) it has been described by the author (Van Bemmelen, 1949). For the western end of the Mediterranean the author came to a similar conclusion (Van Bemmelen, 1952). Yemel'yanow et al. (1964) remark that the sialic crust is absent in various parts of the Mediterranean. The collapse of the Thyrrenan centre of orogeny in Late Cenozoic time is a classical example of such an oceanization.

The problem of oceanization has been discussed by Stille (1948, 1958), Van Bemmelen (1957, 1958), Beloussov (1962), Glangeaud (1962), Fairbridge (1965), and others.

It is a formidable geochemical and petrological problem because it involves the removal of 30–40 km of sialic crust and its replacement by simatic matter. Nevertheless the diagnositic geological facts are too solid to deny them. The depth of the Moho discontinuity is not a permanent feature (Van Bemmelen, 1958, 1964b, p.422).

Kushiro and Yoder (1964) draw attention to the fact that the density change of the basalt (or gabbro) - eclogite transformation is gradual. Therefore a sharp change in the velocity of the seismic waves would not be expected. It seems unlikely that the Moho itself can be attributed to such transitions. If the Moho moves up and down, we have to accept migrations of matter of different chemical composition.

The "basaltic" composition of the crustal matter between the Moho and the Conrad discontinuities, still tacitly accepted by Subbotin et al. (1965a,b,c), is nowadays seriously questioned. Den Tex (1965) supposes that the higher density in the lower part of the crust can also be the result of the highly metamorphic state and mineral paragenesis of the more acid sialic matter (gneisses). It need not always have a basaltic or gabbroic composition.

If we accept the postulate that the Moho discontinuity is the result of a contrast of chemical composition and not of a phase-transition, then there are several theoretical possibilities for changes in the crustal thickness:

(a) Removal of material from the top by erosion and tectonic decollement (e.g., Van Bemmelen, 1960; Hsu, 1965).

(b) Removal of material from the base by subcrustal erosion (e.g., Gilluly, 1955; Gidon, 1963, 1965).

(c) Tectonic stretching or compression (e.g., Heezen, 1960; Holmes, 1964, fig.798, p.1100).

(d) Moreover, the average chemical composition of the crust can be changed by the intrusion and extrusion of more basic magmas ("basification") of the crust (e.g., Van Bemmelen, 1958, 1961; Beloussov, 1962).

If no tectogenesis or volcanism accompanies the removal of crustal matter (such as is the case in the Black Sea area), then only the second possibility seems to give a solution.

Perhaps the following model might provide an acceptable working hypothesis for the process of oceanization in such a region, i.e., the replacement of sial by sima, due to corrosion from below.

Basaltic magma can probably be segregated by the upper mantle. This magma will migrate upwards because its density is lower than that of the surrounding parent material. On reaching the Moho discontinuity, however, the further ascent is impeded by the overlying sialic layer of lower density. Having a relatively high temperature this superheated basalt will cause a partial melting, migmatization and mobilization of the base of the sial layer. In the further stages of this process the cooling basaltic magma, together with the mobilized sialic matter, will flow off sidewards, being replaced from underneath by fresh supplies of hot basalt magma.

In this way a corrosion of the crust will occur by a circuit of mantle matter reaching down to about 200 km depth. Such circuits may have various forms, depending on the rheidity of the matter concerned. The sideward flow may follow the base of the crust. Cooling may produce a reconsolidation of the migmatites and magmas of basic and acid composition at the crustal base. In that case the crustal thinning above the top of the circuit would be accompanied by a crustal thickening in the adjacent areas.

However, it is also possible that the spreading top of the circuit bends downwards, taking the mobilized acid matter with it towards greater depths, where it will pass (with the basalt) into high-density phases, which have no tendency to reascend. In that case the upward flow of hot basalt magma will really remove the sial and "burn" holes of various extent into the sialic crust.

This process of oceanization seems to occur in such areas as the marginal sea basins along the western side of the Pacific, in the Caribbean area, the Gulf of Mexico, the Mediterranean. It is a physico-chemical corrosion of the crust caused by circuits in the upper part of the upper mantle (the asthenosphere).

This type of oceanization has another mechanism than the formation of new ocean basins, like the Atlantic and Indian Oceans. These new oceans probably result from a gravitational decollement of the sialic cover, due to mega-undatory uplifts (Van Bemmelen, 1964a,b,c, 1965a,b). The corresponding circuits of matter reach to much greater depths, down to the lower mantle. The oceanization in the Caribbean area, however, was a physico-chemical process caused by the upper mantle.

At this stage of our considerations concerning the problem of the distribution of the continental and the oceanic type of crust, the following major question has to be posed: Was the Pacific Ocean always an ocean, a primeval ocean, surrounded by the continental crust of Gondwana and Laurasia? Or did it also once have a sialic crust, which was subsequently destroyed and removed by sima corrosion? Several arguments might be advanced in favour of the latter supposition. As far as we know it has no old detrital sediments, as it should have, if it was always surrounded by continental areas of great age. If we no longer consider the Pacific Ocean as the scar of the moon, torn from its side, this fundamental asymmetry of the earth's surface is difficult to explain (Carey, 1963).

If we accept Berlage's theory, that the earth's surface was covered by satellitic matter at an early stage of its history, then a more even distribution of the sialic crust should be expected. We should then distinguish three major areas of sialic crust, largely covered by more or less shallow seas, namely Laurasia, Gondwana, and "Pacifica". The removal and the digestion of the sialic crust of Pacifica would then merely be in a more advanced state than the physico-chemical oceanization in its marginal realms and in the Tethys zone between Laurasia and Gondwana. We might even say that this early removal of the sialic crust from Pacifica had provided the continental fragments of Laurasia and Gondwana with greater liberty for their sideward drifting movements, which process is so characteristic for the third phase of the earth's evolution.

The alternative solution is, that the central part of the Pacific originally was a primeval ocean, and that the marginal parts were partly continental and partly oceanic receptacles with detrital sediments derived from the surrounding continents; thereafter these marginal zones have been overridden by the Pacific-petal drift of the surrounding shields. The water of the Pacific Ocean, which was expelled by the restriction of its area, filled the newly formed Atlantic and Indian Oceans in the wake of these drifting continents.

The general conclusion of this chapter is that the earth's history can be divided into three major phases: (I) The acquisition of an outer sphere composed of satellitic matter; (II) the transformation of this sphere, and (III) its incorporation. This new model of the earth's evolution is used as basic concept for the analysis of its structural features in the following sections.

THE RELATIVISTIC CONCEPT OF STRUCTURAL EVOLUTION

Geology is still a young science in the full bloom of its evolution. It has not yet completely settled upon basic principles. Of course, the general laws of the physico-chemical behaviour of matter are also valid for the material of which our planet consists. They represent the *immanent properties* of its matter (Auger, 1963; Simpson, 1963). But the processes causing the evolution of the earth are so complex that geoscientists could not yet agree on a general historical outline, which represents the *contingencies* of the earth's evolution.

At first the limited frame of the observations of the field geologists allowed them to explain the structural features only by mechanical processes of restricted extent. Their models reached neither deep nor far. For the earth as a whole a simple model sufficed, namely the theory of contraction due to cooling, which caused a wrinkling skin, like that of a dissicating apple. Thus the geologists of this older period used "fixistic" models for the explanation of the structural evolution.

However, the accumulating geological data, spreading over the entire surface of the earth, led to conflicting views, when the models for the regional interpretations were compared. The nappes of the Alps, recognized at the beginning of the twentieth century, needed mechanical explanations which also involved the adjacent regions. Paleoclimatological environments indicated very different distributions of the climatic belts in the past.

The Alpine and circum-Pacific mountain belts, the parallelism between the coast lines of some continental shields, the volcanic and seismic belts - all these features appeared to be of such a great extent, that their explanation demanded mechanical models which reached far beyond the direct observations of the field geologists. For a long time, therefore, scientists pondered on their solution (e.g., Bacon in 1620; Placet in 1668; Von Humboldt in 1800; Snider in 1860). These studies led to some interesting "mobilistic" concepts on the origin of the earth's features (Taylor in 1910; Wegener in 1912).

There was a very strong opposition against continental drift by geophysicists and stratigraphers (e.g., Schuchert). The latter tried to explain faunal relations by bridges (isthmian links) and lost continents (Appalachia, Lemuria, etc.).

The present author tried to find an intermediary solution by means of his "undation theory". This geodynamic concept distinguishes between differential vertical movements of the earth's surface, due to mass-displacements in depth (primary tectogenesis), and gravitational reactions which strives for a reduction or elimination of the accumulated potential energy (secondary tectogenesis).

Large horizontal displacements of nappes, such as the East Alpine Nappes in Europe and the Djambi Nappes in Sumatra, were explained by the sideward shift of the undatory uplift (see Holmes, 1964, fig.820, 821, pp.1140-1144). These views could still be considered to be more or less fixistic because the postulated mass displacements in depth could be restricted to the tectonosphere s.str., i.e., to the outer 100 km of the earth. The mechanical influence of these migrations of mass did not surpass the regional limits.

However, the post-war developments of the geo-sciences indicate more and more that also great lateral movements of vast crustal shields have to be taken into account. No traces have been found of the disappeared land bridges or the engulfed continents. Instead, many transcurrent faults with off-sets of hundreds of kilometers are now recognized. The amazing youth of the ocean floors becomes more and more apparent. The paleomagnetic data of the continental shields indicate that important translations and rotations have to be applied before the paleo-isoclines form the consistent pattern of the magnetic dipolar fields for the periods concerned. All these diagnostic data strongly confirm that the mobilistic concepts have a great deal of truth in them.

Bullard (1964) writes in his concluding remarks to the symposium on continental drift of the Royal Society in London that "nearly all speakers concerned with the evidence derived from comparison of the continents and from paleomagnetism, have interpreted their results in terms of movements of the continents". On the other hand, the ignoring of and arguments against continental drift are still so severe that Beloussov (1962, 1965, 1966), Subbotin et al. (1965) and Carr (1966) still do not believe in the existence of major lateral flow and tangential movements of extensive crustal shields.

The way out of this controversy between mobilism and fixism - recently represented by the contributions to the London Symposium on continental drift (Blackett et al., 1965, Bullard et al., 1965 and Runcorn, 1965), and by the contributions to the special issue of *Tectonophysics* on the upper mantle and its relation to crustal structure (Subbotin et al., 1965a,b,c) - can be found by means of a relativistic analysis of the geodynamic processes (Van Bemmelen, 1962, 1964a,b,c, 1965a,b). The mass-displacements, causing the structural features of the earth, are the integrated result of geodynamic processes at various depths. Distinction has to be made between several components of the movements. For the mechanical explanation of the geodynamic process it is not sufficient to use a merely fixistic model or a merely mobilistic one.

