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CHANGES OF SEA-LEVEL

RESULTING FROM THE

INCREASE AND DECREASE OF GLACIATIONS

BY

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WITH THREE FIGURES AND ONE PLATE

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WILHELM RAMSAY, in the course of researches into the Quaternary changes of level in Fennoscandia, found his attention attracted to the big, general eustatic rising and falling of the sea-level, resulting from the increase and decrease of glaciations. During the winter of 1927 he began to write a popular paper on this subject. It was to be the preamble to the invitations to the »promotion» (conferring of the degrees of M. A. and Ph. D.) which the faculty of Philosophy at the Helsingfors University intended to solemnize that year, at which function Professor Wilhelm Ramsay acted as »promotor». In the course of the work the account became too voluminous, while the theme itself seemed to be not quite suitable for the purpose intended. He therefore further developed the subject in a more scientific manner, and, though simultaneously engaged on several other works, he had before he died almost finished a paper on the subject, written in English. The lack of the finishing touches is most noticeable in the chapter last but one. Since the death of Professor Ramsay, in 1928, a relatively abundant supply of literature dealing with these subjects has been published, and to some extent contributes to the solving of problems touched upon in this paper, but it has been thought better not to make any additions or amendments, with the exception of a few foot-notes, and the paper is therefore issued in close agreement with the original manuscript. The language has been somewhat revised by Mrs. Lily Björling, while the unfinished final chapter and the list of references have been added and completed by the Editor, as fully as this was possible in the entire absence of any notes by the author. In the same way, one here and there comes across gaps in the manuscript, which it has not been possible to fill up, in ignorance of Professor Ramsay's conception of the connexion between the conditions in question.

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MATTI SAURAMO.

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The Problem.

Soon after exposition of the theory of the Ice Age by AGASSIZ, MACLAREN pointed out a considerable sinking of the sea-level as a consequence of the great glaciations. Since then many geologists and geographers have treated the same theme: — the decrease of the water of the sea by the formation of the big ice-caps and the increase of this water by the melting away of such ice. Below is given a list of authors and their estimates of the lowering of the sea-level at the maximum of the Quaternary glaciations, according to a paper by DALY (1925).

Author	Date	Estimates in metres
G. Maclaren	1842	107—213 (350—700 feet)
E. Benoit	1863	»less than 1 mm»
J. Croll	1866	610 (2000 feet)
A. Tylor	1868, 1872	183 (600 feet)
T. Belt	1874	305—914 (1000—3000 feet)
W. Upham	1878	914 [1]) (3000)
A. Penck	1881	66,5 (the northern hemisphere only)
E. von Drygalski	1887	150
A. Penck	1894	150
W. Upham	1896	46 (150 feet)
F. Nansen	1904	100—200
R. A. Daly	1910	46 (150 feet)
W. B. Wright	1914	82—122 (260—400 feet)
R. A. Daly	1915	50—60
W. J. Humphreys	1915	67
A. Penck	1922	40 (for the last glaciation, not the maximum)
F. Nansen	1922	130 +
W. Ramsay	1924	300 +
R. A. Daly	1925	50—60

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[1]) This estimate of 3000 feet refers to the equatorial belt and a large proportion of the assumed depression of the sea-level was attributed to the gravitational attraction of the ice.

The surface of the sea fell during each Ice Age, and rose following the amelioration of the climate in interglacial and postglacial times. As thick ice-caps cover large parts of the earth even now, it is not impossible that during interglacial epochs, when the climate was warmer and the land ice of less volume than at present, the sea may have stood at higher levels than is now the case.

These eustatic changes of the sea-level have until lately been overlooked by most geologists, and some writers have even expressed the opinion that the sea-level was constant or nearly constant during the whole Quaternary period (*e. g.* BENOIT above, DE GEER 1887). Even though the importance of the eustatic oscillations, in addition to the isostatic crustal movements, had been emphasized by DALY, W. B. WRIGHT, NANSEN (1922), RAMSAY (1924a) and others, they have not been taken into consideration, or have been regarded as of little signiticance, in most of the newer Scandinavian publications on Quaternary changes of level.

The possibility of great eustatic shiftings of the position of the sea-level seems to be regarded with disfavour, because such shiftings complicate the relatively simple scheme of elevation and depression of the earth-crust, by the aid of which the Quaternary changes of level in Fennoscandia and other formerly glaciated regions have hitherto been interpreted.

Moreover, this tendency to estimate within as narrow limits as possible the changes of the sea's volume which are caused by glaciations and deglaciation originates, in part, in the actualistic or uniformitarian views predominating in our science and restraining the geologist from admitting that conditions formerly were very different from the present ones. Modern handbooks and scientific papers generally assign rather small vertical dimensions to the former inland ices. The height of the North American ice-sheet or the great European one for instance, as assumed by many authors, is lower than that of the recent inland ice of Greenland and Antarctica. Also the thickness of these now-existing ice-caps is underestimated, even though such estimates are counter to the opinion of those who have investigated these regions.

Most authors who have during the last few decades treated the questions of eustatic changes of level caused by glaciation and deglaciation seem inclined to place the lowest limit of the sinking of the sea somewhere between the estimates of DALY and NANSEN. Several objections have been raised against a lowering of 300 m or more proposed by me. This assumption was, indeed, not founded on any calculations. Therefore, I will now try to reach more convincing results by an examination both of the circumstances which may have caused an increase or decrease of the volume of the water in the sea, and of the phenomena bearing witness to such an increase or decrease.

The Dimensions of now existing Ice-caps.

According to HESS (1904), 15,200,000 km² of land are icecovered at present, i. e. about 3 % of the surface of the globe and about 10 % of the continental areas. The main part thereof is occupied by the ice of Antarctica, abt. 13,000,000 km², and by the Greenland ice, 1,900,000 km², together 14,900,000 km² or fully 98 % of the whole glaciated area of the globe. The glaciers in the temperate and warm zones together cover an area of only 70,000 km², or less than 0.05 % of the mainland area, and 0.5 % of the total glaciated area.

Neither HESS (1904) in his handbook, nor HOBBS (1911) in his treatise of existing glaciers, gives any statement of the depth of the ice streams in the mountains, but we find in HEIM's Gletscherkunde (1885) the following information on the Alpine glaciers: »Hängegletscher haben hie und da Spalten, die bis auf den Grund gehen. In solchen Fällen wurden 10, 20, 30 bis 50 m Eisdecke gefunden. Durch Schwinden der Gletscher im Zeitraum 1850 bis 1883 hat sich an mehreren Stellen noch nahe am Ende die frühere Dicke als über 100 m direkt erwiesen. — — Aus der Talgestalt oder aus der Bewegung und Abschmelzung lassen sich hie und da ziemlich sichere Schätzungen gewinnen, die auf 200, 300, 400 und noch mehr Meter ansteigen. — — Es ist ganz gewiss, dass die grossen Gletscher I. Ordnung sehr oft zwischen 200 und 400 m Dicke in den Alpen aufweisen und dass noch grössere Beträge vorkommen. Über die Dicke der Firnmulden ist es noch schwieriger, Anhaltspunkte zu gewinnen.» These figures refer, however, only to the centre of ice streams, as the latter thin out at the sides. Still greater thicknesses — perhaps up to 1000 m — seem to be attained by some big glaciers in the Himalayas. It may not be an exaggeration to assume the average thickness of the glaciers of the temperate and warm zones as being 150 m. This figure is of little account in the computation of the total volume of the recent glaciations, as the glaciers in question form an exceedingly small part of the whole.

Neither have I found much information relating to the thickness of the smaller Arctic ice-caps. The Malaspina glacier, the bottom of which probably is at or below sea-level, attains a height of 200 m a little inside its margin and of approximately 500 m at the foot of the mountains, its average thickness thus being about 300 m. The rock ground penetrates the surface of many of the smaller Arctic ice-caps, but in other places the ice-filled valleys and depressions are very deep and large, so that I think an estimate of 300 m as the average thickness of the Arctic glaciers and ice-sheets, except the Greenland one, cannot be excessive.

For Greenland, NANSEN estimated (1889) the thickness of the ice over which he walked at from 1800 to 2500 m. Later authors consider these figures too high and improbable. Thus, HESS (1904) suggested that the figures 400—600 m for the average thickness of the Greenland ice might be closer to reality. The question was recently again reopened by MEINARDUS (1926) in a paper concerning the hypsographic curves of Greenland and Antarctica and the normal surface form of an ice-cap.

MEINARDUS has measured the areas between certain isohypses on maps of Greenland published by DE QUERVAIN and LAUGE KOCH, and also on maps of Antarctica — though the latter are certainly not so complete as those of Greenland — and has compared them with each other and the areas of corresponding hypsometric zones in Africa, Asia and all continents (except Antarctica) together. Part of his figures are tabulated below.

The areas of the hypsometric zones:

	0—200 m.	200 —500 m.	500 —1000 m.	1000 —2000 m.	2000 —3000 m.	More than 3000 m	Total Millions km²
a in 10,000 km²							
Greenland	16	22	20	65	92	5	2.2
Antarctica	70	54	101	375	625	175	14.0
The Continents	4850	3250	2600	1800	500	500	135.0
b in percentage							
Greenland	7.3	10.0	9.1	29.5	*41.8*	2.3	100.0
Antarctica	5.0	3.9	7.2	26.8	*44.6*	12.5	100.0
The Continents	*35.9*	24.1	19.3	13.3	3.7	3.7	100.0

The hypsographic curves (Fig. 1, after MEINARDUS), drawn on the basis of the above figures, show a difference in character between the curve of the non-glaciated continents and those of Greenland and Antarctica. The former curve, as well as those of Africa and Asia, is concave, those of Greenland and Antarctica are decidedly convex, if we leave out of consideration the coast belts bare of ice and the Antarctic shelf ice. The hypsometric zones between 1000 and 3000 m embrace 72 % of the whole area of Greenland and Antarctica, but only 17 % of the continents. This hypsographic contrast between the glaciated countries and those free from ice proves that the surface configuration of the former is determined essentially by the land ice, not by the rocky ground. Ice constitutes here the main part of the land and the form of its surface is nearly the same that a viscous mass acquires on a horizontal substratum, when fed by the addition of substance at its centre. (MEINARDUS, W. THOMSON 1894.)

MEINARDUS gives for Greenland the average height of 1650 m. For Asia the average height is »only» 940 m, for Africa 750 m, for Australia 350 m, for Europe 300 m and for all continents together (except Antarctica) 700 m.

The Greenland ice-cap itself has a still higher average height, 1900 m, according to MEINARDUS, and as he estimates the mean elevation of the rock ground beneath the ice at 500 m, this leaves a thickness of 1400 m for the ice-sheet.

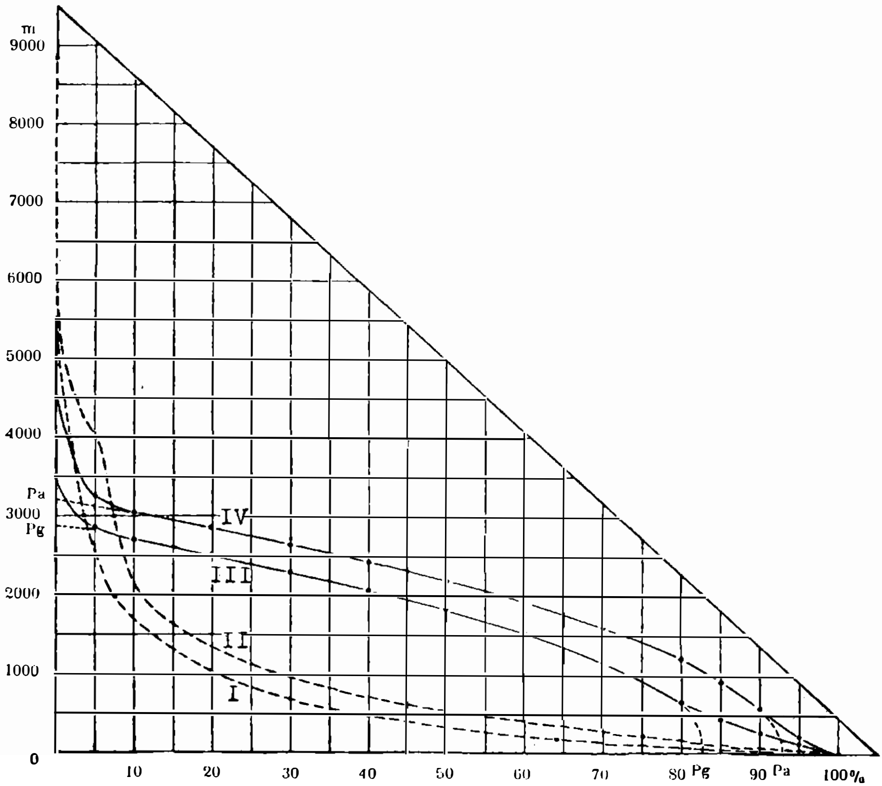

Fig. 1. Diagram, after MEINARDUS, showing the hypsographic curves of (I) all land-surfaces (excluding Antarctica), (II) Asia, (III) Greenland, (IV) Antarctica (hypotetical). Pg = the parabel of Greenland, Pa = the parabel of Antarctica. The area is given in percentage of the total area of the continents.

The highest part of the Antarctic ice-cap lies about 3000 m above sea-level. Higher mountains rise in its marginal parts, *e. g.* Markham Mountains, 4600 m. MEINARDUS computes the average height of the whole continent to be a little more than 2000 m, and the average height of the parabolic hypsographic curve for the surface of the ice-cap to be 2150 m. Within some regions the ice certainly hides high rock ground, indicated by the configuration of the surface of the ice and the direction of the ice flow. A lofty table land in all probability forms the central part of the continent, but in other regions the ground beneath the ice must be low and in certain areas very likely lies even below sea-level.

Estimates of the thickness of the Antarctic ice differ considerably. CROLL's suggestion of a height of 24000 feet (7312 m) in the centre of the land has now purely historical interest. In contrast to this is the very low estimate by WRIGHT and PRIESTLEY of 609 m (2000 feet) as a maximum of thickness. In the opinion of these authorities on the glaciology of Antarctica: »It would be surprising, if the thickness of the ice-sheet exceeded 2,000 feet at any point away from the head of a glacier, and this figure seems an outside estimate. It appears, therefore, that the sheet, though of enormous extent, may actually contain less ice than any one of the great Pleistocene ice-sheets of the northern hemisphere. Its outward movement appears to depend upon the slope of the land, like a mountain glacier.»

However, in view of the fact, that the mean elevation of the Antarctic continent greatly exceeds the mean heights of all other continents, and considering the characteristic convexity of its hypsographic curve, we cannot fail to regard these features as being due to the inland ice, which forms such a considerable part of the land mass that it determines the height of the continent and the configuration of its surface, independent of the rock ground.

MEINARDUS has, in his paper, made no estimate of the average thickness of the Antarctic ice-sheet. To my question if he could and would express any opinion on this subject, I received a kind and obliging answer, from which the following lines are published with the permission of the writer:

Göttingen, 24. März 1927.

