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Geology. — *"The Coral reef problem and Isostasy".* By Prof. Dr. G. A. F. MOLENGRAAFF.

Translated from the Dutch, somewhat revised and augmented.

(Communicated in the meeting of June 24, 1916).

The question of the origin of coral islands (barrier reefs and atolls) has of late been brought to the foreground again by the recent publications of DALY [1]) and DAVIS [2]).

It is generally known that according to DARWIN's theory a considerable subsidence of the floor of the ocean over extensive areas is one of the necessary conditions for the formation of barrier reefs and atolls. While DARWIN's theory has maintained itself splendidly, at any rate in its main principle, against the numerous and manifold objections raised against it more especially after the Challenger expedition, still the great crustal movements which it requires always remained its weakest point which did not meet with general approval.

DARWIN [3]) speaks expressly of real subsidence of the floor of the ocean itself, from which the coral formations, barrier reefs and atolls, rise. This real subsidence is very considerable; DANA [4]), in connection with DARWIN's theory of the coral islands, assumed that since the tertiary period in the Pacific alone a region extending over 15 to 30 million square kilometres must have sunk 1000 to 1600 metres.

Depressions on such a scale of a considerable portion of the earth's crust, although not impossible, are not very likely [5]). They have

1) R. A. DALY. Pleistocene glaciation and the coral reef problem. Amer. Journ. of Science 4, XXX, p. 297, 1910, and The glacial-control theory of coral reefs. Proc. of the Amer. Acad. of Arts and Sciences **51**, p. 157, 1915.

2) W. M. DAVIS. A SHALER memorial study of coral reefs. Amer. Journ. of Science 4, XL p. 223, 1915.

W. H. DAVIS. The origin of coral reefs. Proc. Nat. Acad. of Sciences. I. p 146, 1915.

— Extinguished and resurgent coral reefs. Proc. Nat. Acad. of Sciences. II. p. 466, 1916.

— The origin of certain Fiji atolls. Proc. Nat. Acad. of Sciences. II. p 471, 1916.

— Problems associated with the study of coral reefs. The Scientific Monthly. II. p. 813, 1916.

3) CH. DARWIN. On the structure and distribution of coral reefs. Chapters V and VI.

4) J. D. DANA. Manual of Geology. Fourth, last edition 1896, p. 350.

5) It should be remarked that for the greater, central part of the Pacific all that is known until now about the relief of the bottom, tends to prove that this downward movement, if it has taken place at all, could not well have been compensated by a more or less equivalent upheaval of regions of comparable extent, since the atolls and islands encircled by barrier reefs in this ocean appear to stand on somewhat elevated strips of the bottom of the ocean, which are surrounded by still deeper basins. Compare: MAX GROLL. Tiefenkarten der Oceane.

remained a moot point and the papers published by DALY and DAVIS mentioned above deal mainly with this point, DAVIS' conclusion being that subsidence on a considerable scale, as postulated by the theory of DARWIN-DANA, is indispensable, while DALY on the contrary gives and upholds an explanation of the origin of coral islands in which subsidence of the floor of the ocean is *not* put forward as a necessary condition.

DAVIS, in his paper, has worked out a point of view to which DANA had first drawn attention. DANA [1]), independently, derived a strong argument in favour of DARWIN's theory and one which DARWIN himself had not yet used, from the contours and the relief of the islands which are surrounded by barrier reefs, and especially from the submerged or "embayed" valleys occurring on those islands.

DAVIS tested and verified the value of this argument by investigations in a large number of coral islands in the Pacific and proved that where barrier reefs occur, the fringed coasts are indented almost without exception and possess "embayed valleys".

Finally DAVIS by clear reasoning [2]) arrives at the result that only the subsidence-theory of DARWIN and DANA leads to a satisfactory solution of the problem of the origin of barrier reefs and atolls.

DALY maintains, more emphatically than PENCK [3]) had done before, that in the pleistocene period the storing of large quantities of water in circumpolar icecaps must have lowered the sea-level in aequatorial regions as much as 50 to 60 metres, which caused a corresponding equal lowering of the plane of abrasion and of the final base-level in those regions, whereas after the close of the glacial period a rise of the sea-level must have occurred of about the same amount caused by the melting of those icecaps. During this last rising of the sea-level or apparent subsidence of the land according to DALY and on account of it, the formation of the barrier

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Veröff. des Inst. für Meereskunde. NF. A. 2. 1912. A non-compensated subsidence of such a considerable part of the Pacific since the tertiary period would have caused an apparent general rise of all continents — calculated from their present size — of about 120 metres. One might expect to find at least some indication of such an upheaval, but this is not the case.

1) J. D. DANA, in United States WILKES' Explor. Expedition, Geology p. 131, 1849, and W M. DAVIS. DANA's confirmation of DARWIN's theory of coral reefs. Amer. Journ. of Science 4. XXXV p. 183, 1913.

2) Very interesting in this respect is DAVIS' preliminary paper, entitled: The Home Study of Coral Reefs. Bull. Amer. Geogr. Soc. Vol. XLVI. p. 561, 1914.

3) A. PENCK, Morphologie der Erdoberfläche III, p. 660, 1894.

PENCK thinks it possible that during and on account of the pleistocene glaciation the sea level has been lowered as much as 150 metres.

reefs and atolls took place. That such fluctuations of the sea-level, as DALY assumes, caused by the pleistocene glacial periods, have indeed taken place can hardly be doubted.

