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BEARING OF THE TERTIARY MOUNTAIN BELT ON THE ORIGIN OF THE EARTH'S PLAN[1]

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Introduction

One of the grandest facts which the science of geology has established up to the present time is the existence of a great world-belt, or girdle, of Tertiary fold-mountains almost encircling the earth. This mountain

[1] Manuscript received by the Secretary of the Society October 4, 1909.

belt comprises the entire Pacific coast of the two Americas and of Asia and extends westward along the southern border of Asia and Europe to the Atlantic coast in Spain and Morocco. In the Malay archipelago the belt branches to the eastward and sends an arm around the northern and eastern sides of Australia, but the mountain ranges of this branch are mostly submerged, and are now represented only by island chains, including New Guinea, New Caledonia, New Zealand, and many smaller islands. Excepting the gap between New Zealand and southern Chile, the Pacific Ocean is completely surrounded by the Tertiary mountain belt. This fact rests upon a sound basis of observations, and is one of the most comprehensive and deeply significant things which mankind has yet learned with certainty concerning the development of the earth. The Tertiary mountain belt is a large element in the earth's plan, and a satisfactory explanation of its origin is a desideratum of the first order.

Under the various forms of the contraction hypothesis of mountain making, this mountain belt has been ascribed to horizontal thrust movements directed from the ocean toward the land. The cause assigned is subsidence of the earth segment which underlies the ocean—a consequence following, according to some, upon secular cooling and contraction, and this has been the dominant view; but upon planetesimal settling and solidification, with some cooling and contraction, according to others, and upon original differences of density, with molecular changes and expansion, producing deep-seated movements from the oceans toward the continents, according to still others.

The remarkable relation of the Tertiary mountain belt to the Pacific Ocean is the thing which is usually most emphasized in discussing the origin of these mountains, and principles based on the supposed meaning of this relation have been applied to other mountains as well, for it is claimed that the relation indicates an oceanic cause which is general in its application. But the fact should not be overlooked that this same mountain belt forms an important part of the periphery of all the continents excepting Africa, and since the belt as a whole falls naturally into divisions or parts corresponding to the several continents to which it has peripheral relations, the question arises as to whether these parts may not be causally related to their associated continents rather than to anything in the oceanic areas.

The several continental divisions of the belt show characters which seem to correspond roughly to continental magnitudes. For example, Asia, or, more accurately, Eurasia, with small parts of northern Africa and Alaska, stand together structurally as one continental unit and constitute by far the greatest of the continental bodies. Asia proper is the main, central part of this vast crustal sheet, but even this part alone is considerably greater than any other continent. The peripheral mountain ranges of Asia show prominently certain forms—chiefly curved, arc shapes—which are scarcely recognizable or are generally inconspicuous in the peripheral ranges of the other continents. The mountain ranges and plateaus of Asia are greater in every way than those of other continents—greater in areal extent, in height, mass, and breadth of plan. It is a question to be determined whether all these distinguishing attributes are not due mainly to the fact that Asia, considered as a dynamic unit of the earth's crust in the process of diastrophism or mountain making, is larger—greater in extent and mass—than any other similar unit.

If a crust-flake, like that which we call Asia, should move a given distance as a unit, it would certainly produce greater results in crustal deformation than would arise from the movement of a flake having only one-tenth of its magnitude, and the difference in the results would be still greater if the larger flake moved several times farther than the smaller one. The products might differ not merely in magnitude, but to some extent in kind also. Australia is a continent of the same type as Asia, but it is relatively feeble in its development; its peripheral ranges are relatively weak. They are mostly submerged, and, so far as known, they show none of the peculiar forms which characterize the great peripheral belt of Asia.

Figure 1 shows the location of the Tertiary mountain belt. Later researches seem to suggest some slight additions in eastern Asia and in the western and southwestern Pacific, but these are welcome changes and are not discordant.

The mere existence of this vast mountain zone encircling the earth is of itself a remarkable thing, but its significance is prodigiously increased when the distribution and age of these mountains are taken into account and when some of their structural or tectonic relations and characteristics are analyzed. The entire belt is essentially of one age, all made or largely augmented within the limits of one definable and relatively short and recent period of geological time. Moreover, this period of diastrophism is the last or most recent of the great mountain-making epochs—the nearest to us in time. For this reason partly the mountains of this belt are all relatively young—so new that there has not yet been time for them to be destroyed or very greatly reduced by erosion. This is one of the chief reasons for their great height in many places and for the relative youthfulness of their physiographic expression. It is also a reason for the relatively unmodified state of the tectonic lines which they mark, for these lines have not been disturbed or disarranged by any im-

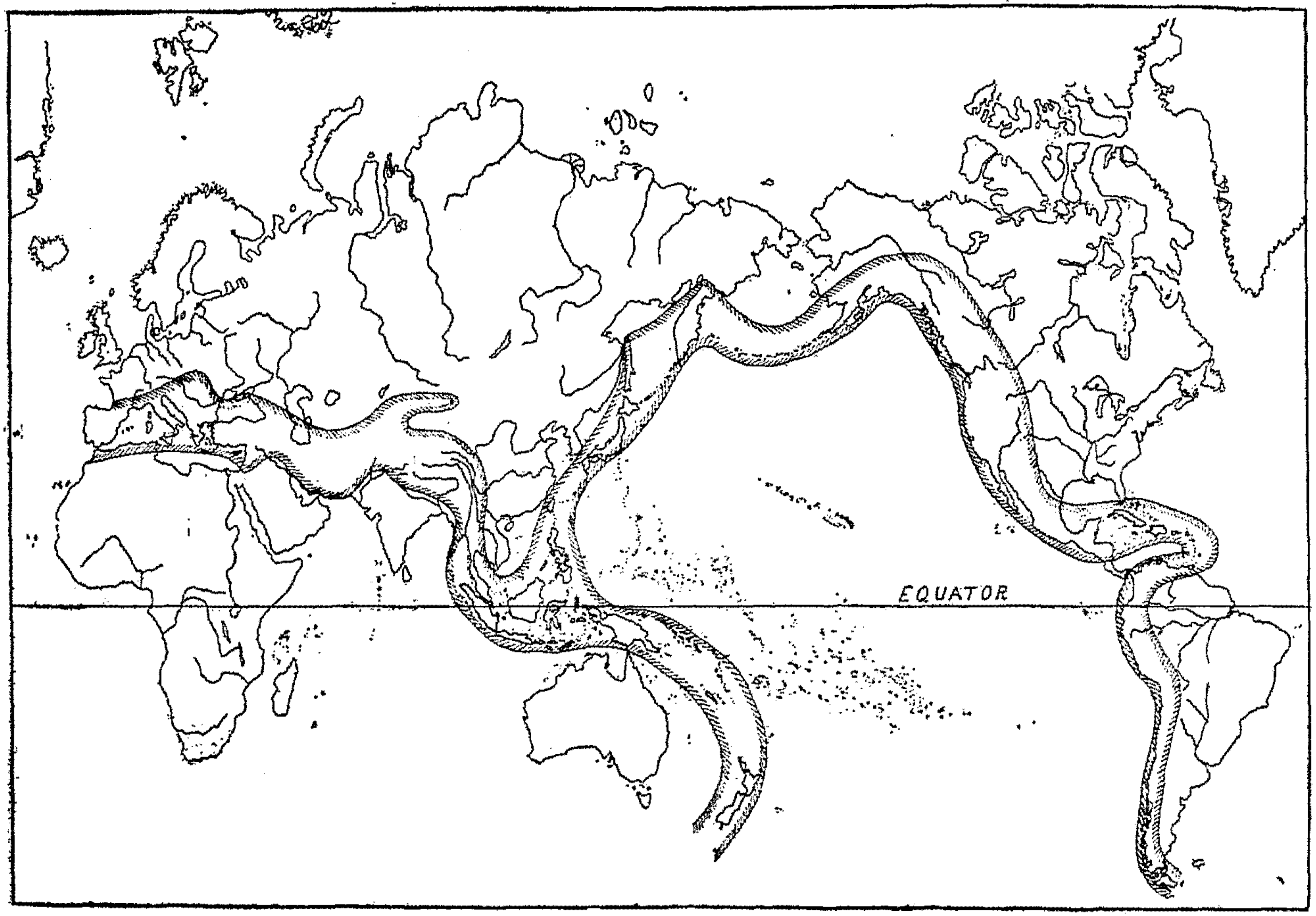

FIGURE 1.—*The World on Mercator's Projection*

Showing the distribution of the Tertiary mountain belt. (From the Berghaus Physical Atlas, 1892.)

portant mountain making of later date. They retain substantially unchanged the forms which Tertiary diastrophism gave them. Hence, whatever characteristics or peculiarities of form or plan mountain-making forces are wont to impress upon their products, these ought surely to be discernible in a mountain system which is at once the newest and most extensive upon the earth. Indeed, the Tertiary mountain belt stands out so prominently as the product of a recent, distinct, and apparently completed epoch of mountain making that within certain limits it can be studied by itself, without much reference to older mountain-making epochs.

It is admitted by all that the mountains of the great Tertiary belt, like the older ranges of fold-mountains, were produced chiefly by compressive forces acting in a horizontal direction, and that the total amount of compression involved is equivalent to many miles of horizontal movement of the earth's crust. What was the nature of those movements? In what direction did the crust move in producing the Tertiary mountains of Asia—from the ocean toward the land or from the land toward the ocean? This is the crucial point.

There is a considerable body of facts which bear strongly upon this question; a few of the more important are briefly set forth below in a discussion of the origin of the Tertiary mountains, and the conclusions thus reached seem to throw some new light on the origin of the earth's plan.

