KONINKL. NEDERL. AKADEMIE VAN WETENSCHAPPEN – AMSTERDAM
Reprinted from Proceedings, Series B, **70**, No. 5, 1967

GEOLOGY

ON THE ORIGIN AND EVOLUTION OF THE MOON AND THE CRUST OF THE EARTH. I

BY

R. W. VAN BEMMELEN, H. P. BERLAGE AND W. NIEUWENKAMP

(Communicated at the meeting of June 24, 1967)

Summary

The authors discuss the possibility that the Earth's crust has been obtained from without and the further geological evolution of this envelope of foreign satellitic matter. It appears that this concept provides a satisfactory model of the Earth's evolution in the light of modern geonomic data. Three main phases can be distinguished. During the first phase the envelope of satellitic matter has been acquired. During the second phase this envelope was transformed into the primeval sialic crust. During the third phase the Earth's mantle started the progressive incorporation of the sialic crust.

Contents

1. *Introduction*

Two opposing concepts on the origin of the Earth's crust are tenable, (1) the material of the Earth's crust has been derived from within, from the Earth's silicate mantle, (2) the material of the sialic crust has been obtained from without, namely from satellitic matter.

The first opinion is the classic one, and still the current view of the majority of geonomers. For instance SUBBOTIN *et al.* (1965a, b, c) open their preface to a series of interesting papers on the structural evolution of the Earth's crust with the sentence: "The mantle of the Earth gave rise to the crust". However, recently GERSTENKORN (1955, 1957), BERLAGE (1948–1966), SAFRONOV (1964), DONN *et al.* (1965) – see also the discussion between POLLARD (1966) and DONN *et al.* (1966) – have put forward the idea that the Earth's crustal matter might have been acquired from without, during the first stages of the Earth's evolution.

It is the purpose of this paper to discuss this second possibility, and its consequences for our views on the crustal evolution.

Radiometric age determinations of the sialic rocks indicate that granitic rocks existed already about 4.10^9 years ago. This means that sialic crustal matter was already present shortly after the formation of our planet, which occurred according to recent estimates about $4{,}7 \cdot 10^9$ years ago. The segregation of an acid crust from the more basic mantle of the Earth would probably be a rather slow physico-chemical process of differentiation; therefore geochemists have difficulties to understand how the great bulk of the Earth's sialic crust could have been produced at such a high rate and in a relatively short time.

Moreover, 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) basaltic (basic, simatic) magma suites, and (b) granitic (acid, sialic) suites. KING (1965) comes also to the conclusion that there was and is a simultaneous availability of basic and acid magmas. The coexistence of magmas of contrasting composition without appreciable mixing might indicate a different descendence (a different origin) of these two suites of silicatic magmas.

It is easy to understand that the original planetesimal matter after its clustering together and the forming of our planet according to the cold-earth hypothesis of UREY *et al.*, split up into a metallic core and an outer mantle of basic silicates ("sima"). But it is difficult to explain the presence of yet another layer, namely the sialic crust. The latter seems to be a foreign element to the main body of our planet.

These considerations make it desirable to consider more closely the geological consequences of the second concept, i.e. the acquisition of the Earth's sialic crust from without. Could it be that this concept eliminates the forementioned difficulties, and that it promises to give a more adequate solution for the major problems and facts of the Earth's evolution?

VAN BEMMELEN (1966a) distinguishes three major phases in the Earth's evolution (Fig. 1).

The first phase lasted about $0{,}5 \cdot 10^9$ years. It was characterized by a great rate of impact of meteoritic matter, and the surface was probably anhydric. During this phase the overpowdering of the proto-planet with satellitic matter may have occurred according to BERLAGE's views (see 2.).

The second phase lasted about $3{,}5 \cdot 10^9$ years. The hydrosphere was formed at its beginning. During this very long phase the layer of satellitic matter was transformed into the sialic crust, such as it is nowadays exposed in the old continental shields. This process of transformation may have occurred according to a theory of the persedimentary origin of the sialic crust developed by NIEUWENKAMP (1956, 1965) (see 3.).

The third phase commenced at the beginning of phanerozoic time about $0{,}7 \cdot 10^9$ years ago. During this phase the present ocean basins were formed. The original granitic crust was progressively incorporated by the Earth's mantle by means of the formation of high density mineral phases of the components of the granitic crust. The remaining parts of the latter formed continental shields which emerge more or less highly above sea-level, and which obtained a freedom for lateral drift movements, according to the views elaborated by van Bemmelen in his papers on mega-undations (see 4.).