»— — — — — —. Dass es sich dabei nur um ganz rohe Schätzungen handeln kann, versteht sich ja von selbst, und ich habe deshalb auch, wie Sie richtig vermuten, davon abgesehen, in meinem Aufsatze irgend welche Angaben darüber zu machen. Bei Grönland liegen die Verhältnisse schon klarer, weil mittlere Höhe und Fläche des vereisten Gebietes nun einigermassen bekannt sind, und nur die Annahme der mittleren Höhe des Felsenuntergrundes noch unsicher bleibt. Bei der Antarktis sind aber alle drei Grössen: Mittlere Höhe, Fläche des vereisten Gebietes und mittlere Höhe des Felsenuntergrundes nur annähernd zu bestimmen oder zu schätzen. Trotzdem kann der Versuch, die mittlere Mächtigkeit der Eisdecke zwischen Extremwerte einzugabeln, wohl gemacht werden, wenn, wie im vorliegenden Falle, das Bedürfnis vorliegt, wenigstens einen möglichen Wert für gewisse andere Berechnungen zu benutzen.

Als mittlere Höge des von Inlandseis bedeckten, schildförmig gewölbten Teiles der Antarktis (also ohne die flachen Randgebiete a. a. O. S. 99 unten) habe ich in meinem Aufsatze (a. a. O. S. 100) 2150 m angegeben, den Fehler schätze ich auf ± 10 %. Fur die mittlere Höhe des festen Felsenuntergrundes setze ich schätzungsweise 650 m, Fehler ± 20 %. Dann erhalte ich für die mittlere Eisdicke 2150—650=1500 m ± 20 %. Das Areal des gewölbten Teiles des Inlandseises habe ich in meinem Aufsatze zu 13 Millionen qkm angenommen. Die Eismenge des gewölbten Teiles der Antarktis ist somit 1,500× 13 Millionen = 19,5 Millionen cbkm. — — — — —

Ich bemerke nun zu obiger Annahme über die mittlere Höhe des Felsenuntergrundes (650 m ± 20 %) noch Folgendes, um auch zu den möglichen Extremwerten zu kommen.

650 m ist die abgerundete durchschnittliche Höhe der drei Südkontinente (Afrika 750 m (von mir neu berechnet, s. Pet. Mitteil. a. a. O. S. 99. und Anm. 6) auf S. 97.), Südamerika 580 m, Australien 350 m. Areale: 30, 18 bezw. 9 Millionen qkm). Ich nehme also an, dass der wahrscheinlichste Wert für die Antarktis durch die Höhe der Südkontinente gegeben ist. Aber die Unsicherheit ist natürlich gross. Wenn ich als Extreme, die noch denkbar sind, 500 m (angesichts der doch grossen Höhen der Ostantarktis als Minimum) und 800 m (als Maximum Asien hat 950 m) annehme, so kann ich das mit 650 m ± 20 % ausdrücken (oder 650 m ± 150 m).

Mit 650 m als Subtrahent von 2150 m erhielt ich oben 1500 m als mittlere Eisdicke. Auch diesem Wert haftet also eine Unsicherheit von entsprechender Grösse an, ausserdem aber wird noch die Unsicherheit von 2150 m, die ich auf ± 10 % oder — 200 m schätze, beeinflusst. Ich setze daher für 1500 m einen Fehler von ± 20 % oder ± 300 m an.

Zusammengefasst entsteht aus den obigen Überlegungen folgende Übersicht:

Wahrscheinliche mittlere Höhe des antarktischen Eisschildes
2150 m ± 10 % (± 200 m)
Wahrscheinliche mittlere Höhe des Felsenuntergrundes
650 m ± 20 % (± 150 m)
Wahrscheinliche mittlere Mächtigkeit des Inlandseises
1500 m ± 20 % (± 300 m)
Mögliche maximale mittlere Mächtigkeit des Inlandseises
1800 m
Mögliche minimale mittlere Mächtigkeit des Inlandseises
1200 m.

In meinem Aufsatze »Über den Wasserhaushalt der Antarktis» (Nachrichten der Gesellschaft der Wissenschaften zu Göttingen 1925, Math.Physikal. Klasse S. 184 ff) habe ich auf Seite 188 bereits angegeben, dass die Mächtigkeit der Eisdecke m i n d e n s t e n s a u f 1 0 0 0 m zu veranschlagen ist. Die obigen Werte bestätigen und ergänzen diese Angabe. — — —.»

The estimates of the height of the rock ground beneath the Greenland and Antarctic inland ice — obtained by comparison of these glaciated continents with the other continents free from inland ice — as computed by MEINARDUS and some other authors, are based on the conception that Greenland and Antarctica occupy the same position in relation to their subjacent masses that the other continents do. But in the same manner as the formerly glaciated parts of North America, Europe, etc, have risen when released from the load of ice, so Greenland and Antarctica must rise if their ice once vanishes. Then, however, their rock surface will be lifted to a higher level than it occupies at present, and to a higher level than anticipated in the estimates mentioned above. A continent which, if it were relieved of its load of ice and elevated to isostatical equilibrium, would occupy a level comparable with that of the non-glaciated continents, must have sunk, under the weight of the ice, to a certain depth below that level. I think, therefore, that Greenland and Antarctica are depressed in this way, the more so that their ice has surely lain in its present position since the last Ice Age.

Thus, if the average thickness of an ice-sheet is T and the density of the ice D and that of the subcrustal magma d, and, further, m is the average sinking of the continent, when isostatical equilibrium is reached, we get

$$DT = dm \text{ and } m = \frac{DT}{d} = 0.3T,$$

if $D = 1$ and $d = 3$.

The figures 0.3 T show also the extent of the elevation of the continent after its deglaciation. If, for example, the average thickness of the Greenland and Antarctic ice is that assumed by MEINARDUS (1400 m resp. 1500 m), the former continent should, if free from ice, rise on an average 420 m, and the latter continent 450 m. Added to the heights of the rock ground, as estimated by MEINARDUS (Greenland 500 m, Antarctica 650 m), these elevations should give a mean height of 920 m for Greenland, and 1100 m for Antarctica. These continents would then, even if bared of ice, be the highest of all continents.

If we assume, however, that the rock ground of a continent covered with an ice-sheet would when the ice sheet has vanished, rise to an average height of h, corresponding to estimates in accord with the mean heights of other continents, we must suppose that the rock, under the load of the ice, is depressed to a certain depth of q, below the level of the expected average height of h. If H be the mean height of the covering ice-sheet, the average thickness of this ice- sheet is H—h+q. If D = 1 and d = 3, as above, then we get at isostatical equilibrium

$$(H - h + q)\ D = qd$$

and find the depression

$$q = \frac{D(H—h)}{d—D} = 0.428(H—h)$$

or, if the land ice has not the full density of 0.9, q is about 0.4(H—h).

At the margin of the ice-sheet and in its surroundings, this depression of the continent will meanwhile not be noticeable at all, or only in a small degree. The heights of the mountains and valley bottoms should probably not be noticeably different from those in other continents comparable with the one now in question, but the inner part of the continent is sunken in the form of a trough.

The average thickness of the ice-sheet which covers such a continent is

$$H - h + q = H—h + 0.4\ (H—h) = 1.4(H - h).$$

If we, *e. g.*, suppose that Antarctica (H = 2150) would have, when bared of ice, an average height (h) of 650 m in accord with the heights of other southern continents (see MEINARDUS above), the average thickness (T) of its ice-sheet must be, with regard to the isostatic rising of the land,

$$T = 1.4(H—h) = \text{abt. } 2100 \text{ m},$$

and for Greenland (H = 1900 m and h = 500 m), we should get

$$T = \text{abt. } 1960 \text{ m}.$$

These results are a consequence of the assumption that Greenland and Antarctica, if deglaciated, may have heights only of the same order of magnitude as certain other continents compared with them. But, if we accept the very low estimate of PRIESTLEY and WRIGHT (609 m, see above) for Antarctica, and that of HESS (max. 500 m) for Greenland, the consequence is that these Arctic and Antarctic lands must, even when bared of their ice-sheets, have the highest mean elevation of all continents.

We arrive at about 1580 m as the mean height of an iceless Antarctica by subtracting from its actual mean height (2000 m) the abovementioned 609 m for the ice and adding to it the isostatic uplift ($0.3 \times 609 = 183$ m) which would follow deglaciation. For Greenland a similar calculation gives about the same figure. Such average heights would be more than the double of that of all continents together (700 m), and also greatly exceed the average of the highest of the continents, Asia (950 m).

These alternatives — very great thickness of the ice-sheets or very great average height of the ice-covered rock surface on the two glaciated Arctic and Antarctic continents — raise the following questions: Are Antarctica and Greenland so high (average about 2000 m) because they are formed mainly of ice, or would they, even if bared of ice, be the loftiest (averagely) of all continents and are they just in consequence thereof covered with their great inland ice-masses? With regard to the hypsographic curves of Greenland and Antarctica, so different from those of all other continents, and showing the pronounced form of a land ice which has filled completely the deeper parts and unevenesses of subjacent rock surface, and extends as a huge shield high over its irregularities, one is inclined to answer the former question in the affirmative. It is, however, possible that also ice-sheets of less thickness are able to fill the greatest unevenesses in the land forms and give convexity to the hypsographic curves. The descriptions of Greenland given by LAUGE KOCH suggest that the two great elevations of the ice surface are assignable to the subjacent rock masses. Likewise, the information concerning Antarctica gives us to understand that the inland ice has not the ideal shield shape independent of its substratum, but that its forms are determined in many respects by the substratum. Also for these reasons PRIESTLEY and WRIGHT think that the Antarctic ice no longer has its former full thickness, but is »starving».

Our conception of the conditions discussed will determine our estimate of the total volume of the recent glaciations. Meanwhile, there are not sufficient observations, investigations or conclusive demonstrations available to decide the answer to the alternative questions above. I will, therefore, try to ascertain the probable vertical dimensions of the great recent glaciers and ice-caps in an indirect way, *viz.*, so that starting from the different estimates of the thickness of the big inland ice-masses, I will first calculate how much the volume of the sea would increase, if the now existing ice-caps and glaciers were to melt away completely, and then see which of the resulting raised sea-levels is in the best accord with statements of preglacial and interglacial marine shore lines.

The existing ice-caps and glaciers are thus assumed to have the following volume.

	area in million km²	average thickness in m.	volume in millions km³
Glaciers in the temperate and warm zones	0.07	150	0.01
Glaciers and smaller icecaps in the polar regions	0.186	300	0.37
The Greenland ice, Meinardus' estimate	1.87	1400	2.62
The Antarctic ice » »	13.00	1500	19.5
			Total 22.50

The shelf ice around Antarctica, and other floating ice, is not taken into account, as its melting would not increase the sea's volume.

The melting away of the above mentioned 22,500,000 km³ of land ice would add 20.2 million km³ of water to the sea and raise its level about 55—56 m.

Earlier authors have calculated such an assumed rising of the sea-level as follows: MACLAREN (1842) 30 m (100 feet), W. B. WRIGHT (1914) at least 40 m, DALY (1915) 11—25 m, HUMPHREYS (1915) over 40 m (Greenland computed to give 6 m, Antarctica 34 m,) and all other land ice, more than 25 m. (NANSEN 1922).

The bottom of the sea would sink isostatically under the greater load of the increased water masses, as likewise the continents must rise when liberated from their ice-caps. When complete isostatical equilibrium was reached, the depression of the ocean parts of the earth's crust would have forced as much subcrustal »magma» out of its place as flowed in under the lifted continents. The effect of this would be to diminish—by about 30 % of the increased depth of the sea—the rising of the sea-level caused by the melting away of the continental ices (the density of the ice being 0.9, and that of the »magma» 3.0). (NANSEN 1922).

Meanwhile, the above hypothetical isostatical depression of Antarctica and Greenland is not taken into account when calculating the volume, 22.500,000 km³, of ice which melted away would raise the sea-level 55—56 m. The sinking of the sea-floor and the rising of the continents owing to the removal of the ice or watermasses from the latter to the former presupposes, however, such a depression of the ice-covered continents, and this depression holds just the quantities of ice which, melted and added to the sea, would balance the lowering of the sea-level from the rising level of 55 m due to melting of the 22,500,000 km^3 of ice, in which the masses in the isostatic depressions were not included. If this depression under the ice is complete, its ice volume, 8,900,000 km^3, covers in the form of water fully the 30 % of sea-level's sinking by the isostatical readjustment between ocean bottoms and the continents liberated from ice. If the depression beneath the ice has not reached its fullest possible extent, this readjustment will also lower the sea-level so much less, and the ice masses corresponding to the depression suffice to compensate this lowering.

For these reasons, I hold it probable that the complete vanishing of the land ice would raise the sea-level 55—56 m, this figure being the maximum.

The Sea-level during the Preglacial and Interglacial periods.

The hypothetical case, the total vanishing of the land ice on the earth or its reduction to smaller dimensions than at present, can be thought to have occurred during warm interglacial epochs or to have existed before the first Pleistocene Ice Age. Possibly many of the raised shores observed at numerous places all over the globe were formed by a higher stand of the sea-level owing to this cause. A shore-line corresponding to the vanishing of all land ice should then lie 55—56 m above sea-level, and raised shores formed when the ice had but partly melted away are to be found at levels below that strand-line. However, such shore lines, formed by a certain eustatic rising of the sea connected with a decrease of the glaciations, can be expected to occupy the same level over all the earth only if the isostatic readjustment between the oceanic and continental parts of the earth-crust kept pace with the removing of the weight of the water (ice) from the ice-covered continents to the sea, and if no other crustal movement lifted or brought down the land mass.

These conditions were, however, certainly not wholly realized. For improbable as is the complete melting of the land ice and the filling of the sea before the isostatic sinking of the sea-bottom and the rising of the deglaciated continents started, as unlikely is the completion of this isostatic movement coincident with the ending of the melting of the ice and filling of the sea. We may only call to mind the fact that Fennoscandia and other formerly glaciated areas have risen long after they were free from ice, and that they are still rising.

Further, by these isostatical readjustments the flow of the subcrustal masses was certainly not direct from the suboceanic area to the subcontinental ones and inversely, but the semasses were forced by glaciation and deglaciation also to and from the continental areas adjacent to the glaciated areas, as we know was the case with Fennoscandia and its surroundings.

For all these reasons, the shore lines of eustatic origin can have been tilted out of their horizontality, and even in the parts of the globe, which were not glaciated in the Quaternary time, we may find shore lines dating from one and the same stage of an eustatic rise of the sea-level more or less above or below the expected normal level. In the formerly glaciated regions, the changes of level have evidently resulted both from isostatic crustal movements and from eustatic oscillations of the sea (RAMSAY 1924b).

Many considerable changes of level certainly have their origin in the late-Tertiary orogenic crustal movements and their subsequent effects in Pleistocene time. They have not only displaced landmasses to higher or lower levels, they have also widened or reduced the basin of the ocean, and have in this way given rise to eustatic changes of level, added to or subtracted from those originating in the decrease or increase of glaciation.

In spite of all these complications, it seems to me that it should be possible to recognize, among the numerous Pleistocene »terraces» and raised shore lines reported from different parts of our globe, those corresponding to interglacial or preglacial epochs when the glaciers and ice-caps were considerably shrunken or had disappeared entirely.