Fixistic mechanical models may be sufficient for the field geologists with their regional framework of observations and interpretations, whereas for geonomists with their global field of reference the explanation of the observations needs more mobilistic models. This situation bears some analogy to the problems of geometry, which can be explained on the basis of the Euclidean premises when applied to structures of restricted extent; but other geometrical postulates have to be applied for the study of structures on a global or universal scale.

If there is continental drift, then the mechanical model for the explanation of the drift cannot be used unmodified, without a further elaboration of the explanation of geodynamic phenomena on a much smaller scale. There is no simple mechanical coupling between the geotectonic movements of continental drift and the tectonic deformations of restricted areas; though this is often implicitly suggested by protagonists of the theory of convection currents. There are important shifts in the time of the occurrence of the more or less continuous continental drift and of the more spasmodic regional orogenies. It is this time factor, this historical aspect, which induces the geologists to accept a more complicated chain of processes. The endogenic energy can be transformed and temporarily stocked at various levels into different types of potential energy. These buffers in the release of endogenic energy will result in reactions which are delayed many tens of million years. This time factor of the evolution is often underestimated by less geologically and more physically trained geonomists. The latter generally prefer coherent mechanical models of convection currents and their dragging or pushing of the crust, whereas the more physico-chemically trained geologists realize more readily the presence of intervening buffer phases in the release of endogenic energy. A draft of this complicated chain reaction of the earth's evolution has been outlined by the author (Van Bemmelen, 1964c, table IV).

The relativistic concept of "Stockwerk" tectonics (Van Bemmelen, 1962, 1964c, 1966b) is an elaboration of similar thoughts, put forward by Wegmann in a series of papers spread over a life time (Wegmann, 1930, 1947, 1951, 1953, 1955, 1956, 1965).

The following components of the geodynamic processes can be distinguished:

(1) Drift movements of crustal shields with respect to other parts of the earth's surface, related with physico-chemical processes in the lower mantle (mega-undations).

(2) Differential vertical movements of continental extent (geosynclines, geotumors, platform rises and subsidences), related with physico-chemical processes in the upper mantle (geo-undations).

(3) Lateral displacements of smaller crustal units, flow movements and mushrooming diapirism of the migmatitic base of the crust, related to physico-chemical processes in the upper part of the upper mantle, called asthenosphere (foci of orogenesis).

(4) Formation of mountain systems and island arcs, related to mass-circuits in the crust or tectonosphere s.str. (meso-undations).

(5) Formation of epidermal structures due to more restricted uplifts accompanied by downslope folding and thrusting. This type of geodynamic process is related to migrations of matter inside the underlying, more competent crystalline basement complex, such as the diapiric emplacement of batholiths (minor-undations).

(6) Deformations of the sedimentary skin by migrations of matter inside this epiderm of the solid earth, such as selective plastic flow of sediments, halokinesis, laccolithic intrusions of magma (local undations).

The relativistic analysis of the geodynamic processes leads to the distinction of various structural levels ("Stockwerke", "étages structuraux) down to great depth. Not only a "super-structure" and "infra-structure" (De Sitter and Zwart, 1960), not only the epiderm, mesoderm and bathyderm (Van Bemmelen, 1954; Aubouin, 1965), but also the upper mantle (with an asthenospheric upper part and a sclerospheric lower part) and even the lower mantle are of importance for the development of the structural features at the earth's surface.

THE ALPINE CYCLE OF OROGENY

In the section on the three main phases of the earth's evolution it has been pointed out that the geological premise of uniformitarianism cannot be fully applied for the first and second major phases of the earth's evolution.

Fundamental changes in the character of the geodynamic processes did occur in the past. Therefore, if we want to study the mechanism of orogenesis, we should at first restrict ourselves to the youngest orogenic cycle, which produced the Alpine Mountain system. The rules and laws of mountain building, the theory of geosynclines, the character and distribution of the volcanic activity, the features of the oceans, - these and other aspects of the geological evolution may be extrapolated backward to not more than some $3 \cdot 10^8$ years in the past without due closer testing. Even for the Hercynian and Caledonian orogenies the general circumstances and the course of events may have differed greatly from those of the Alpine cycle of mountain building.

Therefore - to be on the safe side - we shall first try to apply the relativistic concept, outlined in the preceding section, to the post-Carboniferous Alpine cycle of orogeny. In order to do this the initial situation should be reconstructed. Thereafter, an analysis has to be made of the geodynamic processes which led to the structural features of the present.

The reconstruction of the initial situation is already a very difficult task. Many authors have applied mobilistic concepts, only insufficiently testing them with the diagnostic facts of the local or regional geology.

We even do not know with certainty whether there was a primeval Pacific Ocean or a ubiquitous sialic crust covered by more or less shallow seas. De Booy's (1966b) analysis of the detrital components of sediments indicates that - as far as we know - the sediments laid down at the beginning of a period of geosynclinal subsidence were always deposited on a sialic basement complex. There was, for instance, no wide oceanic area with a simatic floor in the eastern part of the Tethys, as indicated by several reconstructions (Wilson, 1963; Van Hilten, 1964; Wunderlich, 1964). Jongmans (1940, 1941) remarked that the east Asiatic *Cathaysia* flora is mixed with the Australian *Glossopteris* flora in New Guinea (see Van Bemmelen, 1949, Vol.IA, pp.62, 701).

It seems that the classical reassembly by Wegener (1920) of the continents for the Late Carboniferous still is a rather good attempt for such a reconstruction. It may be crude in its outlines, but it more or less satisfies the test of the paleoclimatological data (the distribution of the Permo-Carboniferous glaciations and of the other paleoclimatic belts of Laurasia and Gondwana: Köppen and Wegener, 1924). Moreover, this reconstruction puts the Indian east coast along the Australian west coast, as is confirmed by Ahmad (1961); this is, for instance, not the case in Du Toit's (1937) reconstruction.

So we prefer to use the figure of Wegener (1920, fig.23, p.61) as our starting point, suggesting, however, the following two major alterations: (1) The distinction of "Pacifica", and (2) the operation "Tethys Twist" (Fig.2).

(Ad.1) It is supposed, according to Berlage's theory, that the entire earth was initially enveloped by a layer of satellitic material, which was transformed into a sialic crust, locally thick and of cratonic character, elsewhere thinner, more mobile and covered by seas. Three major crustal areas are distinguished: (1) Laurasia and (2) Gondwana in which the major cratonic shields of the present day continents were grouped; and (3) Pacifica, which may have consisted of thinner parts of the sialic crust, covered by seas (see also the section on the present structural features of the earth).

(Ad.2) The *operation "Tethys Twist"* has been applied to Wegener's reassembly, as suggested by Van Hilten (1964, p.50). Van Hilten remarked that gathering all continents into two separate blocks (Gondwana and Laurasia) rather than a single Pangaea, appeared necessary to prevent superposition of parts of these continental blocks, which would otherwise have occurred in Permian and Early Mesozoic time, according to paleomagnetic evidence. The character of the shearing between these blocks is evidenced by many dextral strike-slip faults found in the Tethys shear zone (Pavoni, 1961, 1962, Ashgirei, 1962). De Boer's (1963, 1965) paleomagnetic record of the Vicentinian southern Alps indicates that this area originally formed a part of Africa (from Permian up to Eocene time), and that it rotated with Africa anti-clockwise about 50° around the Late Paleozoic South Pole.

In Van Hilten's (1964) reconstruction of the Late Paleozoic

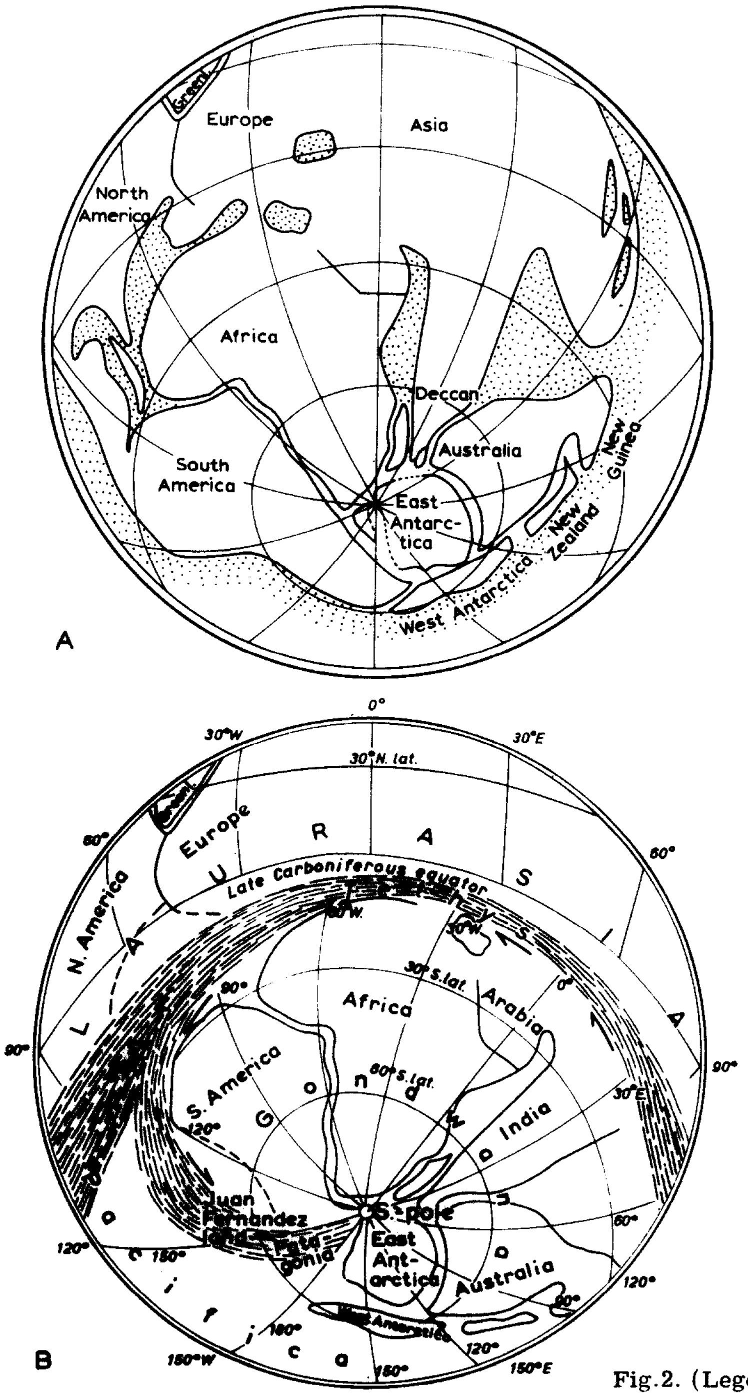

Fig.2. (Legend see p.99).

paleogeography the eastern part of the Tethys zone shows a wide oceanic area. This does not conform to De Booy's findings and the mixing in New Guinea of the Chinese *Cataysia* and Australian *Glossopteris* florae. Therefore we prefer to accept the presence in Late Carboniferous time of a more or less continuous sialic crust, which extended from Gondwana to Laurasia. This crust has been deformed plastically by the Tethys Twist, the dextral shear faults being only discontinuities in a wide belt of more or less plastic torsional deformations. This process of deformation of the basement complex was accompanied by geosynclinal subsidence and the sedimentation of the Permo–Mesozoic geosynclinal deposits. It is very difficult to find traces of this torsional deformation of the basement complex in the facies of the Alpine sequence on its top. During the Permo–Triassic the connection between the Laurasiatic and Gondwana sialic crusts were probably never entirely severed by wide, interjacent stretches of simatic oceans. Later on, however, in younger Mesozoic and Cenozoic time, the process of Mediterranean oceanization (to be discussed later) probably destroyed extensive source areas of the sedimental detritus. These source areas were situated not only along the margins, but they also formed median masses which emerged from the Tethys sea. Therefore it will be hardly possible to prove or to disprove the Tethys Twist by means of De Booy's method of detritus analysis. Geotectonic and paleomagnetic researches seem to be more appropriate in this respect.