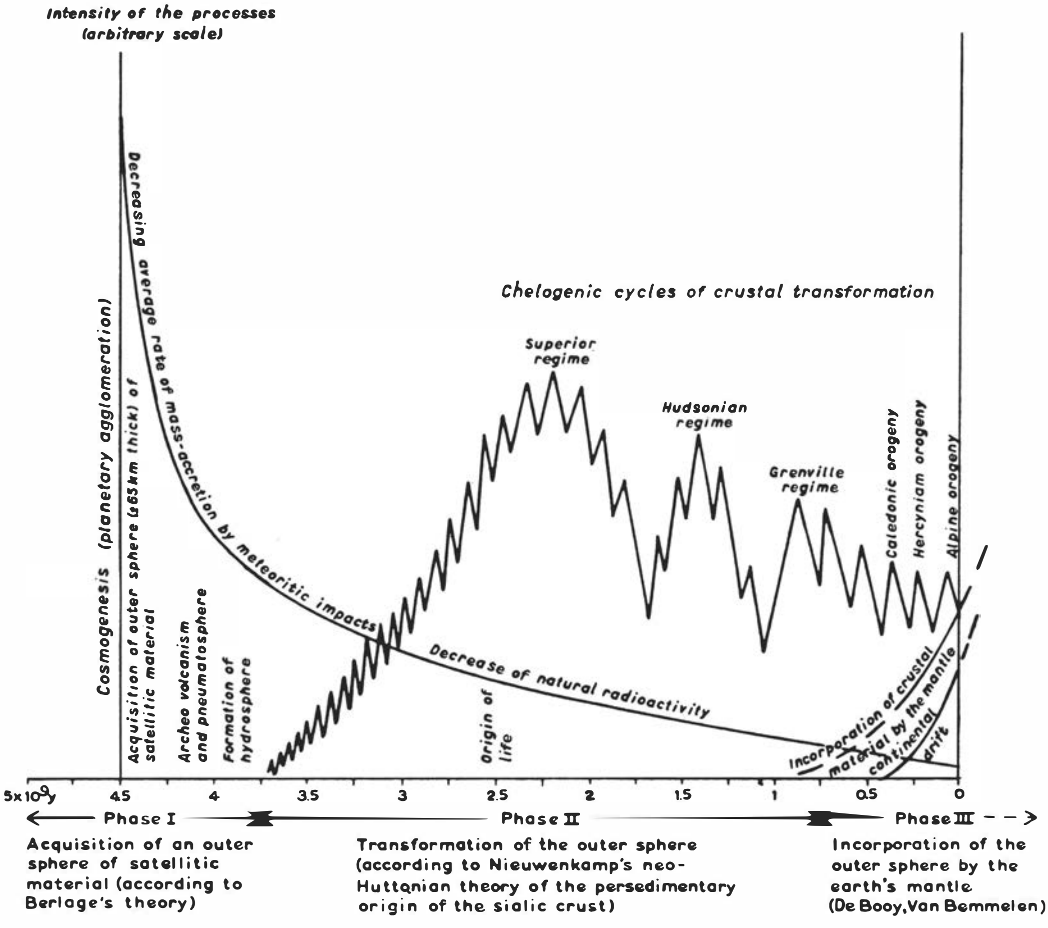

Fig. 1. Partition of the evolution of the Earth's crust in three phases.

2. *Phase I of the Earth's evolution, the acquisition of an outer layer of satellitic matter*, by H. P. Berlage

When the origin of the Moon is considered, very often only two extreme possibilities are distinguished. The Earth should have launched the Moon or have captured the Moon.

Spontaneous fission of Proto-Earth into present time Earth and Moon is highly improbable, because the angular momentum of the common body can never have reached the required value. G. H. Darwin was the first to suggest that fission of Proto-Earth might have been promoted by resonance, but Jeffreys pointed out that tidal forces and deformations of planets are not in linear relation. This excludes a significant contribution of resonance to the Moon's birth, even if the unreasonable smallness of the ratio of the masses of the two separating bodies, 1: 81, is overlooked.

A certain amount of propulsion of the Moon by the Earth is not excluded. RINGWOOD (1960), WISE (1963), CAMERON (1963), *et al.* hinted at some possibilities, in particular the variation of internal potential energy into kinetic energy of axial rotation, during the settlement of the Earth's denser materials to the core. However, there are serious objections to this theory. The Moon can hardly have been propelled into a closed orbit around the Earth. Moreover, the Moon should have been launched beyond Roche's limit in order to survive. The author's impression is that we have realized in our space age that launching the Moon from the Earth and have her is an operation so complicate as to be plainly impossible.

The opposite view is the capture of the Moon by the Earth. It has gained many supporters. G. H. Darwin's theory of the tidal interaction between Earth and Moon has been revised recently by GERSTENKORN (1955) and MACDONALD (1964), with the aid of modern computers. These two investigators concluded that at a certain time the Moon circulated round the Earth at a distance from the centre of no more than 2,89 and 2,72 earth-radii respectively.

How and when did the Moon come so near the Earth? The only way of capture is such that the Moon started to move around the Earth in the retrograde sense. Consequently, the Moon approached the Earth by tidal interaction and spiralled inward towards the critical distance which Roche indicated. Because the average density of the Earth is 5,52 and the average density of the Moon is 3,34, Roche's limit is about 2,9 earth-radii.

According to both Gerstenkorn and MacDonald, during the time of closest approach the inclination of the lunar orbit and the obliquity of the Earth's equator changed rapidly. The Moon's orbital plane passed over the poles, the Moon's orbital motion changed from retrograde to direct. Gerstenkorn is ready to assume that in the course of this dangerous operation pieces of the primitive Moon were detached. Part of this matter may have fallen on Earth. ALFVÉN (1965) and KOPAL (1965) are inclined to follow this view and to explain the characteristic features of the lunar hemisphere facing the Earth by its disruption, while transgressing Roche's limit. The conclusion of these authors is that the present Moon emerged safely from the danger zone. Since this emergence the Moon receded from the Earth. It has now arrived at roughly 60 earth-radii distance from the centre.