Our interest is thus directed to Pleistocene shores in regions which were not covered by land ice. The authors describing such shores generally inform us that several »terraces» appear above each other. These shores are considered to be Quaternary, partly because of their »young» appearance and their concordance with recent geography and topography, partly because of the similarity of the fossil fauna on them to that of recent date, partly because they lie on rocks of Pliocene or other pre-Pleistocene age. The best developed among them are terraces formed by abrasion or accumulation, and also deltas. Where several such shores appear in different levels above each other, as is general, the lower are younger than the higher. It seems from some descriptions, and is stated by many authors, that the transgressions during which the terraces were formed were preceded by regressions. To explain the development of marine Quaternary terraces on such coasts some authors have deduced from these facts series of oscillations either of the sea-level or of the earth-crust.

The highest marine terraces said to be Pleistocene lie in many places 60—100 m, even 200—300 m or more above sea-level, and above them there lie in some regions still higher Pliocene and Miocene shores. These facts show that the development of the orocratic conditions of the Pleistocene period from the earlier Pediocratic (RAMSAY 1924 b) continued and culminated during the first half of the Pleistocene period. I need not enumerate here the various evidences and statements in hand for the now existing mountainous and broken relief having been formed in so late a time. Marine layers of the youngest Pleistocene age and Pliocene marine terraces at levels of a thousand metres and more in some localities, and contemporary formations of the same kind at or below sea-level in other places, are evidence of changes of level of such extent having taken place since then, *i. e.* during Pleistocene time.

It was the Alpine orogeny that led to the now existing relief. The Pediocratic conditions prevalent till then were above all disturbed by the isostatic rising of the thickened sialic matter in the orogenic zones. Next, tectonic displacements of other parts of the earth-crust contributed to the increase of the differences between higher and lower tracts.

The greatest share in the high elevation of the continents and landforms is attributable to the enlargement and deepening of the ocean basin, as an effect of diastrophism. It is well-known to geologists that the regressions were the greatest, *i. e.* the capacity of the ocean basin greater than usual, after the orogenetic phases in the earth's history, and this fact stands in obvious connexion with the tectonic displacements of the crust of the earth and the rearrangement of the continental blocks during the periods of great diastrophism. We meet, also after the period of the Alpine orogeny, with a great general regression, the Pleistocene, and with the fragmentary structure of the continents. The latter is nowadays interpreted by two different theories. On the one hand we have the SUESS doctrine of the sunken former continents in places now covered by many ocean areas. If the Atlantic, the Indian Ocean and other seas have such an origin, the ocean basin must have been enormously enlarged. On the other hand we have the WEGENER (1928) theory of the wandering continents. According to this theory the thickening of the earth's crust in the zones of mountain-making and the gliding away of the continental parts of the crust from each other also bring about a huge increase of the ocean basin. Both interpretations lead to the same result; in the widened and deepened basin the surface of the sea sank, and the continental blocks rose higher above it than before.

In consequence of this, the base level sank and a cycle of powerful erosion began, or perhaps, more correctly speaking, successive cycles, if the enlargement of the ocean basin advanced intermittently. The increased erosion unloaded mighty quantities of rock material from the continents, which rose still more owing to this cause. Hereby the rising of the mountains in the young — the Alpine — zones was hastened, but also other regions rose for the same reason, and the higher, the more they had below them »sialic deplacements» from former orogenies (Caledonic or Hercynic).

The appearance of several terraces or raised shores above each other, and the indications of transgression having occurred on them, have been interpreted by some authors (DE LAMOTHE and others) as evidence of eustatic lowerings of the sea-level by enlargements of the ocean basin, alternating with eustatic rising of the surface caused by the sedimentation of terrigenous material in the sea. A calculation (cf. LAGOTALA 1924) shows, however, that this geological process has not the effect assumed. Further, the isostatic rising of the continents freed from the sediment material and the depression of the sea-bottom under its load, will together result in displacement of the sea-level greater than the rising of the sea-level due to the same mass of sediment. It is more probable that also eustatic transgressions can result from diastrophistic events which reduce the capacity of the ocean, or from rising of parts of the sea-bottom with the same effect. All great general regressions during the orogenetic phases in the earth's history have been succeeded by general very extensive transgressions during the anorogenetic phases, *i. e.* the capacity of the ocean basin enlarged by diastrophism is again diminished by crustal movements, for the mere filling with sediments is not sufficient to cause transgressions. There is, however, reason to think that at least some of the Pleistocene terraces were formed by transgressions caused by the melting away of the land ice.

Whatever the interpretation of the circumstances touched upon above may be, the fact remains that the evolution of the continents and oceans during the transition from the Tertiary to the Quaternary period tended towards highly orocratic conditions and very great regression of the sea. According to the outline given above, the principal cause of the elevation of the continents and the enlargement of the ocean basin lay in the Alpine diastrophism, but the resulting changes of sea-level were eustatic in the first instance. The shore lines dating from one and the same stage cannot, however, on all coasts now lie at the same level above the sea, and shore lines from different stages have not at all places preserved their parallellism, because the continents have also moved and this in different ways.

Meanwhile, the diastrophism which caused the recent geographical and hypsometrical conditions may have relaxed or dwindled during the progress of the Pleistocene period, and these conditions existed in the main when the Quaternary Ice ages set in. The land surfaces on which glacial and interglacial sediments have accumulated, or which have been affected by glacial agencies, are closely related to recent topography, and glacial and interglacial deposits fill valleys concordant with the recent ones. That being the case, it is not improbable that the shores formed by the transgressions of the sea in consequence of the decrease or vanishing of the land ice during warm interglacial periods could be found on the coasts of countries which were not glaciated, at levels corresponding to the rise of the sea caused by the ablation of the land ice, or not far above or below these levels.

Quaternary Shores on the Coasts of the Mediterranean.

DE LAMOTHE has in several publications shown the appearance of a series of raised marine shores in Algeria and Tunis, lying at levels of 325 m, 265 m, 204 m, 148 m, 100 m, 60 m, 30 m and 19 m. Those above 100 m are held by many authors to be of Pliocene age, and DE LAMOTHE himself (1923) described a Pliocene fauna from a terrace at the level of 148 m.

On the opposite side of the Mediterranean, at Villefranche, in the neighbourhood of Nice and Monaco, DEPÉRET (1906) has observed Pleistocene shore lines at the levels of 100 m, 60 m, 30 m and 13 m and regards them as corresponding to those on the Algerian coast.

In Sicily and Calabria and other parts of Italy, GIGNOUX (1913) has made a close study of the marine Pliocene and Quaternary deposits and shore lines. The oldest post-Pliocene deposits show a fauna containing, besides the »banale» or still living forms in the Mediterranean, shells of *Cyprina islandica, Mya truncata, Panopaea norwegica, Trichopteris borealis, Buccinum andatum, B. Humphreysianum, Chrysodomus sinistrosa* and other Atlantic and northern forms not nowadays existing in the Mediterranean. They indicate a climate colder than at present and they certainly lived during some of the great Ice Ages. These deposits are found in great extent at Palermo and along the northern coast of Sicily, whence the corresponding epoch and stage has been named »Sicilian» (by DÖDERLEIN). The real fossilferous layers of these deposits occur at relatively low levels, but the bathymethrical indications of the fossils suggest that they existed at a depth of 60—70 m, and GIGNOUX, therefore, believes that a very distinct shore line at the level of 80 m in the neighbourhood of Palermo shows the height to which the surface of the sea rose in the Sicilian transgression. He recognizes corresponding shore lines in Calabria and in the neighbourhood of Livorno at levels of 80—100 m and has found below these also deposits containing Sicilian fauna. DEPÉRET coordinates with these assumed Sicilian shores the terraces found by him in southern France at 90—100 m above sea-level and by DE LAMOTHE at 100 m in Algeria.

According to GIGNOUX, among the raised shores below that taken as the Sicilian, at 80—100 m, those at the level of 35—38 m are especially pronounced in Sicily and Calabria. Besides the still extant Mediterranean species, the deposits on these terraces contain such belonging to warmer regions and now living on the Atlantic coast of Africa (Senegal), *viz.: Strombus bubonius, Conus testudinarius, Tritonidea viverrata, Natica lactea, Pusionella nifal, Cardita senegalica, Mactra Largillieri, Tugonia anatina, Tapes senegalensis* and others. The same fossil fauna is found in Algeria and Tunis on the raised terraces up to the one at the level of 30 m in DE LAMOTHE's series of shore lines, and also on the coasts of Spain at levels held to correspond to the former, and at 34 m above the sea at Villefranche according to DEPÉRET. In view of the almost similar level (26) 30 m—35 (38) m) of the raised shores and the characteristic *Strombus* fauna, and in accord with DE LAMOTHE and DEPÉRET, GIGNOUX considers that these terraces and their deposits belong to a distinct Quaternary stage and epoch named Tyrrhenian (by Issel). The usual level of this epoch is, however, exceeded in some cases. Terraces with *Strombus* fauna lie at about 100 m above the sea at Ravagnese and Rovereto, south of Reggio, on the east side of the Straits of Messina.

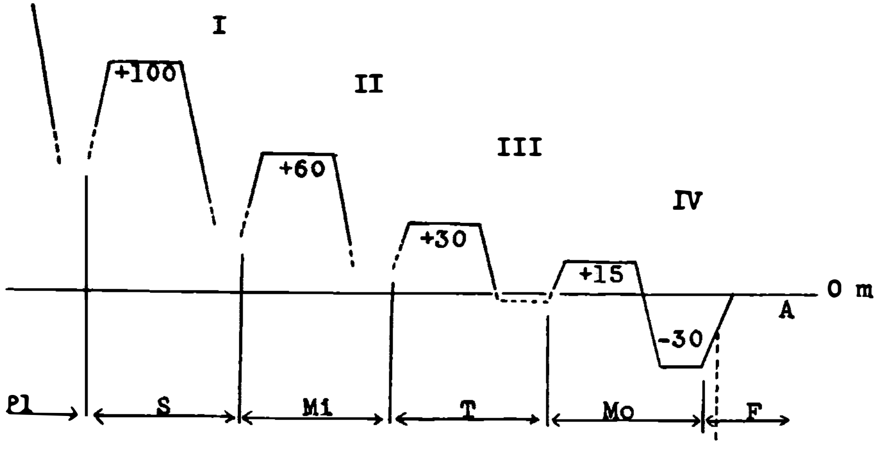

Fig. 2. Diagram, after G. DUBOIS, showing the relation between glaciations and changes of sea-level in the north-west of Europe. Pl, Pliocene; S, Sicilian; Mi, Milazzian; T, Tyrrhenian; Mo, Monastirian; F, Flandrian (Postglacial); A, Actual. I, II, III, and IV, Gunz, Mindel, Riss and Würm Glaciations.

Below the Tyrrhenian shore with *Strombus bubonius* fauna (30—35 m), other distinct »terraces» with warm fauna (*Strombus bubonius,* etc.) occur at the level of 15 m in the countries investigated by GIGNOUX. DEPÉRET calls this stage the Monastirian, and coordinates it with DE LAMOTHE's terraces at 18 m on the southern side of the Mediterranean, and with the terraces of equal height on the northern side.

DEPÉRET adds a further stage, a shore line called the Milazzian, at the levels of 55—60 m between the Sicilian and Tyrrhenian shores, and arrives thereby at an outline for the Quaternary shores, which is made clear in fig. 2. According to DEPÉRET and DE LAMOTHE this outline applies not only to the Mediterranean regions, but also to the Atlantic coasts of Africa and Europe and probably holds good over all the globe.

The starting-point for DE LAMOTHE and DEPÉRET is the conception that the raised shores in question are parallel with each other and the sea; the changes of the sea-level from the older higher shore lines to the younger lower ones and to the present sea-level being interpreted by eustatic oscillations of the sea. Regressions have been caused by the enlargement of the ocean basin, transgressions by the accumulation of sediments in the basin. Objections have been raised against these explanations, *e. g.* by OSBORN and LEVERETT (1922). Complete horizontality and parallelism can hardly be preserved by the strand lines, and the older these are, the greater is the possibility of disturbances, not the least in the zones of young mountain making. Indeed, this is exactly the case in the Mediterranean regions.

Not even the lowest of the terraces, the Monastirian (13 m—20 m) and the Tyrrhenian (30 m—35 m), realize the above mentioned conditions of horizontality and parallelism. The actual figures for definite localities vary still more (Monastirian: 15—22 m, Tyrrhenian: 25—38 m). It should, however, be noted that the statements of level very seldom refer to observed and well defined real shore lines (in the sense in which we determine the shore lines in Fennoscandia), but to the more vague situation of »terraces», which term seems to include shelves and littoral plains of accumulation or abrasion, beaches, fotmer shallow sea-bottoms off the shore, shell banks etc. Even very great divergences appear. GIGNOUX mentions that the upper terrace with *Strombus bubonius, i. e.* the Tyrrhenian terrace, which lies between 30—35 m according to the outline above, occurs at Reggio (see above) at the level of 100 m above the sea, »précisément en un des points de la Mediterranée qui s'avèrent comme les plus instables».

Still less we can *à priori* expect that the higher shore lines, the Milazzian and Sicilian, should have remained in the general horizontality assumed by

DE LAMOTHE and DEPÉRET, and the method of coordinating them only according to their level above sea can lead to false conclusions. With regard to the fact that young marine Pliocene and Pleistocene shores appear at various levels, from beneath the sea up to 1000 m and more, one should bear in mind that the shores from any older Pleistocene epoch can show great differences of height at different places, even in regions which were not covered by land ice. As an example of this we can take the Sicilian stage and its shores.

In the eastern parts of the Mediterranean region the shell fauna characteristic of this Pleistocene stage is found in deposits which are mentioned as occurring at 300 m above the sea in Rhodos, and at 180 m on Kos. In the island of Sicily itself, the Sicilian fossiliferous layers lie 10—15 m above sea-level, but the corresponding shore is supposed to occur at 30 m (see above), and with this the Sicilian terraces at 90—100 m in the western part of the Mediterranean are coordinated by DEPÊRET. However, no Sicilian fossils are found on or off these latter shores. On the contrary, the most typical representatives of the Sicilian stage are dragged up from the depth of 100—200 m, even from 500—700 m, on the sea-bottom E. of Cape de Creus at the eastern end of the Pyrenees. Crustal movements have evidently to a great extent removed the Sicilian deposits and shores in the Mediterranean. HAUG sees in their deep submarine occurrence off Cape de Creus an indication of a Pleistocene tectonic sinking (effondrement) of this part of the sea-bottom. I, for my part, am more inclined to think that these submarine layers of the Sicilian have remained nearly at the level where they were formed, but that the occurrences on Sicily, Rhodos and Kos have been raised with the rising land in these regions, renowned as very unstable, as also GIGNOUX supposes that the Tyrrhenian at Reggio (see above) has been displaced after its formation.

The Sicilian fauna indicates conditions of a more Atlantic and northern type than those of the present Mediterranean climate and such fauna must have lived in this region during a period or periods of great glaciation in Northern Europe, the Alps and other parts of the earth. The *Strombus bubonius* fauna, again, in the Tyrrhenian and Monastirian deposits, with its Senegalian form, indicates a warmer climate in the Mediterranean than that of recent date, and existed there in all probability during interglacial periods. In consequence of the genial interglacial conditions, the ice-caps were reduced to a smaller size than at present and the surface of the sea might have stood at the levels indicated by the raised Tyrrhenian and Monastrian shores. The shores considered as Sicilian ones may from this point of view, as belonging to some Ice Age, not have been formed at levels above those of interglacial age, as during the great glaciations the surface of the sea must have sunk considerably beneath the present surface. Also for this reason I believe that the Sicilian fossiliferous beds in Sicily, Calabria, Toscana, Rhodos, Kos etc. were lifted from their original situation by the rising of the land masses in the Mediterranean zone of orogeny, and as their homotaxis with other formations from some great Ice Age seems beyond doubt, their elevated situations teach us that considerable vertical displacements of the earth's crust have taken place in these regions in times more recent than some great Pleistocene Ice Age.