Suess' Interpretation of the Plan of Asia

In his great work, "The Face of the Earth," the eminent Austrian geologist, Eduard Suess, has devoted much space to the consideration of the continent of Asia. As a result of his extensive studies, Suess reached the conclusion that, in consequence of the cooling and shrinkage of the earth as a whole, all parts of the crust have settled or sunken down toward the center, the ocean basins most and the high continental areas least. A few quotations will show the general character of his conclusions. After noting the contrast between the outlines of the ocean basins and the structure of the continents, Suess remarks that *"these ocean basins are areas of subsidence"*[2] (II, 536). "As soon as we recognize the ocean basins as sunken areas, the continents assume the character of horsts" (II, 537). *"The crust of the earth gives way and falls in; the sea follows it.* But while the subsidences of the crust are local events, the sub-

[2] Unless otherwise stated, all quotations from Suess are from "The Face of the Earth," authorized English translation by Sollas. Reference is made to volume and page. All of the italics in the quotations belong to Suess. Four parts of "The Face of the Earth," in three volumes, have been published at the time of this writing.

sidence of the sea extends over the whole submerged surface of the planet. It brings about a general negative movement" (II, 537-538). All changes affecting the height of the sea at one time over the whole globe Suess designates as "*eustatic movements*" (II, 538). "*The formation of the sea basins produces spasmodic eustatic negative movements*" (II, 538). "*The formation of sediments causes a continuous, eustatic positive movement of the strand-line*" (II, 543). In other words, a sinking of the sea floor at any place lets the ocean down from its shores all over the earth, while the piling up of sediments in any part gradually raises the level of the whole ocean. In this way Suess accounts for some, but not all, of the ancient strand-lines now found above ocean level.

Referring to Asia and Eurasia, Suess defines their structure and growth in different words at different times, according to the various points of view from which he contemplates the subject. "Asia consists of an obstructive fragment of Indo-Africa—the peninsula of India— . . . and of a great piece of the earth's crust folded to the south. The folds, however, are interrupted and separated by platforms which lie between them like rigid blocks, although in the platforms themselves we may also recognize the traces of much older folding in the same direction" (II, 195). "*The whole southern border of Eurasia advances in a series of great folds toward Indo-Africa;* these folds lie side by side in closely syntactic arcs, and for long distances they are overthrust to the south against the Indo-African tableland" (I, 596).

Among the several continents Asia seems to afford the most perfect expression of Suess' idea. He describes the ancient "vertex," or central land of Siberia around which the rest of Asia, especially to the east, south, and west, appears to be arranged in roughly concentric zones. This relation finds its most prominent expression in the trend lines of the mountain ranges. The vertex occupies a large region lying chiefly north, northeast, and northwest of Irkutsk, in Siberia. The vertex itself is very old, being capped by horizontally bedded pre-Cambrian strata which appear to have suffered no notable disturbance since their deposition. The surrounding lands are disposed mostly in bands or zones of rocks of younger age, the nearest to the vertex being of Paleozoic age, followed farther out by Mesozoic, and lastly by Tertiary. Thus, going southward from the vertex, the mountain ranges are composed of successively younger strata folded and faulted by horizontal compression, until along the margin of the continent the peripheral ranges belong to the great Tertiary belt. Each belt of folded strata was subjected to horizontal compression in such a way as to make a mountain range usually in the form of an arc opening northward or toward the vertex, and roughly concentric with it.

That he does not stand alone in his understanding of the structure and relations of the mountains of Asia, Suess makes clear in the following passage:

"The uniform structure of the Asiatic mountains has been recognized by all the most eminent authorities on this part of the world, and has been variously described according to the point of view of each observer. In Siberia, Semenow speaks of a succession of terraces; the Gobi, together with the Khingan, forms the highest step; the country of the Amur, with Sikhota-Alin, the second; the sea, with its island arcs, the third. In China, Richtnofen was impressed with the idea that the whole country sinks in great flexures to the Pacific Ocean. In Japan, Naumann compares Asia to an elevated domelike protuberance surrounded by peripheral fractures. As one stands in front of the overfolded chains of the Himalaya, says Griesbach, there seems to have been a movement of the whole mass of Asia toward the south" (III, 7).

From the Philippines to Alaska the whole front of Asia is adorned with a wonderful series of island arcs which have been likened to festoons hanging from the continental border. Concerning the origin of these, Suess says:

"Thus the east Asiatic coast does not resemble a series of independent ranges advancing toward the sea, but rather a *stupendous virgation extending over the whole breadth of Eurasia*, the successive divergence of the same folded systems which, closely crowded together in the interior of the continents, form the great and lofty highlands. In this divergence each of the great branches shows near its extremity—that is, toward the ocean—a tendency to recurve to the north, and thus arise the island festoons of east Asia" (II, 195-196).

In a general survey of the island arcs, Suess mentions the following: the arc of the Liu-kiu Islands, of South Japan, of North Japan, of central Yezo and Sakhalin, of the Kurile Islands, and a fragment of arc in central and western Kamchatka. To these must be added the most perfect arc of all, the arc of the Aleutian Islands, which Suess, however, regards as independent. All these island arcs are, of course, mountain ranges submerged beneath the ocean.

Westward from the Philippines the peripheral mountain arcs continue, and are thus enumerated by Suess:

"Five great arcs turned toward the south align themselves one after the other across the continent; these are the Malay arc, the arc of the Himalaya, the shattered outer arc of the Hindu Kush, the Iranian, and the Dinaro-Tauric arc. To these must be added still another—that which, distinguished by somewhat different characters, surrounds the western Mediterranean" (I, 505-506).

Referring to the southern part of Eurasia, which comprises the great peripheral mountain belt with which we are here most concerned, Suess says:

"A great part of this folding is of recent age, or has been continued into very recent times; it is not certain that the movement has ended" (I, 597).

And in the summary of his chapter on the relations of the Alps to the mountains of Asia, he says:

"Thus we see that since the Middle Tertiary period, and up to still more recent times, important tangential movements have taken place, and have thrown into folds a sea-bottom which extended through the middle of Europe and Asia" (I, 507).

The ranges here referred to were formed out of sediments laid down in the ancient greater Mediterranean, which Suess calls the Tethys, and of which the modern Mediterranean Sea is only a remnant.

Thus, in brief, Suess finds Eurasia to be a great unit of continental growth which has advanced to its present state by well defined steps from early, smaller beginnings in the far north. First, there was the ancient "vertex" in Siberia. This is an ancient plain, marking the planed-down surface of still more ancient rocks, which, through all the steps of continental development since pre-Cambrian times, have remained remarkably stable and free from disturbance. This plain has not been folded by any of the Paleozoic or later folding movements which have brought into being the great mountain ranges that run in concentric lines around its southeastern, southern, and southwestern sides. Through very long periods of relative quiet, sediments accumulated in the border of the sea surrounding the vertex. Then in relatively short periods of diastrophism or crustal deformation these sediments were squeezed and thrust horizontally in southerly directions—that is, toward the sea—and folded into the mountain ranges. This cycle of continental growth was repeated three times, and produced successively in three periods of folding the three principal mountain systems which characterize Eurasia. In the beginning there were several smaller separate continental elements, and they were not welded together into the one great continental unit of Eurasia until the last or Tertiary folding period. It was this last and by far the greatest of the mountain-making periods since pre-Paleozoic times that brought Eurasia to its present state.

Figure 2 shows the trend lines of the Tertiary fold-mountains of Eurasia. The older lines are omitted. The shaded parts, comprising the peninsulas of India and Arabia and part of Africa, represent the obstructive fragments of the ancient Indo-African continent against which the southward folding of the western half of Eurasia was thrust.

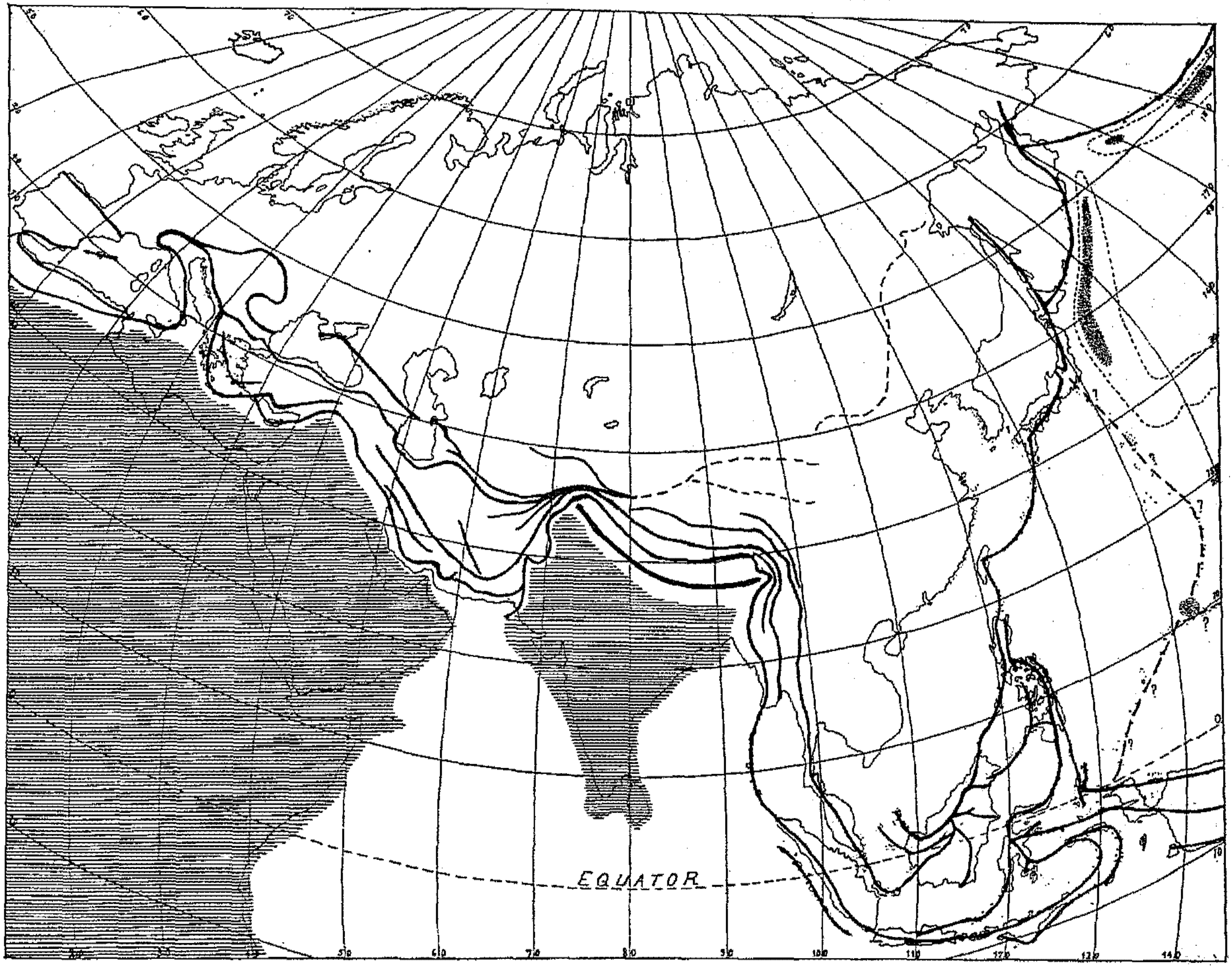

FIGURE 2.—*Eurasia*

Showing the extent and general relations of the Tertiary ranges of fold-mountains which form the peripheral system. Shows also the irregular trends of the European ranges, the Iranian and Malay earth-lobes, the Himalaya re-entrant, the island arcs of eastern Asia, the Ladrone arc, the Tuscarora and part of the Aleutian frontal deeps, and the meeting place of the Australian and Asiatic fold-lines in Borneo, Celebes, and Halmahera.