On the other hand, the present author, when looking backward as far as Gerstenkorn and MacDonald, is afraid to find the Moon completely destroyed, resolved in small particles, as a ring, like Saturn's ring, with an average radius of about 2,8 earth-radii, spinning round the Earth in the direct sense, just inside Roche's limit. Encouraged recently by Öpik (1961), Ruskol (1963, 1966) and Whipple (1964), he wishes to ask again the following question. Why assume catastrophies, such as an expulsion or a capture of the Moon by the Earth, why not assume that our Moon originated as all planets and all regular satellites did? They were no doubt (Berlage 1962) agglomeration products of concentric dust rings, derived by accretional instability from the initial dust disks spinning round their primaries.

Proto-Earth is an agglomeration product of one of the dust rings, turning round the Sun. The Earth again, during its final condensation, obtained a dust disk spinning around it in the direct sense. The only abnormal property of the Earth's disk, when compared with the primeval disks of the other planets, was its large mass. This must have amounted to roughly 0,028 earth-mass (Berlage, 1959).

Our terrestrial disk's natural course of evolution is associated with maximum transformation of potential energy into kinetic energy, while its total angular momentum and total energy remain constant. Fig. 2 illustrates the opposite ways of energy transformation associated with the two specific radial density undulations impressed on the dust disk, which limit the number of major satellites to one (b) or two (a) (Berlage, 1948).

The natural course of evolution is indicated by the condition that the excess of the sum of the white surfaces over the sum of the black surfaces is greatest. This condition is satisfied in case a. The excess of the sum of the black surfaces over the sum of the white surfaces is greatest in case b.

Consequently, the generation by a planet of only one regular satellite is excluded. A planet acquires at least two regular satellites of major importance. Mars, in possession of two small satellites, Phobos and Deimos, shows us what even a tiny planet can achieve, when operating with the greatest possible efficiency.

Hence, the Earth with only one regular satellite, is to be regarded with suspicion. This, in a sense, was done by all those suggesting some catastrophy, in particular a capture of the Moon by the Earth. Strictly speaking, the matter due to form the Moon was captured by the Earth in its early state.

When reviewing the arguments for a capture of the Moon in its final state, perhaps the main one is that the Earth, average density 5,52, apparently contains iron and nickel in a much greater percentage than the Moon, average density 3,34. If Earth and Moon were built up out of the same substances in the same proportions, how could such a difference be explained. Do we have to look for a birth of the Moon in a different district of the solar system? This is the reason why Mars and Moon were grouped together by Alfvén (1954) and others, in a sense similar to the grouping of Pluto and Triton.

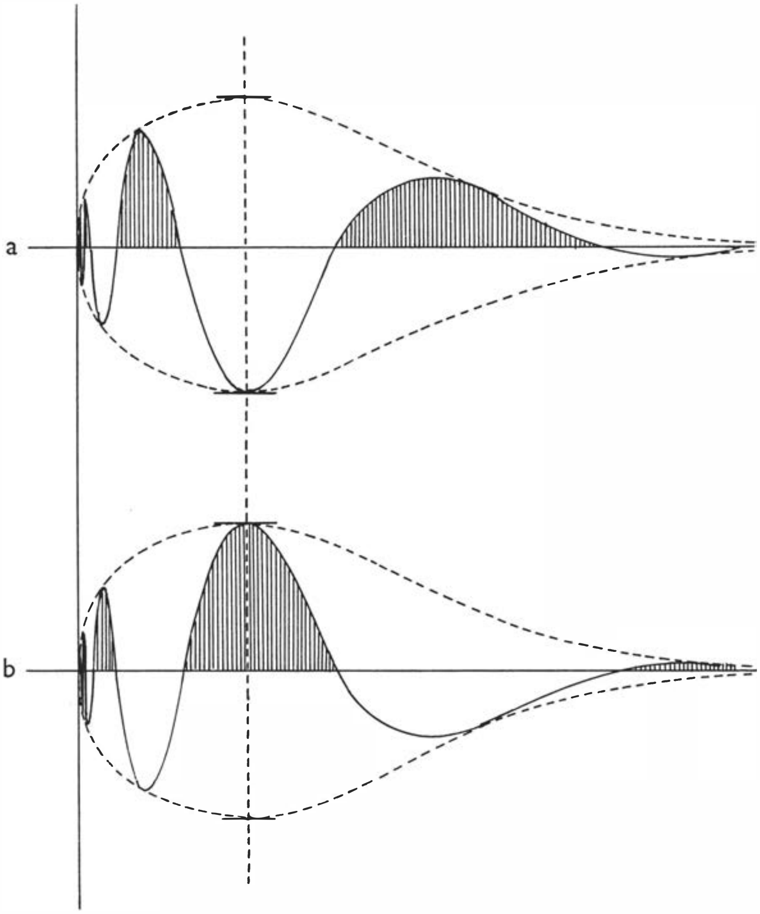

Fig. 2. Opposite ways of exchange of potential and kinetic energy in a dust disk spinning round a massive central body.

A number of geophysicists pointed out the possibility that the Earth's core does not consist mainly of iron and nickel, but mainly of a high-pressure phase of silicates. The discrepancy between the average densities of Earth and Moon could be removed in this way. However, the innermost terrestrial planet, Mercury, has an average density of 5,46. It is the smallest terrestrial planet, its mass amounting to 0,054 earth-mass, and it could never have reached this density, if it did not contain iron and nickel in a higher percentage than the Earth.

Evidently the development of a dust disk, spinning round a massive primary body, leads to a concentration of the heaviest materials towards the centre. This would explain equally the high density of the Earth relative to the low density of the Moon. The substances contained in the Moon are similar to those contained in the Earth's mantle.