The remarkable shelf seas of the East Indian Archipelago, such as the Java sea and the Sahul bank, strongly support DALY's theory. From the geological structure of these two regions may be inferred that they have not been affected by the strong contrasting crustal movements which in recent geological times have either caused the very uneven relief and the complicated topography both of the land and the seabottom in the eastern part of the East Indian Archipelago or at any rate have made it much more prominent. The Java-sea is shallow [1]) and has a very constant depth which, on the average, does not deviate much from 50 and 60 metres, which is exactly the figure accepted by DALY for the rise of the sea-level (apparent subsidence of the land) in aequatorial parts since the pleistocene epoch. The same holds good for the Sahul bank. In both the Java-sea and the Sahul bank the bottom of the sea at present gives the impression of a submerged, strongly peneplainized land-surface. The mature forms of erosion which are met with on the islands of Bangka and Billiton, the Karimata islands and in West Borneo, which may be said to show a near approach to a peneplain, justify the surmise that those groups of islands are nothing but the harder more resistant parts or monadnocks left by erosion in the broad peneplain which in pleistocene times, the ocean-level being lowered, has been formed between the mountain-land of Sumatra and Java on the one hand and that of Borneo on the other. In late- and post-pleistocene times this peneplain has been submerged through the rise of the sea-level to a depth of some 50 to 60 m., by which submergence the present Java-sea was formed with its remarkably constant depths. In a similar way the Sahul bank was submerged along the north-west coast of Australia, a shelf thus being formed of equally remarkable constant depth.

In DALY's "glacial-control theory" a factor is brought forward for the origin of barrier reefs and atolls, which certainly has been of primary importance for the possibility of the formation of many of those types of coral-reefs.

Marine abrasion in the pleistocene period at lower sea-level,

[1]) Quite erroneously WEGENER quotes the floor of the Java-sea as an example of a shelf of great depth, according to him about 300 m. The words "Getreuer Querschnitt durch den 'Javaschelf" (true section through the Java shelf) accompanying his figure 10, had therefore better been omitted. Compare A. WEGENER. Die Entstehung der Kontinente und Ozeane. p. 36, Braunschweig 1915.

followed by an apparent subsidence of the land caused by a rise of the sea-level, as DALY imagines, has created the conditions necessary for the origin of many barrier reefs and atolls; in a still larger number of coral reefs it has equally certainly determined their present shape as well as that of the submarine platforms from which they rise, and finally it has had its share in the formation of all of them.

Yet it appears to me not yet definitely proved that the "glacial control theory" is sufficient to explain the origin of all barrier reefs and atolls.

This theory gives no explanation of true or apparent subsidence of the land of considerably over 50 or 60 m., which must be admitted in order to explain the formation of several barrier reefs and atolls, e.g. of the numerous atolls which in the Pacific rise individually with very steep slopes from abysmal depths and do not stand connected with others on relatively shallow submarine platforms. True or apparent subsidence of the land of considerable amount is in my opinion indispensable for the explanation of the origin of those. In fact, for many islands surrounded by barrier reefs, a subsidence, certainly exceeding 60 m. must be inferred, with almost absolute certainty. according to DAVIS, from the occurrence and the shape of the "embayed valleys". Also, on the Funafati atoll the well-known boring in the lagoon has proved a subsidence of at least 75 m. and the boring on the reef there has made a subsidence of ± 340 m. probable.

To sum up I think we may conclude that the problem of the origin of the coral islands is at the present moment in this stage that it is pretty generally conceded that a subsidence of the ocean-bottom, either true or apparant, must be assumed for the regions where barrier reefs and atolls are found. Considerable uncertainty and diversion of opinion however still exists as to the amount and the cause of this subsidence.

A glance at a map showing the geographical distribution of coral-reefs shows that they occur in regions so much varying in geological structure that we can hardly expect the causes of subsidence to have been the same in all cases.

In fact subsidence of the land can be explained without much difficulty by crustal warping (or folding) where it is found to be restricted to the coasts of continents or to islands which are closely related to continents and rise from the same submarine platform as the continent does, as is the case in the southwestern part of the Pacific, which stands in close relation to the Australian continent.

The name south-western part of the Pacific I use here in denoting the part, west of the Kermadec and Tonga deep-sea troughs (see fig. 1), i. e. exactly the part which GERLAND [1]), with respect to its