In view of these circumstances, it is very uncertain if all terraces and shores at levels of 80—100 m above sea-level can be accounted as Sicilian ones, as has been done. At least, such an assumption must be confirmed by the occurrence of typical Sicilian fossils.

The original shores of Sicilian age must be presumed to have been formed at depths considerably below the recent shores, and thus still deeper beneath the interglacial terraces and beaches, because this age was a time of great general glaciation. In my opinion, the submarine Sicilian beds east of Cape de Creus have remained nearly in the level where they were deposited, the ocean (and the Mediterranean sea) being then considerably shallower than nowadays. The deposits, and probably also the shores of Sicilian age, thus lie in the normally expected situation relative to those of Tyrrhenian and Monastirian age, or below them. The 100 m strand line at Villefranche (see above) cannot indicate a shore of Sicilian age. Even with HAUG's interpretation (see above), a combination of this strand line with the fossiliferous beds at the bottom of the sea in the western Mediterranean will in many respects lead to contradictory consequences.

Where the Sicilian beds and shores lie high above sea-level and above the Tyrrhenian terraces, as in Sicily, Calabria, Rhodos and Kos, we may draw the conclusion that the crustal movements in the Mediterranean zone of orogeny, which have lifted the Sicilian beds and shores after the Sicilian epoch, have done the greater part of this work before the Tyrrhenian epoch, after which the rising has, however, continued in some places (Reggio, see above).

Another circumstance speaking for a lowering of the surface of the sea in the Mediterranean during the Ice Ages, *i. e.* during the Sicilian epoch, is the existence of the river valleys now filled with the waters of the Dardanelles and the Bosphorus. The threshold of the Bosphorus lies 42 m below sea-level, according to MAKAROW (1885), and has the form of a river channel, the drowning of which is considered by many authors to be caused by land sinking in connection with the young tectonic disturbances east of the Mediterranean region. It seems to me more probable that the channels of the Dardanelles and the Bosphorus were eroded during the Ice Ages, when the surface of the ocean lay deeper than the bottom of these channels. The Black Sea was then isolated from the Mediterranean Sea and formed a big lake, the water of which cut an outlet through the land barriers between Europe and Asia. This lake in the basin of the Black Sea received waters not only from its present drainage area, but also the glacial water from the big land ice north of the Carpathians and Southern Russia, and further the immense masses of water which came from the Aralo-Caspian lake through the Manytch valley. The Aralo-Caspian lake received tributary waters not only from the Wolga side but also from the West Sibirian Ice lake (MOLTSCHANOW 1926).

In view of the above-mentioned possibility and even certainty of shore lines having been removed and disturbed by the crustal movements in the Mediterranean zone of orogeny, it may appear useless to look there for shores which could indicate the eustatic rising of the sea-level owing to reduction of the glaciations during interglacial or preglacial epochs warmer than at present. Nevertheless, the attempt shall be made.

Among the shores in the scheme of DEPÉRET—Sicilian at a level of 80—100 m, Milazzian at 55—60 m, Tyrrhenian at 30—35 m and Monastirian at 18—20 m (see fig. 2 on p 21) — the uppermost cannot belong to the ones desired. They lie much above the levels to which the sea would rise, even if all land ice vanished (p. 16). Further, the true Sicilian terraces with fossiliferous deposits indicate Ice Ages prevailing on the earth, *i. e.* times of greatly lowered sea surface. They occupy their high positions only in consequence of crustal movements (see above). The primary situation of the Sicilian strand is below the present sea surface (Cape de Creus, Dardanelles and Bosphorus, see above).

The shores accounted as belonging to the Milazzian stages (55—60 m above sea-level) might perhaps be thought to have been formed at the highest possible levels to which the sea would rise if the present land ice vanished completely, but seem too high even in such case. I have found no lists of fossils from these shores. If the Milazzian stage was a preglacial or interglacial stage with so warm a climate that the deglaciation must have been total, the shell fauna on its terraces must contain many tropical forms. But not even the *Strombus bubonius* fauna is mentioned as reaching to these levels (exception: Reggio, see p. 21). The Milazzian stage and its shores are not observed at all by GIGNOUX in his broad study of the marine Pleistocene formations in the western Mediterranean, and they seem to appear but vaguely, if at all, on the coasts of Africa and Europe outside the Mediterranean. I think, therefore, that the socalled Milazzian terraces have no direct connexion with the eustatic rising of the sea consequent upon the melting away of the landice.

According to the opinion expressed on p. 18 and p. 17, crustal movements have disarranged the original horizontality and parallelism of the preglacial and earlier glacial strand lines to such a degree that their relation to eustatic changes of sea-level can be discussed only after the forms and situations of the shore surfaces from these earlier Pleistocene stages have been studied and exactly determined (Strandfläche, RAMSAY 1926). However, as these crustal movements have relaxed during later Pleistocene epochs, there is reason to suppose interglacial and postglacial shore lines were less removed from their primary position, and one has greater possibilities to coordinate them on the ground of their nearly corresponding levels. I, therefore, accept the Tyrrhenian and the Monastirian terraces as defined shores for definite Quaternary stages of eustatic oscillations of the sea, in accordance with DE LAMOTHE, DEPÉRET and GIGNOUX. The cause of the rising of the sea to these levels was reduction of the glaciations.

Many circumstances speak for the interglacial ages of the Tyrrhenian and the Monastirian epochs. The coincident rising of the sea-level and appearance of the Senegalian fauna point to the decrease of the land ice caused by greater warmth. Many fossil remains of the higher land fauna found on the terraces in question belong to forms characteristic of certain interglacial epochs. Palaeolithic implements and dwellingplaces found in the Tyrrhenian and Monastirian shores or in their vicinity give similar information.

The Tyrrhenian terraces in the Mediterranean region are situated at levels of between 30 m and 35 m, according to DEPÉRET, but the variations of height are still greater. The vagueness of the statements certainly depends on many different causes. A main part is due to vagueness in determining the shore line itself (see above), and further to the obvious fact that in many cases no exact levellings have been undertaken, but only estimates of the heights of the shores above the sea been made. The variations of the levels from place to place can also be a reality, the original horizontality of the shore surface having been lost by later crustal movements. Finally, there is the possibility that the Tyrrhenian terraces were formed not by one, but by two different interglacial transgressions of the sea-level, separated by an Ice Age with considerable regression and lowering of the sea-shore. If these risings of the sea-level have not exactly covered each other, the height of their terraces can differ, the one being better developed at some places than the other.

The height of the Tyrrhenian terraces above the sea does not reach the limits to which the sea could rise by complete vanishing of the glaciations, though a considerable part of the land ice — approximately nearly two thirds, or more than the half — melted away.

The Monastirian stage corresponds probably with the last interglacial epoch. Its terraces (15—18 m) indicate a diminishing of the glaciations by about a third. An Ice Age with very low sea-level must have occurred between the Tyrrhenian and the Monastirian stages.

One is hardly on the right track in combining the Tyrrhenian and Monastirian stages with the two last glacial epochs in the Alps, as has been done by DEPÉRET with the aid of the river terraces in the Rhone valley.

Interglacial Shores.

If the Tyrrhenian and Monastirian shores have the origin understood above, corresponding strand lines must appear on the sea coasts in all regions which were not glaciated, and should give us a very dependable means of homotaxis between Quaternary stages in different quarters of the earth, when determining their age in relation to the respective shores. I have earlier (RAMSAY 1925) directed the attention of the prehistorians to the two following important consequences of the eustatic changes of sea-level, due to the decrease and increase of glaciation:

During the Ice Ages, when the surface of the sea stood at a low level, more or less extensive regions of land, now covered by sea, extended off the present coasts. The conditions of climate and of life in general prevailing there were those relatively most favourable to man, and these were the regions mainly peopled during glacial periods. Many such regions were perhaps the primeval homes of the civilizations which appear during the following interglacial and postglacial epochs.

During interglacial and postglacial epochs, when the surface of the sea was higher, it rose to higher or lower levels on the continents, depending on the climate and the degree in which the land ice decreased. The strand-lines and river terraces then formed on the borders of the transgressions are synchronous on all coasts of the oceans. In the relation of prehistoric settlements to such terraces and strand-lines we have perhaps the most reliable medium of homotaxis between archaeological periods in widely separated parts of the globe.

Such attempts at coordination of the Quaternary shore lines within more or less wide regions have also been made, *e. g.* by DEPÉRET (1906) and others, most recently by G. DUBOIS (1924). The former has parallelized terraces on the Atlantic coasts of Africa and Europe with such on the Mediterranean and found correspondences with the Tyrrhenian and Monastirian stages, or the two shore formations of interglacial origin, according to my opinion. Several localities are mentioned, from Senegal (Dakar) in the south to Portugal in the north, where terraces of these kinds occur. The fossil shell fauna on them indicates a climate at least as warm as at present, or in some cases warmer.

The stated levels, however, are generally 5—10 m lower than those held to be normal by DEPÉRET (Tyrrhenian: 30—35 m, Monastirian: 18—20 m), which circumstance is explained as follows: »que les auteurs se sont plus préoccupés de l'altitude des depots fossilifères que celle des lignes de rivages correspondantes.»

On the western coast of France, the lower shore, the Monastirian, is the most conspicuous, but also higher shores which could belong to the Tyrrhenian stage have been noted by some authors, whilst others call their existence into question.

On the south side of the Channel, at about 30 m above sea level, DE LAMOTHE mentions a Quaternary bed with marine fossils indicating a climate warmer than that of recent time. The shore line itself must occur somewhat higher up and probably be Tyrrhenian. G. DUBOIS remarks, however: »Dans le Nord de la France le Tyrrhénien est douteux à l'état marin, le Monastirien est nettement représenté.»

On the northern coast of the Channel, the known Pleistocene marine beds of Selsey Bill and West Wittering contain *Pecten polymorphus*, *P. opercularis*, var. *Audouini*, *Lutraria rugosa*, *Chiton siculus*, *Pleurotoma Bertrandi* and other species not thriving nowadays north of Madeira and the sea off Portugal. DEPÉRET coordinates these beds with other marine Quaternary beds — their faunas mostly the same as the present — occurring on the southern coast of England beneath the »head» or »rubble-drift» and upon the remarkable preglacial (W. B. WRIGHT) abrasion terrace in pre-Pleistocene rock, running from the southern shores of Ireland and Wales to Dover in the east. The shore line corresponding to these marine deposits is, according to DEPÉRET, obvious (trés nette) and lies 30—33 m above sea level. According to British authors the circumstances are not so clear. The character of the shell fauna certainly sets the interglacial age of the Selsey Bill and West Wittering deposits beyond doubt, but the corresponding shore seems to have been hidden under the rubbledrift or blotted out in other ways by the influence of the great glaciations which extended not far away.

Farther towards the north of Europe, the interglacial shore lines are generally effaced by the former great glaciations. The Norwegian »strand-flate» represents, however, abrasion terraces of such ages, according to the interpretation of NANSEN (1922). There are such at three different levels: 30—40 m, 15—18 m and a submarine one. The first of these terraces corresponds well enough with the Tyrrhenian and the second with the Monastirian terraces in the Mediterranean area.

The circumstances referred to support the following suggestions:

Evident or certain analogies to the called Sicilian and Milazzian shores do not appear on the African and European coasts beyond the Mediterranean. It seems probable that these higher raised Quaternary terraces are peculiar to the zone of young orogeny.

On the other hand, outside the Mediterranean area there are sea shores at levels corresponding to the Tyrrhenian and Monastirian ones, and fossils indicating a former more genial climate occur in these shores. Further, closer study will certainly afford evidence of the worldwide existence of these two stages of eustatical rising of the sea during interglacial epochs when the climate was warmer than at present. The Tyrrhenian stage perhaps includes also two interglacial transgressions, both reaching nearly the same level.

It is very enticing to extend the comparison of the Pleistocene shore lines to all sea coasts in countries never glaciated. The literature dealing with such regions frequently gives us information relating to marine littoral beds, »terraces» and raised beaches of young geological age. Most of these statements are too vague for a decisive coordination of the formations described by the authors with similar formations in other regions. One looks in vain for exact measurements of their height above sea-level. We mostly meet with rough estimates in round tens of metres or feet, *e. g.* 20—30 m, 60—80 feet. I have, therefore, given up this alluring idea, and will try connexion only with some raised shores on the other side of the Atlantic.

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Emerged coastal terraces and submerged wave-cut platforms are the most striking features of the seaward slope of the Island of Haiti. Some of these are several kilometres wide, and at certain places as many as 28 terraces one after the other have been measured between sea-level and 400 metres above sea-level. They are of Quaternary origin and their present situation is mainly attributable to crustal movements and to eustatic oscillation (Woodring etc. 1924).

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Interglacial River Terraces.

The terraces on the lower courses of the rivers running to the sea seem to illustrate the eustatic changes of sea-level during the glacial and interglacial epochs in a plainer manner than do the raised shores.

All these rivers disembogue (end) in drowned valleys, if they are not prolonged by deltas or shortened by the abrasion of the coast. Their base level was once lowered by a general regression of the sea, followed by a eustatic transgression up to the present level of its surface. We can further prove that the bottom of the river channels in the ground beneath the valley fillings lies deeper than the present river beds and in the lowest parts of the rivers runs far below the sea. Peat bogs, stub layers and other supramarine formations form part of these now submarine valley fillings. On the other hand, on all the same rivers, remains of former valley fillings occur in the form of terraces high above the present river beds. Such terraces lie there, one above the other, *i. e.* younger and younger accumulations have filled the valleys eroded in the older ones. (Fig. 3).

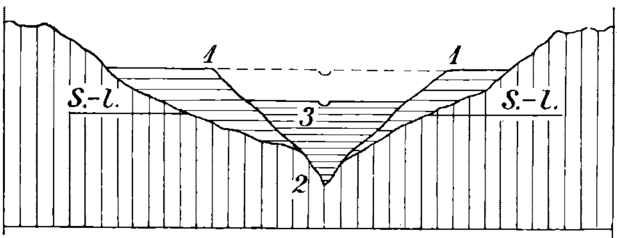

Fig. 3. Diagram of a younger valley-filling (3) in an older one (1). The younger valley-filling, with the river-bed, corresponds in height with the recent sea-level (S. — l.). Before this stage, the sea occupied a lower position and the river eroded a deep valley in the older filling, which in its turn had been doposited in an older valley in the substratum (2), during a period, when the sea stood at a higher level than the present one

Some authors have compared these alternations of erosion and accumulation and the terraces formed thereby with the glacial gravel plains and terraces in the Alps and surrounding countries, according to the scheme of PENCK and BRÜCKNER. Accumulation in the river valleys should thus correspond with glacial periods, erosion with interglacial epochs. In this way *e. g.* DEPÉRET, by combining the river terraces of the Rhone, has conceived the idea of the Tyrrhenian and Monastirian stages being glacial. A kindred conception appears in the interpretation of the Nile terraces by BLACKENHORN (1921), *viz.*, that heavy rainfalls increased the transport and accumulation by the river during pluvial times synchronous with the Ice Ages, and then filled the valley with the terraces, while a dry climate with slight accumulation and erosion prevailed during Interpluvial (= Interglacial) and postglacial times. Similar views are expressed regarding the terraces of many other rivers by several authors.