Now, as we know, the Earth must have endeavoured to produce two major satellites. The distances from the centre where these satellites grew are deducible from the basic scheme of any planetary and satellite system, designed by BERLAGE (1959). Our present Moon originated at a distance from the centre of 5,8 earth-radii. The same distance was assumed by ÖPIK (1961) on other grounds. The Moon's heavy colleague originated close to the Earth's equator, and a third satellite was due to originate at a distance of $5{,}8^2$, or roughly 34 earth-radii.

As regards the masses m_1, m_2 and m_3 of the three satellites in outward succession, BERLAGE (1959) obtained the relations $m_2/m_1 = 0{,}76$ and $m_3/m_2 = 0{,}00058$. Hence, a satellite of about 1.3 times the Moon's mass was united with the Earth. The third satellite was very small and can only have existed as a ring of meteoritic bodies. These planetesimals are likely to have bombarded the Moon, creating its prominent maria and the most impressive impact craters, when the Moon, during its recession, passed the distance of 34 earth-radii.

Tidal theories agree that this must have happened roughly 2000 million years ago, and hence at least a significant, although perhaps relatively short, part of the Moon's life must have elapsed before it crossed this danger zone. As a matter of fact, according to FIELDER (1963) and HARTMANN (1965), even the majority of the lunar craters should have been formed previous to the maria.

Moreover, the puzzling lunar moments of inertia may have been determined largely by the fall of the heaviest planetesimals and the structure and consistence of the maria caused by them. Even if the strongest impacts occurred mostly on the Moon's hemisphere projected in the direction of the Moon's orbital motion, it may explain the singular morphology of the Moon's hemisphere facing the Earth at the present time, because tidal interaction may well have turned the Moon through 90 degrees since its critical passage through the belt of planetesimals.

The inner satellite of roughly 0,016 earth-mass can only have existed as a ring of dust or grains, spinning round the Earth inside Roche's limit, following Saturn's example, but in a narrower and denser string along the equator. It was united with the Earth by viscosity, and should have covered the Earth's mantle with a crust of roughly 65 km average thickness, of typically satellitic material, in what may have been a relatively late stage of the Earth's primitive evolution.

This coverage may have left detectable traces in geologic history.

3. *Phase II of the Earth's evolution, the transformation of the outer layer into a sialic crust,* by W. Nieuwenkamp

All over the continents the crystalline formations show a broad similarity in the component rocks and in the patterns in which these are arranged; they have much the same appearance whether seen in large tracks in the old shields, in high plateaus or in the cores of mountain chains, or whether brought to the fore from underneath a thick sedimentary cover in deeply eroded cañons or through drilling.

On the other hand owing to their great complexity no two are exactly alike, an experienced field-petrographer might claim to be able to recognize every larger suite of exposures as to belong to a certain individual formation. Every formation may thus be said to have its peculiar characteristics; nevertheless it is not possible to arrange them according to some significant principle. As regards age many strenuous attempts failed to bring to light a secular trend in any observable property.

In so far as petrological research leads to clues about the way in which crystalline rocks have been formed, it has to be concluded that the processes of rock formation have been going on in virtually the same way during the 3400 million years which encompass the geologically observable part of the Earth's history.

Surely our knowledge of the Earth is uncomplete and unsatisfactory as long as we do not know how it came into being. For most geologists, therefore, it is disappointing that their own methods of investigation fail to give any clue about the birth of our planet. Far back in the history of human thought speculative imagination evolved vague concepts about the creation of the Earth and the Heaven. Since the scientific revolution most naturalists, like Leibniz, implicitly accept the premiss that the Earth should contain a category of primary rocks from which secondary rocks were derived. This urge to find indications for a more primitive stage in the Earth's development is prompting many lines of research, in the hope of hitting upon some significant deviation from the principle of uniformitarianism. However, although the composition of basalts, granites, slates, and many other rock types of widely different age has been studied in minute detail (trace elements, fractionation of the isotopes of carbon and sulphur, etc.) no secular trend composition could be found. Every instance of investigation merely served to corroborate the picture of stricktest uniformity. This result is disturbing to those who feel that somehow geological and petrological observations should be able to inform us about the origin, if not of the Earth itself then at least of its crust (the lithosphere).

It has to be remarked, however, that some of the most creative minds on record in the history of geology were not desirous to find an evolutionary trend; that they did not see any sign of a beginning was completely satisfactory for Hutton and Playfair. They liked to compare their system of the Earth with the planetary system; conforming to Newton's laws, the motions of the planets and their satellites could be followed up and predicted in minute detail, whilst no observational evidence gave any hint as to how these celestial bodies had ever been set on their paths. Indeed, for these authors it would have meant an imperfection in the work of the Creator if it would bear the marks of having been put together in a certain way at a certain time. This attitude of mind is analogous to the apparently widespread belief, that – in order to be perfect – a piece of earthenware should not bear a visible imprint of the potter's thumb.

Just as the centrifugal force in the planetary system is steadily counteracted by gravitational attraction, so in Hutton's system the continents which are destroyed by weathering and erosion are for ever again repaired by the solidifying and heaving power of the Earth's central fire.

The most cogent reason, why this cyclic aspect of the Huttonian theory of the Earth could not be accepted is to be sought in the developments of physics in the 19th century, which were devastatingly adverse to the enormous length of time involved. Namely the budding science of thermodynamics taught scientists to draw a sharp distinction between 'heat' and 'temperature', while demonstrating that the geothermal gradient represents a heat flow, which results in an incessant and irretrievable loss of heat from the Earth. Moreover the resulting rate of cooling could be easily estimated. As it was impossible to imagine an acceptable means of counteracting this loss of heat Kelvin's calculation carried full conviction: he came to the conclusion that the lithosphere started its career less than 100 million years ago as a first crust of consolidation around an incandescent, molten globe.