In order to get some idea of the original paleogeographic situation in Late Paleozoic time which satisfies the geological as well as the paleomagnetical data, we rotated Wegener's Gondwana reassembly clockwise some 50° around the Late Paleozoic South Pole. The position of this South Pole according to Wegener differs somewhat from the position accepted by Van Hilten (1964) on account of paleomagnetic data. But this is not significant for the operation "Tethys Twist".

The torsional anti-clockwise rotation of Gondwana after Late Carboniferous does not interfere with the paleoclimatic zones, according to Köppen and Wegener (1924).

Paleogeographically, this operation "Tethys Twist" brings northern Africa into a more central position opposite Eurasia. In this position, the Mauretanides, extending at present along the northwestern margin of Africa, do not represent the counterpart of the Appalachian system along the eastern margin of North America, as was suggested by Soughy (1962). The Mauretanides were situated in Late Carboniferous time probably opposite Asia Minor. Instead, the Caribbean area and the present north coast of South America were situated more or less opposite to the present east coast of North America. This position is not in disagreement with the recent analysis of our paleogeographic knowledge of the Central American and Caribbean area by Weyl (1965). This Caribbean area might represent the westward extension of the Mediterranean Tethys zone.

The present fit between the coast lines of northwestern Africa and

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Fig.2. A. Reassembly of the continents in Late Carboniferous time, according to Wegener (1920). B. Reassembly of the continents in Late Carboniferous time after applying to it the "Tethys-Twist", according to Van Hilten (1964).

eastern America, established by Bullard et al. (1965, fig.8), can be explained in two ways[1]:

(1) It is the result of the drifting part of North America and northwestern Africa, more or less at right angles to their present coast lines, similar to the parallelism between the coast lines of South America and Africa.

(2) Or this parallelism is the result of the dextral shear in the Tethys zone in Permo–Triassic time, which brought northwestern Africa opposite to the east coast of North America: only later, in younger Mesozoic time, was this section of the shear belt widened by the second phase of the Atlantic Mega-Undation (Van Bemmelen, 1964b). The second solution is preferred in this paper. Illies (1965a) also reaches the conclusion that the rifting of the Paleozoic continents followed preferentially old lineaments that had previously acted as wrench faults.

The paleomagnetic data indicate that Spain was a sliver block between Europe and Africa and that it came into its present position due to the westward drift (De Boer, 1963, 1965). Therefore, we did not distinguish in Fig.2B the position of Spain before the Tethys shear.

The "Tethys Twist" also explains the zoogeographic isolation of the Australian continent with respect to the distribution of the tetrapodes. Teichert (1958) writes: "Absence of important stegocephalian and reptilian land fauna in continental deposits of Late Paleozoic and Mesozoic age is regarded as a further evidence of Australia's early isolation as a continent". Westoll (1965, p.19) writes in relation to the fauna of the Karroo Beds: "Elements of similar faunas (*Lystrosaurus*, *Thecodont*, *Archosaurus*) are found in India, but are surprisingly absent or rare in Australia".

In Late Paleozoic time the Australian part of Gondwanaland could only be reached over land, across the glaciated South Pole area. At its other side it bordered on the Pacific Ocean. During the Tethys Twist in Permo–Triassic time it was brought closer to southeastern Asia, but it was still separated from Laurasia by the Tethys shear-belt, a mobile zone of islands and sea-straights. The younger Mesozoic and Cenozoic drift movements caused a renewed isolation, by the widening of the Indian Ocean at its rear side, whereas the Indonesian area was continuously an archipelago with a rapidly changing relief.

In the preceding papers on mega-undations (Van Bemmelen, 1964b, 1965a) the author came to the conclusion, based largely on geotectonic evidence, that the Atlantic and the Indian Ocean Mega-Undations both started in Permo–Triassic time, in an area situated somewhere southeast of South Africa (see Fig.6). The i_0- and a_0-centres were situated in the neighbourhood of Wegener's South Pole for Late Carboniferous time. Van Hilten (1964), as well as the

[1] A third possibility has recently been suggested by Carr (1966), who tries to explain these geotectonic trendlines from the viewpoint of permanency of continents. But Carr uses for his argumentation a too restricted spread of geonomic data. For instance, the geological knowledge about wrench faults and the paleomagnetic data are left out of the account. However, the history of the mechanical evolution of the earth's crust is so complicated that it can be analysed only when the entire field of earth-sciences is used in testing the possible models; and not only a selection of some of their aspects. Therefore, the explanation of the fit of the coastlines (between North and South America on the one side and Europe on the other) from the standpoint of fixism is not further considered in this paper.

present author (1964b), pointed out that the Southern Hemisphere could have been subjected to either an asymmetric expansion of the earth or the formation of a mega-undation. This would result in a state of torsional stresses because the southern bulge tended to rotate more slowly. Finally a belt of dextral shear would come into existence between Gondwana and Laurasia. This belt of dextral shear is indicated schematically on Fig.2B.

The southern bulge of the earth will have developed gradually and we cannot expect that the surrounding shear zone immediately had its maximum diameter. If a bulge originated in the neighbourhood of the Late Paleozoic South Pole, it is probable that its growth caused a torsional strain with dextral shear movements in a belt, which developed from the centre of the growing bulge outward like a *spiral*, until the maximum diameter was attained; finally the shearing occurred all along a circular zone, parallel to the equator.

This postulate or "prognosis", derived from the mechanical model, fits remarkably well with "diagnostic data", obtained by recent geonomic researches. Menard and others distinguish in the southeastern Pacific a system of rises, partly parallel to the East Pacific Rise, which they call the "Galapagos Rise" (Menard et al., 1964, Menard, 1965). This structural feature of the earth's surface extends in a semi-circuilar way from Panama along the Galapagos Islands to the Easter Island fracture zone. After a considerable sinistral offset by the latter, its course continues along the Chile Rise till its crest reaches South America at about 40° lat. The northwestern–southeastern structural grain of the Patagonides in the southern tip of South America might be the result of the Tethys Twist, which may have started in the i_0–a_0 area, southeast of South Africa (Fig.2B; see also Fig.6).

According to the way the Patagonides are cut off obliquely along the present coast line, Illies (1960) postulates that the southeastern Pacific, off the west coast of Southern Chile could not have been a primeval ocean. He supposes the presence of a lost continent, which he calls the "Juan Fernandez Land". This continental area has disappeared since then and now an oceanic crust is present, as was established by modern oceanographic researches.

The volcanic porphyrite formation of Jurassic–Lower Cretaceous age, along the west coast of Chile might be related to the volcanic intrusions and extrusions which accompanied the basification and ultimately to oceanization of this Juan Fernandez Land. We will return to this problem in the section on the present structural features of the earth. For the analysis of the course of the Tethys shear-belt the foregoing preliminary discussion may suffice. Paleomagnetic data indicate that the Tethys zone, from which the Alpine Mountain system arose, began in Permo–Triassic time as a huge dextral shear zone. Geotectonic and oceanographic data indicate that this shear zone developed progressively around a mega-undatory bulging up of Gondwanaland, which had its centre somewhere southeast of South Africa.

We do not yet know whether this bulge of the Southern Hemisphere represented a real expansion of the geoid, or that it was volumetrically compensated by the subsidence of surrounding belts of the earth's surface. In the latter case the increasing angular momentum of the bulge, and the decreasing angular momentum of the belt of subsidence (which might have coincided with the Tethys belt) would have promoted the torsional effect and the magnitude of the dextral shear in the Tethys zone.

Thereafter, in younger Mesozoic time, an oceanization occurred in some parts of the shear belt (Juan Fernandez Land, Caribbea). The question might be posed, whether this transformation of sialic into simatic areas was restricted to the Tethys zone of shearing, or that this was a more general process.

This type of oceanization took place also along the western margin of the Pacific Ocean and in the Mediterranean area (see also the section on the present structural features of the earth and Fig.8 in that section). Therefore it might even be possible that such a process has been active since Precambrian times in the entire Pacific area, transforming "Pacifica" into the present Pacific Ocean with its simatic crust.

As yet we do not possess enough diagnostic data to answer this question. Perhaps the Mohole will give us more insight into the enigma of the Pacific. But, most probably, the oceanization of the sialic crust in marginal parts of the Pacific and the plastic distortion of the Tethys belt gave the sialic shields, which occupied Gondwanaland, more freedom for an Indico-fugal drift movement. The upbulging of Gondwana gave the sialic crust a tendency to spread under gravity. It became loose and disrupted into some large fragments (Africa, India, Australia, Antarctica). The accompanying tensional strain in the top part of the bulge gave rise to basaltic intrusions and extrusions (Karroo Plateau Basalts).

So, after the initial dextral shear movements in the Tethys zone, this belt was subjected to the compressive action of the spreading Gondwana shields.

During the Permo–Triassic phase of geosynclinal subsidence of the Tethys zone a flow of mechanical energy had been directed into the Tethys and the underlying upper mantle. This energy was temporarily stocked as physico-chemical energy by means of transitions into high-density phases and the isostatic subsidence of the latter. But towards the end of the geosynclinal phase, in Jurassic and Lower Cretaceous time, this energy was partly released by the reheating of the subsiding high-density material and the segregation of basalt magma. This basic magma ascended, having a lower density than its parent matter. On reaching the sialic crust, the overheated basalt magma caused a corrosion and a thinning, or even a complete removal of the sialic crust. This process of oceanization of the sialic crust will be discussed hereafter; but it is mentioned in the present context, because it is another major factor which allowed the Gondwana fragments to spread still more effectively.

The mass circuits in the upper part of the upper mantle, whicn caused this crustal corrosion, also gave rise to the onward rafting of smaller crustal units. At the surface, parts of the geosynclinal zone emerged and adjacent tracts subsided more deeply. This was the flysch phase of the Alpine orogenesis.

Finally the restauration of the isostatic equilibrium in the flysch belts produced the actual Alpine Mountain ranges. This uplift was followed by gravitational reactions of spreading. This is the molasse phase of the Alpine cycle of mountain building.