In my opinion (RAMSAY 1925, 1926), the circumstances may be explained in quite the contrary way. The valleys were filled with accumulations, of which the terraces remain, during interglacial epochs, when the surface of the sea and the base level was lifted by the reduction of the land ice, while the river valleys and channels were eroded during the Ice Ages, when the surface of the sea and the base level were lowered beneath the present sea-level owing to the great glaciations. The probability of this theory is corroborated by the close coincidence of the levels of the river terraces, in the vicinity of the sea, with the shores supposed to be of interglacial age. I refer to the best known river terraces, those of the Somme, the Seine (COMMONT, DEPÉRET, DE LAMOTHE), the Loire (FERONNIÈRE 1913, CHAPUT 1919), the Garonne (BLAYAC 1916), of the Thames in England (DEWEY), and of the Belgian rivers (RUTOT 1903).

They are especially well developed at two levels, the upper (30—35 m) corresponding to the Tyrrhenian stage, the lower (18—20 m) to the Monastirian one. Palaeolithic implements and dwelling places of several different ages are found at both levels.

Still higher terraces are reported from these valleys, but no corresponding raised sea shores are observed for them. If their origin is similar to that of the lower ones (at 30—35 m and 18—20 m), the coast must have extended far from the present one and a broad strip of the coast land have been abraded away since then. Such events, if of actual occurrence, must have taken place before the first great Ice Age, or latest during that Age. When the margin of the great North European glaciations lay north of the Straits of Dover, enormous masses of water streamed through these straits, *viz.*, all water flowing from the melting margin of the land ice, from England in the West to the Western Carpathians in the East by way of the »Urstromtäler». As the sea-level was greatly lowered, the powerful stream deepened and widened the valley of the Channel, and the affluents from both sides did the same with their valleys. A broad front was in this way prepared for the attack of the sea when it rose again.

The Lowering of the Sea-Level during some Quaternary Epochs.

As the sea-level may have risen during the interglacial epochs because of the decrease of glaciation, it sank during the Ice Ages owing to increased glaciation. The sea shores were removed below and more or less far from the present ones. The continents then enclosed great parts of the shallow sea areas, and these now submerged regions, as favoured by a better climate than the higher land, were encroached upon by the richest vegetation and fauna and had probably the densest population of those times. Numerous submarine finds of peat bogs, stub layers, land mammals and Stone Age implements point to this.

All river mouths on the sea in regions never glaciated are, if not filled by accumulation or shortened by abrasion, drowned valleys, beyond which the submarine river channels can in many places be followed to a greater or lesser depth; such channels with a depth of 20—40 m are quite usual, according to charts and information in geological or geographical papers. But far deeper channels exist, for example the Hurd Deep (172 m) in the English Channel, the Indus Deep (300 m) and the Ganges Deep (700—1000 m), not to speak of the Congo Deep (descending below 1200 m), La Fosse de Breton in the Bay of Biscay and other abysses. Round the North Atlantic and the Arctic Ocean, the submarine prolongations of the fjord bottoms reach the margin of the continental shelf at depths of about 400 m or more (NANSEN 1922), and at the same depth the submarine valley in the Barentz Sea, south of the Bear Island, the Norwegian Channel and the S:t Lorenzo Channel end in the ocean.

At least the submarine channels with moderate depths of 200—400 m seem decidedly to be formed by subaërile erosion, according to the authors who have discussed this question. Even the continuations of the fjord valleys and similar submarine valleys (*e. g.* the Barentz valley) are held to have such an origin or to be the work of the ice streams. Many authors, however, ascribe a tectonic origin to the deepest channels in the continental shelf. Good reasons for such an interpretation are given (GORCEIX 1922) concerning la Fosse de Cap Breton.

In a very interesting study MOLENGRAAFF (1922) has shown that the Sunda plateau was main land in very recent Pleistocene time, uniting Java, Borneo and Sumatra with the Malacca Peninsula. He estimates the lowering of the sea-level at about 150 m.

The growing up of the coral reefs from the bottom of the ocean presupposes a low sea-level (shallow water) when the reef building began, and increase of the depth since then, according to the theory of DARWIN. DALY (1915) in his renowned glacial control theory connected this decrease and increase of the sea's volume with the great Quaternary glaciations and deglaciations. He supposes that the base of the reefs grown *in situ* lies at the depth of about 60—70 m, at which depth submarine plateaus should be especially common and well developed. The coral masses forming also the deeper parts of numerous reefs and coral islands are assumed to be clastic accumulations of fragments, not the original construction of the polyps. The borings on the Funafuti atoll, however, pierce grown coral reef at a much greater depth than that of the plateau level according to DALY, and a mechanical piling up of such high coral masses beneath the reef itself is not easy to understand, without assuming that reefs have grown up from the greater depths. Therefore, the considerable depths of coral reefs and coral islands bear witness, anyhow, to the growing up of the coral reefs from sea-bottom on which the coral masses repose. Such negative changes of the sea-level can depend on the sinking of the sea-bottom, as formerly generally assumed, and the load of the coral reef itself must in part cause depression, but a very great part of the increase of the sea's depth is certainly to be ascribed to a general Quaternary great transgression after regression of considerable extent.

The circumstances mentioned give evidence of considerable general eustatic oscillations of the sea-level during the Pleistocene period. The cause of these oscillations may be changes in the capacity of the ocean basin caused by crustal movements, or changes in the sea's volume by addition or diminution of water. Both have probably occurred, the former cause predominating during the early part of the period, the latter since the beginning of the first Ice Age. An estimate of the quantity of water consumed by the great glaciations can give us a certain idea of the sinking of the sea during an Ice Age.

Such a calculation postulates the glaciations of an Ice Age having been contemporaneous in the different parts of the globe. Reasons for this assumption are not given here, I refer readers to the literature of Quaternary geology where the question is dealt with. Only by such an assumption can we explain how the increase and decrease of the land ice could cause rising and sinking of the sea-level. If the glaciations of different regions had alternated, no eustatic variations of the sea-level, or only small ones, would have appeared.

The calculation is based on the statements of the areas formerly glaciated and on estimates of the thickness of the vanished glaciations. The latter factor can vary according to the author's view, the former one will be free from uncertainty, when once all parts of our globe are geologically surveyed, especially with regard to the traces of Quaternary glaciations. Notices of glaciations in districts hitherto considered as nonglaciated are still received. Even regions frequently crossed and examined by geologists can have surprises in store, as *e. g.* Siberia, of which more in the following.

The Glaciation of Siberia.

According to the usual presentation of the Quaternary glaciation at its maximum, only the western part of Siberia was covered by land ice, in connection with the North European land ice, while the greater part of the country, especially its eastern areas, was free from glaciation. This conception is based partly on the opinion (TCHERSKI 1893 and others) that moraine and other glacigenous formations do not occur there, partly on a theory (WOYEIKOW 1881) that conditions were such, because snow fell so scantily even during the Ice Ages that no perennial nevées or more considerable land ice appeared.

OBRUCHEW (1926) gives in his »Geologie von Sibirien» a somewhat modified picture of the Quaternary glaciation there, but even this relation is conservative in comparison with the conception newly expressed by MOLTSCHANOW (1926), according to whom the whole northern part of Siberia from the Ural to the Pacific and the 60th degree of latitude in the south was ice-covered. It seems as if he on the whole gives valid reasons for this opinion.[1]

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[1]) Here it appears apposite to cite a statement touching the most recent researches into the conditions of Quaternary glaciation in Siberia, in the area of Indigirka River, by S. W. OBRUCHEW (1927):

»Die Expedition hat eine beträchtliche frühere Vereisung des Gebietes festgestellt. Die Gletscher reichten wie im Werchojansk-Gebirge, so auch in den neuentdeckten Ketten bis zu 600—700 m Seehöhe herab und hatten eine Länge von 100—150 km und mehr. Die Breite der vereisten Gebiete betrug in jedem Gebirge bis zu 300 km. — In den neuentdeckten Ketten war die Vereisung - - - von alpinem, am flachen Nord- und Nordostabhang von skandinavischem - - - Typus.»

Wenn man die Ergebnisse meiner Expedition mit denjenigen der Forschungen von A. GRIGORJEW, der 1925 im mittleren Teil des Werchojansk-Gebirges Spuren von drei Eiszeiten beobachtete, von denen die erste sogar das Lenatal erreichte, ferner mit denen der Expedition von URWANZEW auf der Halbinsel Taimyr, wo Eiszeitspuren sogar im Niveau des Sees Pjassino entdeckt wurden, und derjenigen von GORODKOW im Becken des Pur zusammenstellt, der Endmoränen durch das Waldgebiet vom Oberlauf des Wach bis zum See Pjaku-tö (das ergibt eine Strecke von 550 km von WNW nach OSO zwischen dem 64° und 62° n. Br. nördlich vom Mittellauf des Ob) verfolgte, so kommt man zum Schluss, dass die Vergletscherung von Nord-Sibirien viel grossartiger gewesen ist, als bisher angenommen wurde, und vielleicht die ganze Nordhälfte des Landes einnahm.

The Siberian land ice formed the continuation of the European glaciation. Its southern margin reached at its maximum about 60° N in the Ural and ran thence eastwards over the River Ob near its junction with the Irtysh, and then along the upper course of the first-named river, where end-moraines appear at Surgut. According to MOLTSCHANOW, it was the early glaciation that caused the actual deviation of the river to the west. The ice boundary went, farther eastwards, over the Yenisei north of the Pit Mountains, which were themselves glaciated, and continued along the northern slopes of the mountainous highlands in the southern part of Siberia. Terraces and glaci-fluvial accumulations in the valleys there show that these were obstructed by land ice flowing from the north and that ice lakes formed in consequence, as MOLTSCHANOW informs us. He is inclined to see indications of the extent of the ice margin in the river beds of the Angara and the upper Lena.

Wide ice-caps covered the Transbaikalian mountains, the Yablonoi and the Stanovoi mountains, as shown on the map in the work of OBRUTSCHEW, quoted above. Great areas of land ice are marked also north of the Yablonoi mountains, and possibly all these ice-caps joined a great inland ice in the eastern part of Siberia. MOLTSCHANOW seems to be of this opinion and assumes, without detailed statements, a general glaciation of the northern part of Siberia, southwards to 60°.

Along the northern coasts of Asia, from the Vaygach strait to the Taymyr peninsula, MIDDENDORFF and other Russian explorers, as also members of the A. E. NORDENSKIÖLD and NANSEN expeditions, have found moraine, and v. TOLL has stated that it occurs even at the Anabar river.

It is therefore very probable that moraine and other glacigenous formations may appear in the whole North Siberian area between the Arctic Ocean and the above-mentioned southern margin of the land ice. OBRUTSCHEW has indicated such formations on his map, however, only in some relatively small districts between Ob and Yenisei and by the upper Khatanga. Glacigenous deposits are in general not reported from the region in question, but so-called Quaternary marine beds — or »marine clay with boulders» (Marine Tone mit Glacialgeschieben) — occupy wide areas.

The case of these presumed marine deposits is probably similar to that of the »marine boreal transgression» in the north of Russia. This latter was represented as of great extent on the general geological map of Russia (5d. 1897) and is still represented in this manner on many maps and in the literature. It was held to be postglacial, or younger than the last Ice Age. The interglacial age of the true marine beds in these deposits was manifested by my researches (1898, 1903) and by WOLLOSSOWITCH (1900). I emphasized, thereby, that such true marine beds occupy only limited areas in the lower parts of the valleys of Dwina, Mezen and Petchora, while the main part of the deposits consists of silty moraine which contains, beside boulders, shells of marine molluscs, *i. e.* moraine formed in great part at the cost of layers originally deposited on the floor of the Arctic Ocean, the White Sea and their low level surroundings, submerged during interglacial epochs. The ice streams passing over them from the north and north-west dragged great masses of this material far into the interior of North Russia and mingled it with the other ingredients of the moraine.

All descriptions of the presumed marine Quaternary deposits (»mit Glazialgeschieben») in Siberia point to the same fact, *viz.*, that these consist of moraine in which marine sediments are mingled. Their extent shows how far towards the south glacigenous formations are spread.

This trailing southwards by the land ice of marine sediments from the Arctic Ocean and the northern coasts presupposes a corresponding direction of the ice movement. I think that this indeed existed.

By researches concerning the spread and transport of boulders from the nephelite-syenite area on the Kola peninsula (1912), I found that the ice masses coming from the Ural and Novaya Zemlya had joined with those coming from Fennoscandia during the maximum of glaciation, and that the ice streams ran from the common ice shed towards the south and south-east into the north of Russia on the one side, and towards the north and north-west in the basin of the Barents Sea on the other side, where they, in my opinion, met with ice streams from Franz Joseph Land. In view of this, NATHORST held possible an extension of the glaciation from the Ural and Novaya Zemlya into Spitzbergen and Bear Island and this is very probable in view of certain glacial striae observed on the latter land. NANSEN is also of the opinion that the relatively shallow Barents Sea was completely filled with land ice during the maximum of glaciation. Such a huge mass of land ice issuing from Novaya Zemlya and the North of the Ural must have been counterbalanced by an ice-mass of corresponding size on the eastern side of this ice shed. That can only have been a mighty ice-sheet filling the Kara Sea and continuing in over Siberia; it could have dragged up the sediments from the sea-floor and trailed them far inland.

South of the great Siberian land ice, the highlands in mountain districts in southern Siberia and in Mongolia were glaciated to a considerable extent (according to OBRUTCHEW and GRANÖ).

Ice-dammed lakes existed in the valleys drained northwards, as pointed out by MOLTSCHANOW, and the greatest of these lakes covered wide areas in the western part of Siberia between the southern margin of the land ice and the higher land and mountains surrounding the upper courses of the rivers Tobol, Irtysh, and Ob and their affluents. Quaternary limnic deposits are there stated to occur at many places (TCHERSKI, etc., cfr. OBRUCHEW), and the most likely interpretation of these occurrences is the hypothesis of one (or more) wide ice lakes, which hypothesis is supported by a good deal of information about terraces on the slopes of the shores of the supposed lake. The water must have flowed out to the Aralo-Caspian depression, in some pass south of the river Tobol (abt. 200 m?).

The Siberian Stone Ice.

The stone ice (Steineis) of New Siberia is usually held to be the last remnants of the Siberian Quaternary land ice, in accordance with the interpretation of it as »fossil glacier ice» (»fossiler Gletscher») by VON TOLL (1895). VON TOLL himself presented, however, the most convincing facts in favour of the fluviatile origin of the stone ice at the delta of the Lena, in the Yana land and several other places in the north-east of Siberia. His explanation of theNew Siberian stone ice as dead glacier makes, therefore, a surprising impression. The only fact adduced in proof of his opinion is the very coarse quality of the ice grains in some portions of the stone ice, but this is not valid, as ice crystallizations of quite considerable diameter appear in many other kinds of ice, and not in glaciers alone.