Kelvin's estimate represents for the geologists a disquietingly short time. The crust of consolidation could not have grown to any great thickness, for a geothermal gradient near to the surface of 30° C per kilometer simply meant that at a depth of 50 km a temperature of 1500° C is reached. Such a high temperature being above the melting temperature of most rocks at the surface the conclusion was drawn that the Earth consisted of a globe of molten magma surrounded by an eggshell-thin solid crust. Towards the end of the 19th century this romantic picture had so much persuasive power that it came to represent the 'official truth'.

The corresponding petrological theory—which may here be called 'classical magmatism', for convenience sake—has been expounded in the first place by ROSENBUSCH (1898) in such an authoritative manner that soon the great majority of geologists was convinced that it was nothing but a straightforward statement of fact. True, Rosenbusch explained that his definition of igneous rocks as "parts of the molten interior incorporated in a geological formation" could not be gainsaid, because if a melt has played a part in the making of a rock, then this melt was certainly in deeper levels before its intrusion or extrusion. Though Rosenbusch did not explicitly presuppose an entirely molten state of the Earth's interior, nobody failed to recognize the implication of a worldwide subterraneous ocean of magma. Since Rosenbusch so many aspects of the concept of classical magmatism had to be tampered with in the course of the twentieth century, that indeed scarcely any part of it can be held upright nowadays. Nevertheless, the older generation of petrologists still senses a distant rumble of that magma-ocean at the mere mentioning of 'igneous rocks'. And generally 'magmatic differentiation' still evokes the picture of at least a number of intra- or subcrustal 'magma chambers'.

Thus the concept of classical magmatism could hold its grip on geological thought for many decades, even against the most opposite modern developments in petrology and geophysics.

Seismic observations and measurements of tidal deformation of the surface of the solid Earth have shown that the interior is too rigid to be molten in the sense of our daily experiences. Moreover the absolute age of some rocks proved to exceed thirty times the original estimate of the Earth's age made by Kelvin.

The fundamental difference between the Huttonian and the classical point of view concerns the provenance of the rockforming constituents. For Hutton these are derived always from the destruction of older formations. For the classical magmatic concept, on the other hand, the constituents are largely juvenile additions, derived from primary magmas at greater depth. The absence of an evolutionary trend in the composition of the crystalline rocks, the geophysical doubts about the presence of a subcrustal magma-ocean, and other progresses in geonomy are all more in favour of the Huttonian concept. Yet this has not incited the magmatists to a fundamental revision of the classical doctrine.

As early as the end of the 19th century SEDERHOLM (1923) studying the crystalline shields, envisaged already the possibility of magma-formation by melting of previously existing rocks, 'palingenesis'. Since then, the intensified study of deeply eroded crustal formation revealed the presence of large amounts of rocks which are certainly of sedimentary provenance.

It is nowadays perfectly clear that a large part of the sialic crust above the Moho is derived from sediments. Petrologists like BARTH (1962) arrived at the conclusion that at least the overwhelming majority of the crustal rocks – if not all – have once been sediments. The experimental work in the laboratory, which was at first undertaken to elucidate the theory of magmatic differentiation (BOWEN, 1928) now emphatically demonstrates that at least part of the granites is derived from sediments, composed of sands and clays (WINKLER, 1965).

These results stand in contrast to the ideas of the supporters of classical magmatism, which lead to the premiss that the total volume of sedimentary rocks in the crust is but small, corresponding to a global envelope of some 800 meters mean thickness. SHAND (1943) called sediments 'sawdust, as compared to the living tree of primary rocks'. The magmatists had to acknowledge that cyclic processes were active in the formation of sedimentary rocks; but such secondary rocks were hardly considered a subject worthy of study.

Hutton of course got full recognition for his interpretation of older basalts and of a number of plutonic rocks as resulting from extrusions and intrusions of magmatic melts. But he considered his view of cyclic repetition of sedimentation and palingenesis as his main achievement. This latter concept was so completely forgotten that it was sometimes even thought that classical magmatism was an elaboration of Hutton's theory. We come to the conclusion that Hutton was correct in stating that cycles of rock decay and reconstruction have been reworking the same material since the formation of the oldest rocks now found. But then we are not in a position to derive from the petrological study of rocks any clues as to how these cyclic processes were set going. There still is the gap of information between cosmogony and geology. The only result of our considerations is that we possess nowadays a clearer insight into the geological situation at the younger side of this gap. On the other hand, cosmogony now presents a picture of the Earth's state at the older side of the gap. So the construction of a bridge between both realms (astronomy and geonomy) becomes a challenge to both parties.

Berlage (1959) suggests that the newly formed Earth was initially surrounded by a satellitic dust-ring, like the one around Saturn. This ring came gradually nearer to the Earth and then showered down upon it. As the mass of this ring would have been about 4/3 times the mass of the Moon, a simple calculation shows that it may have imparted to the Earth its almost total moment of rotation.