These tectonic movements of the Alpine system are probably composed of three components of different magnitude and of a different extent of their fields of influence.

(1) *First-order gravitational tectogenesis*. The spreading under gravity of the sialic crust, which was elevated by mega-undations.

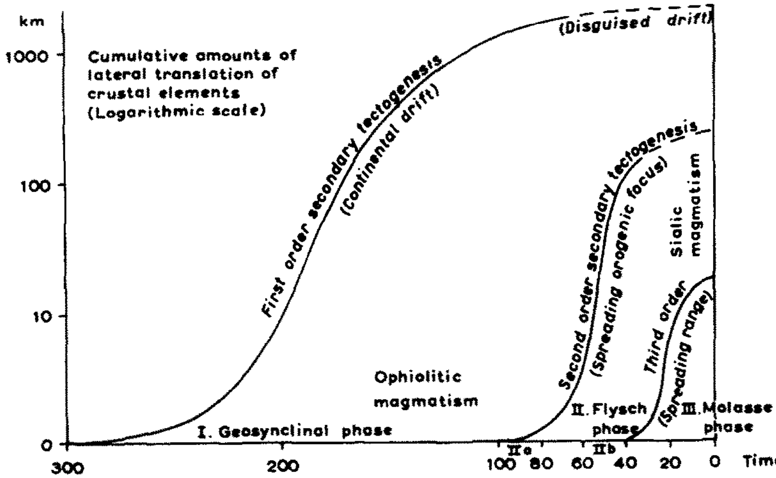


Fig.3. Graphic representation of the relativistic concept of the Alpine orogeny.

(2) *Second-order gravitational tectogenesis*. The rafting of the crustal units by geo-undations inside the geosynclinal belts.

(3) *Third-order gravitational tectogenesis*. The gravitational spreading of meso-undatory uplifts of mountain ranges. These three vectors occurred super-imposed on one another, as is indicated on Fig.3.

The geosynclinal phase (I) was accompanied by transcurrent faulting and continental drift. Towards the end of the geosynclinal phase the regeneration of basaltic magma caused ophiolitic intrusions and extrusions. Around the foci of oceanization flysch troughs were formed, and parts of the basement complex, together with their sedimentary cover, were rafted into these troughs. This is the second major phase of the Alpine orogenesis, called the flysch phase (II).

During the third phase, called Molasse phase (III), the piles of Pennine and East Alpine Nappes, formed during the preceding phase, were elevated isostatically. The palingenic acid magmas, which were present in the deeper Pennine structural units, intruded locally as stocks and small batholiths. These intrusions may also have given rise to external volcanism of calc-alkaline magma suites. The sedimentary cover locally slid from the shoulders of the rising mountain ranges, giving rise to epidermal nappes, which were folded and compressed at their frontal side, whereas stretching and tectonic denudation occurred at their rear side.

Thus the sideward displacement of crustal elements by continental drift (I) can be overshadowed by rafting movements around the foci of mountain building in the geosynclinal zone (II). Later still, the gravitational reactions to the isostatic adjustments (III) may overshadow all other vectors of movement (Fig.3).

These three phases of Alpine orogenesis are illustrated by Fig.4 and 5.

Fig.4 illustrated schematically the development of the Tethys belt between Europe and Africa.

Phase I: At first the torsional stresses between Gondwana and Laurasia caused dextral shear faults and plastic[1] deformations of the interjacent

[1] "Secular plasticity" as defined by Wunderlich (1965).

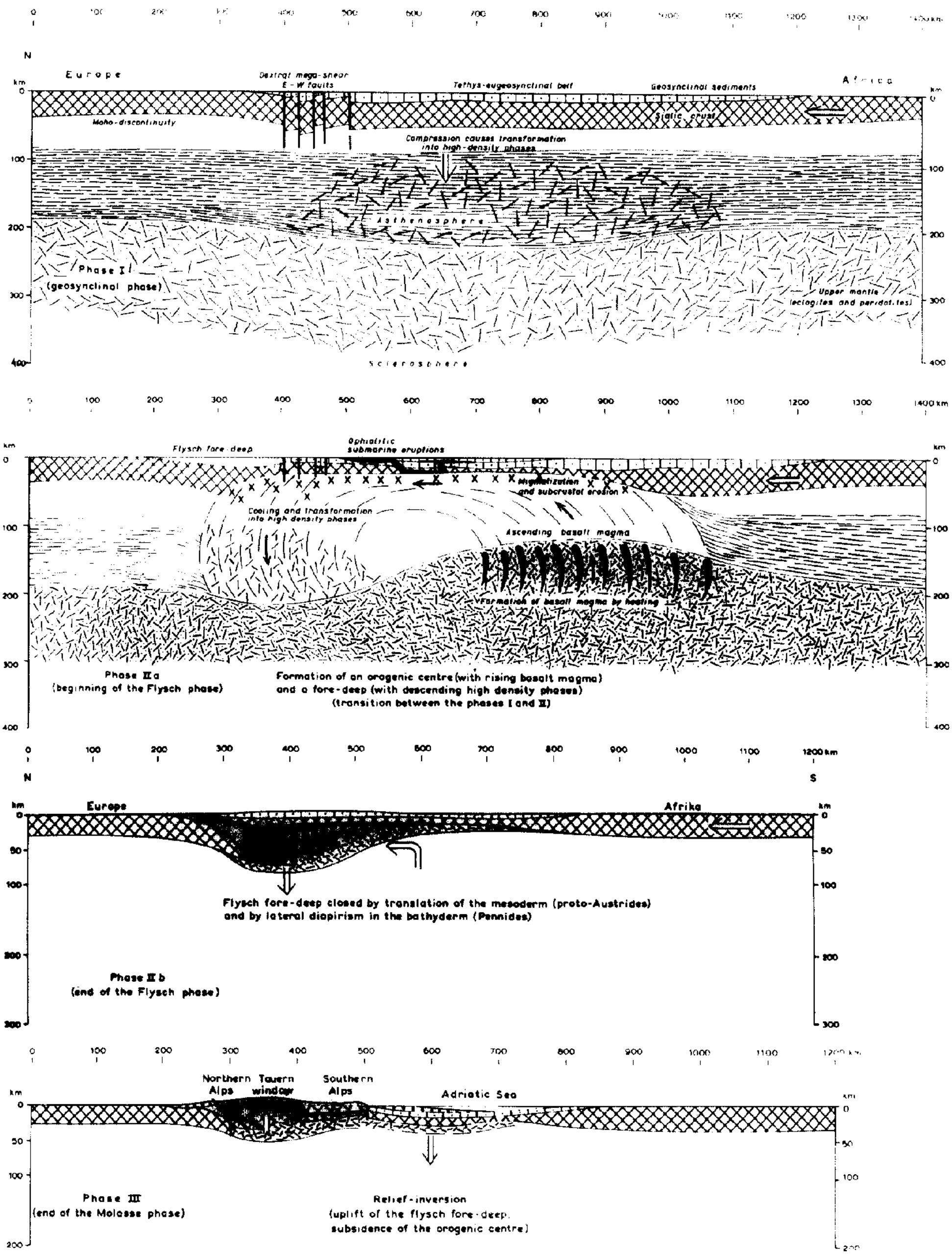


Fig.4. Four stages of the evolution of the Tethys-geosyncline.

crustal zone. In those places where the shear zone cut across still active sections of the Hercynian Mountain system, and where palingenic granitic magmas were still present in the bathyderm, the dextral shear faults could tap these pockets of acid, gas-laden magma. This caused fissure eruptions of ignimbritic character, producing, for instance, the so-called "quartz porphyrites" of lower Permian age. These ignimbrites are found all along the Insubric lineament between the central and the southern Alps from Lugano to the Semmering near Vienna. Stratigraphically they are interrelated between the basement complex and the pile of geosynclinal sediments. At the other places this shear zone cut across crustal areas, which were more stable at the time. In Indonesia, for example, no Hercynian orogenesis is known, and the main unconformity occurs there between the Middle and the Upper Triassic (Van Bemmelen, 1949, 1954).

The displacement of Africa, away from the i_σ-centre, was opposed by the European Shield; therefore the crust of the Tethys belt was not only subjected to plastic deformations and shear movements at right angles to this barrier, but this part of the crust and the underlying structural levels were also subjected to an increase of the confining stresses. This increase of compression promoted the transformation of mineral phases underneath the Tethys belt into phases of higher density. Thus the isostatic equilibrium was disturbed and a slow subsidence of the Tethys zone started, which was compensated by sedimentation in shallow seas on top of the subsiding crust.

Phase IIa: The slow subsidence of the geosynclinal zone during the first phase had transferred matter from the top of the upper mantle to greater depths, where it was slowly heated, either by conduction or by turbulent movements[1] in the asthenosphere. This reheating led to a partial, eutectic melting and the (re)generation of a basaltic magma. The latter, due to its density, which was lower than the surrounding parent matter, migrated upward, assembled into greater masses; and finally it produced an upward flux of basalt magma. This hot basaltic magma migmatized and mobilized the base of the overlying sialic crust.

The progressive supply of basaltic magma from beneath replaced the mixture of basalt magma and acid migma on top. This mantle crust mixture flowed off sidewards, thus corroding the crust at its base. Sooner or later this mixture of molten matter had to bend downward in order to close the buoyant circuit of basaltic magma in the asthenosphere. The downward branch of this circuit transported sialic matter to greater depths. During this downward flow the mineral components of the crust were transformed into high-density phases of such a character that they found in depth a new position of stable physico-chemical equilibrium, according to the temperature and pressure conditions occurring at that depth.

These circuits of matter in the asthenosphere, occurring at the end of the geosynclinal phase, caused not only a thinning of the crust by corrosion at its base, but it was also reflected at the floor of the geosynclinal sea by uplifts and downwarps, which became the centres of the subsequent orogenesis. Emerging areas were eroded and the marginal deep troughs filled by flysch deposits (with turbidites in the central parts of the deep trenches, and submarine slides along their margins).

Occasionally the rising basalt magmas could reach the floor of the

[1] Defined by Wunderlich (1965) as "secular turbulance".

geosynclinal sea, especially in those places, where the progressing dextral shear movements locally opened fissures in the crust. These basic to ultrabasic intrusions and submarine deep water extrusions are the well-known ophiolites, serpentinites, and pillow lavas, which are characteristic for the eugeosynclinal circumstances of the alpine orogenic cycle. The ophiolites generally are of Jurassic and Lower Cretaceous age. Their occurrence is an indication that the eugeosynclinal phase was coming to an end; crustal erosion was preparing orogenic foci in the mobile belt and the flysch phase was initiated.

Phase IIb: Towards the end of the flysch phase the crustal mobilization and oceanization in orogenic centres had proceeded to such an extent, that the subcrustal circuits of matter produced mushrooming and sidewards diapiric intrusions of the migmatites, accompanied by the outward rafting of overlying remnants of the sialic crust (with the geosynclinal sediments riding passively on their back). Examples of such bathydermal mobilizations and deformations by flow movements have been described from older, deeply eroded shields, e.g., by Wegmann (1930, 1965) and Haller (1956).