The trend-lines of the mountain ranges as shown on this map are, of course, somewhat distorted, especially in eastern Asia and in Europe, but they are much less distorted than when represented on Mercator's projection, and the proportions of the parts of Eurasia are more nearly true. The dotted areas east of Japan and south of the Aleutian arc are frontal ocean deeps.

Suess' Method of Interpretation

Suess interprets the structure of Asia chiefly by a study of the horizontal plan of its mountain ranges. These ranges mark the main structural or tectonic lines of the continent, and in the peculiar arctuate forms which characterize them, in the relation of the arc-shaped ranges to one another, in their magnitude, arrangement, and distribution with reference to the continent as a whole, and also in their relative ages and the order of their formation, Suess finds a stronger and more certain light shed upon the structure of Asia and upon the origin of that structure than in all other evidence combined. Suess has reached his grand conclusions as to the direction of crustal creep and horizontal thrust, not by the usual method of studying outcrops and cross-sections, but by a study of the trend-lines of the mountain ranges which were produced by these movements.

This method is unique, but it grew naturally and easily out of the study of the facts observed, and is not a fanciful invention of the imagination. As Suess has said, the arc-shaped ranges of Asia have deeply impressed all the students of that continent. They are the most remarkable and significant thing which the researches in that continent have revealed. While similar investigations have been carried on in all the other continents, this method of interpretation was not developed in any of them, for the evident reason that no other continent has mountain systems which reflect in their plans such simple and unequivocal expressions for the dynamic forces involved in mountain and continent making. But, having been developed in Asia, this method may possibly be applied with success to the interpretation of the other continents.

So strongly significant of crustal movement in one general direction are the lines of the mountain plan of Asia that no geologist who at the outset was free from strong hypothetical preconceptions has failed to agree with Suess in his general interpretation. Not that the other geologists join with Suess in the details of his particular hypothesis of the causes of Asiatic structure, but the general consensus of opinion among European students of Asia agrees with him in his broad conclusion that the mountain ranges were produced by tangential or horizontal thrusts acting in a general way from northerly to southerly directions.

No other method of studying the products of diastrophism or earth-deformation with the object of learning their causes gives anything like so much promise of final success as this, for none takes hold in such a broad, deep way. Suess' method is adapted to include and comprehend the broadest possible relations and aspects of the phenomena of crustal deformation. The facts dealt with by this method are not a more or less unrelated aggregation of minutiæ, as is too often the case with collections of outcrops and cross-sections; their scope and breadth are commensurate with the extent of the mountain ranges themselves or even with that of whole continents. Indeed, it is one of the objects of the present paper to endeavor to show that the method of Suess is applicable not merely to Asia and Eurasia, but to the whole northern hemisphere and to the southern hemisphere also, and hence to the whole earth; and finally, that the conclusions reached by a broad application of this method point even now very clearly to the general nature of the processes which have produced the earth's plan.

After noting the advances made by Reyer and Bertrand in the methods of study of mountain ranges in transverse section, Suess makes the following remarks on the value of his own synthetic method:

"A study of the mountain chains in transverse section is, however, only one part of our task; we must also investigate them in horizontal projection—that is, in plan. There was a time when every single anticline of the Jura was regarded as an independent axis of elevation; then it became clear that such a collection of parallel anticlines must have a common origin; next it was seen that there is a certain dependence between the Alps and the Jura; finally, the influence of the obstacle presented by the Black Forest was recognized, and it became evident that the Alps and the Jura were only parts of the southernmost, innermost, and most recent of three crescentic systems of folds which have arisen one after the other across central Europe since the close of the Silurian epoch. Thus with our increasing knowledge we are led to the conception of units of a continually ascending order, and the several anticlines of the Jura now appear to us as parts of an organic whole.

"To continue this method of synthesis, to group the folded ranges together in natural units of a still more comprehensive character, and to explain by means of a single simple expression as large a part as possible of the terrestrial folding—such is the task which now awaits the geologist. The *plan of the trend-lines*, written by nature on the face of the earth—this it is which he has to determine" (III, 3).

In the present paper Suess' method of interpretation from the trend-lines of mountain ranges is followed throughout, and is extended to the largest possible units. But his conception of the manner of deformation, by oceanic depression and tangential thrusts directed toward the oceans from certain northern vertices, or horsts, of relatively restricted area, is not adopted. In its stead an attempt is made in the closing part of this paper to determine in a general way the nature of the causes producing the tangential thrusts, particularly by a study of the largest definable units of deformation and by the groupings which the similar and dissimilar characters of these units suggest in relation to possible causes of deformation. The conclusion reached is one which Suess himself hints at in one of his later works, where he recognizes the possibility of a much broader cause than that which he discusses in the first three volumes of "The Face of the Earth."

Eurasia, the greatest Unit in the Earth's Plan

Significance of the peripheral Mountain Arcs of Asia

Throughout his whole discussion of the mountain systems of Asia, Suess dwells continually on the significance of the mountain arcs, and especially on those of the peripheral belt. He notes that they all bend to the southward—to the southeast from eastern Asia, to the south from southern Asia, and to the southwest and south from southwestern Asia; that they are overthrust against the northern side of the obstructing tableland of Indo-Africa, and show peculiar forms which arise from adaptation to the form of the obstructing mass; that the island arcs along the east coast, where no obstruction was met, bend out even more perfectly toward the deep depression of the Pacific; that the southward bending of the arcs indicates a connection between the different parts of all this vast region and must have arisen from a common cause, and finally that these characters all contribute to the conclusion that the entire peripheral mountain system of Asia was folded toward the south by horizontal thrust forces acting in that direction. It seems impossible to contemplate a plan of the trend-lines of the peripheral ranges, such as is shown in figure 2, without reaching these conclusions.

The trend-lines show, with two or three exceptions, simple arc-forms bending to the south along the entire front from Asia Minor to Alaska. Their simplicity of form and their relations to one another are such as seem to be attributable only to a single thrusting force acting throughout the whole process of folding substantially in one direction, for there appears to be no evidence of complexity resulting from thrusts in different directions, such as is found in Europe. The arc of the main range of the Himalaya is about 1,500 miles long and is a curve of wonderful simplicity and perfection. It is an almost perfect arc of a circle with a radius of nearly 1,300 miles, and its curvature is remarkably perfect for a feature of this kind. The island arcs off the east coast are almost as nearly circular in their curvature. But westward from Burma the first range, omitting the Himalaya arc, shows many irregularities that break up the simplicity of its curves.

From Asia Minor to the Philippines the peripheral belt of Tertiary folds is not a single folded line, but consists of two or three lines, sometimes more, lying one behind the other. From the Philippines to Alaska, however, the Tertiary belt is a single fold-line, so far as known. The reason for this difference is not known with certainty. As Suess says, we do not know the character of the platforms upon which lie the seas behind the island arcs; there may be other weaker, lower fold-lines behind the arcs, or the platforms may be composed of ancient, crystalline rocks which moved as "plates" without parallel foldings. In Europe and western Asia the resistance of the Indo-African plateau may have contributed largely to the making of parellel fold-lines, but this would hardly apply to the Malay arc between Burma and the Philippines. Nevertheless, the absence of any obstruction along the east coast would seem to have favored simpler results there.

The peripheral mountain arcs form a continuous frontal fold for the whole southern border of the continent, and are apparently all of one age. Regarded as a product of crustal deformation, this fold appears to be a unit in both extent and time, and it is therefore a unit in dynamic process also. A mighty creeping movement of the earth's crust from the north toward every part of the vast periphery appears to have taken place, and the area of earth-crust involved appears to have been as great or greater than the entire expanse of Asia. This idea is very different from the conception of Suess, who pictures the ancient vertex in Siberia as the center from which all the movements took place, the vertex remaining unmoved, while the crust around it moved away in slightly divergent southerly directions.

THE HIMALAYA RE-ENTRANT AND THE MALAY EARTH-LOBE

The most pronounced departure, however, from a fairly even front for Asia is found in the contrasted forms of the Himalaya re-entrant and the Malay earth-lobe. If we contemplate the plan of the trend-lines, as shown in figure 2 for these two features, it seems apparent that it was the obstructing action of the Indian peninsula which produced the great Himalaya re-entrant. It was the tremendous resistance offered by this fragment of the ancient Gondwana-land which held back the advancing folds to the line of the Himalaya. The effect seen in horizontal plan is as though India had held back an advancing curtain in a very pronounced way, as indeed it did, for the curtain was the crustal sheet of Asia.

The occurrence of such an obstruction in the way of the southward moving crustal sheet must necessarily have produced some very characteristic effects, and some of these effects could be anticipated with much confidence by the application of well-known principles. It would be expected, for example, that the folds would be most closely pressed together at the most northerly point of the resisting obstacle, where the obstructing effect would be greatest, and that the folds would bend or lap around on either side of the obstructing mass so as to inclose it within a re-entrant angle of the general front. It would be expected also that the vertical component of movement expressed by positive elevation of mountain ranges and plateaus would be greatest against that same point.

All these effects are conspicuously present in the Himalaya re-entrant. The Pamir plateau, the highest on the earth, is close north of the extreme northern point of India, and it is here that the great Hindu-Kush, Kuen-Luen, Altai, and other ranges converge in the Pamir plateau, with the northwest end of the Himalaya range abutting against its southern side. The Himalaya is the most majestic mountain range on the earth and some of its peaks are the highest. Who can doubt that the great height of Gaurisanker and the Pamir are due chiefly to the intensified elevation caused by the obstructing action of the Indian peninsula?