The satellitic matter around any massive central agglomeration probably obtained a disc-like structure which subsequently split up in rings. This model suggests that the shower of satellitic dust on the Earth was concentrated in the equatorial belt. Here a belt of over 100 km height would have been formed, if the Earth was strong enough to support such an additional load. As this was certainly not the case, such an equatorial belt will have sagged down and spread during its accumulation. At the same time, a vigourous attack by weathering and denudation will have set in, if an atmosphere and a hydrosphere were already present at the very outset. We have but few data at our disposal concerning the chemical composition of the ring of satellitic dust that showered on the Earth. It is possible to accept a suitable composition so that the outer Earth, as well as the early oceans and atmosphere might be derived from this ring. By such a supposition we have merely shifted the problem of the chemical contrast between the Earth's mantle and its more peripheral parts from geonomy to cosmogony.

In a first attempt to elaborate an idea about the composition of the early Earth it is desirable to design a clear hypothetical model. This facilitates the verification of our model by means of van Bemmelen's method of prognosis-diagnosis (1961). We can try to derive the logical consequences of this model (the predictions or prognoses) and then look for observations that confirm or refute the functional correctness of the model (the diagnostic facts). In the case of the cosmogonic starting point we may suppose that the initial overall composition of the Earth is comparable to the mean composition of the present day mantle and the core. It can then be presupposed that this initial composition corresponds closely to the weighted mean of the meteorites which are at present still falling down on the Earth. We need not yet specify in how far the present core of the Earth had already been formed at the very onset, or whether it resulted from a gradual segregation of heavier portions during an appreciable stretch of time of the subsequent terrestrial history.

According to this model of the initial Earth, before the infall of Berlage's satellitic ring, the mean composition would have been ultrabasic, without hydrosphere or atmosphere. On such an Earth possibly nothing much happened, because it was a situation, comparable to that which is now widely accepted for the Moon and for Mars.

According to this view the differentiation into ultrabasic and basic to acid matter had already occurred in the pre-geological stage of planetogenesis, during which the planetary disc of matter had split up into a central body of high-density material, surrounded by satellitic rings which consisted for the greater part of material with a relatively low density. The inner one of these rings then showered down on the primeval Earth, supplying the constituents of the outer sphere of the present Earth.

In this inner ring of satellitic dust H_2O was possibly present in the form of ice crystals; a number of anions were combined in salts like carbonates, sulphates, etc. The nitrogen of our atmosphere may have occurred in this ring in the form of NH_4Cl. If all of the 4.10^{15} metric tons of N_2 now present in the atmosphere are derived from this ammonium-chloride, then at least 10^{16} tons of chlorine must be present somewhere on Earth. This prognosis leads to no contradiction, as this amount of chlorine is somewhat less then the total amount of Cl now found in the oceans.

Anyhow, such planetogenesis would have resulted in a situation with strong physico-chemical contrasts, in which the geochemical cycles of petrogenesis in the Earth's outer shell would be set going. The initial situation was characterized by a high equatorial belt, which protruded highly into the atmosphere, whereas the water of the primeval hydrosphere was moved towards higher latitudes.

The departure from isostatic equilibrium in the equatorial belt will have taxed to the utmost the strength of the Earth as a whole. Mass circuits will have resulted, affecting also deeper domains of the mantle and causing early precursors of van Bemmelen's mega-undations. At the same time weathering, erosion and sedimentation set in at a lively pace, accomplishing a highly effective separation of the satellitic dust into silica-poor carbonate rocks and sand-clay sediments. These heterogeneous sedimentary masses were caught up in vigorous circuits, and they were partly dragged down into greater depths, where metamorphism and anatexis occurred as soon as the appropriate high temperatures were obtained.

Berlage's way of setting the petrogenetic processes going has the advantage of vigour and efficiency. There is only a rather short time available for the oldest known rocks, now surviving, to have been formed: some hundreds of million years. These oldest known crystalline rocks are undistinguishable from the younger ones, which bears out the conclusion that the rockforming cycles were already persuing a repetituous course some 3500 million years ago. The sedimentary processes had already separated the constituents of the original satellitic dust into rocks of different composition. This mineral separation which was operative during the first major phase had proceeded to such an extent that further recycling could not improve the individualisation of rock types, already present at the start of the second major phase of the Earth's evolution. A kind of balance had been obtained between selective sedimentation and random homogeneization during palingenesis.

The supposition that the sialic matter of the present crust was already concentrated in the inner ring of satellitic dust during cosmogenesis may lead to interesting consequences as regards the subsequent thermal history of the Earth. We have to envisage an uneven distribution of the radioactive elements. As we know, these elements, characterized by large ionic radii, do not enter dense packings. Perhaps even a large part of them came down with the dust ring and was concentrated in the equatorial belt. During and after the accumulation of this belt radioactive heat will have started to flow into the Earth. Apart from heating by compaction and possibly by exothermal geochemical processes inside the Earth, such an inflow of heat will have been an important factor. It is possible that a reversal of the geothermal gradient was produced at a certain depth. This inversion occurred at first only slightly lower than half way down the bulge or layer of ring-material, but it will have subsequently descended into the mantle. The resulting rise in temperature made the mantle more mobile, and even a segregation of eutectic masses of basaltic magma may have been the result. These magmas of mantle provenance ascended owing to their relatively lower specific density and they started to invade and assimilate the sialic crust, as envisaged by van BEMMELEN'S concept of *Mediterranean oceanization* (1966a).

Considerations according to the neo-Huttonian line of thought, as outlined in this chapter, are of course ill suited for the elaboration of definite concepts about the beginning of the Earth's evolution as well as about changes in the course of the geological development; the processes have the appearance of going on 'for ever'. The cyclic processes of rock decay and reconstitution are located mainly in the lithosphere and in the upper part of the mantle. Van Bemmelen's suggestion that lumps of the lithosphere are being swallowed up and digested (assimilated) by the mantle seems to be startling at first sight. It is the exact opposite of the classical doctrine, still commonly, though often tacitly, held, which says that the crust and the hydrosphere are continuously growing in bulk as a consequence of juvenile additions from depth.