In the Tethys belt the tectogenesis of the flysch phase produced the nappes of Pennine character, with cores of mobilized sial. The Pennides are overlain by the proto-East Alpine Nappes or proto Austrides (Van Bemmelen, 1960).

The movements of spreading of the orogenic foci caused the closing of the flysch foredeeps.

In places there was also an advance of promontories of the African Shield, which still had the tendency to spread under gravity in centrifugal direction from mega-undatory uplifts to their rear. This occurred, for example, in the southeastern Alps, as indicated by the paleomagnetic studies of De Boer (1963, 1965) and by the regional tectonic analyses of the southeastern Alps by Van Bemmelen and Meulenkamp (1965). Between France and the Black Sea a promontory of the African Shield advanced northwestward, between northwest–southeast sinistral strike-slip faults at its port, and northwest–southeast sinistral strike-slip faults at its starboard side (see also the section on the present structural features of the earth and Fig.6 in that section).

Phase III: The great mobility (rheidity) of the Tethys belt with its corroded crust had resulted in intense crustal deformations without great contrasts of elevation. The preceding flysch phase has been characterized as the deep phase of Alpine orogenesis (German: "Tief-orogene Phase"). The elevations of the sea floor hardly emerged above sea level and the subsiding trenches were quickly filled by sediments and nappes. No great contrasts of relief could be maintained for a geologically considerable time. However, the piling of the nappes and the cooling beneath the surface, the dynamometamorphism of the sediments involved, all these processes resulted in an increase of the crustal strength.

Moreover, the closing of the flysch troughs by piles of Pennine Nappes, overridden by the proto-East Alpine Nappes, had locally disturbed the isostatic equilibrium. This fundamental change in the general geomechanical circumstances led to a third phase of the Alpine orogenesis, the uplift of the former flysch troughs into mountain ranges. This uplift was accompanied by mass-circuits of more restricted extent. The rising belts were volumetrically compensated by the subsidence of side deeps. As the crust was considerably stronger than during the preceding flysch phase, these ranges could reach great heights above sea level, and they had steep faults, which in parts coincided with the former strike-slip faults of the geosynclinal phase (e.g., the insubric fault line; see De Jong, 1966a).

Along these lines of weakness still molten remnants of the acid magma and migma in the cores of the Pennine Nappes could ascend in places. They formed the well-known series of plutonic tonalitic bodies along the Insubric fault line of the southern Alps. Still farther south, more basic (basaltic) magma also could penetrate to the surface, e.g., along the Bassano fault (De Boer, 1963).

The detrital products of the erosion of these young Cenozoic Alpine ranges were partly coarsely clastic, and they were deposited as molasse sediments in the side deeps. This molasse phase has been characterized as the high phase of Alpine orogenesis (German: "hoch-orogene Phase").

In the origenal centres of the Alpine orogenesis the cooling and crystallization of the rising front of basic magma dominated. This resulted in an increase of density and a general tendency to subside isostatically. Thus the molasse phase generally shows an inversion of the relief: the rise of mountain ranges from the flysch fore deep, and the subsidence of the partly or entirely oceanized centres of orogenesis in the Tethys zone.

In the cross section of the East Alps (Fig.5), this orogenic evolution had finally produced layers with different speeds of the seismic waves, as has been ascertained by the seismic researches in recent years (Closs, 1964; Prodehl, 1965). The zone of 7.4 km/sec at the base of the Alps, which reaches a depth of 56 km, is interpreted (according to the foregoing schema of evolution) as a mixture of basalt magma with high density phases of sialic material of the upper mantle. It is a kind of mantle crust mixture (Cook, 1962), which forms the base of the Alpine "root" or "asthenolith".

The seismic zones of the foreland extend more or less horizontally into the body of the Alpine ranges. This is an unexpected result of these modern seismic researches, because the orogenesis probably produced a much more complicated structural pattern. The present author is of the opinion, that these seismic horizons do not indicate the actual internal structure, but that they represent levels with increasing elastic properties of the mineral phases due to an increase of metamorphism. Den Tex (1965) has pointed out that the layer between the Conrad and the Moho discontinuities of the foreland shields does not have a homogeneous basaltic or gabbroic character as is generally accepted (Subbotin et al., 1965). The deeper crustal layer probably consists of a mixture of metamorphic rocks with mineral paragenesis corresponding to the conditions of higher pressure and temperature (e.g., cordierite–garnet–sillimanite gneisses).

Also in the Alps such layers of progressive metamorphism with depth will have been formed. These zones of increasing metamorphic grade will determine the seismic properties much more strongly than the complicated orogenic structures will do. The latter need not be reflected by the speed of the seismic waves.

In Fig.5 the stages of the structural evolution of the Alps have been depicted in somewhat more detail for the phases IIa, IIb and III in the realm of the East Alps. It has to be realized, however, that only the crude outlines of this new model have been given in Fig.4 and 5. In the future this model might serve as a starting point for a more detailed series of genetic sections, based on more diagnostic facts concerning the geological and geophysical circumstances.

For instance, Trümpy (1965) recently published a composite north-northwest–south-southeast section across the West Alps. The formation of this section has been analysed by means of a series of somewhat more detailed genetic sections, which range in time from the Triassic (some $2 \cdot 10^8$ years ago) to the end of the flysch phase (some $4 \cdot 10^7$ years ago).

In the first three of these genetic sections (Middle Trias, Middle Lias, Lower Malm) we recognize at the base of the geosynclinal sediments the post-Hercynian volcanites, which erupted along the initial shear faults. Moreover, a series of sliver blocks and troughs is depicted, which were probably formed by the dextral shear movements in the Tethys geosyncline according to our model. In Lower Cretaceous time the ophiolitic magma reached the floor of the geosynclinal troughs (end of the geosynclinal phase).

In Upper Cretaceous time, some ninety million years ago, the flysch phase began, with the emergence of areas farther south, and the thrusting forward of the crustal sliver blocks. This second phase ends at the transition of Eocene–Oligocene with the appearance of the synorogenic Alpine vulcanites (especially andesites), which indicate the beginning of the uplift of the molasse phase, with its tonalitic trusions and volcanic eruptions along fault lines.

The profound influence of the dextral shear movements on the facies distribution in the Tethys geosyncline has also been stressed by De Jong (1966a). This author remarks that the sudden transition from north–south facies zones in the southern Alps, south of the Insubric line, into the east–west trending narrow facies belts of the central and northern Alps, can be explained by east–west trending strike-slip movements in the basement complex of the geosyncline, which were active before the overthrusting movements.

Studies about the historical sequence of the structural events, like those by Tollmann (1963), Trümpy (1965), Clar (1965), De Jong (1966a,b), and others, will certainly promote the further elaboration in more detail of the crude picture of Alpine orogenesis outlined by the present author in the preceding pages. The model of evolution, presented in Fig.4 and 5 attempts in the first place to form a bridge between our concept of geotectonic processes on a global scale and those of the orogenic processes on a more restricted (regional) scale. Only by paying attention to the setting of the orogenic processes in the more general scheme of global evolution will it be possible to apply the principles of relativistic structural analysis. Only in this way may we hope to arrive at a mechanical model (working hypothesis) which corresponds fairly well with our knowledge about the contingencies of the geodynamic evolution (its historical sequence of events) on the one side, and the fundamental laws of physics and chemistry (the laws according to immanent properties of the material) on the other.

THE PRESENT STRUCTURAL FEATURES OF THE EARTH

In the foregoing section we attempted to draft a new mechanical model for the Alpine orogenesis according to the relativistic principle of structural analysis. We now turn our attention to the picture of the structural features of the earth's surface in the present time. In this section we will try to understand the formation of these tectonic features in the light of the new concept of