A large area of Asia north of the Himalaya is a high plateau with lofty mountain ranges. At the east the Himalaya range ends abruptly on the Brahmaputra at the great bend, and several lesser mountain ranges wrap themselves around the east end of the Himalaya, some of them changing their trend from due east and west, north of the Himalaya, to northeast and southwest south of the great bend. The simplicity of the relations of all these features is such that the obstructing action of India to the southward advance of the crustal sheet seems the only possible explanation.

From the eastern end of the Himalaya the trend of the peripheral range runs far to the south, curving gradually to the east, and returning northward through the Philippines to Formosa. This great excursion of the peripheral ranges to a point seven hundred miles south of the equator incloses an immense area, including the South China Sea, the Java, Celebes and Sulu seas, the Gulf of Pegu, the islands of Sumatra, Java, Borneo, Celebes, and Philippines, the Malay Peninsula, Burma, Siam, Annam, and part of southern China. This immense area is far too great to be classed as a mere arc along with the other mountain arcs; it is in truth a great earth-lobe, analogous to some of the great ice-lobes of the Pleistocene ice-sheet of North America. Suess himself suggests this comparison in one of his later works, where he says:

> "One can also recognize a certain resemblance between these curved chains [of Asia] and the course of the moraines, and also the forms of the glacier lobes which Chamberlin draws across the east of the United States."[8]

Its periphery is made up of six or seven lesser mountain arcs joined end to end in a curving course, so as to define the boundaries of the lobe. On its base between the eastern end of the Himalaya and the Island of Formosa this lobe is about 1,700 miles across, and from base to outer extremity it measures about 2,500 miles. It is interesting to note that the Malay earth-lobe presents certain well marked antitheses to the Himalaya re-entrant, and that they are all dynamically normal. Corresponding to a region of relatively free and partly dispersive crustal movements, without obstructing masses, the peripheral ranges of the Malay lobe have comparatively low altitudes, and further, corresponding to an axis of more extensive and perhaps more rapid crustal movement, some of these ranges show unusual volcanic activity. The Java arc in particular is a veritable fire line, and its relatively low mountain basement is almost entirely covered up by volcanic products. Here, then, was the relatively free spreading of a great earth-lobe, the thrust forces dying out in dispersive movements, while in the more severely compressed and overheightened Himalaya and the Pamir we see the effects of crustal movement retarded by a great and effectively resistant obstruction.

There seems to be little doubt that the projection of this remarkable earth-lobe so far to the south on a path lying next east of the Himalaya is in some degree a compensation for the obstructing effect of India. The advance of the crustal sheet in the region north of Indian was so strongly retarded by the Indian mass that the force of the movement against the Himalaya was partly deflected eastward into the Malay lobe. In this way the thrust forces running south along the axis of the Malay lobe were intensified and accelerated, just as a stream of water, meeting an obstruction which fills half the width of its channel, is retarded and slightly raised against the obstruction, only to rush with accelerated velocity through the remaining constricted space. If there had been no obstructing Indian peninsula, it seems likely that these two areas would have been equalized, and that the front line of Asia would have run in a broad curve sweeping from the east end of Arabia to Formosa, without, in all probability, reaching farther south than the tenth degree of north

[8] Bulletin of the Geological Society of America, vol. 11, p. 105.

latitude. In the following passage Suess describes an interesting relation between the Himalaya and Malay arcs:

"We shall show later, with greater detail than we have yet done, that the Himalaya actually terminates on the Brahmaputra. There are chains lying behind the Himalaya joining the meridional chains of Yunnan which pass the end of the Himalaya and are continued in the Malay arc. This arc we have traced through the Banda Islands as far as the coast of New Guinea. But although to the south it passes considerably beyond the equator, yet in a tectonic sense it lies wholly behind the Himalaya, or if we were to number the great folded ranges from the exterior inwards, the Himalaya would receive the number 1 and the Malay arc the number 2" (II, 195).

In the region of Borneo, Celebes, and eastward there are some singular complexities of the trend-lines. These, however, do not belong to Asia alone and will be considered under a separate head.

On the map (figure 2) a broken line is drawn from the west end of New Guinea toward the northeast to the Ladrone Islands, and thence northward to the great fossa in Hondo, Japan. This line appears to mark a submerged mountain range, as shown on bathymetric maps, and probably represents a broadening or uncompleted enlargement of the Malay lobe. This, however, is a matter for further investigation.

Along the south or east front of some of the interior mountain ranges of Asia, Suess, Richthofen, and others have described what they call disjunctive lines or faults with great downthrow to the east, south, or southeast. Along these lines great platforms broke from the high central plateau and settled toward the Pacific. It may be that this movement was secondary or reactionary, and was caused by a too great elevation of the lands of central Asia at the most active stage of folding.

On the west side of India the crustal sheet pressed southward into the gap between the resistant masses of India and Arabia, and formed another distinct feature which we may call the Iranian earth-lobe. It is much smaller than the Malay lobe, but is, nevertheless, distinctly accentuated by the obstructing action of India. The front range of this lobe has two small, sharp re-entrants which appear to correspond to saliences of the obstructing mass. One is on the east side and incloses the plain of Katschi in northeastern Beluchistan; the other is toward the west side, and is marked by the northward bending of the Strait of Ormuz. The Ahkdar Mountain range attains an altitude of more than 6,000 feet back of Muscat, on the east coast of Arabia. This range runs northward into the Strait of Ormuz with decreasing altitude, as though pitching downward to the north under the Iranian earth-lobe. As the Persian Gulf and the Tigris-Euphrates Valley appear to be a sunken fore-land, so the Strait of Ormuz appears to be a passage over a depressed mountain range.

West of the lower course of the Indus the Kirthar range runs directly south, and then curves southwestward toward the sea at Cape Monze. It appears to continue some distance to the southwest beneath the sea, for the soundings show a deep trough extending back to the northeast along the north side of the submarine line of the range. The position of this range suggests a folded arc curving toward the west through the northern part of the Arabian Sea, but remaining undeveloped. Its trend suggests a continuation in the Ahkdar range of Arabia, which curves back toward the north on the west side, but present knowledge indicates the latter range to be older and to belong to the ancient Indo-African tableland. These features invite further investigation.

THE PERIPHERAL RANGES IN EUROPE

The trend-lines of the Tertiary mountain ranges of Europe are much more complicated than those of Asia. They show a tendency to a dominance of east and west trends, although the Apennine and Dinaric ranges, with northwest-to-southeast trends, form a marked exception, and a considerable part of the Carpathian fold takes the same course. The most remarkable forms, however, are the sharply bent arcs of short radius, the Roumanian arc, the arc of the western Alps, and the arc of the Betic cordillera at the western end of the Mediterranean. All of these present sharply convex fronts toward the west.

In discussing the trend-lines of the European ranges, however, Suess departs somewhat from the methods and principles which he has used so successfully in Asia, and his language in some passages seems to contradict that of others. In Asia, Suess found the direction of overthrusts in the peripheral belt to be invariably toward the south, thus agreeing well with his conclusions on the direction of tangential thrust from the southward convexities of the arcs, and the evident southward compression against India. But one can not be sure upon which kind of evidence he relies the more, overthrusts or direction of arc bending. On the whole, one is inclined to believe that he relies more upon the latter; yet, when he passes over to Europe and discusses the ranges there, he finds a confusion of trend-lines among which, although east-and-west lines are dominant, others are prominent, the Carpathians and the Alps especially showing northward convexities. The three arcs sharply convex to the west Suess attributes to a tangential thrust from the east. The arcs of the Carpathians and the Alps are convex to the north, and from his point of view indicate tangential thrusts in that direction. The arc of the Apennines is slightly convex to the northeast, while the great curve made by the Apennines and the Atlas of northern Africa is convex to the southeast. The southern range of the Atlas is nearly a straight line, and the Pyrenees, like the Caucasus, are substantially rectilinear.

But, in addition to the northward bending which Suess finds in the Carpathians and the Alps, he finds also that both of these ranges are strongly overthrust toward the north, and that the older ranges also show great overthrusts toward the north or northwest, as in Belgium, Scotland, etcetera. In Scandinavia, however, the greatest of all the overthrusts is toward the east-southeast. On these evidences Suess concludes that the thrust forces in Europe acted mainly toward the north, or contrary to their direction in Asia, and, what is much more important, his language seems to convey the idea that the whole crustal movement in Europe was toward the north. This conclusion he seems to rest on the few cases of northward convexities with associated northward overthrusts.

In some of his broad, generalized statements Suess' words seem to imply clearly enough a general southward tangential movement in Europe the same as in Asia, as, where he says: "*The whole southern border of Eurasia advances in a series of great folds toward Indo-Africa*" (I, 596). Again, in enumerating the continental units he mentions first, "*Indo-Africa,* the greatest tableland of the earth, limited on its northern border, from the point where the Wady Draa discharges into the Atlantic Ocean to the mouth of the Brahmaputra, by the folds of Eurasia advancing to the south" (I, 600). But in discussing the relation of the Alps to the mountains of Asia he says:

> "We observe as a remarkable phenomenon that from the Caucasus onwards [westward] the tangential movement is not, as in the Asiatic chains, directed to the south, but to the north, and that on the northern border of the Carpathians all the indications appear of an extensive overthrusting on to two forelands of completely different structure, the Russian Platform and the Sudetes" (I, 500).

In the next paragraph he observes that "it would seem as if in Asia tangential movement or lateral compression had occurred almost exclusively in the direction of the meridians of longitude, but that here [in Europe] it had taken place also in the direction of the parallels of latitude, and it is precisely in this region that the Carpathians are driven out toward the north in so striking a fashion."

In these last two passages, and in others that might be quoted, Suess seems to abandon in part his broader method of interpretation for the older method, which depends mainly upon the study of local structural details, and in doing this he seems to lose sight of a very important distinction which ought to be kept constantly in view. Overthrusts and local convexities of trend-lines may not accord with the direction of general crustal creep in the same region, and surely it is of the first importance to determine correctly the larger of these facts—the direction of the general crustal creep. This can be done safely only by the broadest possible methods, such as have been used for Asia. Indeed, it is by an extension of the reasoning for Asia to the European field that this question can be most clearly and safely determined.