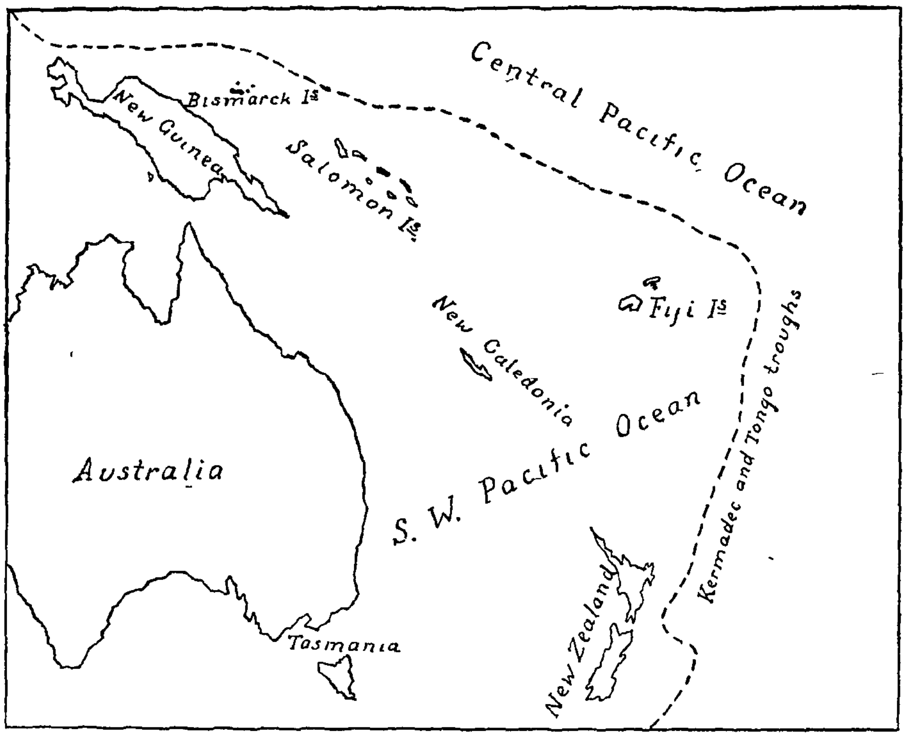

Fig. 1. ----- Boundary-line between the southwestern and the central part of the Pacific Ocean.

structure, as the south-western part of the Pacific, contrasts to the north-eastern part, which I shall call the central part. MARSHALL [2]) also admits as the south-western border of the main (true, great or central) Pacific a line drawn along the Kermadec and Tonga troughs and from there along the north side of the Fiji archipelago, the New Hebrides, the Salomon Islands, etc.

Depressions, such as are found in this south-western part of the Pacific, appear to have been chiefly caused by crustal movements of opposite direction, so that a subsidence in one part of the region is more or less compensated by an upheaval in other parts. In this south-western part of the Pacific one finds, besides indications of

[1]) G. GERLAND, Vulkanistische Studien I. Die Korallen-inseln vornehmlich der Sudsee. Beitrage zur Geophysik II. p. 29, 1895.

[2]) P. MARSHALL, Oceania, Handb. der reg. Geologie VII. Heft 2, p. 28 and 32, 1911.

very considerable subsidence, in many islands the proofs of recent very strong upheaval In New Guinea tertiary deposits have been observed to occur on the highest mountain tops (Carstensz-top, 4780 m., and Wilhelmina-top 4750 m.) and in the group of the Fiji islands [1]) some regions have in recent times been raised 300 m., while parts only a few kilometres distant show traces of strong subsidence and submergence.

As to the real or apparent subsidences of lesser or larger extent in true oceanic regions, not compensated by counter-movements, such as are generally assumed to have taken place in the Central Pacific as well as in the Indian Ocean and also in a small part of the Atlantic, no satisfactory explanation of their mode of origin has as yet been given and great uncertainty continues to prevail on this head.

Now it is clear, that, before we try to suggest any explanation, the question has to be considered how far the assumption of the subsidence of true oceanic islands is supported by facts. Such consideration proves that although the assumption of subsidence is indirectly supported by the convergent evidence of many facts, yet until now, only one fact is known, which gives direct evidence of subsidence and, consequently, disappearance below the sea-level of an oceanic island.

This fact is the subsidence recently proved with certainty by boring on the island of Bermuda. Bermuda-Island is the only oceanic island in the Atlantic lying within the limits of the geographical distribution of the reef-building corals. Bermuda-Island, or the group of the Bermudas, is at the surface entirely composed of reef-limestone. It rises on a submarine bank or shoal which is strongly elongated in a south-east and north-west direction. This shoal is 51 km. long at a depth of 100 fathoms and is surrounded on all sides by a sea of an average depth of 4500 m.

The deep boring referred to was made in the island in the year 1912 at a point situated 42 m. above sea-level. It proved that Bermuda Island consists of a volcanic mountain, built up of a series of superposed banks of basaltic volcanic material, the probably truncated top of which now lies somewhat more than 75 m. below sea-level.

On this truncated cone or platform rests the so-called Bermuda limestone, a reef-limestone extending upwards to the surface of the sea, the portion of the island projecting above the sea also consisting of it.

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[1]) E. C. Andrews. Relations of coral reefs to crust movements in the Fiji-islands. Amer. Journal of science. XLI. p. 141, 1916.

The lowest and oldest part of this cap of limestone is of late-eocene or early oligocene age. PIRSSON [1]), who examined the boring material, was able to prove that in eocene time Bermuda Island projected from the sea as a volcanic island and that, probably after the volcanic activity had subsided, it was wholly or partially truncated by wave-action. During that process and afterwards the island gradually sank to a depth of somewhat more than 75 metres below sealevel and it was during this period of subsidence that the reef-limestone was built up on the top of the sinking island. The limestone probably always reached about to the surface of the sea and hence grew thicker at the same rate as the island subsided.

The fact that in some hills the Bermuda reef-limestone is now situated over 40 m. above the sea, proves that the subsidence did not proceed continually without true or apparent opposite movements [2]). The main movement, however continued to be downward. It first made itself felt probably in pre-eocene times and has very likely amounted to some hundreds of metres in total.