The latter concept, however, leads to a formidable difficulty. According to the concept of juvenile additions it is necessary to accept the condition, that there was continuously a well-balanced production of volatiles (like water, chlorine, boron) as well as of the more refractory, rockmaking materials (in the form of magmas). Without such a perfect balance – incomprehensible as it is – the hydrosphere and the lithosphere could not have maintained a constant composition in the course of thousands of million years. Nevertheless, the atmosphere, hydrosphere and lithosphere seem to have preserved a remarkably constant composition throughout geological history. The correctness of this statement is borne out in every instant, where a new technique permits a closer determination of the syngenetic concentration of the (non-radiogenic) elements in ancient and younger formations. A recent example is the determination of the boron content of illites, which appears to be the same in illites of 2000 million years age and in present-day illites (REYNOLDS, 1965; GREGOR, 1967).

Van Bemmelen's opposite idea that the Earth is in the act of digesting its envelope of foreign satellitic matter, has the enormous advantage that it does not evoke difficulties of this kind. If parts of the crust are removed in a way that is not correlated with its composition, clearly the remaining parts will not be changed in this respect. Hence the continental shields will expose rocks which still bear witness of the long continued cyclic processes by which they have been formed.

GEOLOGY

ON THE ORIGIN AND EVOLUTION OF THE MOON AND THE CRUST OF THE EARTH. II

BY

R. W. VAN BEMMELEN, H. P. BERLAGE AND W. NIEUWENKAMP

(Communicated at the meeting of June 24, 1967)

4. *Phase III of the Earth's evolution, the partial incorporation of the sialic crust*, by R. W. van Bemmelen

In the last decade some important aspects of geonomy have become much clearer. For instance:

1) The youth of the present ocean basins.
2) The existence of mid-ocean rift-belts.
3) The knowledge about great strike-slipfaults in oceanic as well as continental crustal areas.
4) The paleomagnetic indications for continental drift (Blackett *et al.* 1965).
5) The sedimentological and petrographical knowledge about the sialic character of the basement complex underneath the initial sediments of (eu)geosynclinal areas (De Booy, 1966a and b).
6) The physico-chemical knowledge about the high-density phases of rock minerals under conditions of high pressure and high temperature (Researches of the geophysical laboratory of the Carnegie Institute at Washington D.C., and other geochemical laboratories).
7) The geophysical and geological insight that certain continental areas with deep Moho have been transformed in the course of time into semi-oceanic to oceanic areas with a shallow Moho (Caribbea, according to van Bemmelen, 1958; Japan Sea, according to Beloussov and Ruditch, 1961; the Mediterranean Basins like the Thyrrenean Sea, according to Yemel'yanov *et al.*, 1964).

All these and other diagnostic facts of modern geonomy have to be taken into account in our concepts on the evolution of the Earth. All theories on geological evolution, and the explanation of the present structural features of the Earth's surface have to be tested in the light of this new evidence. The greater part of the current views, based on the so-called classical and generally accepted concepts, might then appear to be utterly outdated.

Also newer hypotheses, which are based only on a restricted field of evidence – ignoring the other fields of modern geonomic research – will almost certainly appear to be inadequate models.

A preliminary synthesis of this rapidly growing wealth of the older and newer diagnostic facts has been given by VAN BEMMELEN (1966a). For details the reader is referred to other publications of this author (1964a, 1964b, 1965a). Here only a broad outline can be given.

Van Bemmelen's concept is based on the premiss of the acquisition by the Earth of an outer envelope of satellitic matter, about 65 km thick, during the first major phase of the Earth's evolution. In other words, it starts with Berlage's view that the crustal matter has been acquired by the Earth from without. This meteoritic matter probably derived from a second, but undeveloped satellite of about 1/60 of the Earth's mass, forming a dust ring inside Roche's limit, like the ring of Saturn.

During the second major phase of the Earth's evolution (after the condensation of a hydrosphere) this envelope of satellitic matter has been transformed into the sialic crust, by means of chelogenic cycles of orogenesis (SUTTON, 1963). This transformation of the original satellitic dust caused the growth of the metamorphic and granitized nuclei of continents at the cost of the still mobile interjacent areas. This process is known as the growth of the continental shields, an idea which has been specially advocated by STILLE (1924).

However, the crustal shields of sialic matter were not separated by interjacent areas of an oceanic (or simatic) crust, as is the present situation. There was an outer layer of satellitic matter rich in silica, which enveloped the entire Earth. This layer was invaded by swarms of juvenile basalt magma from the mantle, cycled and recycled by erosion and sedimentation, cooked and recooked into granitic magmas, metamorphosed and consolidated into shields, occasionally remobilized and again invaded by juvenile magmas, etc. This very long lasting process of crustal transformation during the second part of the Earth's evolution probably occurred according to Nieuwenkamp's neo-Huttonian concept of the persedimentary character of the sialic crust. At the end of this second major phase the Earth was probably entirely enveloped by a sialic crust, which was covered for the greater part by shallow seas.

The present continental shields are only remnants of this precambrian sialic crust. Towards the end of the second cycle the endogenic heat of the Earth, which had caused the transformation of the original satellitic envelope, was able to start the third and latest phase of the evolution of the Earth's crust, i.e. its incorporation.