In Asia the proof that the crustal sheet moved southward as a unit does not rest alone on the existence and relations of the single frontal fold-line, but upon the whole belt of subparallel Tertiary ranges, extending from the Philippines to Asia Minor. The belt as a whole is peripheral in its nature; it is the crumpled margin of the crustal sheet. The belt continues into Europe with about the same width and in the same general relations—as a peripheral belt along the southern margin of the continental sheet.

Suess remarks that there is no natural line of demarkation between Asia and Europe, and Penck happily describes Europe as "peninsular Eurasia."[4] Suess points out the fact that the fold of the Caucasus appears to continue into Europe in the Roumanian arc, the Carpathians, and the Alps, while the Taurus fold continues in the Dinaric range of Europe. In short, the Tertiary fold-belt extends right through from Asia into Europe without any change, except that its simplicity in Asia is replaced by complexity in Europe. The general relations are absolutely identical.

Broad facts like these are of a much higher order of value in determining the direction of general crustal creep than are facts relating to overthrusts and occasional exceptionally directed convexities of trend. The peculiarities and exceptional features in Europe may be explained by other causes, and can not be safely set up as proof of the direction of general crustal movement.

There are at least three causes for irregularity among the trend-lines of the European ranges. The first and most important is the relative smallness of the European crustal sheet, with consequent feebleness of the thrust forces; second, the obstructing and complicating action of block-like masses of the older European ranges, where included within the belt of the Tertiary folds; and, third, the tangential thrust from the east, producing the Roumanian, Alpine, and Betic arcs, as described by Suess.

[4] Science, February 26, 1909, p. 322.

The crustal sheet or "plate," as Suess calls it, lying north and northwest of the European Tertiary ranges, was quite small as compared with that which lay to the north of the Himalaya and the Malay and Iranian earth-lobes, and it was the magnitude or mass of this "plate" which in each case determined the power of the crustal advance and probably also the horizontal distance of the advance. In Asia the Tertiary advance closed and completely overwhelmed the ancient greater Mediterranean Sea, the Tethys of Suess, whereas in Europe the same movement fell far short of this result and closed only a part of the sea, leaving the modern Mediterranean in its present state. It can not be doubted that the southward pressure of the creeping crust was far greater in Asia than in Europe. Where the forward movement of the crust was more vigorous, as in Asia, minor causes tending to interfere and produce irregularities were overwhelmed; but in Europe, where the movement was relatively feeble, the minor forces were favored and the impress of their action remains today.

The thrust from the east, seen in the Roumanian, Alpine, and Betic arcs, appears to have been a deflected force arising probably from the resistance of Indo-Africa to the southward crustal movement in Asia. Although it produced locally a marked effect, it was apparently a relatively feeble force.

On general principles one is inclined to believe that forward overthrusts—that is, moving in the same direction as the general crustal creep, like that at the base of the Himalaya—are likely to be of greater extent than underthrusts which only produce the effect of overthrusts in a backward or opposite direction. Agreeably with this idea, the great overthrust to the east-southeast in Scandinavia has a length of nine degrees in latitude and a known width of over 100 kilometers. This is much more extensive than any of the others in Europe, and the others are all in the opposite direction. It seems probable, therefore, that the Scandinavian case is a true forward overthrust, while the others in Europe are southward or southeastward underthrusts. This, of course, does not take away the appearance of overthrusting in these latter cases, but the tangential force which affected the mass above the thrust plane is in such cases to be regarded as a reflex thrust force, directed backward over the advancing undermass. The upper mass in a case of underthrust might be described as a backward overthrust in distinction from a forward or true overthrust.

The resistance of the African plateau may also have contributed something to the irregular forms in Europe, especially in favoring the persistence of some of the Mediterranean basins, or possibly the making of them. The Atlas Mountain ranges of Africa belong structurally to the

Tertiary folded system of Europe and to the peripheral system of Eurasia.

Since there is no ground for separating Europe from Asia as dynamic units in the Tertiary deformation, they should be taken together as one unit, and the Tertiary ranges of the entire peripheral belt should be regarded as the product of southward creep of the entire crustal sheet of Eurasia. But there is still a little more to be added even to this great unit.

THE ARC OF THE ALEUTIAN ISLANDS

Suess regards the arc of the Aleutian Islands as an independent line, not to be counted with the island arcs of eastern Asia, and he counts it as a distinct and separate element in enumerating the boundaries of the Pacific. This is only partly justified, for this arc is, in fact, distinctly Asiatic in all its characteristics and affinities. The Asiatic character of this arc is strongly shown in its pronounced curvature and its grand sweep. It is, indeed, the most perfect of all the island arcs, and, like the arcs of the Kuriles and north Japan, has a long, narrow ocean deep close in front of it. Its backland belongs about two-thirds to Asia and one-third to North America. The mountain chain which forms the arc rises from the sea as it approaches Alaska, and continues in the same curve to the highest part of the Alaskan Mountains.

While the Aleutian arc is a perfect type of the Asiatic arcs, no such arc occurs in either of the American continents. Probably Suess regarded it as independent, because it is so situated that it could not be related to his Siberian vertex in the way that he finds the other island arcs to be; but this is not believed to be an essential distinction. That part of Asia which forms the backland of the western part of this arc is just as much a part of the great crustal sheet of Eurasia as any other part, and the distinctly Asiatic type of the arc shows that whatever special conditions determined the peculiarities of the other island arcs affected the backland of the Aleutian arc in the same way.

When the Asiatic character of the Aleutian arc is recognized it becomes at once apparent that the crustal sheet of Eurasia is not limited on the east by a line through Bering Strait dividing this arc and its backland, but includes the whole arc and the whole of its backland. Thus, Asiatic character is carried eastward to the heart of the Alaskan Mountains, where the curve of the Aleutian arc meets the Cordilleran ranges of North America in a sharp angle. This meeting point falls near the 148th meridian of west longitude, and when we consider continental boundaries with reference to Tertiary diastrophism, we must include in the crustal sheet of Eurasia all that part of Alaska which lies west of this meridian.

Thus Eurasia, considered as a crustal unit in the Tertiary movements, includes all of Europe with the Atlas ranges and Canary Islands of northwestern Africa; all of Asia excepting the peninsulas of Arabia and India, and in addition all that part of North America which lies west of the mountain angle of Alaska. It seems certain that all this vast crustal sheet was affected by a horizontal creeping movement in the Tertiary age, that it all moved in a southerly direction substantially as a unit, and that the entire belt of Tertiary fold-mountains which forms its southern periphery was made at that time and by that movement.

FRONTAL OCEANIC DEEPS

The deepest parts of the ocean are found mostly in long, narrow troughs closely parallel to the continental borders, especially that of eastern Asia.[5] The position and relation of these deeps are truly remarkable. The Tuscarora deep, with a depth of more than 5 miles, is the deepest abyss now known. It lies in front of the Kurile Island arc and the arc of north Japan (see figure 2). An even more remarkable deep is that which lies close along the entire front of the great curved arc of the Aleutian Islands and includes the Supan and Maury deeps. This trough is partly shown in figure 2. The principal frontal deeps are shown in figure 7.

Other deeps in the same relation, but smaller, occur along the east side of a submerged escarpment running north from New Zealand. These lie in the northwest part of the more extensive Aldrich deep. There are deeps along the west coast of South America, such as the Bartholomew, Richards, and others. Deeps with circular or irregular outlines occur in other relations not so clearly dependent upon adjacent land-masses. Such are the deeps of the Atlantic and the line of deeps running north from the Aldrich deep through the middle of the Pacific. The Challenger deep is near the junction of the Ladrone and western Caroline Island chains, while the Wharton deep lies partly between Australia and the Malay arc. Deep holes, like the Bartlett and Weber deeps, are characteristic of all the Mediterranean seas.

The Tuscarora deep and that in front of the Aleutian arc seem clearly linked causally with the continental border and the great mountain ranges

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[5] See Sir John Murray's "Bathymetrical chart of the oceans." Scottish Geographic Magazine, vol. xv, no. 10, October, 1899; opposite p. 560. Reproduced in Chamberlin and Salisbury's Geology, vol. i, p. 10. The portion covering the Atlantic Ocean is reproduced as plate 4, facing page 217.

which stand adjacent to them. They are of the nature of sunken or depressed forelands, and are apparently due to the stupendous weight and pressure of the adjacent ranges. These arcs are no doubt more or less overthrust upon the ocean floor, and the troughs are probably due in part to elastic yielding and perhaps in part also to plastic flow.

The most strongly marked deeps are close in front of island arcs which represent submerged mountain ranges. Evidently the reason that the Tuscarora and Aleutian deeps remain unfilled today is that the ranges to which they are related have remained submerged, have suffered little or no erosion, and hence have supplied very little sediment. Other similar frontal depressions situated close to continental lands which supplied great quantities of sediment have been partly or wholly filled. Such are the valleys of the Ganges and Indus in India, the Tigris-Euphrates Valley and the Persian Gulf, and also the Adriatic Sea and the Po Valley. Such troughs, growing deeper while sediments are being deposited in them, furnish a possible explanation of certain sedimentary strata whose great thickness and shallow-water character seem to demand subsidence during deposition.

The fact that the greatest deeps, both unfilled and filled, lie close to the front of the peripheral ranges of Eurasia, the greatest of the continental units, adds one more significant group of facts to the great aggregate, showing how much more vigorous were the Tertiary crustal movements there than in any other part of the world; and they join with the other evidences mentioned above, which show a general southward crustal movement for the whole of Eurasia.

The Relation of North America to Eurasia

THE MOUNTAIN KNOT OF ALASKA

In his earlier writings, Suess regards North America as a continental unit which moved in harmony with the Tertiary movement of eastern Asia—that is, it was folded toward the Pacific Ocean. Referring to North America, Suess says: "So far as folding is known in this continent, it appears to be everywhere directed to the west" (I, 600).

It may be observed here, however, that the Tertiary folds bordering the Pacific are mainly folded toward the *southwest*, rather than to the west, as Suess states, and that only in the States of Oregon and Washington are they folded to the west.

On the same page Suess observes further that—

"After having described the manner in which the syntactic arcs of the great chains push forward against the north of the Indian Peninsula, we observe that a similar advance of syntactic arcs takes place toward the north of the Pacific Ocean, and that a special tectonic homology exists between that fragment of ancient table-land and this part of the ocean."