A part of this movement, namely the portion that took place since the pleistocene period, has probably been caused by a rise of the sea-level as explained in DALY's "glacial-control theory", but not the entire subsidence can be explained in this way. First, it is too great considering that the island lies at 35° N. lat., but moreover the movement had already begun in oligocene time, as PIRSSON shows. Besides in the same borehole at 290 m. (935 feet) below sea-level, volcanic material was met with again which proved to be well rounded by water and showed traces of subaerial weathering, which fact, even if it were supposed that here a part of a submarine gravel cone was struck, leads one to suppose that the island has subsided considerably more than 75 metres.

This borehole has revealed the fact that where nowadays Bermuda island rises from the ocean, submarine volcanoes once were active, of which finally one or more rose above the sea, that these volcanic islands gradually sank away and disappeared under the ocean-level since a period preceding the eocene and that their subsidence for a long time has been compensated by the accumulation of successive streams of basaltic lava. The layer struck in the borehole at a

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[1]) L. V. PIRSSON. Geology of Bermuda island. Amer. Journ of Science. XXXVIII. p 189, 1914.

[2]) HEILPRIN estimates the average amount of the upheaval preceding the present condition of Bermuda Island at 80 feet at least. A. HEILPRIN, The Bermuda-islands. Philadelphia 1889. p. 46.

depth of 290 m., composed of material, showing the effects of subaerial weathering, proves that the island once rose above the sea, probably before the eocene period. In eocene times or shortly afterwards this was again the case but later the volcanic activity ceased and the gradual subsidence was then no longer compensated by the accumulation of volcanic material; consequently the volcanic cone ultimately disappeared below the sea and now lies at 75 m. below sea-level, covered by a cap or crown of reef-limestone which nowadays rises fairly high above the sea in some places. In spite of the upheaval proved by this latter fact this remarkable boring justifies the conclusion that the general trend of the movement of the oceanic volcanic group of the Bermudas has for a long period been downward.

What may be the cause of such downward movements?

It seems to me that from the theory of isostasy we can make some deductions, suggesting a possible or even probable explanation.

The doctrine of isostasy developed from a hypothesis (PRATT's hypothesis) to a well-founded theory by numerous investigations, especially by HECKER and HAYFORD, presupposes that on the average the mass of the terrestrial crust is heavier under the oceans than under the continents.

It may be assumed that the outer crust of the earth consists chiefly of sediments and other rocks of an average density of $\pm$ 2.6—2.8, *of which gneiss and granite are the principal types*, grouped together by SUESS as sal and sometimes also called lithosphere in a more restricted sense, while under this acid crust a shell of more basic rocks follows with an average density of $\pm$ 3, to which SUESS has given the collective name sima, and which is also named barysphere in contradistinction to lithosphere. Basalt is a type of these latter rocks and the whole sima has been called by DALY "basaltic substratum".

In order to explain isostasy we might imagine that the outer acid crust is thicker under the continents than under the oceans, but it may also be supposed that this lighter granite-gneiss crust also comprising all sediments excepting the thin pellicle of oceanic (pelagic) sediments, does not form a closed shell round the terrestrial globe, but is in general restricted to the continents, so that under the oceans the sima or basaltic substratum must immediately follow under the certainly not very thick cover of oceanic sediments.

This second explanation is considered the more likely one by

DALY[1]); it has been especially brought to the fore by WEGENER[2]) and is also accepted by ANDRÉE[3]) and DACQUÉ[4]).

From it follows that the continents must be considered as flows of salic composition, floating in the sima in the same way as icebergs do in water, being submerged[5]) with about 95°/₀ of their mass.

Moreover the very fact of the existence of isostasy everywhere on earth, as proved by the observations and considerations of HECKER, HELMERT and HAYFORD, leads to the conclusion that the sal as well as the sima, as soon as the masses are considerable, behave under the influence of gravity like bodies with some degree of plasticity[6]) and that this plasticity is somewhat more developed in the sima than in the tougher sal. It is exactly through this plasticity, however small it may be, that isostasy is maintained and that notwithstanding various geological factors which continually disturb the isostatic equilibrium the isostatic compensation is even at the present day still fairly well complete in most places on earth.

Smaller masses, however, are often not compensated. The Olympus mountain range e.g. in the state of Washington shows a fairly great positive anomaly of the value g, i.e. of gravity. Now this range stands upon and in the salic block of the American continent, which has sufficient rigidity to bear and support this isostatically non-compensated body. It may be assumed that isostatically non-compensated nuclei on or in the continental blocks can remain very long in a condition of apparent stability.

The matter is quite different, however, for true oceanic islands, i.e. islands whose base is not connected with any continental block. Such islands rise directly from the ocean-bed and have never formed part of any continent.

1) R. A. DALY. Igneous rocks and their origin, 1914, p. 164.

2) A. WEGENER. Die Entstehung der Continente und Oceane, p. 19. Braunschweig 1915. WEGENER on pp. 15—19 pleads convincingly in favour of this view. WEGENER had already published the main outlines of his hypothesis in the Geologische Rundschau III, 1912, p. 276.

3) K. ANDRÉE. Ueber die Bedingungen der Gebirgsbildung, p. 32, Berlin 1914.

4) E. DACQUÉ. Grundlagen und Methoden der Palaeographie, p. 96, Jena 1915.

5) This simile has also been used by PICKERING and later again by WEGENER l. c. p. 19.