All other circumstances mentioned by VON TOLL argue against the stone ice in question being fossil glacier ice; above all, there is not a trace of moraine, nor of material for such, neither upon the ice nor within it, and in all probability not beneath it either. The fluviogenous origin of the stone ice is evidenced: by the occurrence of stratification, by the alternation with beds of sand, silt and peat, by the brown colour and the content of humus and fine particles of mud, by layers upon the ice, not only of peat, but also of inorganic silt and sand, which only running water could bring there, and finally by the appearance of the stone ice only at relatively low levels, up to 30—40 m above sea-level.

The stone ice on the New Siberian Islands is fluviogene, as are the other stone ice formations described by VON TOLL and others. It is a remnant of a wide delta, of which the stone ice at the mouth of the Lena is another portion. Only such a connexion with the main land explains the occurrence of mammoths on the islands. The Lena was the river that brought the water which congealed into stone ice, and also the sand, silt and mud which it contains.

»Taryns» and other fluviogenous ice deposits are known from Siberia, Ice deltas are formed also in the north of Europe, where frozen flood ice appears by rills and brooks, often brown with humus, and grows as a delta during the winter, to vanish again when the warm season sets in. In the climate of northern Siberia, however, such formations become perennial and grow bigger from year to year. An Ice Age gave the very conditions needed for their development. The water of the Lena and other rivers running northwards to the Arctic Ocean, cold already at its sources, was refrigerated on the way to the North, to congeal and build a delta, which in the case of the Lena extended far beyond the New Siberian Islands. Ice probably filled also a great part of the valley.

As the climate got milder, the water of the rivers no longer froze, and could transport mud, silt and sand to the river mouths. The sediment beds upon the stone ice may have such an origin. Finally, the melting away of the ice delta commenced. The present occurrences of stone ice are, of course, remains of ice deltas from the last Ice Age.

The above explanation of the stone ice at the mouth of the Lena and on the New Siberian Islands leads to the conclusion that the district along the Lena was not covered by land ice during the last Ice Age and separated the western Siberian ice-cap from that in the East.

Areas without Outflow.

The glacial water from the land ice in Siberian ran to the ice lakes, especially to the great lake in the southwest of the country, and thence to the Aralo-Caspian depression, which got a further supply of water from the land ice in the North of Europe by means of the Volga drainage and from the ice-caps of the surrounding mountains. In this way, the depression was filled to the brim, and the water gradually became fresh, while during times of greater evaporation and smaller supply the water was salt — as it is now — and the lakes occupied only a part of the area having no outlet. Such filling of the basin with fresh water must have taken place during each more considerable Ice Age and alternated with decreasing of the water and increase of the salinity during preglacial, interglacial and postglacial epochs with arid conditions of climate. These circumstances explain the changes of the water fauna in the younger deposits in the Caspian and Volgian districts and also the Pleistocene transgressions and regressions there. (A. P. PAWLOW has recently (1925) given a good synopsis of these).

When the Aralo-Caspian lake was widest during the Quaternary time, it extended northwards to Kazan or perhaps to Nijni-Novgorod (HAUSEN). Its shores are to be found at levels between 50 and 75 m in Baku, at about 90 m near Surakhany, 116 m near Apsheron or at an average of 100 m above the present level of the Caspian Sea (26 m), or about 75 m above sea-level according to SJÖGREN (1888). The shores mentioned probably belong to several different stages of elevated surface of the water, and point to very recent tectonic dislocations which may have disturbed the original levels of the shore lines.

These shores are situated higher than the pass between the Aralo-Caspian basin and the Black Sea, *viz.*, the threshold in the Manytch valley. By the filling of the former basin the surface of the water consequently extended also over the area of the latter basin, which was then still separated from the ocean by land. This circumstance stands in concordance with our knowledge of geological history in the Black Sea region.

Towards the end of the Neogene period, this region was a part of the Sarmatian continental Sea, separated from the Ocean. Upon the Sarmatian deposits in it follow the Pontian, which ANDRUSSOW (1897) divides into five stages: 1. the Meeotian, 2. the Pontian (*sensu stricto*), 3. the Kimmerian, 4. the Levantian and 5. the Quaternary-Mediterranean. The first four of these show a gradual diminishing of the salinity of the water. Marine forms prevail in the Meeotian beds, associated, however, with brackish forms. The latter become more and more dominant in the Pontian and Kimmerian layers, and the Levantian, finally, is a fresh water facies with species *Unio*, *Vivipara*, *Planorbis*, etc.

Immigrated Pontian forms in the Caspian deposits and Caspian ones in the Black Sea area, as also Ponto-Caspian forms in the Manytch valley indicate open connexion between the different regions, at least on the northern side of the Caucasus. Straits are supposed to have existed also on the southern side.

The basin of the Black Sea was in existence before the Pontian epoch, (ANDRUSSOW), shells of Pontian brackish water forms (*Dreissensiae generis species non paucae*) brought up from its bottom being proof of this. The Pontian continental Sea (or lake) reached also the Marmora Sea, as shells of *Dreissensia rostriformis*, etc. found on its floor inform us, and brackish water forms of the Ponto-Caspian fauna are observed by ENGLISH (1904) in a raised beach at Cape Hora, near Gallipoli, at the level of 130 feet (=39 m). The land threshold separating the Pontian sea region from the ocean had, according to ENGLISH, just the height of that beach, and when the water rose still higher and transgressed the pass (about 40 m above sea-level), a river began to flow there and eroded the channel of the Straits of the Dardanelles. This resulted in a sinking of the water in the Pontian area and the formation of a river, which eroded the channel of the Bosphorus. The events assumed above presuppose that the surface of the ocean stood considerably lower than at present, a condition which may have existed during an Ice Age.

The upper Pontian is placed in the uppermost Pliocene, or by some authors in the Pleistocene layer. Gravel and boulders indicating the neighbourhood of land ice and glacigenous formations have been observed in Levantian beds.

A summing up of the above-mentioned facts gives us the following succession of geological events. The Aralo-Caspian depression and the Black Sea basin existed essentially in their present state as early as at the end of the Pliocene or beginning of the Pleistocene periods, but the Black Sea basin was still barred by land from the ocean. The Pleistocene deterioration of climate approaching with increasing glaciation, these basins were gradually filled with water. The Aralo-Caspian Lake and the Black Sea were connected in one level, their originally salt or brackish water was diluted with fresh water and the salt and brackish organisms yielded to fresh water forms as mentioned above. During the Levantian epoch the water finally reached its highest level, transcended the threshold by the Dardanelles and began to erode the channels of the Dardanelles and the Bosphorus. The fall of the streams was considerable and their water masses enormous, for they were formed not only of all the water that the Donau system brought from its drainage area and from the glaciers of the Alps and the Carpathians, besides all the water from the lobes of the North-European land ice reaching the rivers in the South of Russia, but also of the immense masses of water which the Aralo-Caspian depression received from the Volga side, from the great Siberian land ice and from the glaciated mountains in the South of Siberia and in Turkestan. Through the Bosphorus and the Dardanelles passed all the glacial water from the Eurasiatic land ice between the Western Carpathians and the upper course of the South Russian rivers.

There existed on the whole only two great outlets for all this glacial water, the Straits of Dover (see above p. 31) and the Bosphorus and Dardanelles. The erosion reached far beneath the present sea-level, because it was the time of great glaciations.

As the water sank in the Ponto-Caspian region owing to erosion of the outlet, the Aralo-Caspian lake was isolated from the Black Sea district, and erosion began also in the Manytch valley. The base level sank to the bottom of the Bosphorus, the rivers running to the Pontic Lake deepened their valley considerably, as their drowned ends with the limans show (SOKOLOW, 1903).

By the rising of the sea-level during the interglacial and postglacial epochs, the river channels of the Bosphorus and the Dardanelles were drowned. Salt water penetrated into the Black Sea, killing the Levantian (fresh water) fauna and bringing in the now existing forms with many of the species characteristic of the Sicilian. This circumstance explains the many resemblances between the organisms in the Black Sea, the North Sea and the Atlantic, though they are separated by the Mediterranean, where these species are not now in existence.

In the manner understood above, low sea-level with erosion in the Bosphorus and the Dardanelles and deepening of the valleys of the rivers running to the Black Sea could have alternated with rising of the sea-level and drowning of the valleys by the repeated glacial and interglacial epochs.

The Aralo-Caspian Lake, like the Black Sea or Pontic Lake before the erosion of the outlet, was thus during the Ice Ages filled with water masses not permitted to be stored there by the present climate and probably also not by interglacial conditions. In the same manner numerous other continental basins nowadays dry must have collected part of the water of the hydrosphere. Lakes of greater size than the present ones certainly existed in the arid regions of Central Asia, rising perhaps to the lowest pass of their borders. We see the same in other deserts. The surface of the Dead Sea, for instance, lay 400 m higher than at present, and extended far into the North Arabian desert, allowing habitations to flourish in Palaeolithic times where no permanent dwelling is possible in our times. The classic works concerning Lake Bonneville and Lake Lahontan give us the evidence that the North American continental basins were all waterfilled during the Ice Ages. This was certainly the general case over all the earth, at least in desert areas in the neighbourhood of glaciations.

PENCK (1894) has estimated that the filling with water of the continental basins now empty would deprive the ocean of so much water that its surface would sink 8 metres. To this volume, the bodies of water in the ice-dammed lakes may be added, but as perhaps not all the desert basins were brimful of water, I will take only the estimate of Penck into calculation.

The Total Area of the Glaciations.

The glaciations had at their maximum about the extent shown on the map, pl. I. The principal difference from former presentations is the greater extent of the ice-sheet in the Barents Sea and Siberia in accordance with the reasons given above (p. 34). The former greater land ice of Greenland is assumed to extend to the margin of the shallow sea area, this assumption being made in the case of North America also. These two ice-caps are not joined, however, for even if Baffin's Bay and Davis Strait certainly were ice-covered, the ice was floating, owing to the depth of the sea, and should not be taken into calculation, its formation or vanishing not changing the sea-level. For the same reason, I suppose that the Antarctic land ice did not exceed the shallow sea zone.

It was not possible to enter all former glaciations on the map, and the contours of the different ice-caps are greatly generalized and some of them highly approximative, *e. g.* in Siberia. The areas of the ice-sheets of greater magnitude are measured and computed on maps on a larger scale.[1] The extent of the glaciations of mountain districts in the temperate and warm zones is estimated in the following schematic manner.

The recent glaciation of the Alps comprises about 3,900 km^2, while the greatest Quaternary glaciation covered about 150,000 km^2. The maximum area of the glaciation was therefore 35 times greater than the present one. No statements of the corresponding relation in other districts are available, but information in the literature and on maps shows that even *e. g.* in the Caucasus and the Himalayas the glaciations once covered twenty to forty times greater areas than nowadays. The more the mountains now rise above the snow-line or the glacier line, the less was the relative increase of the glaciation during the Ice Age, the smaller the recent glaciations, again, the more considerable was the relative increase. The Quaternary glaciation of mountain districts now free from glaciers was, of course, infinitely greater. In the general absence of maps with precise information, I have assumed the proportion between the former and the recent glaciations in the mountains in temperate and warm zones to be 35: 1. I think that this figure is not exaggerated.

The area of the different ice-caps would then have been as follows during the maximum of glaciation.

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[1] The extent of the Quaternary glaciation in Tierra del Fuego and southern Patagonia, more especially the Straits of Magellan, has been represented in conformity with the report of the results of the *Expedition of the Geographical Society of Finland* to Tierra del Fuego in 1928—1929, under the leadership of Professor V. AUER, with Dr. H. KRANCK as geologist.

North Europe and West Siberia	13,000,000	km²
East and South East Siberia	3,242,000	»
Altai and other Highlands south of Siberia	567,000	»
The Faroe Islands	4,500	»
Iceland	131,000	»
Greenland	2,966,000	»
North America	16,750,000	»
Glaciations in the temperate and warm zones	2,450,000	»
Patagonia and Islands in the Antarctic Ocean	1,376,000	»
Antarctica	14,500,000	»
Total sum	54,986,500	km²

The total area of land ice during the greatest Quaternary glaciation was thus about 55 million km^2, or 3.67 times the total of the recent ice covered areas.

The Thickness of the Quaternary Ice-sheets.

In a district like the Alps, where not only the configuration of the upper surface of the glaciation is exactly determined (PENCK) but also the forms of the ground once ice-covered are known in their least details, the dimensions of the ice masses can be accurately measured and calculated. HEIM (1921) estimates the average thickness of certain glaciers in Switzerland. For far the greatest part of the mountains formerly glaciated, we may be content with rough estimates, unfortunately very uncertain. Observations concerning the highest situated side moraines, erratics and striated surfaces show the surface of the vanished glaciers to have been many hundred, even 1400—1500 m above the valley bottom in the Alps, and up to one or two thousand metres and even more in the Himalayas. These figures are, however, maxima, as the glaciers thin out both upwards in the firn basins and downwards at the glacier ends and also towards the valley sides. We are therefore certainly in the right if we assume the average thickness of the ice in the Caucasus, the Himalayas and other of the bigger glaciated mountain territories to have been at least the same as in the Alps. I have assumed this for half of the area of »Glaciers in the temperate and warm zones». For the other half, embracing the small area districts of this group, I have calculated with an average thickness of 150 m, or the same as for the recent glaciations in the said zones (p. 15).

The average thickness of the glaciation in the mountain territories in eastern Siberia is taken at 1400 m, or somewhat less than COLEMAN gives for the Cordilleran ice-sheet in North America and the recent Greenland ice-sheet.

The thicknesses of the huge Quaternary ice-sheets have been estimated by several authors, partly by comparison with the surface forms of the recent Greenland and Antarctica ice, partly by calculations founded on the isostatic depression they caused, as evidenced by the raised beaches. The latter method could give good results, if the surface of the sea had been at the same level all the time, and if the elevation of the marine limits were the true measure of the total depression caused by the ice load. The sea-level rose, however, as the glaciation decreased, and as the ice-sheet became thinner even the land had time to rise, before it was liberated from ice and the sea could cut in its highest mark there. Moreover, the raised marine limits belong to the late-glacial time after the last Quaternary Ice Age, not to the maximum of glaciation. A comparison with the great recent glaciations undoubtedly gives better results.

The Greenland and the Antarctic glaciations are thought generalized to ice-sheets with circular bases, according to the areas measured by MEINARDUS (p. 8) for different hypsometric zones. Their surfaces show them in vertical sections (Figure 1). of nearly the same curve forms as the halves of very flat rotation ellipsoids, or very near the theoretical form of plastic substances (wax, pitch) which flow freely on a horizontal substratum. The greater the mass, the flatter its form becomes, *i. e.* the greater is the diameter in proportion to the height, just as in a bun, a loaf and a great cake. The thickness does not by far grow in the same degree as the breadth. The ratio between the radius of the ice-sheet of Antarctica, 2058 m, and that of the Greenland ice-cap, 761 m, is 2.7: 1, while between their greatest heights, 3200 m and 2800 m respectively it is 1.14: 1. The increase of the radius from 761 m to 2058 m or by 1297 m gives, correlated with the increase of the greatest height, 400 m (3200—2800 m), an increase of 30 centimetres per km. This figure may be a little greater, seeing that the heights of the Greenland and the Antarctic ice-caps are reckoned from sea-level, while the margin of the Greenland ice-cap actually on an average lies higher than that of the Antarctic one. But also the difference of the mean heights of the two glaciations (2150—1900 m) or 250 m, gives an increase of only 19.3 centimetres per km. This gradient of the surface is, of course, much greater near the margin and becomes 0 in the centre.