From these passages it seems clear that Suess regarded the Cordilleran ranges of British Columbia as pressing toward the southwest to meet the eastern end of the Aleutian arc pressing toward the southeast, and this is apparently the true relation. There was thus a convergence of crustal movements in the mountain knot of Alaska, and it was the conflict of these movements which intensified the mountain making at the angle and gave the mountain knot its greater breadth and height. Figure 3 shows the mountain knot, with part of the Aleutian range which enters it from the southwest and part of the Cordilleran range which enters it from the southeast. The shaded part is 5,000 to 10,000 feet in altitude and the black parts 10,000 feet or more.

The morainic accumulations of the Pleistocene ice-sheet in North America present homologous forms that are very instructive. These are the interlobate moraines which were produced in re-entrant angles of the ice-front, where the fronts of two adjacent great lobes of the ice-sheet came together on converging lines. The mountain knot of Alaska is in a precisely similar sense an interlobate form—a confusion and intensifying of mountain making in the angle between two great earth-lobes, or two crustal sheets moving on converging lines. Just as interlobate moraines are higher, more bulky, and more tumultuous in form than either of the single morainic ridges approaching the interlobate angle, so the mountain knot of Alaska is broader and higher than either of the ranges approaching it. If the Cordilleran ranges of British Columbia had been folded toward the northeast—that is, away from the ocean—there would be no reason for the existence of the mountain knot; and still less if we suppose, further, that the eastern part of the Aleutian range had been folded to the northwest. There would then be diverging movements from the place of the mountain knot—a condition hardly favorable for the formation of such a feature.

American geologists, following H. D. Rogers, Dana, Leconte, Dutton, and others in their interpretation of Appalachian structure, made many years ago, derive the thrusts producing the folding of that range from the direction of the Atlantic Ocean. No doubt this is correct so far as relates to the immediate thrust forces involved—that is, to those which affected the upper or outer parts of the crustal sheet and produced the Appalachian folds. But these authors make no distinction between the relatively superficial thrust movements and the deeper general creeping movement which involved the whole crustal sheet of the continent, as it was then, and reached downward to or into the zone of rock flowage. The variously directed thrusts which affect the more superficial parts may, according to local conditions, act in any horizontal direction, but usually either in the same direction as the general crustal movement or in the opposite direction. The same idea was later applied to the Rocky Mountains and to the Cordilleran ranges bordering the Pacific, and the thrust forces there were derived from the Pacific depression.

FIGURE 3.—*Alaska*

Showing the mountain knot, part of the Aleutian Island arc, and part of the Cordilleran ranges of British Columbia and Alaska. The arrows show the supposed direction of crustal movements.

It seems certain, however, that the relation of the Cordilleran to the Aleutian range in the mountain knot of Alaska shows that the general crustal movement of North America in the Tertiary age was toward the Pacific, and hence that the great eastward and northeastward overthrusts of the Rocky Mountain region are in reality underthrusts, or reflex overthrusts, directed backward over the southwestward general crustal movement. At these localities the southwestward underthrust of the deeper parts was the primary movement, and the apparent northeastward overthrust observed in the superficial parts is regarded as secondary and reflex in its nature.

As shown in the two quotations given above from Suess, this was in substance his original interpretation of the part played by North America in the Tertiary mountain making which set the present boundaries to the Pacific. He regarded the crustal sheet of North America as folded southwestward toward the Pacific. Thus, on principles derived from his study of Asia, Suess generalized from Eurasia to North America, and concluded that the latter, like the former, had been folded toward the great ocean.

When Suess arrived at this generalization he had accomplished a great and magnificent result for geology, for he showed that North America, like Eurasia, had been affected in Tertiary times by a crustal movement in a southerly direction—not exactly to the south, but southward with a strong deflection to the west, though not more strongly than was the southward movement in eastern Asia deflected toward the east. In this conclusion Suess had completed in rough outline the Tertiary tectonic history of the northern hemisphere. He had put both of the great northern continents into the same category with reference to Tertiary crustal movements. Regarding each northern continent as a crustal unit, Suess found that Indo-Africa had remained stationary, or at least without tangential movements, but that both Eurasia and North America had been affected by tangential movements in the same general direction—that is, toward the south. It should be noted that in this distribution there is a certain relation to latitude, for Indo-Africa, lying mainly in the tropical regions, remained unmoved, while Eurasia and North America, each extending vast areas far to the north, both of them into the arctic regions, crept away to the south.

Here, then, is a fact as broad as the northern hemisphere. Both of the only two continents whose crustal sheets reached far to the north moved in the Tertiary age from north to south. Such a fact as this may be taken as the concrete expression of a general law of wider scope. Thus, if the forces of Tertiary diastrophism caused the earth's crust to move from north to south in the northern hemisphere, may we not take this distribution of the deforming force to be characteristic and fundamental? Putting it in abstract form, may we not say that the deforming force caused crustal creep from high latitudes toward low latitudes? But if this statement expresses the truth it ought to be as applicable to the southern hemisphere as to the northern, and here we are naturally inclined to turn to the antipodes to see what the evidence is there.

However, before turning to this new field there remains one other important body of facts which bears strongly upon the direction and amount of movement of the North American crustal sheet.

GREENLAND, THE GREAT NORTHERN HORST

If further evidence were needed to make sure that in the Tertiary diastrophism North America moved toward the southwest—toward the Pacific and the Tertiary fold mountains along its border—it may be found in the remarkable relation of Greenland to North America.

Suess remarks that "Greenland is a horst of the first order between two or more sunken areas of different age" (II, 294). But Suess' conclusion was based mainly on different evidence from that offered here.

A map of Greenland and its environs on a large scale shows some remarkable characteristics in the outlines of the channels, straits, and bays on its northern and western sides. These are shown fairly well in figure 4.

Amid such a tangle of irregular straits and channels as separate the islands of the archipelago west of Greenland, it is quite surprising to find a passage so straight and persistent as that which separates Grant Land, Grinnell Land, and Ellesmere Land from the north part of Greenland. It seems like a distinct rift-line, and the question arises as to the direction and amount of movement along it. It is quite different in character from the great rifts or fault lines which Suess supposes to form the sharply cut boundaries of the east and west sides of India, Africa, Madagascar, and Greenland. It is a relatively narrow passage, and one seems driven to the conclusion that the displacement along it was a horizontal movement parallel with the rift. In looking for the direction, it seems impossible to suppose Greenland to have moved toward North America and the land on the west side of the rift relatively in the opposite direction, for in that case the movement would only have made Baffin Bay, Davis Strait, and the Labrador Sea more narrow, and there would be no reason to expect any element of parallelism in their sides. Besides, if Greenland was formerly farther east the straight coast along the north side of Peary Land would not necessarily be related to or determined by the course of the rift; it might be so related or it might not. Further, there is no independent evidence that Greenland has moved at all, but in the mountain knot of Alaska we have independent evidence that North America has moved toward the southwest. Thus we may conclude, at least provisionally, that it was North America that moved away from Greenland, not *vice versa*.

If, then, by reversing the process, North America be in imagination pressed back northeastward to a complete union with Greenland, it is evident that the Labrador Sea, Davis Strait, and Baffin Bay would be

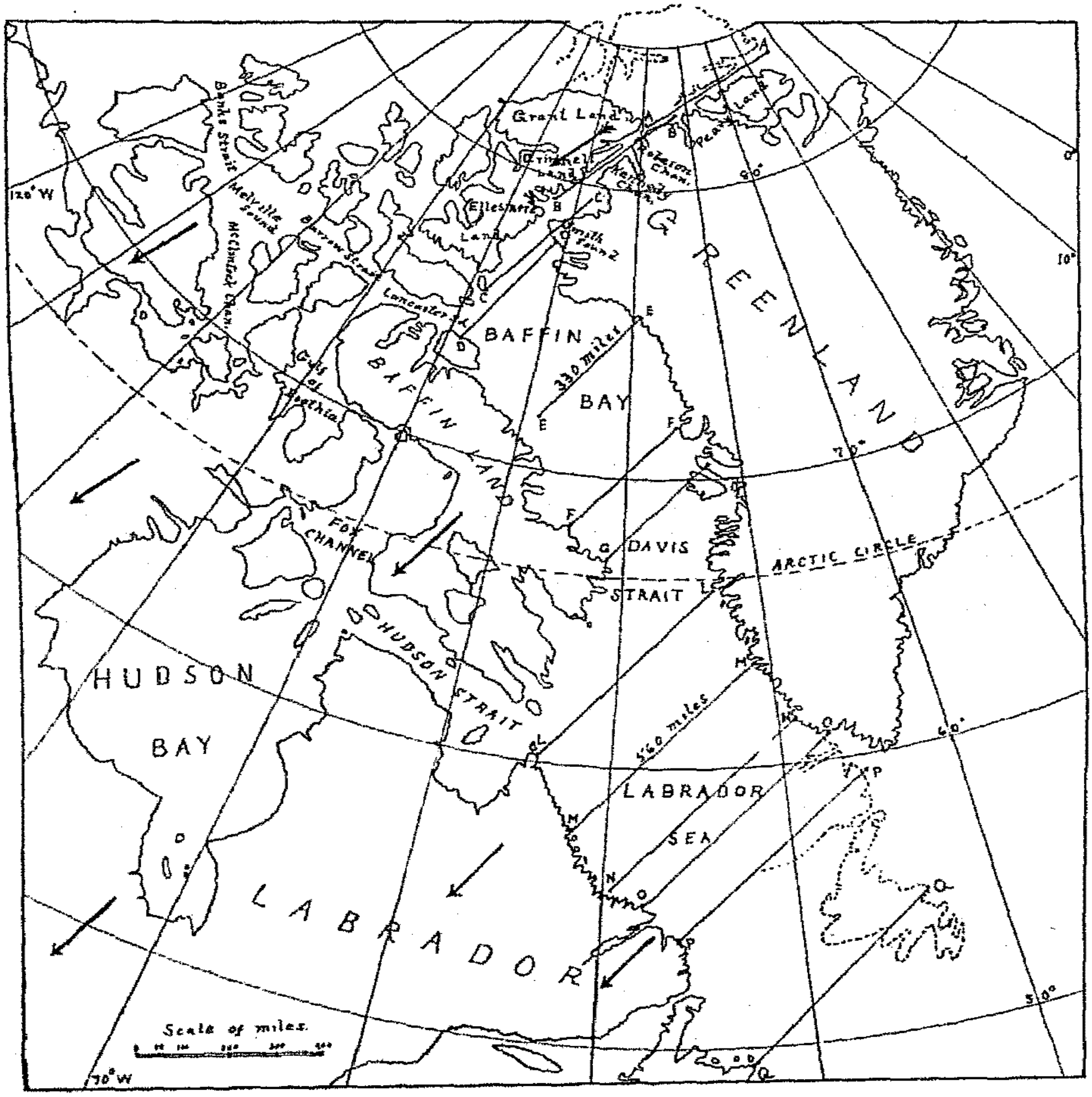


FIGURE 4.—*Greenland and the Arctic Archipelago*

Showing the rift valleys on the northwestern and western sides of Greenland. The arrows show the supposed direction of crustal creep and the lines AA, BB, etcetera, show the supposed distance of movement.

closed and obliterated entirely, and that Grant Land, Grinnell Land, and Ellesmere Land would be thrust northeastward past the north end of Greenland along the line of the rift—that is, along the line of Smith Sound and Kennedy and Robeson channels produced.