6) CHAMBERLIN compares the plastic yielding and consequent lateral horizontal outward flow of the continental masses ("outward creep of the continents") under the influence of gravity so far as the character of the movement is concerned, with the behaviour of glacier-ice under the same influence.

T. C. CHAMBERLIN. Diastrophism and the formative processes III. Journal of Geology. Vol. XXI, p. 577—587, 1913.

These islands as far as they are not composed of reef-limestone, are found to consist, exclusively of volcanic material, as a rule of basaltic or allied rocks[1]). The non-volcanic or not entirely volcanic islands in the Pacific are restricted to the south-western part which stands in close relation to the Asiatic and Australian continents, while on the other hand not only in the Pacific, but also in the Atlantic all true oceanic islands are composed of volcanic rocks.

Such true oceanic islands, as far as they have been studied, are not isostatically compensated and, without exception, show a larger or smaller positive anomaly of gravity[2]).

The position of these islands is exceptional, resting immediately on the sima and being rooted into it, and not being supported by much larger masses of salic material, by continental blocks, as is the case with the incompletely-compensated or non-compensated nuclei in and on the continents.

It appears to me that, on account of the isostasy itself, these volcanic islands, rising directly from the plastic sima as cones or groups of cones of considerable bulk, cannot always remain in existence[3]); *under the influence of gravity they will without exception yield and sink down slowly but gradually and if this movement is not counteracted by other forces they must disappear below the sea and finally approach more and more the form of the ocean-bed, being welded again with and incorporated in the sima below the ocean bottom.*

In such islands conditions must be exceptionally favourable for the formation of barrier reefs and in case of total submergence, of

[1]) The reader is referred to: G. GERLAND. Vulkanistische Studien. I. Die Koralleninseln der Südsee. Beiträge zur Geophysik. II. 1895, p 29–34, where in a convincing discussion it is rendered all but certain that all coral islands of the central Pacific rest on a volcanic base; and R. A. DALY. Problems of the Pacific Islands Amer. Journal of Science XLI, 1916, where on p. 153 it is pointed out that the statements about non-volcanic continental rocks occurring in some of these islands are not certain and require revision.

[2]) E. BORRASS. Bericht uber die relativen Messungen der Schwerkraft mit Pendelapparaten in der Zeit von 1808 bis 1909. Verh. der 16ten Allg. Conferenz der internat. Erdmessung III. Berlin 1911.

[3]) WEGENER (l. c. p. 13) probably had this idea in his mind and it evidently led him to suppose that these volcanic oceanic islands should in reality be isostatically compensated, although the contrary has been proved, and that they could not well be entirely composed of volcanic material but ought to contain a nucleus of salic (continental) material, which should be relatively very large, since about 95 % of it must be hidden under the sea-floor immerged in the sima. In my opinion these suppositions being, contrary to all observed facts, must be regarded as exceedingly improbable.

atolls. As a matter of fact within the geographical limits of the reef-building corals exactly these islands are almost without exception surrounded by barrier-reefs and the great majority of the atolls occur exactly in the same areas where both volcanic islands and barrier-reefs are found.

In appears to me that the yielding and slow sinking of the volcanic islands under the influence of gravity.[1]) *must be regarded as the cause of the downward movement of large amount and long duration which must be assumed in order to explain the formation of barrier-reefs and atolls in true oceanic regions, the cause of which had as yet not been ascertained.*

By accepting this hypothesis which restricts the subsidence to the islands themselves and their direct basements[2]) and does not postulate large crustal movements nor great displacements of masses, one can meet the most serious of the objections, raised against the theory of DARWIN-DANA, even by its adherers, which were mentioned in the beginning of this paper.

It is clear that the rate of sinking of all volcanic oceanic islands will always depend on the local composition of the island and of the sima of the underground and that moreover by various influences this movement can be counteracted either really or apparently.

Thus the subsidence can temporarily be counteracted *in reality* by diastrophism and also by variations of the sea-level, as e.g. by the general lowering of the sea-level in early pleistocene times, to which PENCK and later especially DALY in his "glacial control theory" have drawn attention; *apparently* it can be counteracted by prolonged volcanic activity, by which such islands might gain

[1]) The effects of crustal warping of the ocean floor caused by diastrophism e.g. by folds, will have just as little chance to remain in existence. After having been formed the elevated portions will yield and sink away again by the influence of gravity, although in all probability very slowly.

[2]) G. GERLAND in his very important paper cited above also assumes that not the floor of the Pacific itself has subsided He wants to restrict this downward movement to the tops of the volcanoes which, as he thinks, may move upwards as well as downwards under volcanic influence. Compare l. c. p. 56: "Senkung und Hebung der Koralleninseln sind Erscheinungen gleicher Art und zwar beide Erscheinungen, welche dem Vulkanismus der Erde angehören". (Sinking and rising of the coral islands are phenomena of the same order, both of them belonging to terrestrial volcanism). He does not try to explain the cause of the subsidence of the volcanic cones, although he takes subsidence to be well proved. He remarks on this point l.c. p. 66: "Das Sinken zu erklären vermag ich nicht; man gestatte mir nur, auf einzelne hierhergehorige und, wie mir scheint, sichere Thatsachen hinzuweisen". (The subsidence I cannot explain; I only beg to draw attention to facts pointing to it which I regard as well established).

in height more by the repeated accumulation of fresh volcanic products than they lose by the slow process of plastic subsidence.