The Greenland ice-sheet rises more steeply than the Antarctic one. On the former ice-sheet the 2000 metre level lies about 200 km from the margin, and the 3000 metre level about 600 km, while these heights on the latter ice-cap are reached only at 450 km and 1300 km respectively. These figures are, of course, purely theoretical averages. We find in nature the 2000 metre surface level on Greenland at the distance of 160—180 km from the ice border in the depression between the northern and the southern blocks (L. Koch 1923), and at about 220 km in the northern part of the territory.

The great Quaternary ice-sheets were, at maximum of glaciation, of about the same order of magnitude as the recent Antarctic land ice. It is therefore probable that their surface had a similar height and form. Not far (abt. 200 km) from their borders they reached the level of 2000 m, and over 3000 m in the central parts. In comparisons with the recent glaciations the area alone can, however, not be decisive; it is rather the true distances from the ice border to the ice shed which determine the slope and elevation of the surface.

The land ice which covered the North of Europe, Siberia and a great part of the Arctic Ocean had originally grown up in three different districts, the British Isles, Fennoscandia, and the northern end of Ural together with Novaya Zemlya. At maximum glaciation, the ice streams from the three foci coalesced and formed a single big sheet, with a common ice shed extending from the British Isles to Novaya Zemlya. The mighty ice in the North Sea was no longer maintained by glacier streams from Britain and Scandinavia, but was fed by atmospheric circulation in the same way as other parts of the big ice-sheet. Similar conditions existed in the area between Fennoscandia and Novaya Zemlya. The British Isles were high enough to preclude a direct movement over them to the Atlantic, and even if the Scandinavian mountains were surmounted, their resistance nevertheless caused the excentric displacement of the ice shed (in a NW direction from the centre). The ice-cap was, thus, not so enormously high that the ice streamed quite independent of the underlying topography. The distances from the ice shed to the southern and south-eastern borders of the ice-sheet were 1500—2000 km or more than twice as great as those of the Greenland ice and nearly the same as those of the Antarctic ice. I think, therefore, that the hypsometric conditions of the Quaternary ice-sheet in the north of Eurasia approach the recent Antarctic conditions, as do also the areas of both these glaciations. Not far from the southern margin (about 200 km) the surface of the ice had risen to 2000 m and the centre parts were enclosed by the isohypse of 3000 m, the ice reaching 3400 m in some parts. These figures indicate heights above the recent sea-level, the estimates (of the elevation of the ice surface) issuing from the land South from the glaciation. As the sea-level, according to the views expressed above, was lowered during the Ice Ages, the surface of the ice lay during maximum of glaciation perhaps 200—300 m higher above the then existing sea-level. The slopes towards the Atlantic were steeper than on the continental side.

With the aid of isohypses drawn according to the assumptions made above an average height of 2150 m is found for the Eurasian glaciation. The mean height of the recent land surface which was covered by this ice sheet is about 200 m, but only half of the sheet lay upon it, the other half extending over recent sea-area. A deduction of 100 m from the 2150 m gives an average thickness of 2050 m, as I will not add any estimate for the sea area, because there the ice-sheet probably had a steeper slope and not much greater thickness than on the land area. Moreover, only the ice-caps, or those parts of them which lay above the present sea-level with the earth crust in the same position as at present, may be taken into account in a computation of the sinking of the sea-level owing to glaciation. The ice masses descending below this level occupy as much space of the ocean basin as the water consumed for their formation, or perhaps even a little more.

Actually, the crust did not remain in its original position under the load of ice, but yielded, as the obvious traces of land sinking (raised shores) during the last Ice Age inform us, and the depression was much more extensive during former Quaternary Ice Ages, as shown by the Eem beds in the Netherlands, Northern Germany and Denmark, and further by the marine interglacial deposits in the Neva valley (YAKOVLEW), near Lake Onega (WOLLOSSOVICH) and in the Dvina, Mezen and Petchora regions (see p. 35 »marine boreal transgression»). In this way, land ice could be brought below the level of the recent sea surface and must be observed in the calculations. We take also into consideration that the ice-cap must have grown thicker in the same degree as the substratum yielded, for only so could it preserve the shield form of the upper surface.

We assume that the density of the ice is 0.9 and that of the magma yielding to the depression 3.0, and set the average thickness of an ice-sheet calculated as above (the Eurasian) on the assumption that the land occupied its present position (no depression of the crust) = h and the average thickness of the same ice-cap by isostatic equilibrium after the crust sank under the load of the ice = H. The depression of the crust is then H—h. By this equilibrium we get

$$(H - h) \times 3.0 = H \times 0.9$$

whereof

$$H = 3\ h/2.1.$$

Thus, if the average thickness of the Eurasian glaciation (h) be 2050 m, without regard to the isostatic depression, the average thickness by isostatic equilibrium (H) is 2928 m. A similar computation for the central parts of this glaciation gives thicknesses of 4500—5000 m.

The westernmost part of the North American glaciation, the Cordilleran ice-sheet (about 1 million km^2), was a huge Alpine glaciation with wide piedmont glaciers. It did not pass the highest peaks of the Cordilleras and the Rockies. »Erratics, and sometimes boulder clay and striated surfaces, are found in central parts of the region up to 8,000 feet, and several valleys go down to 1,000 or 1,500 feet above sea-level; so that at those points there could not have been less than 6,500 or 7,000 feet of ice. The average thickness of the Cordilleran ice sheet can hardly have been more than 4,000 or 5,000 feet, however», (COLEMAN). Theus, a mean thickness of about 1500 m.

By far the greater part of the North American glaciation is composed of the Kewatin (about 4 million km^2) and the Labrador (about 10 million km^2) ice-sheets, together with the glaciations of the Arctic Archipelago. This wide continental ice with its closed isometric form has certain analogies with the recent Antarctic ice-cap, such as the great area and about equal distance from the margin to the centre, no mountains or peaks rising above the surface, etc. I think, therefore, we are justified in ascribing to it at least the same heights in the central parts and the same average height as we have for the ice of Antarctica, or somewhat greater in view of its somewhat bigger area. COLEMAN assumes, by referring to the facts we know about the heights and slopes of the North American ice in its border zones, and calculating with a slope of ten feet per mile, heights of 11,000 or 12,000 feet for the central parts of the Kewatin and the Labrador sheets, that is 3400 to 3600 m, or even some hundred metres more than the ice attains in Antarctica.

For these reasons, I assume that the North American glaciation (except the Cordilleran sheet) had an average thickness similar to or somewhat greater than that of the Antarctic ice-sheet, or 2200 m. The mean height of the recent land surface covered by that ice is about 200—250 m. As about 1/4 of the glaciation extended over recent sea-area, only 3/4 of the land height, or 180 m, is subtracted from the average height, and thus we obtain the average thickness of 2020 m for the North American glaciation (except the Cordilleran sheet), if no addition is made for the sea-area and the recent position of the earth's crust is assumed. The depression to isostatical equilibrium under the load of the ice being taken into consideration we find the average thickness

$$H = 3 \times \frac{2020}{2.1} = 2886 \text{ m.}$$

The Antarctic ice-cap was formerly mightier and greater and reached higher up on the surrounding mountains than nowadays. I have drawn its border along the margin of the continental shelf and added 100 m to the recent probable average thickness (1500 m according to MEINARDUS), thus computed an average thickness of 1600 m without the isostatic depression, and with it

$$H = 3 \times \frac{1600}{2.1} = 2286 \text{ m.}$$

The Argentine glaciation must have shown a certain resemblance to the Cordilleran ice-sheet in North America: an Alpine glaciation with large piedmont glaciers. Its area was somewhat smaller than that of the recent Greenland ice, which is compared with the Cordilleran sheet by COLEMAN. I assume an average thickness of about 1800 m, with the isostatic depression taken into account. This value is 300 m greater than that of the Cordilleran sheet, according to COLEMAN, as the area is greater, but still not so great as that of the Greenland ice (see below).

For Greenland I have taken the average thickness, as computed by MEINARDUS for recent conditions, increased by 100 m, or 1500 m. In this value, the isostatic sinking is ignored. Its added effect gives

$$H = 3 \times \frac{1500}{2.1} = 2140 \text{ m.}$$

Iceland was completely covered by an ice-cap extending to the margin of the shallow sea area. If only some metres higher than the loftiest part of the land, it reached 2120 m above present sea-level, 2/3 of it being the average height, and the average height of the land surface taken therefrom approximately 400 m remains as the mean thickness of the ice. With the increase due to isostatic sinking, the figure is 600 m.

The Faroe ice-cap may have had an average thickness of 400 m.

Total Volume of the Quaternary Glaciations and Decrease of the Ocean Water.

With the above figures for the areas and varying thickness of the Quaternary glaciation at its maximum, we obtain the volume of the ice masses, as below:

Region of Glaciation	Area Million km²	Average thickness Metres	Volume Million km³
Eurasian North	13.00	2927	38.05
Eastern Siberia + Kamtchatka	3.24	1500	4.86
Altai and other highlands in S. Siberia	0.57	600	0.34
The Faroe Islands	0.0045	400	0.01 !
Iceland	0.131	600 !!	0.8 !!
Greenland	2.97	2140	6.36
North America, Cordilleran Sh.	1.00	1500	1.50
» » main part	15.75	2886	45.45
Mountain regions in temperate and warm zones	2.45	400 !!	0.98 !!
Patagonia, etc.	1.37	1800	2.46
Antarctica	14.50	2256	33.14
The North Siberian Stone Ice delta ..			0.70
			134.65 km³

If the volume of the recent glaciations, 22.50 million km³ + the postulated 8.32 million km³ in the isostatic depressions on Greenland and Antarctica, or together 30.82 million km³, be subtracted from the above total of the maximum glaciation, 103.82 million km³ of ice remain. Melted, they should give (density of ice = 0.9) 93.4 million km³ of water. This figure represents the reduction of the ocean's present volume which would take place through the appearance of an Ice Age with glaciation of the extent of the Quaternary maximum.

The said quantity of water would form a layer 254 m deep in an ocean with the recent area of 366 million km². At this depth the horizontal section of the ocean is about 338 million km², upon which the water mass in question would form a layer of the thickness of 276 m. The decrease of the sea's depth by the supposed formations of ice-caps would then be about 267 m. To this figure may be added the 8 m (p. 41), which the continental basins now empty would take from the sea when filled, the total reduction of the depth of the ocean being thus 275 m.

This reduction of the sea's depth is, however, not identical with the eustatic changes of the sea-level ascribed to the supposed glaciation. The change of level is the result of two different components. The one is the decrease and increase of the sea's depth owing to the increase and decrease of the ice-caps, the other is effected by the isostatic rising and subsidence of the floor of the sea, as a consequence of the removal of the ice and water masses from the oceans to the continents and inversely. Both components are eustatic, but they work in opposite directions.

The values of the thicknesses in the above calculations are based on the assumption of a depression of the glaciated areas to isostatic equilibrium. If we assume, further, that the forcing out of »magma» from the regions below the ice-loaded areas was completely levelled and balanced by the influx of »magma» below the earth-crust in the ocean areas, where the bottom rose by diminution of the ocean's depth and weight, this elevation would be a third of the thickness of the vanished water layer (275 m), or 92 m if the density of the »magma» is taken = 3.0. Thus, the result of the eustatic changes of sea-level by glaciation of the supposed dimensions would be equal to the reduction of the sea's depth, less the rising of the sea's surface (as the bottom rises), or 275—92 = 183 m.

It is easily understood that the above-mentioned third (92 m) of the reduction (275 m) of the ocean's depth contains the same quantity of water as the land-ice filling the continental depressions formed by the weight of the ice-caps. Therefore, the thickness of the ice-caps, if estimated without regard to the isostatic depression, *i. e.* at the same distance from the earth's centre as at present also during the Quaternary glaciation (cf. p. 44) gives, multiplied with the areas, an ice volume containing the quantity of water in the two-thirds (183 m) of the layer subtracted from the ocean, and the resulting change of level can be found direct by such a calculation. (Many of the estimates mentioned on p. 49 are made in this way). But it is necessary to bear in mind that this change of level is the result of the two different components pointed out above. It may, happen, and is probably usually the case, that the isostatic movements of the continental and ocean areas do not keep even pace with the removals of ice and water masses, which caused these movements.

As is well known, the rising of the earth-crust continued long after the areas were liberated from glaciation, and by the glaciation of these areas the subcrustal masses yielding to the depression brought about large swellings of the earth-crust in their surroundings. These elevations were not levelled during the course of an Ice Age, at least not during the last one, for many circumstances speak for their still remaining, even if lowered and enlarged, at the end of the glaciation (NANSEN, W. B. WRIGHT, RAMSAY, DALY, DUBOIS and others). Their existence influenced the change of sea-level in two ways. On the one hand, the less the swellings round the glaciations were smoothed out, the less was also the isostatic rising of the sea-bottom and the surface of the sea in consequence thereof. On the other hand, the longer the swellings existed, the more they counterbalanced the sinking of the glaciated areas and the assumed increase of their thickness (p. 46), *i. e.* the more they delayed the sinking of the sea-level by diminution of the water in the ocean. Especially the swelling of the continental areas at the margins of the ice-caps counteracts' the isostatic rising of the bottom and the consequent rising of the sea-level. But the swelling of ocean areas around the glaciations, as for example round Antarctica, Greenland and the seaward slopes of the American and Eurasian glaciat'ons, must diminish the capacity of the ocean basin and on this way cause a rising of the sea-level.

With regard to these circumstances and the values for the changes of the sea-level calculated above, the figure 183 m represents a minimum never reached, however, because the presupposed complete isostatic equilibrium did not come about, and the figure 275 m represents a maximum never realized, as considerable elevations of regions outside the isostatically depressed glaciated areas must have diminished the capacity of the ocean basin and in consequence led to a rising of the sea-level. The actual reduction of the sea's average depth owing to the glaciations can, in my opinion, have reached the greater of the values (275 m), but the resulting changes of sea-level on the coasts of the non-glaciated regions were perhaps nearer to the smaller figure (183 m).

Not even the greater of these values approaches the figure of 300 m or more for the reduction of the sea's depth by maximum of glaciation, a hypothesis I advanced in a former paper (1924 a). I based my opinion on an assumption that the great Quaternary ice-caps were considerably thicker than even the greatest recent glaciations, but I find it now more adequate to compare them direct with the Greenland and Antarctic ice. It is, however, not impossible that the ice masses of the maximum glaciations were more important than estimated above. If, for instance, also the eastern part of Siberia was covered with a great ice-cap connected with the western ice, as MOLTCHANOW thinks, a large addition to the glaciations comes from that quarter. Further, many of the former firns and glaciers could have been greater than assumed, and finally, it is possible that the big Quaternary ice-caps were higher and thicker than the great recent glaciations, in spite of their areas and radii being about the same. Bodies of very viscous plastic substances upon a horizontal substratum can, namely, assume greater height and convexity by larger supply of matter, while by reduced supply they shrink and flatten. Many authors believe, indeed, that the Greenland and Antarctic glaciations are »starving» and shrunken in comparison with the Quaternary glaciations in their maximum and most active condition, as they brought boulders from the centre of the ice-covered area to its margin at distances of about 2000 km, *e. g.* the boulders from Elvdalen in Sweden and from Umptek on the Kola Peninsula carried far to the south-east in Russia, or, according to COLEMAN, boulders from the Laurentian area near Hudson Bay to the foothills of Southern Alberta, depositing them, too, at a level of 4,500 feet (1500 m).