It is surprising what relations a few measurements reveal in this region. Suppose Grant Land to have been situated formerly close north of Peary Land, from which it was then separated only by the rift valley. Its position in this relation is sketched in a broken line in figure 4, and shows the east coast of the two regions to form a nearly north-and-south line. If a straight line AA be drawn along the axis of the rift from a point close off the extreme eastern end of Grant Land to another point similarly related to the extreme eastern end of Grand Land *in its assumed former position*, the length of that line is about 330 miles. It is noticeable that the rift valley curves slightly to the south as it runs along the northwest coast of Greenland, and perhaps eastern Grant Land should have been placed a little closer to Peary Land. But if the lines BB, CC, DD, EE, FF, and GG be drawn nearly parallel to AA, it will be found that some of them, especially DD and FF, connecting the opposite shores of Baffin Bay, are of the same length as AA, and that EE and GG are suggestively near the same length. It is certainly significant that the distance across Baffin Bay on lines parallel to AA are so nearly of the same length. Baffin Land, therefore, appears to have been pulled away from Greenland in the same direction as Grant Land, and, what is more significant, it appears to have moved the same distance. If this be true, then we may believe that the bays or inlets marked on opposite sides of the rift valley at the ends of the lines BB and CC were offset by the movement and were formerly exact opposites. Too much importance ought not to be attached to these two lines now, but it is not impossible that the correspondence of these features may some day be proved by geological investigations.

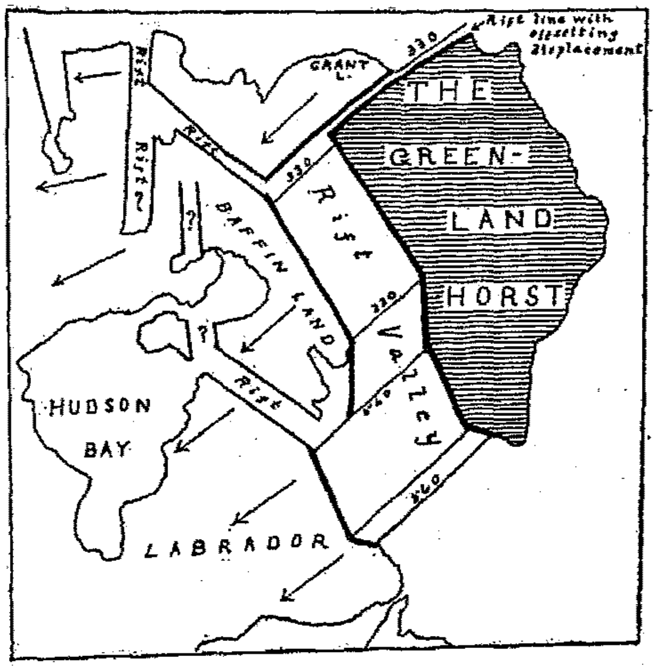


FIGURE 5.—*Diagram of Greenland Rifts*

Shows offsetting rift on northwest side of Greenland, open rifts of two widths on the west side, and several smaller subsidiary rifts farther west. The arrows show the direction of crustal movement, Greenland remaining stationary.

Up to this point some doubt might be entertained as to the supposed value of these relations and measurements. But one further fact of a strongly corroborative character remains to be mentioned. Although Grant Land and Baffin Land moved over 300 miles to the southwest, they did not move as far as did Labrador and the main body of the continent. The relation of the coast of Labrador to the west coast of the south part of Greenland is truly remarkable. This is shown by the lines LL, MM, NN, and OO. These lines are parallel with the lines DD and FF on Baffin Bay, but they are considerably longer, being each about 560 miles. Thus for a distance of about 450 miles the two shores of the Labrador Sea, although now 560 miles apart in the direction of the rift along the northwest side of Greenland, are almost exactly parallel and the geological age and structure of the rocks, so far as known, are the same. If the crust pulled away evenly, as these facts suggest, one would expect Grant Land and Baffin Land to be separated from the main body of the continent by other narrower rifts. Such rifts may be represented by the long, straight channel of Lancaster Sound, Barrow Strait, Melville Sound, and Banks Strait. A longer, less continuous passage, probably representing a wider rift, follows Hudson Strait, Fox Channel, Gulf of Boothia, and McClintock Channel.

We seem to have here a great irregular rift line along which North America has been torn away from Greenland. One part, extending along the northwest coast of Greenland, is a longitudinal rift, a great fault line with horizontal offsetting displacement. The other part, comprising Baffin Bay, Davis Strait, and the Labrador Sea, is a transverse rift along which one side was pulled horizontally away from the other. The two together are over 2,500 miles long. Then there are also the lesser transverse rifts mentioned above.

Perhaps no one of these measurements or relations taken by itself is of much value, but the assembled group makes a strong case for the pulling away of North America from Greenland. The Labrador coast is high and bold, and the Greenland coast facing it is moderately so. Both coasts have deep water close off shore. The parting of these shores can hardly be more recent than the Tertiary, nor is it easy to believe that it is much older. Even if it was so recent as the Tertiary, it is quite surprising to find the opposite walls of a rift 450 miles long pulled 560 miles apart, and still remaining so strikingly parallel; and this, in spite of all the elements of irregularity which might be expected in such a movement, in spite of the largely accidental relation of the sea surface to the rift walls, and in spite of all the erosion that has taken place since. It seems altogether incredible that such characters should have been preserved from times much older than the Tertiary. Labrador is solidly intact with the main body of the continent, and the rift of the Labrador Sea may therefore be taken tentatively as an approximate measure of the distance of the horizontal crustal movement of North Amrica in the Tertiary diastrophism.

M. L. de Launay, probably following the suggestion of Suess, placed a Tertiary rift along the axis of Baffin Bay, Davis Strait, and the Labrador Sea, and also one on the east side of Greenland and southward through the Atlantic, but he does not appear to have noticed the longitudinal rift on the northwest side and the very significant measurements on the lines parallel with it.[6]

On the remaining sides of Greenland there are no suggestive parallel coasts. But it seems certain that the crustal sheet of Eurasia pulled

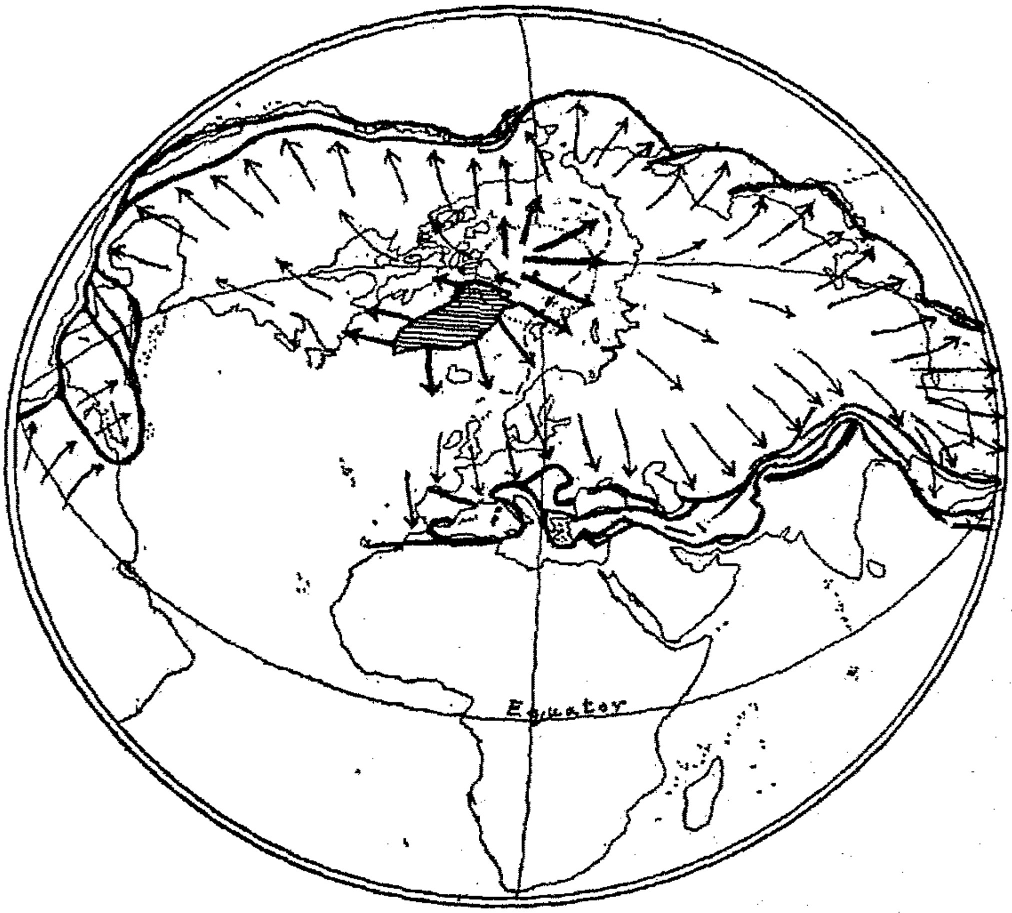


FIGURE 6.—*The Landsphere*

Showing the relation of Greenland to the surrounding continents and to the peripheral mountain ranges of Eurasia and North America. The light arrows show the direction of crustal creep and dispersion. The heavy arrows radiating from Greenland and the pole show roughly by their lengths the relative distances the continents have moved toward lower latitudes. The longest arrows point toward Asia, the shortest toward North America. The broken line north of Asia marks the edge of the continental shelf.

away from the east side of Greenland and from the region of the pole north of Greenland for a distance two or three times as great as the parting between Greenland and Labrador. These relations are roughly sketched in figure 6. It seems probable that the northwest coast of Nor-

[6] La Nature, January 21, 1905. Abstract in English: Literary Digest, March 18, 1905, pp. 396-397.

way was once united to the east coast of Greenland, although they are now over 1,000 miles apart, and the same may have been true of the northwest sides of Scotland and Ireland. There is less reason to think that the rifts on the sides toward Eurasia are wholly of Tertiary age; they may have been made partly at an earlier time, as suggested by Suess.