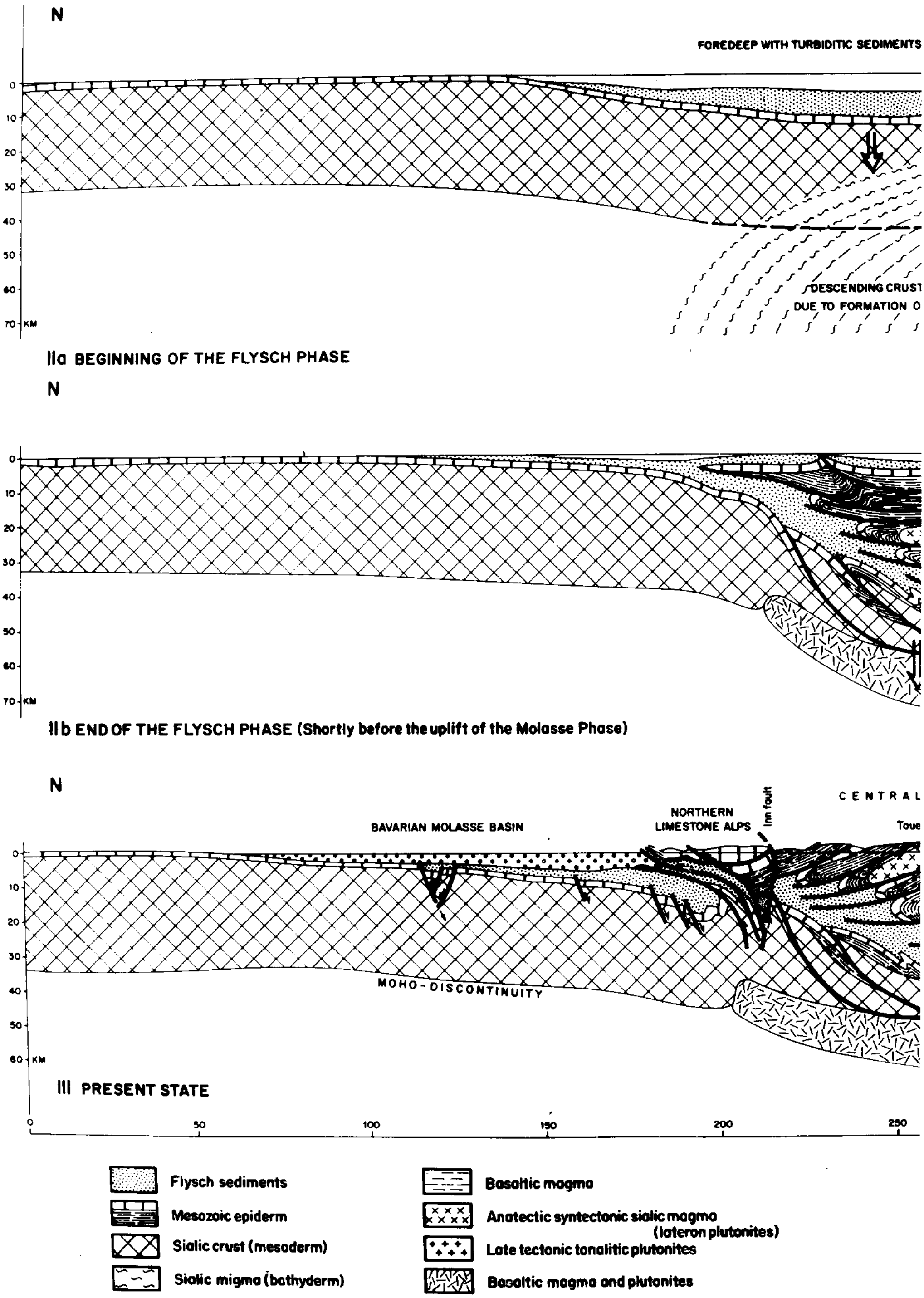
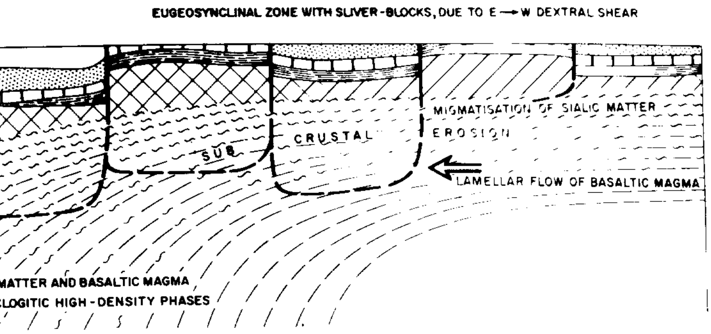
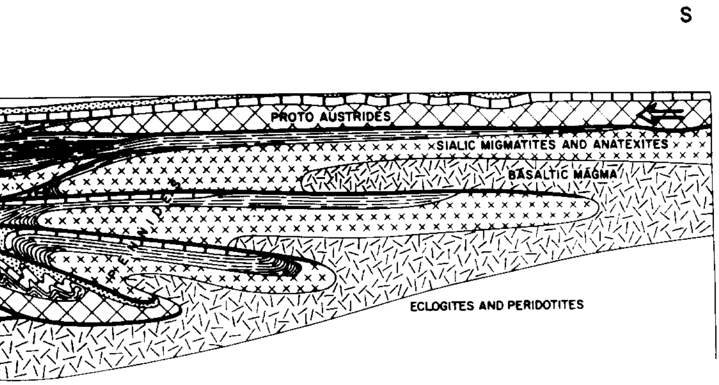
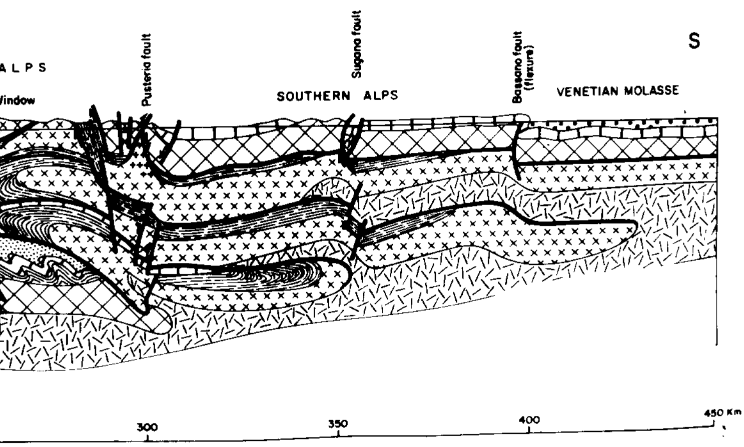


Fig. 5. Three phases of the evolution of the eastern Alps.


S
EUGEOSYNCLINAL ZONE WITH SLIVER-BLOCKS, DUE TO E → W DEXTRAL SHEAR
MIGMATISATION OF SIALIC MATTER
SUB
CRUSTAL
EROSION
LAMELLAR FLOW OF BASALTIC MAGMA
MATTER AND BASALTIC MAGMA
LOGITIC HIGH-DENSITY PHASES


S
PROTO AUSTRIDES
SIALIC MIGMATITES AND ANATEXITES
BASALTIC MAGMA
ECLOGITES AND PERIDOTITES


S
ALPS
Window
Pusteria fault
SOUTHERN ALPS
Sugana fault
Bassano fault (flexure)
VENETIAN MOLASSE
300
350
400
450 Km

Crests of mega-undations (and volcanic rift-belts, parallel to them)

Aseismic non-volcanic lateral ridges

Direction of continental drift and indication of the causative mega-undation

Direction of drift in the simatic crust

Transcurrent faults (mega-shears)

Alpine mountain ranges and island arcs

Pacific type of coast line

Atlantic type of coast line

Former western boundary of Gondwana (at the time of the Late Paleozoic "Tethys

Siberia-America suture line

aI - III, iI - IV, pI - IV, AfrI - III: Successive phases of the Atlantic, Indian-ocean, East Pacific, and African Mega-Undations sensu lato

a° - i°: Late Paleozoic site of initiation of the Atlantic and Indian-ocean Mega-Undation

Fig.6. Schematic map of the geotectonic features of the worl

Siberia
(Angara)
Mongolia
Baikal Lake
Man-
churia
CHINA
Tibet
INDIA
EUROPE
Black S.
ranean S.
CA
Afr II
Afr I
Afr III
iII
iIII
iIIIα
iIIIβ
iIIIγ
iIIIδ
i°
iI
a°
aIII
aIV
pII
Carlsberg R.
Chagos-Laccadive R.
Mascarene Plateau
Ninety east Ridge
Crozet Plateau
Kerguelen Plateau
AUSTRALIA
HAWAIIAN RISE
DARWIN
RISE
T I C A
Scale along the central meridian
0
1000
2000
3000
4000
5000 KM

")

the earth's evolution, which has been expounded earlier in the section on the three main phases of the earth's evolution and according to the mechanism of gravity tectonics in various structural levels ("Stockwerk" tectonics), as expounded in the last two sections. A schematic picture of the structural features of the earth is given in Fig.6.

The first aspect drawing our attention is the vast extent of the oceans and seas (ca.70% of the area), which are underlain by a simatic type of crust. In the section on the three main phases of the earth's evolution we posed the question, whether the sialic cover had always occupied such a small portion of the earth's surface or even less (according to the principle of the growth of the continental shields); or whether the present area of the sialic crust, covering only 30% of the earth's surface, is only the remnant of an acid layer which once enveloped the entire globe.

Is the present display of sialic material the result of a gradual physico-chemical evolution of the mantle, segregating granitic matter from within? If so, the present volume of the sialic crust would represent a maximum, reached after some billions of years of geological evolution. In the section on the three main phases of the earth's evolution some objections have been advanced against this point of view. It appears that a sialic crust was already present about $3.5 \cdot 10^9$ years ago (Donn et al., 1965). We do not know of any physico-chemical process of differentiation of the earth's mantle which is capable of producing sialic matter in such quantities at such a high rate. Though this is a weak argument, it makes us sufficiently sceptical about the validity of postulating an endogenic origin for the sialic crust to consider also the probability of the opposite view, namely the exogenic origin of the sial.

Berlage's theory on the cosmogenesis is strictly based on the immanent, physico-chemical properties of the material which once formed the disc of planetary matter around the sun. It leads to the conclusion that the earth has been covered in a very early stage by an envelope of satellitic material. The sialic matter, which is now present in the form of isolated continental shields, would represent remnants of a layer of satellitic material acquired from without. In the beginning, this layer enveloped the entire earth with an average thickness of 65 km. In the course of the geological evolution it was metamorphosed into the sialic crust. Finally, the physico-chemical evolution of our planet led to an incorporation and digestion of this foreign matter.

According to this view the sialic crust, which occupies at present about 30% of its surface, would not be the maximum of sial the earth ever had, but on the contrary the very minimum. Never in its history had the earth possessed so little sialic crust and so much oceanic crust. We have advanced in the section of the three main phases of the earth's evolution some arguments which are in favour of this new concept: for instance, the oceanization, which seems to be active in the third phase of the earth's evolution; De Booy's view on the former distribution of the sialic basement complex.

We will now study the present structural features of the earth's surface, discussing the question of how far our knowledge about their character and origin agrees or disagrees with this new model of the earth's evolution.

First of all the margins of the sialic continent and its sideward transition into the simatic oceanic crust, require attention. Suess has already distinguished two types of coasts. The *Atlantic type of coasts* is fractured. The continental shields are limited by coast lines, the course of which is independent of the internal structural pattern of the continent. The *Pacific type of coasts* is orogenic and volcanic. The mountain ranges of the marginal zone of the land extend parallel to the general course of the coast line.

It appears that the Pacific type of coasts extends along the frontal side of the drifting continental shields, and the Atlantic type is found at their rear side. Moreover, systems of sinistral strike-slip faults are found along their port, whereas systems of dextral mega-shears occur along starboard. These geotectonic features are considered in relation to the mid-ocean rift and ridge systems in the Atlantic and Indian Oceans by means of the concept of mega-undations and their stepwise evolution during post-Paleozoic time (Van Bemmelen, 1964b, 1965a). Geological, paleoclimatological, paleomagnetic, and other geonomic investigations indicate that the direction of the drift movements has been Indico- and Atlantico-fugal, whereas they were Pacifico-petal. The successive directions of these drift movements, caused by the consecutive phases of evolution of the Indian Ocean and Atlantic Ocean Mega-Undations, are indicated by arrows on the continental shields (Fig.6).

The Indian and Atlantic Oceans are - at least for the greater part - new ocean basins with a simatic type of crust. These new ocean basins are probably the result of a decollement and spreading under gravity of the overlying sialic crust, due to mega-undatory uplifts. The mechanism of oceanization by spreading of the crust under gravity might be called the *Atlantic type of oceanization*. The type areas for the initial stages of the Atlantic type of oceanization are the Red Sea and the Gulf of Aden (Illies, 1965b; Laughton, 1966). This Atlantic type of oceanization seems to be less probable for the Pacific Ocean, because of the Pacifico-petal direction of the drift movements of the surrounding continental shields. These drift movements considerably reduced the Pacific area; the water that was crowded out at the frontal side of the drifting continents filled the new ocean basins at their rear.

There seems to be, however, yet another type of oceanization, which produced the smaller sea basins of Mediterranean character, and of the marginal seas at the concave side of the east Asiatic island arcs.

The author (Van Bemmelen, 1958, 1961) proposed a different process for this *Mediterranean type of oceanization*, namely a "basification" of the continental crust by physico-chemical processes, such as corrosion from beneath by rising, overheated basaltic magma. These volcanic processes of intrusion and extrusion caused an increase of the average density, thus inducing isostatic subsidence. The subsidence may also have been promoted by transition of minerals into phases of higher density in the downward currents of the asthenospheric mass circuits (see, e.g., Fig.4, phase IIa).

The physico-chemical principle of "basification" was applied by the author to the Caribbean area (Van Bemmelen, 1958, pp.11–17), and by Beloussov and Ruditch (1961) to the Japan Sea.