We will, therefore, examine how the extent of the Quaternary regression, as evidenced by several phenomena of different kinds, corresponds with the changes of level indicated above.

The Quaternary Regressions.

The observed facts which speak for general, eustatic regressions of the sea during the Quaternary period are the formation of coral reefs at depths exceeding those at which the reef builders live, submarine valley erosion, submarine fluviogene and terrigene deposits far off the sea coasts, shell banks of shallow water forms at greater depths than those at which these species are living, submarine peat bogs and forests, bones of terrestrial animals and stone age implements on the sea-floor.

Coral reefs as a work of the reef builders rise from depths of at least 300—400 m, thus exceeding the measurements given above for the change of level by maximum glaciation, 183—275 m. This circumstance does not force us, however, to look for any other explanation of their growing up from the depths of the sea than the »Glacial control theory» of DALY. In my opinion, it is not improbable that the reduction of the depth of the sea really exceeded the values mentioned, and further, the weight of the coral reefs must have caused an isostatical sinking of the sea bottom, in this way increasing the depth. — DALY holds 50—60 m to be the depth from which the coral reefs have grown up, and according to him, obvious submarine plateaus or surfaces of abrasion generally occur at this level, indicating a long stagnation of the sea's surface just at the transition from regression to transgression. The submarine plateaus at the level mentioned are in many places formed on a foundation of older coral masses, regarded by DALY as clastic accumulations. On p. 33 I have given my reasons for regarding also these deeper parts of the coral reefs as being, mainly at least, the work of the polyps. The borings on the Funafuti atoll reached 334 m and had not even at this depth met the underlying rock. Other reefs stand on less deep ground. MOLENGRAAFF gives, *e. g.* 70—90 m as the depth from which the coral reefs rise on the east side of the Sunda plateau. Many reefs thus rise from depths greater than the 275 m calculated above, or even the 300 m assumed in my former paper (1924a). Others lie within the limit of the less value of 183 m. The submarine plateau level observed by DALY may perhaps have been formed during the last

Ice Age, when the reduction of the sea's depth was not so considerable as by maximum glaciation.

A very great number of the known submarine channels extend on the sea-floor considerably below the calculated values for the changes of level in question, and even below all possible or conceivable values. Among them, we have, for example, the Congo Deep and the Fosse de Cap Breton, for which a tectonic origin is more probable than a fluviogene one (p. 32). Another is the Indus Deep off the Ganges delta. Its situation invites one to combine it with the rivers ending in the delta and to think it a prolongation of their channels during great regression of the sea. An explanation of its depth might be that the whole Bengal delta has sunk considerably under the load of the mighty sediments. Borings in the Ganges valley have pierced many hundred metres of Quaternary fluviogene alluvium, even several hundred kilometres from the river mouth. On the other hand, it is curious that such a channel has remained open in spite of the enormous accumulation of fluviogene deposits there. In view of the circumstances mentioned, neither the Ganges Deep nor the other deep channels mentioned give any indication of the actual reduction of the sea's depth by a glaciation.

The submarine channel (abt. 300 m) off Indus approaches nearer to what might be expected, and if some part of its depth can be ascribed to isostatical depression by sedimentation, this channel ends just where we could expect it to do so, according to the greater of the values calculated (275 m).

The Hudson channel on the slope of the North American continental base sinks, likewise, below the greatest estimated depth for the lowering of the level by a glaciation. But its connexion with the Hudson river valleys seems so obvious that one rejects unwillingly the interpretation that it is a submarine river channel formed during an Ice Age. A possible explanation may perhaps be found in facts connected with the situation of the region in question just outside the great North American glaciation, the depression of which drove up a high and large swell along the ice border (p. 50), so high that the slope where the Hudson deep appears was lifted over the sea-level of that time. The channel could have been eroded in this way, and when the swell was levelled again by the vanishing of the ice sheet, the river channel sank to its present poition below the limit for the sea's reduction by maximum of glaciation. There are some other indications of such a swelling of the earth's crust in these zones. — Further, the depths of the submarine channels in prolongation of the rivers on the Atlantic coast of North America show decreasing depths from the Hudson Deep southwards, corresponding with the decreasing height of the »swell». — — — — —

The S:t Lawrence channel with its prolongation south-west of New Foundland seems as if it could be interpreted in the same way as the Hudson channel, although it lies within the limits of the greatest extent of the glaciation. — —

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A special group of submarine valleys is formed by the channels in the continental shelf round the North Atlantic and the Scandic in the border zones of the great glaciations. NANSEN (1922) has given a very competent study of these. According to him, they form prolongations of the fjords and fjord valleys or obvious valley systems (*e. g.* the great valley and its affluents on the floor of the Barents Sea, and also the Norwegian channel). Their nature as a result of erosion may be fixed beyond doubt, even if glaciers have worked there also, widening them by exaration and filling them by accumulation. They end at the edge of the continental shelf in depths of about 400 m. As known, the depths are generally much greater in the inner parts of the fjords where the submarine channels take their beginning, a fact usually ascribed to the overdeepening work of the glaciers.

The depth at which these channels end is some hundred metres deeper than the expected or assumed sea-level at maximum of glaciation. This circumstance can perhaps be explained in the same way as the deep erosion of the Hudson and the S:t Lawrence channels. But there are also circumstances pointing to another interpretation. The fjord valleys and fjords, in the prolongations of which the submarine channels lie, have a preglacial origin, although they have been widened and deepened by the glaciers, as generally interpreted by all authors having treated this theme. One is therefore ready to ascribe a preglacial age to the submarine channels also, and considering that the base level was lowered to the depth necessary for the erosion of these channels only after glaciation covered the continental shelf, there was no opportunity for such an erosion. For these reasons I think it very probable that the channels were formed before the Ice Age, as the origin of the whole valley topography of the great former glaciated areas of old metamorphic rocks may be preglacial, while the submarine channels in the continental shelf round such areas (North America, Eurasia region, etc) are not suited or estimations of the Quaternary regressions during Ice Ages.

However, they indicate a great regression in Pleistocene time. Fjords (firths) and dissected coasts are characteristic of Fennoscandia, Canada and all other formerly glaciated regions formed of old metamorphic rocks and more or less degraded mountain chains. Leaving out of consideration their glacigene features, their fluviogene origin is obvious. They are drowned valleys, and their depths, or still plainer, the mouths of their submarine prolongations, ending on the edge of the continental shelf, indicate a preglacial regression of some hundred metres, before any glaciations caused a sinking of the sea-level. For the understanding of these circumstances, I revert to the explanation given in an earlier chapter of the origin of the now existing orocratic conditions (p. 17).

As the capacity of the ocean basin was enlarged by diastrophism in connexion with the Alpine orogeny and the sinking of the sea, the continents came to stand higher over the sea-level than before. The lowering of the base level opened a new cycle of powerful erosion, which formed the now existing valley systems and brought away enormous quantities of rock material. The land areas lightened thereby rose still more, and, especially where the sialic crust under them was thick and preserved remains of mountain chains, this elevation has accentuated the hypsometric conditions of precambrian »shields» and the horsts in many orogenic zones once peneplained.

At the beginning of the Pleistocene period, Fennoscandia, the North American Precambrian areas, the Arctic islands and other districts where glaciations afterwards appeared, were over-elevated in this way some hundred metres on the edge of the continental shelf, as the submarine channels indicate, and perhaps more in their central parts. Just this circumstance was an essential condition, if not the cause of the Quaternary glaciations (RAMSAY 1924 a). When glaciated, however, these continental areas were greatly depressed and have never regained their former height. A big part of the depression became persistent. The effect of this appears not only in the submarine channels and drowned valleys — the fiords — round such an area, *e. g.* Fennoscandia, but also in its interior. In my opinion (Atlas 1910), the Baltic, with the Gulf of Bothnia and the Finnish Gulf, fills a broad preglacial valley. I would give the same explanation for the Skagerak (with the Oslo fjord) and Kattegat.

Such a large persistent depression of former higher land after the great glaciation is known from Northern Germany by the researches of LINSTOW (1922).

Whatever the cause may be (possibly melting away of some parts of the sialic matter during the depression), the facts interpreted in the above way are common to all great formerly glaciated regions. The elevation of the continental areas above the sea-level during the beginning of the Pleistocene period is repressed here — so that the preglacial shores lie beneath the present sea-level — in contrast to the recent orogenic belts where the old Quaternary strand lines (Sicilian etc) are considerably lifted in many places.

Only beyond both these kinds of continental areas — the former glaciated regions and the recent orogenic belts — does the earth-crust seem to have been stable enough to afford more certain information of the assumed regressions in connection with glaciations.

From the most varied quarters of the earth authors have remarked upon the submerged valleys and submarine prolongations of the river channels. HULL (1897) was one of the first to direct attention to these phenomena, and among later treatises on the matter we have the very interesting researches of MOLENGRAAFF, concerning the Sunda Plateau. Charts show numerous examples of such phenomena, and the more frequent and the closer the soundings, the more distinct do these features of the bottom relief appear. The depths to which they extend can be discerned on the charts, from some tens of metres to two or three hundred metres, in addition to the still greater deeps mentioned earlier. These differences depend partly on the quality of the charts, partly on the nature of the submarine channels themselves.

The submarine channels are marked on the charts at the mouths of rivers, or at the entrance of the harbours, because of their importance to navigation, but usually no longer appear when the depth exceeds some fifteen or twenty metres, the soundings being too sparse to allow the drawing of any details of the sea bottom. It is, however, very possible that the channels extend deeper than such charts indicate. Districts more particularly mapped and sounded for their practical or scientific interest reveal in many cases really deep-seated river channels and other traces of land sculpture of which the ordinary charts afford no information.

But it is easy to understand that the submarine channels, also for natural reasons, no longer appear to extend to the lowest limit of the sea's regression. The river channels eroded into this sea-level were filled again by accumulation during the transgression of the sea. The river itself heaped terrigenous sediments in its former now submerged bed, and the sea encroaching upon the continental shelf smoothed by its action the unevennesses of the littoral belt. By later regressions of less extent, the river channels were opened or deepened again to this level, but their older, deeper parts were filled still further by sediments transported by the river, and the best preserved among the drowned channels may be the youngest ones, functioning as river beds during the last Ice Age when the regression of the sea did not by far reach the extent of maximum glaciation. Owing to these causes, most of the submerged river beds probably end or become undistinct far above the level of the sea at maximum of glaciation and regression. The distinguishable end depths of these beds indicate, therefore, only a minimum for the lowering of the sea's surface, and for the above reasons, both cartographical and natural, we can expect to find these end depths varying within wide limits.

According to maps and statements in the literature, most of the submarine river channels in districts beyond the former glaciated areas end at moderate depths, from 15 m to 50—60 m. I am inclined to explain these channels as being preserved mainly from the last Ice Age, their prolongations, if such existed at greater depths, having been filled by the rivers' own transport of sediments during the glaciation. The greatest of these end depths, 60—70 m, seem to correspond with the submarine plateau level indicated by DALY (see above) and afford us perhaps information as to the extent of the sea's regression during the last Ice Age. The ending of submerged river beds at lesser depths can also be due to filling, and I think that a closer study of submarine delta formations at the ends of the submerged channels will reveal certain distinct levels, corresponding in my opinion to the different stages of advance of the glaciers (Bühl-, Achen- and others) which interrupted the general retreat. Should this be the case, as I assume, it would provide us with a dependable method of synchronizing these stages of late-Quaternary history over all the earth.

The deepest of the submarine channels in the districts beyond the former glaciated areas should thus give us the minimum of regression during the maximum of glaciation (excluding the Congo etc.).

MOLENGRAAFF, in his Deep Sea Researches, finds that the submarine valley system on the Sunda plateau goes down to 150 m on the slope towards the China Sea. This may be a minimum.

Two great streams, the appearance of which obviously stands in connection with the glaciation of the Eurasian North, are the two outlets of the water-masses from the melting ice, *viz.*, the river in the English Channel and those in the Dardanelles. The bed of the former is very clear (HULL etc) and sinks to 183 m., close to the minimum sinking at maximum glaciation.

The submarine channels which may stand in connexion with the regression during the maximum glaciation thus descend to a minimum of 180 m, corresponding to my figures or even exceeding them.

Quite as conclusive as submarine river channels, perhaps even more convincing, would be submarine delta formations and river deposits.[1]) Such are

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[1]) In this connexion a few words relating to the former delta of the Rhone may not be out of place (H. BAULIG, 1927):

L'auteur s'est proposé d établir: 1° que la surface de la Crau, cône alluvial de la Durance, se prolonge sous la Camargue, avec une pente régulière, jusqu'à l'altitude —50 m.; 2° que, d'autre part, elle se relie à une terrasse de la Durance certainly to be found and are probably common, though not so easily recognizable as the channels, as they are in part of such flat formation that they are not noticeable merely by soundings, and have in part been levelled by the action of the sea during transgression. Samples taken from the bottom of the sea ought to show fluviogene and terrigene material with grains of such size that they can have been spread out on the shelf only by the action of running water, not by the surf of the sea. Many authors (NANSEN and others) consider that the level character of the shelf is in great part attributable to accumulation.

Terrigene sediments below the present sea-level also point in this direction. To this category belong *e. g.* the deposits of weathered gravel and sand containing tin-ore which are found in Java (MOLENGRAAFF) and Tasmania (FAWNS). Also on land the bottoms of the valleys filled with metalliferous gravel lie up to 30 metres below the level of the sea, thus indicating a time of deeper erosion. Later on, when the surface of the sea rose, the river valleys were filled with sediment, of which a great part continues to greater depths.

Finally, reference should be made to the abundant information relating to the submerged forests, and peatbogs, and even to implements from the Stone Age, found *e. g.* on the Dogger Bank in the North Sea. Scientists have in many instances sought merely local causes for such phenomena, or looked upon them as characteristic of certain districts only. Nevertheless, the most divers quarters of the globe yield so much unanimous information of this nature that it is impossible to doubt the occurrence of regressions and transgressions in connexion with the appearance and disappearance of the great glaciations.

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d'altitude relative lentement croissante vers l'amont (de 20 m. près de Lamanon à 30—40 m. en aval de Sisteron), laquelle correspond au maximum de la glaciation würmienne; 3° que, par conséquent, conclusion conforme aux prévisions théoretiques, le maximum du remblaiement fluvio-glaciaire a correspondu à une altitude minimum du niveau marin; 4° qu'au cours de la déglaciation consécutive, la Durance s'est encaissée à l'amont (dégagement de la terrasse) pendant qu'à l'aval son cône alluvial, abandonné à la suite d'un changement de cours, était recouvert par le delta post-glaciare du Rhône (la Camargue).

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