By way of summary, it seems to me that the following conclusions are justified:

In order to explain the formation of barrier-reefs and atolls it is imperative to accept that a subsidence of the land (incl. islands) with respect to the sea-level took place in those regions where they occur, and to explain the formation of very many of these reef-structures in oceanic regions it is equally urgent to look upon this subsidence of the land with respect to the sea-level as having been considerable and to have extended over a long period.

Three cases may be distinguished:

1. The subsidence is the result of crustal movements. Such crustal movements will have been the ruling factors where barrier-reefs are found along the coasts of continents or where barrier-reefs and atolls are found encircling islands which on account of their structure and composition are closely related to neighbouring continents, i.e. in the not truly oceanic regions, as e.g. the whole south western part of the Pacific. These crustal movements [1]) have very likely always had a compensatory character; subsidence of a certain amount in one region being compensated by upheaval of corresponding amount in neighbouring regions and vice versa;

2. The subsidence of the land is only apparent and caused by positive movements of the sea-level, such as e.g. must have taken place in the late and post-pleistocene periods and probably still continue to some extent at the present day as the result of the melting of icecaps which in the pleistocene glacial period had accumulated on the continents - the importance of which movements for the origin of numerous barrier-reefs and atolls has been convincingly shown in DALY's repeatedly mentioned theory;

3. The subsidence of the land is a real one, caused by the plastic yielding of isostatically non-compensated parts of the terrestrial crust in true oceanic regions under the influence of gravity, just as, according to the theory of isostasy, must be expected to occur in all true oceanic volcanic islands. This subsidence may be very considerable and will in fact only stop when such an island has entirely or nearly sunk away into the sima of the ocean-bed or rather will

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[1]) The author, besides the generally accepted orogenetic and epirogenetic movements, also admits the possibility of horizontal movements of continental blocks such as WEGENER assumes in his bold hypothesis about the origin of the continents and oceans.

A. WEGENER, Die Entstehung der Kontinente und Oceane. 1915. Kapitel 5 und 6.

have been recombined with it. Such a movement involves that as a last trace, bearing witness to the former existence of such an oceanic volcanic island, the spot where it once stood can be indicated by an atoll, rising from the bottom of the ocean to the surface. Obviously such an atoll will only be formed if there is a certain ratio between the rate of subsidence of the island and the upward growth of the reefs, whereas moreover the reef must have grown uninterruptedly during the whole period of downward movement.

This harmonic ratio will of course exist in rare cases only and it is to be expected that in many of the sinking oceanic islands the contact with the sea-surface will have been broken, which the upward growing corals are always trying to keep up. It is clear, moreover, that the majority of the bodies built up by submarine volcanic activity will have sunk back again without ever having reached the surface. We may therefore expect that the vestiges of submarine volcanic activity nowadays mainly will be found as a ridge or elevation [1]) of inferior depth to the surrounding sea extending longitudinally in the direction of that line of least resistance of the terrestrial crust, along which the volcanic material was ejected. On this gentle ridge submarine hills must be found, formed by volcanic masses, in all stages of slow subsiding. Here and there from the same ridge atolls will rise up to the surface as colossal reef-built structures, while in other spots, where the volcanic activity lasted longer or still continues, volcanic masses will be found to protude above the level of the ocean to the present day as mountainous islands, surrounded by barrier reefs.

The above hypothesis does not give a satisfactory explanation of the upheavals which occasionally for a time interrupt the process of subsidence and cause some true oceanic coral islands to project fairly high above the sea. In comparison with the overwhelming large number of coral islands for which no rise can be demonstrated, the cases of rising observed are so few that DARWIN, in my opinion rightly, drew the conclusion that the positive movements observed represent oscillations only in a direction opposite to the general downward trend.

From the hypothesis outlined above, some stringent deductions

1) Such submarine ridges of very feeble relief are indeed indicated on the already cited excellent "Tiefenkarte der Oceane" by MAX GROLL. From the most north eastern of these ridges in the Pacific the Sandwich Islands rise above the sea-level.

follow, which will serve to some extent to test its probability. Some of these may be briefly mentioned here.

When a volcanic island, crowned with some form of reef structure sinks down, it may happen, as has been stated above, that the upward growing reef-building corals do not succeed in the long run in keeping in contact with the superficial layers of the ocean which alone present the conditions necessary for their existence. As soon as they have sunk down below the limit of depth down to which reef-building corals can live, they will no longer be able to grow further but together with their basement of volcanic origin they will continually sink deeper and die off. If this be true we may expect to find such sunken reefs at very different depths within the area of the reef-building corals. As far as I know, it has never been described up to the present that in the Pacific fragments of reef-building corals have been dredged from great depths which could not in all likelihood be considered as originating from neighbouring coral islands rising above the sea. But this cannot be wondered at since the number of deep-sea dredgings is not large and next to nothing when we think of the extensive area we have to deal with, so that the chance must be extremely small, that a point where portions of a drowned coral-reef occur, will be hit exactly. Outside of the Pacific, however, viz. in the Ceram Sea, a fact[1]) has occurred which I consider very important.