This Mediterranean type of oceanization by physico-chemical processes has a less deep origin than the Atlantic type of oceanization by gravitational processes. It is indicated schematically in the sections of Fig.7 and 8.

The Mediterranean type of oceanization is a mechanism of swallowing up of the sialic crust by the upper mantle and its "digestion" by means of transitions into mineral phases of higher density and less volume. This type of oceanization is the result of "penetrative convection", of the upper mantle, as defined by MacDonald (1965, p.225); whereas the Atlantic type of

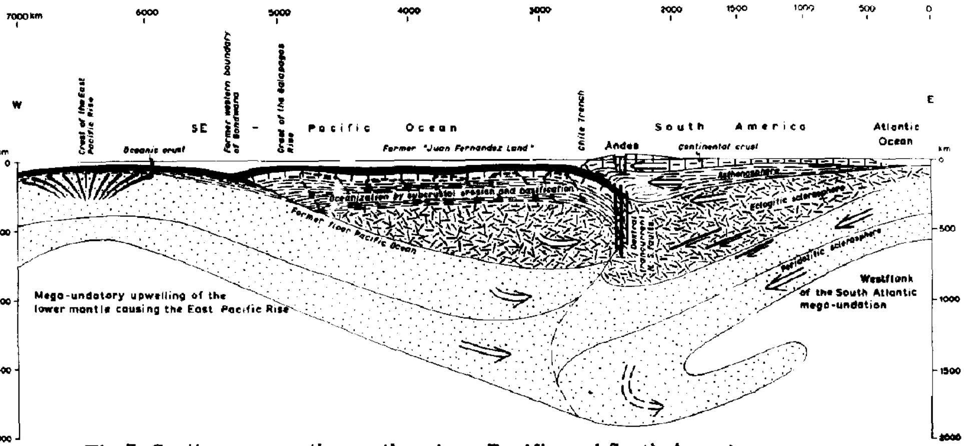


Fig.7. Section across the southeastern Pacific and South America.

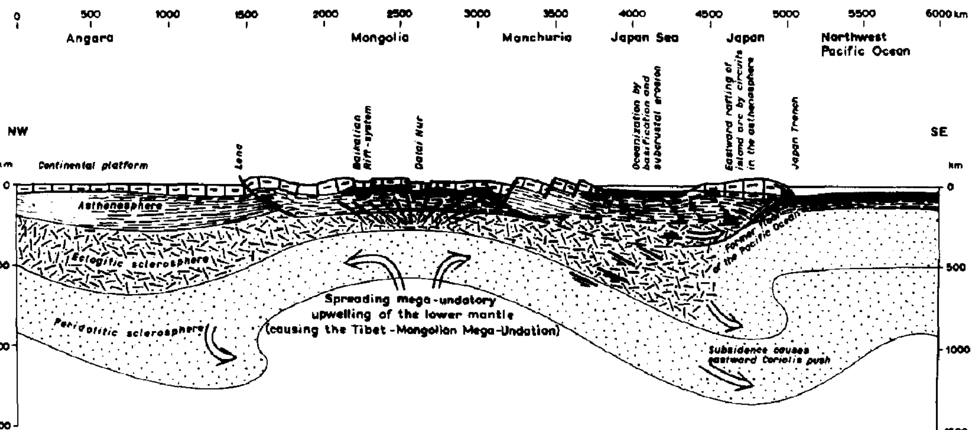


Fig.8. Section across the Tibet–Mongolian Mega-Undation.

oceanization might be interpreted as gravity flow of the outer layers due to "mega-convection" in the entire mantle. The mechanism of this mega-convection might more or less conform to the ideas put forward by Bernal (1961), Orowan (1965), and Van Bemmelen (1964b, 1965a).

A major riddle still is the origin of the Pacific Ocean. Up to now the oceanographic data indicate that it is relatively young, like the Atlantic and Indian Oceans. If so, it might be possible that the area of the Pacific Ocean was also once covered by a (thin) sialic crust and a sedimentary epiderm, forming a crustal area, which might be called "Pacifica". But this sialic cover has been removed during the third phase of the earth's evolution by physico-chemical processes, conformable to those causing the Mediterranean type of oceanization. The other possibility is that the Pacific area really represents a primeval ocean basin. In that case the absence of marginal zones with piles of detrital sediments (derived from the surrounding continents in the course of billions of years) might be explained by the fact that these marginal belts were probably overridden by the surrounding continents during their Pacifico-petal drift movements in post-Paleozoic time.

The sections of Fig.7 and 8 give a schematic picture of the present situation in the southeastern and northwestern margin of the Pacific area. These sections, however, do not represent a choice between both hypothetical models mentioned above.

The section across the southeastern Pacific and South America (Fig.7) needs some closer explanation because here the geotectonic evolution shows a special complication.

At first, in Lower Mesozoic time, the South American part of Gondwanaland could drift unhampered in a westward, Pacifico-petal direction. The frontal part of this drifting shield extended from Patagonia along the Chile–Galapagos Rise to the Caribbean area. In younger Mesozoic time, however, the East Pacific Rise was bulged up, forming a barrier to the west drift.

This barrier caused a deviation of the west drift into a more southward direction. This new drift direction was accompanied by north–south trending, dextral megashear movements, the emplacement of the Andean batholiths in Middle–Upper Cretaceous time, and the eruption of ignimbrites along north–south fissures in the younger Cenozoic.

Mountain ranges of the Alpine type of orogeny, preceded by a geosynclinal phase and basic to ultrabasic ophiolitic magmatites, skirt the northern and northwestern Venezuelan margin. These Alpine ranges end at the Gulf of Guayaquil in Ecuador (see also North, 1965). This Alpine type of mountain ranges may have extended along the Galapagos–Chile Rise, but this section of the Tethys belt has been obliterated by the subsequent process of physico-chemical oceanization (Mediterranean type). In the extreme southern end of South America the Alpine type of mountain ranges can be observed again in the northwest–southeast trending Patagonides. The marginal mountain system has nowhere an Alpine character of orogenesis along the entire western coast of South America, between the Gulf of Guayaquil in the north (ca.5°S) and the Nahnel Huapi massif near Valdivia in the south (ca.40°S). The orogenesis of the mountain ranges of this central section of ca.4,000 km length is typically Andean. There is no clear preceding geosynclinal phase. The older formations, such as the Triassic and the Jurassic porphyrite formations are deposited directly upon the deeply eroded crystalline basement complex of Precambrian and younger Paleozoic rocks. The Mid-Mesozoic volcanic formation might be related with the basification of the Juan Fernandez Land farther west (see also Zeil, 1964, 1965).

In Jurassic, Cretaceous, and Cenozoic time the huge Andean granite batholiths were emplaced. According to the mechanical model proposed in this paper, the rise of these granites might be related to the change of the South American drift direction along the west flank of the East Pacific Rise. This change in the direction of the continental drift caused north–south trending mega-shears in the Andean belt, which were accompanied by compressive stresses in some sections and tensional stresses in other parts.

Later on, the consolidated marginal belt was divided into the longitudinal sliver blocks of the coastal ranges, the longitudinal valleys and the high Cordilleras. The dextral mega-shear movements continued, causing the eruption of ignimbritic volcanic sheets of acid to intermediary composition; and, finally, the high Cordilleras were crowned by andesitic volcanoes.

Allen (1962) supposed that in the Andes the dextral transcurrent movements are still active at the present time; he compares the Atacama fault with the San Andreas fault in North America. The same author remarks that such transcurrent faults parallel to the Pacific coast fail to fit with most of the specific hypotheses of convection and drift that have been presented (Allen, 1965). They occur at right angles to the directions of the postulated movements of flow and drift. The foregoing model, however, analysing the direction of the movements in successive phases and in relation to the changes in the geomechanical circumstances, provides a satisfactory explanation for this difficulty.

The northwest–southeast trending Magellanes fault zone, almost straight and about 600 km long, is a sinistral shear zone at the southern tip of South America (Katz, 1965). This sinistral wrench fault represents the portside image of the dextral shear movements at the starboard of the westward drifting South American continent in Venezuela. The Magellanes fault zone is off-set at its eastern end by a series of sinistral, northeast–southwest trending shear faults. These faults are indicated on the physiographic diagram of the South Atlantic Ocean by Heezen and Tharp (1964). These northeast–southwest sinistral transcurrent faults between Tierra del Fuego and the southern Sandwich Islands are the youngest geotectonic features of this area. Together with the young north–south trending dextral Atacama fault zone, they might represent a conjugate shear pattern, related to the change in Late Mesozoic and Cenozoic time of the drift direction of South America from east to west into northeast–southwest or even north–south.

Summarizing, it can be said that geological observations indicate a type of orogenesis in the central part of the Cordilleras de los Andes (between Guayaquil and Valdivia), which is different from the Alpine orogenesis in the Tethys belt. No ophiolites and no great nappes are known in this part. This central section shows a typically Andean orogenesis.

The original belt of the Alpine orogenesis formerly stretched probably much farther to the west, where now the Galapagos Chile Rise represents its former course (Menard et al., 1964).

The pattern of the structural trend lines of central Asia, as given in Fig.6, differs somewhat from the author's interpretation in his paper on the Indian Ocean Mega-Undation (Van Bemmelen, 1965a, fig.6).

The structural fabric of central Asia has been interpreted as the result of the deformation of the southern part of the Tibet–Mongolian Mega-Undation by the northward-migrating Indian Shield. This picture is consistent with Ritsema's (1966) analysis of fault-plane solutions of the earthquakes in the Hindu Kush area at the northwestern corner of this shield, and also with the geology of Afghanistan according to Ganss (1965).

The Hindu Kush area is subjected to compressional stresses in a south-southwest–north-northeastern direction. The seismic data on the deeper shocks in this area (150–250 km depth) can be explained by the underthrusting of the upper part of the upper mantle belonging to the Indian area underneath the Tibet–Mongolian crustal area. This north-northeast-directed drift is related to the young and active IIIγ-centre of the Indian Ocean Mega-Undation (Van Bemmelen, 1965). Along its port it is accompanied by sinistral wrench faults of Mukur, Chaman, and the Indus Valley (Ganss, 1965). See also the structural sketch map of central Asia, recently published by Desio (1965, table I).

The shallow shocks of the Hindu Kush area are confined to the crust. The solutions of their fault-plane movements indicate upthrusts in a northwestern direction and important transcurrent components. These shallow earthquakes accompany the deformations of earlier structural trendlines, caused by the Tibet–Mongolian Mega-Undation into the present indented tectonic fabric, as indicated by Fig.6.

This geotectonic picture is also in good agreement with the distribution of the earthquake foci in central Asia. According to Båth (1965, fig.4) the central Asiatic earthquake belts resemble the ship-waves and the cross-waves, produced in the water by a northeastward-moving boat. The resisting area in central Asia corresponds with the boat, the bow of the boat being directed toward Lake Baikal.