The basaltic magmas which were intermittently segregated by the mantle, ascended until they reached the base of the granitic crust. These superheated magmas not only caused invasions of dike swarms in the crust and magmatization (with the genesis of palingenetic silicic magma suites), at the base of the crust they also spread sidewards underneath the crust, removing the mobilized sialic matter. After cooling they swept sial to greater depth, where sialic matter was transformed into high-density phases which are stable in greater depths, at higher temperatures and pressures.

These 'eclogitic' mineral assemblages are geophysically, seismically and gravimetrically similar to the 'peridotitic' matter of the outer mantle. Such a removal of sial to greater depths and its incorporation into the outer mantle means a progressive reduction of the bulk of sialic crust and a reduction of its thickness.

In some regions this process can proceed so far that the entire sialic crust is removed and replaced by a simatic crust (of 'oceanic' character). Van Bemmelen calls this process the *Mediterranean type of oceanization.* It is a physico-chemical process, which is accompanied by circuits of matter in the outer 200 or 300 km of the outer mantle, the asthenosphere. The process of Mediterranean oceanization disrupted more and more the continuity of the sialic crust. The present continental shields are but the remnants of the original crust; more than two thirds of the geological data, laid down in the structure and composition of the crust, have thus been definitely destroyed.

Once, there may have existed – apart from Laurasia and Gondwana – a large sialic crustal area in the Pacific, which might be indicated by the name of 'Pacifica', but we have very little direct evidence of this primeval crustal area. West of North and South America land areas were once present, as late as the Mesozoic. GILLULY (1965) discussed the vulcanism, tectonism and plutonism of the Western United States and suggests that the eugeosyncline developed on an oceanic crust. But this supposition is at variance with the findings of DOTT (1966) and DE BOOY (1966a, b). Moreover, EARDLY (1966), discussing GILLULY's paper, remarks that the real problem lies in vizualizing how the gigantic silicic bodies, some with roots to 50 km deep, could have formed in the oceanic crust-eugeosynclinal setting. Moreover, the eugeosyncline was filled by widespread and thick clastic sediments, in part derived from granitic and quartzose sedimentary terranes. The source of these sediments is also a problem. Gilluly and earlier also Eardly suppose the presence of sialic island arcs in the present Pacific Ocean. The question might be posed whether these island arcs did not belong to a more extensive Pacific continent, which has been removed in the course of the Paleozoic and Mesozoic by the Mediterranean type of oceanization. West of South America several authors (ILLIES, 1960, ZEIL, 1960 *et al.*) have supposed a continental area, called Juan Fernandez Land. The oceanization of this sialic area was discussed by VAN BEMMELEN (1966a, fig. 7 on p. 101, 115, 116 and 117). At any rate oceanographic researches (MENARD, 1964) have made clear that the Pacific is a very young ocean, 100–200 million years old, like the Indian and Atlantic oceans. We can merely suppose that the Mediterranean type of oceanization has removed Pacifica almost entirely, whereas this type of oceanization is only in an initial stage in the marginal sea basins of Asia and Australia and in the Mediterranean belt between Laurasia and Gondwana.

The oceanization of the Mediterranean type had also some important physical effects. It increased the contrasts between oceanic seas with a simatic crust and continental shields with a sialic crust. The seas became deep oceans and the remnants of the sialic crust emerged as extensive shields rather high above sea level. Moreover, Laurasia and Gondwana had obtained a free board.

Due to the progressive process of oceanization of the Mediterranean type it is probably this greater freedom of lateral displacements which allowed drift movements of the kratonic fragments of these primeval continents during phase III of the Earth's evolution.

The occurrence of continental drift has become a generally accepted diagnostic fact, since Wegener's bold concept of half a century ago has been broadly confirmed in recent times by oceanographic and paleomagnetic researches.

Of course there still are many problems and uncertainties (see Blackett *et al.*, 1965), but the general geonomic evidence is nowadays too strong to continue denying 'mobilism', occurring during the youngest part of the Earth's crustal evolution.

Van Bemmelen (1964a, 1964b, 1965a, 1966a) has proposed a mechanical explanation of this drift, which deviates from the current model of convection currents. This author's explanation is based on the presence of extensive bulges and depressions of the geoid, with diameters of 5.000–10.000 km and actual amplitudes of some dozens of meters only. These 'mega-undations', are observable by artificial satellites (Kaula, 1963) and they are probably generated by disturbances of the rheological equilibrium and mass-displacements in the lower mantle. The lateral displacements in the outer mantle and crust are not caused by the application of forces from the outside, such as the drag by convection currents. They are autonomous movements, due to the potential gravitational energy present in every mass-element. This potential energy results from upward and downward movements owing to the geodynamic processes in the lower mantle. The process of lateral displacements in the upper mantle and crust may be compared with the differential lateral spreading of a tilted stack of books (van Bemmelen, 1965b, 1966b, 1966c). Thus the highest units, represented by continental shields move farther sideward and at a higher speed than the deeper seated layers of the mantle.

The process of continental drift is accompanied by another type of oceanization, which might be called the *Atlantic type of oceanization*. It is a purely mechanical process, due to the gravity tectonics of the spreading top parts of mega-undations. The drifting continental shields crowded out the water from the invaded oceanic area, whilst in their rear new ocean basins, like the Atlantic and Indian Oceans, have been formed (VAN BEMMELEN, 1966a, fig. 6, p. 111–112).

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