I mean the dredging No. 177, made on Sept. 1, 1900, by the Siboga[2]) in the middle of the Ceram Sea[3]). From a depth ranging from 1633 to 1304 m. over a distance of no less than three nautical miles large quantities of recent reef-building coral were then dredged, which

[1]) After this paper had been read, a second instance came to my notice through the courtesy of Mr. J. W. van Nouhuys, who informed me, that in the year 1914, when commanding the ship Telegraaf of the Government Navy in the Netherlands East Indies he brought to the surface from a depth of 1500 m. some pieces of coral reef limestone at a spot, situated about 30 nautical miles from the nearest shore, of the island of Engano. The exact spot where this deep-sea sounding took place is 5°33′ Lat. and 102°45′ Long.

[2]) It is also possible that similar finds have been been made elsewhere by deep-sea expeditions but have not been recorded. Very remarkable are the results obtained in the year 1899 by the steamer Albatross at the stations Nos. 35, 489 and 112 near the Paumoto archipelago, where from depths of 1462, 1123 and 1568 fathoms resp. so called coral sand was dredged; no coral islands lie at a smaller distance from there than $^1/_3$ degree latitude.

A. Agassiz. The coral reefs of the tropical Pacific p. 25, fig. 2 and Plate 201. Mem. of the Museum of compar. Zoology at Harvard College XXVIII, 1913.

[3]) See Siboga expedition. Vol. I. M. Weber. Introduction et description de l'expédition p. 80, 1902.

had died off and by a thick cover of manganese revealed their long stay in the sea-water after their dying off. The nearest point in these regions where living reef-building corals occur near the surface lies at 42 kilometres from the point where the dredging took place, so that those deep-sea corals could not originate there. In order to explain the result of this dredging I should rather suppose that on that spot in the Ceram Sea from the sea-bottom which lies at a depth of about 1600 m. a drowned coral island rises to about 1300 m. below sea-level. Such a supposition seems justified if it is borne in mind that the Ceram Sea is one of the most remarkable trough-shaped deep basins in the eastern part of the Indian Archipelago, the origin of which is probably connected with crust-movements in pleistocene and post-pleistocene times. They were formed by downward movements, simultaneous with and more or less compensated by elevations of about equal amount of other parts — nowadays highly elevated islands — in that region. Now a fairly large number of cases has already become known which render it probable that subsidence caused by diastrophism [1]), such as took place in the Ceram Sea, can proceed relatively quickly, which is very likely not the case where islands subside through yielding to the influence of gravity — isostatic subsidence — which is to be assumed in the central Pacific. Thus the chance that coral islands may be drowned must be esteemed larger in the former case which is present in the Ceram Sea than in the latter.

Perhaps the remarkable dredging N°. 177 of the Siboga expedition may become the starting point for an explanation of the interesting fact that although the deep sea-basins in the eastern part of the East Indian Archipelago, have been formed by depressions of large amount in pleistocene and post-pleistocene times, reef-structures of the type of the barrier reefs and atolls, certainly within those basins occupy a very modest place.[2])

A second consequence of the outlined hypothesis is that it must not only hold good for the true oceanic volcanic islands in the Pacific but also for those in the Indian Ocean and the Atlantic. Now it is certainly remarkable that for the only true oceanic island which in the Atlantic is found within the area of the reef-building

[1]) Very interesting are the examples of important differential movements by diastrophism since post-pliocene times which LAWSON mentions of the coast and coastal islands of Southern California. A. C. LAWSON, The post-pliocene diastrophism of the coast of Southern-California. Bull. of the Dep. of Geology. Univ. of California I, p. 115, 1893.

[2]) Compare J. F. NIERMEYER, Barrière-riffen en atollen in de Oost-Indische archipel. Tijdschr. Kon. Ned. Aardr. Gen. 2. Vol. XXVIII, p. 877, 1911.

corals, namely Bermuda[1]), it has recently been proved (see above) that the reef limestones which nowadays project there above the sea are the upper portion of a cap or crown of reef-limestone, which is at least 110 m. thick and rests on a sunken basaltic mountain.

All other true oceanic volcanic islands in the Atlantic lie outside the area of the reef-building corals. They are all volcanic[2]) and are situated on the so-called mid-Atlantic ridge ("Mittelatlantische Bodenschwelle"). The Canary and Cape Verd Islands certainly and the Selvagen Islands and the Madeira Group probably are not true oceanic islands, but have once formed part of the European-African continent[3]).

Perhaps we may see in this remarkable mid-Atlantic ridge the final result of volcanic activity along an enormous fracture of the same extent, where from numerous fissures and vents volcanic material was discharged, thus a volcanic mountain chain and cones being formed, which nowadays subside through yielding under the influence of gravity and nearly all have sunk back to a level approaching the average level of the deep submarine ridge. Here and there a few islands, where volcanic activity lasted longer or has existed to this day, still rise above the sea[4]) and others (of which

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1) The West Indian archipelago proper with its numerous coral islands and reef-formations does not belong to the group of true oceanic islands. West India is a region of strong and recent diastrophism, intimately related to the American continent.

2) GAGEL mentions the occurrence of numerous loose boulders of gneiss and granite on Santa Maria, one of the Azores, and adds that these rocks are not indigenous there, but problably have been carried thither during the pleistocene glacial epoch by icebergs. C. GAGEL, Die mittelatlantischen Vulkaninseln. Handb. der region. Geologie VII. H. 10, p. 12, 1910.