The geotectonic pattern of the central part of Eurasia indicates that it has been deformed by means of northwest–southeast slices, which moved northwestward, as is indicated by arrows in Fig.6. This concept of northwestward movements is in contrast to the majority of other geotectonic theories, which accept a southward displacement of Eurasia.

The narrowing of the Tethys zone during the Alpine orogeny can also be explained according to the principle of relativity by supposing that Eurasia moved northward or northwestward over a smaller distance than the shields of Gondwana. The crust in the interjacent Tethys belt had been partly removed by the Mediterranean type of oceanization. This process of the incorporation of sialic crustal material into the upper mantle (in the state of high density phases) gave to the Gondwana shields the freedom to move more north or northwestward than the Eurasian crustal shield at the northern side of the Tethys.

It has to be realized that northwestward displacements of the Eurasiatic crustal units shift the room problem of the jig-saw puzzle to the Arctic, the area of which was restricted. We believe that the elbow-room can be found by the Pacifico-petal drift of North America and the Siberian–American suture in the Verkhoyansk Arc (see Van Bemmelen, 1964b, fig.6, p.404). Perhaps the Arctic area has also been subjected to an early process of the Mediterranean type of oceanization (after the Caledonian and Hercynian orogenies). But also the later, post-Cretaceous, Atlantic type of oceanization influenced the area of the Arctic. The find of the giant, plant-eating *Iguanodon* footprints in Spitsbergen (during the excursion on the occasion of the 21st International Geological Congress in Scandinavia, 1960) proves that these islands were isolated from the European Continent only after the Cretaceous. Thenius and Hofer (1960, p.280) remark that the mammals of Europe and North America were still closely related during the Paleocene and Lower Eocene. These land faunas of both continents started independent ways of evolution in the course of the Eocene, due to a disruption of the land connections. The latter process might be the result of an Atlantic type of oceanization, as was suggested by the author on account of his analysis of the evolution of the Atlantic Mega-Undation (Van Bemmelen, 1964b).

Thus the Arctic room problem can be solved by accepting the idea that North America and Greenland moved over greater distances towards the Pacific and away from the Arctic and Europe, than the distances which Europe and western Siberia covered towards the Arctic.

We come to the conclusion that the relative displacements of the continental shields over the earth's surface started in Late Paleozoic time from the South Pole area of that time. Thereafter, they developed into an Indicofugal and Pacifico-petal drift pattern.

The question arises why the Pacific area was capable of being so much restricted, so that all drift movements could debouch into it? Was the primeval Pacific Ocean covered by a simatic crust? Or did it also have a sialic crust which has been incorporated by the mantle in the course of the third phase of the earth's evolution by means of the Mediterranean type of oceanization?

Berlage's theory leads to the postulate that the geological evolution started with an outer layer of satellitic material which had an average thickness of 65 km. This layer has probably been transformed into the sialic crust in the course of the second phase of the earth's evolution. Thereafter, this sialic crust was partly incorporated during the third phase. If so, then about two-thirds of the geological record has been destroyed.

The aforementioned problem whether the Pacific area represents a primeval ocean basin with a simatic crust or that it has lost its sialic crust, can also be considered in relation to the water balance of the hydrosphere.

If the bulk of the hydrosphere was already present at the end of the first phase of the earth's evolution, and if there has been no considerable contraction or expansion of the earth since that time, then the water of the hydrosphere could have formed an envelope with an average depth of more than 2 1/2 km.

If there were emerging continental areas, as is indicated by the unconformities between the great chelogenic cycles of crustal transformation and metamorphism, then ocean basins of much more than 2 1/2 km average depth should have always been present. According to these postulates the Pacific Ocean should always have been a major receptacle of water, that is a kind of primeval ocean.

The various concepts on the expansion of the earth only increase the seriousness of the problem of the water balance, because the water should have been distributed over a much smaller area. This difficulty is, for instance, an objection to Creer's reconstruction, which tries to fit all continents on a surface area so much smaller that there is no place at all for ocean basins (Creer, 1965).

The water that fills the new ocean basins has to come from elsewhere, whether these basins are formed by the Atlantic type of oceanization or by the Mediterranean type of oceanization. We do not know of any process that could provide so much water during the relatively short time involved in the formation of new ocean basins (some hundreds of million years): neither of any physico-chemical processes which segregated great bulks of juvenile water from without.

Reynolds (1965) presented evidence that the boron content of illites has not varied significantly over the past $2 \cdot 10^9$ years. Gregor (1965) supposes in relation to this evidence, that the hydrosphere reached its present size and attained a dynamic chemical equilibrium with the lithosphere in an area previous to "geological time" as we know it. Its important elements have since then migrated cyclically from sea to land and back again.

Therefore, provisionally we prefer the view that the Pacific area has been a major container of water during the entire, geologically known part of the earth's evolution, whether the Pacific Ocean was underlain by a thin skin of sialic material or by simatic crust.

The Mediterranean type of oceanization of the sialic crust means an incorporation of material from the outer skin into the upper mantle by means of transitions into mineral phases of higher density. These transitions would cause a volumetric compaction[1] of the matter concerned in the order of 10% (see Subbotin et al., 1965b, table VI, p.178). This compaction in combination with the isostatic equilibration of the columns in which these transitions into higher density phases occurred, would increase the contrasts in the earth's relief: deeper sea basins, higher continents.

Egyed (1956, 1957, 1959) has pointed out that (according to paleogeographic maps) since Cambrian time there has been a progressive retreat of (shallow) seas from sialic crustal areas. Egyed interpreted this withdrawal in terms of an expansion of the earth (ΔR ca.0.5 mm/year). However, it is clear that the compaction of matter during the Mediterranean type of oceanization might explain this retreat of the seas from the continents as well.

Recently Subbotin et al. (1965a,b,c) have published a series of papers in which the authors attempt to explain the present structural features of the earth entirely by means of the fixistic concept. The fundamental thesis of this concept is that the upper mantle (the first 500–700 km) is responsible for all the crustal vertical movements and has given rise to the layers of the crust as well as the hydrosphere and atmosphere. This concept is also followed by Beloussov (1966).

The present author agrees with their view that critical thermodynamic conditions in the upper mantle give rise to various processes which change the volume and density of the material. These physico-chemical processes will certainly cause differential vertical movements at the surface, and they will cause also "consequential" flow movements (Subbotin et al., 1965c, p.189).

In the foregoing pages these physico-chemical processes are held responsible for the geo- and meso-undations, more or less in the same way as Subbotin et al. try to explain deep faults, platform depression and uplifts, basins of intracontinental seas, geosynclinal depressions and folded mountains. Flow movements in the asthenosphere are considered to be the consequence of disturbances of the isostatic equilibrium, and the diameter of such circuits of matter is relatively restricted (some hundreds of kilometers at most). The Mediterranean type of oceanization can be explained by these flow movements in the upper part of the upper mantle, called "asthenosphere".

However, the geodynamic phenomena discussed by the Russian authors do not represent the entire picture of the structural features of the earth. They do not explain the formation of the great transcurrent fault systems, which are so clearly discernable in these features (Fig.6). The units of these strike-slip systems can attain a length of a thousand kilometers and more, and each one may cause an offset of hundreds of kilometers (Allen, 1965; Vacquier, 1965). The Russian authors also ignore the paleomagnetic data and

[1] Subbotin et al. (1965b, p.153) use the term "condensation" for such a reduction of volume. But this term is generally used for the volume reduction due to the transition of the vapour phase into the liquid phase. For volume reductions in the liquid or solid phase the term "compaction" seems to be more appropriate. This term is also used for the volume reduction of detrital sedimentary matter due to reduction of the water-content of clay minerals and the reduction of its pore space.

other geonomic facts, which are indicative of the drift of continental shields (Runcorn, 1965; Creer, 1965). Neither do they mention the world-wide system of mid-ocean rises and ridges, the units of which are many thousands of kilometers long (Menard, 1965). These major global features cannot be explained by relatively shallow physico-chemical processes, restricted to the upper mantle. For these largest coherent structural features of the earth, much deeper causative processes have to be accepted; namely the concept of mega-undations generated by the lower mantle. The extent of the mega-undations is so great, that they hardly produce any effects of primary vertical movements. Their top part spreads under gravity almost as soon as it rises (see graph *A* of fig.2 in the analysis of the Atlantic Mega-Undation, Van Bemmelen, 1964b, p.390). Therefore, these mega-undatory components of the vertical movements can not easily be detected by strictly geological methods. Artificial satellites are a new tool for the study of their gravity fields.

The relativistic principle must be used for the mechanical explanation of the various features of the earth. The effects of five classes of differential vertical movements (undations) are superimposed on each other. The resulting movements can neither be explained only in a fixistic way, as is attempted by the Russian school (Subbotin et al., 1965a,b,c, Beloussov, 1966) nor only in a mobilistic way, as is attempted by British and American adherents of the theory of convection currents and continental drift (Symposium on Continental Drift, London, 1964). According to the new model proposed in this paper, both trends of explanation have elements of truth in them, but a relativistic way of synthesis is needed to encompass the entire picture.

The unravelling of the earth's history according to this relativistic interpretation of the geological data is, however, a much more formidable task than the tracing of its course according to merely fixistic or merely mobilistic points of view. The foregoing pages and illustrations represent only a first tentative sketch of such a relativistic model.

CONCLUSION

Two opposing models on the evolution of the earth's crust are possible. The one says that the material of the earth's sialic crust has been derived in the course of some billions of years from the earth's mantle by physico-chemical processes of differentiation and segregation. The other holds that the material of the earth's skin of lower density and higher silica content, has been obtained from without, by an overpowdering of the earth's surface by satellitic matter at the initial stage of its planetary evolution.

The first global concept is the classical one, which has been accepted as an almost unquestioned premise by geoscientists[1].

The second view is relatively new. It has already been suggested by Berlage (1932, 1948, 1951, 1953, 1954, 1957, 1959, 1962) and Gerstenkorn (1955, 1957), but recently also by Safronov (1964), Donn et al. (1965) and others.

In the preceding pages the author has tested the second view with various

[1] The pre-eminence of this postulate is clearly demonstrated, for example, in the papers by Subbotin et al. (1965a,b,c) published in a special number of this journal on the upper mantle and its relations to the crustal structure. The preface to this special number begins with the sentence: "The mantle of the earth gave rise to the crust. . .".

diagnostic facts and rules, established for a great part by post-war researches.

Though the newer hypothesis might be very disturbing to many deeply-rooted classical patterns of thought, this first testing shows that it apparently explains the evolution of our planet much more consistently than the older one.

Therefore, the attention of geoscientists is directed to a cosmogenesis, involving the idea that the crust accumulated from the outside shortly after the earth's agglomeration, as a layer of satellitic dust and fragments. The consequences of this hypothesis should be tested more closely by means of old and new facts, so that eventually it might develop into a theory, which explains the earth's history with increasing precision and in ever greater detail.

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