The evidence considered as acceptable by SCHWARZ for the occurrence of non-volcanic (continental) rocks in some of these islands, is, to quote his own words, "not so good as one could wish for, and could not be admissible were the islands more easy of access, or had a geologist been to the place himself".

E. H. C. SCHWARZ. The rocks of Tristan d'Acunha, brought back by H. M. S. Odin, 1904 with their bearing on the question of the permanence of ocean basins. Trans. of the S. A. Phil. Soc. Vol XVI, p. 9, 1905.

3) C. GAGEL. l. c. pp. 31.

4) The fact, that several of the volcanic islands in the Atlantic, as e.g. Nightingale island and Tristan d'Acunha, are very well cliffed, appears to afford a strong argument against my hypothesis which requires slow but continuous subsidence for these islands also. This argument, however, loses its strength, if it is borne in mind, that the process of cliffing by wave-action is a *rapid* one, especially on these volcanic islands, which are partly composed of incoherent or little coherent ejacamenta (or efflata), and, their coasts not being protected by fringing reefs, are exposed on all sides to the full fury of the mid-ocean waves. The process of sub-

naturally only a few have been discovered accidentally by soundings) still rise to different heights above the average level of the ridge but no longer attain the surface of the sea. Among these latter we mention three submarine mountains [1]) which near the western part of the Azores rise from the bottom of the ocean, which has there a depth of about 3000 m., to respectively 146, 128 and 88 m. below sea-level. The cause for the extrusion of such enormous masses of volcanic material might perhaps be sought in the disruption of the American continent from the European-African one with which it formerly cohered. This disruption was assumed by PICKERING [2]) and TAYLOR [3]) and a plea for it is again brought fore by WEGENER on page 68 of his paper quoted before. On this supposition the mid-Atlantic ridge would in my opinion indicate the place where the first fissure occurred and the sima was first laid bare. From this it would follow logically that the ridge itself must consist entirely of sima and not of sal, as WEGENER assumes on page 69.

Finally it may be remarked that according to the hypothesis put forward in this paper it is not possible that deposits formed on the floor of true oceanic regions will ever be definitely raised above sea-level and so partake in the building up of continents. In accordance with this is what experience had until now taught about the occurrence of fossil deep-sea deposits on the continents [4]). Although their occurrence there is much less limited than is generally supposed, they are exclusively found in geosynclinal regions, i.e. in parts which once, before their folding and forcing up, were deep troughs at a relatively small distance from the edges of continents and by no means true oceanic regions.

APPENDIX.

After this paper had been read, the following contributions to our knowledge of the question at issue came to my notice.

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sidence caused by plastic yielding under the influence of gravity, on the contrary, is a *slow* one. Thus, notwithstanding their slow subsidence these islands may show well developed cliffs by the action of the waves.

1) C. GAGEL. l.c. p. 9.

2) W. H. PICKERING. The place of origin of the moon. Journ. of Geol. XV. p. 23, 1907.

3) F. S. TAYLOR, Bearing of the tertiary mountain-belt on the origin of the earth's plan. Bull. Geol. Soc. of America XXI, p. 179, 1910.

4) G. A. F. MOLENGRAAFF. Over oceanische diepzeeafzettingen van Centraal Borneo. Versl. Afd. Nat. d. Kon. Akad. van Wet. Amsterdam Dl. XVII. p. 83, 1909. (On oceanic deep-sea deposits in Central Borneo. These Proceedings XVII, p. 141.

1. R. A. DALY. A new test of the subsidence theory of coral reefs. Proc. of the Nat. Acad. of Sciences of the U. S. of America. Vol. II p. 664, 1916.

In this paper DALY argues that the observed shallowness of the lagoons as well as the levelness of the great majority of the lagoon-floors do not seem to agree with a legitimate deduction from the subsidence theory of coral reefs, whereas the glacial control theory would afford a reasonable explanation. It seems to me even if we accept the glacial control theory, the principle of subsidence in accordance with DARWIN's theory need not necessarily be abandoned.

An atoll, e. g. the Funafuti atoll, may have been formed under conditions of local subsidence in accordance with the hypothesis explained above, in a time preceding the pleistocene glacial period. During the glacial period the atoll with its moat more or less filled may have been truncated in consequence of the lowering of the sea-level to a level about 50—60 metres below the present sea-level. By this truncation the lagoon-floor attained its levelness, which it has on an average maintained until the present day, although on its rim a new growth of corals has since the close of the glacial period again built up an atoll-shaped reef structure, the visible portion of which determines the shape of the present Funafuti-atol.

2. A. LACROIX. Le soi-disant granite de l'île Bora-Bora. C. R. des séances de la Soc. Géol. de France. Séance du 18 Décembre 1916, p. 178.

In this paper LACROIX proves that the supposed granite (according to Ellis) of the island of Bora-Bora in the group of the Society Islands, is in reality not a granite at all, but a medium-grained olivine-gabbro, an intrusive facies of a basaltic rock, of which the greater part of the island consists.

Bora-Bora is a true oceanic island encircled by a beautiful barrier reef and if it were indeed composed of granite this fact, to quote LACROIX, „entraînerait d'importantes conséquences au point de vue théorique".

LACROIX, however, now has done away with the myth of the occurrence of granite in the Society Islands, and the island of Bora-Bora thus only confirms the rule, which we have accepted, that true oceanic islands are composed of volcanic rocks.