It may be noted that the greatest breadth of the Arctic Ocean, and probably of the parting from Greenland, is toward Asia, including the Aleutian arc. It is widest toward the island arcs of eastern Asia and toward the Malay earth-lobe and India. In figures 6 and 7 one can scarcely fail to see that the western coast of North America shows only faint, incipient arcs, corresponding to less crustal movement and the relatively narrow rift on the west side of Greenland, while on passing to the east coast of Asia the great island arcs bulge boldly into the depression of the Pacific, corresponding to a much more vigorous crustal movement and to a much wider rift between Greenland and Asia.

It is thus seen that the idea of a general crustal creep from high toward low latitudes in the northern hemisphere is borne out, not alone by the peripheral mountain ranges which fringe the southern border of Eurasia and the southwestern border of North America, but also by a rifting and pulling away of the earth's crust on all sides of Greenland, and that the amount of pulling away is least toward the feebler peripheral ranges and greatest toward the stronger.

The following are the faint peripheral arcs of North America: (1) The Alaskan Island arc, comprising the island chain of southeastern Alaska with Queen Charlotte and Vancouver Islands; (2) the Coast Range arc, extending from the Strait of Juan de Fuca to southern California, and (3) the Mexican arc, extending through Lower California and southern Mexico to the Isthmus of Tehuantepec. These arcs are shown in figure 7, but they are all faint and of slight curvature. They show much better in a map of North America drawn on spherical projection.

Suess has much to say concerning the remarkable correspondence of the Paleozoic and older sediments, and also of the mountain ranges on the two sides of the North Atlantic. He describes "The North Atlantic Continent" at some length (II, 220-255), and shows that it persisted until a very recent time in the earth's history. "We have recognized the existence of two continents, of which fragments only are visible at the present day. The first occupied the position of the north Atlantic Ocean, as is indicated by the nature and distribution of the Paleozoic sediments in Europe and America; Greenland is a remnant of it. This ancient continent is the *Atlantis*" (II, 254). Suess dwells upon the likeness of the Carboniferous sediments as being especially remarkable. The other fragmental continent referred to is Gondwana-land.

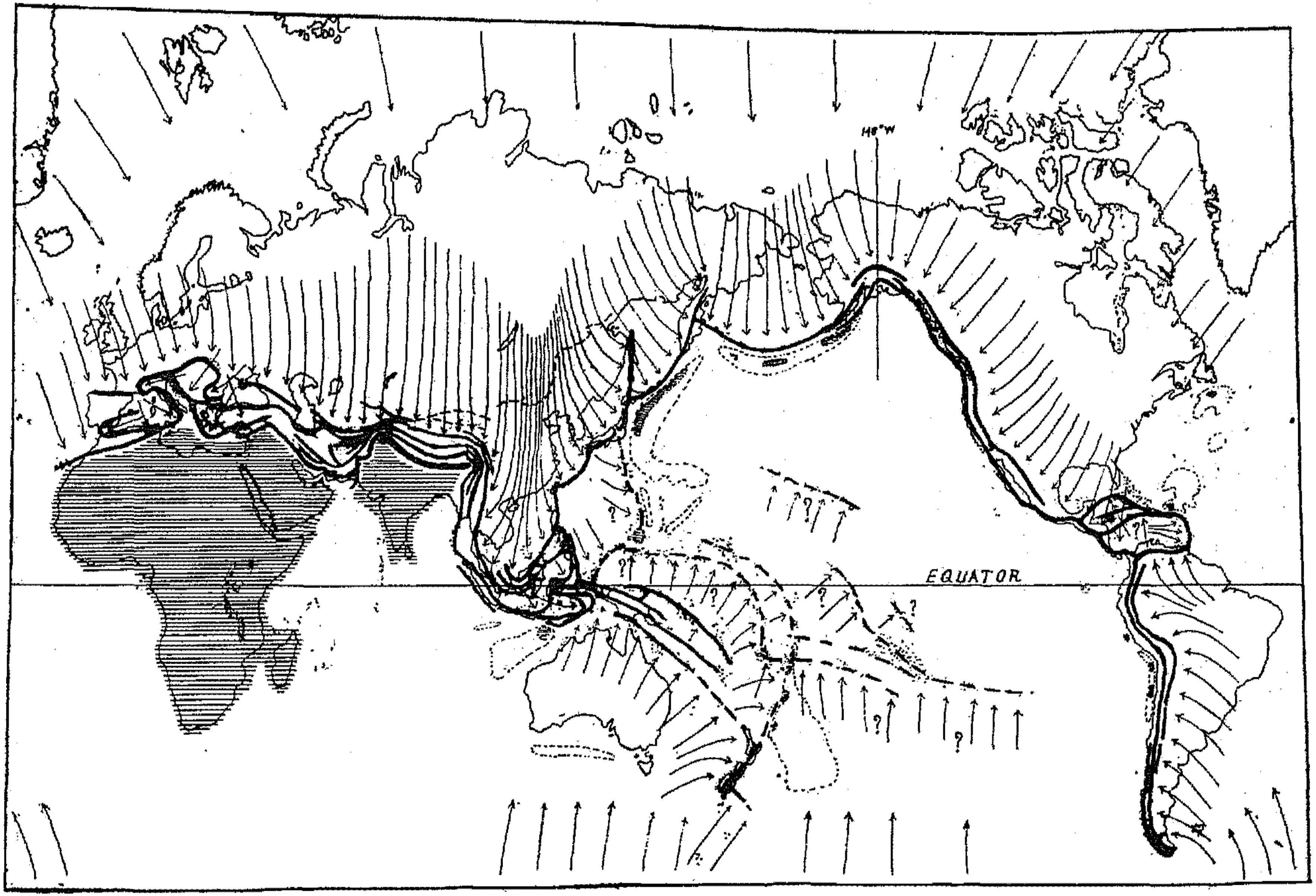


FIGURE 7.—*The World on Mercator's Projection*

Showing distribution of Tertiary mountain ranges in both hemispheres. The arrows indicate roughly the direction and relative amount of crustal movement. The map shows also the positions of the frontal oceanic deeps, the relations of the Tertiary ranges of Europe and western Asia to the Indo-African plateau, and the peculiar plan of the ranges between Asia and Australia and in the Caribbean region.

The recentness of the breaking up of Atlantis, as described by Suess, accords well with the conclusion that the rifts around Greenland are of recent date. The continent was pulled asunder apparently toward the southwest and southeast along a line passing southward from Cape Farewell and dividing around Greenland so as to leave it unmoved.

Penck, after enumerating many similarities between Europe and eastern North America, remarks that these similarities are not superficial.

"In a very remarkable way these two sides of the Atlantic repeat the same structural features; there is an astonishing symmetry, as Eduard Suess has shown so clearly." "It is very interesting to see how the Appalachian region ends at Newfoundland, forming the projecting eastern corner of North America, and just opposite in south Ireland, in south Wales, in Cornwall, and in Brittany the belt of the old Hercynian Mountains of Europe begins. One seems to be the continuation of the other, and such an excellent geologist as Marcel Bertrand maintained that we have here to deal with the two ends of one very extensive belt of mountains which extended through the North Atlantic Ocean. But we must not forget that the missing link between both ends of these supposed mountain chains is longer than their known extent."[7]

No doubt some portion of each of these mountain chains is now submerged beneath the Atlantic. But it seems probable that a considerable part of the present oceanic interval is due to Tertiary and perhaps to older crustal movements which divided the original chain near Greenland and carried the parts away on divergent lines—to the southeast and the southwest. In a later work, referred to below, Suess again dwells particularly upon the remarkable similarities on the two sides of the Atlantic.

In the southern hemisphere South America appears to have crept away to the northwest and Australia to the northeast, but these two continents are nearly 180 degrees apart. Africa holds a medial position remotely suggesting a relation similar to that of Greenland to North America and Europe, but in reality the similitude fails, because Africa is tropical.

Tertiary crustal Movements in the Southern Hemisphere

AUSTRALIA

Passing by Africa and the Antarctic land, there are only two continents in the southern hemisphere, and they are relatively small. Present knowledge of them is rather meager.

In its continental type Australia resembles Asia. Both are roughly symmetrical in form, so far as relates to Tertiary diastrophism, whereas South America resembles North America, being unilateral or asymmetri-

[7] Both passages from *Science*, February 26, 1909, pp. 322-323.

cal in form. The Tertiary fold lines of Australia and South America may be seen in figure 7. In these foldings the main body of Australia appears to have moved toward the northeast, but the movement was relatively feeble. All of its peripheral ranges are submerged in the ocean and are now represented only by chains of islands. New Guinea, New Zealand, and New Caledonia are islands of large size, but most of the islands are small. Between Australia and the equator there are three or four distinct lines trending mostly southeast to northwest. These lines are nearly straight, excepting that toward the northwest they turn to courses due west. Two or three of these lines run through New Guinea, one apparently extending southeast through New Caledonia. This line does not appear to connect with New Zealand. Another strong line runs through the Admiralty Islands, through New Mecklenburg, the Solomon Islands, New Hebrides, and eastern Loyalty Islands.

The alignment of the smaller islands is not clear in some parts, but one quite distinct line appears to begin north of the equator in the Egoi Islands of the western Caroline group, and, after running eastward 1,500 miles, sweeps in a great curve to the south through the Gilbert and Ellice Islands to the Fiji group, where it meets another line from the east. The greater size and height of the islands of the Fiji group as compared with those of the lines that enter it from the north and east reminds one of the island arcs of eastern Asia, where the points of intersection of the arcs are always higher than the arcs themselves, as in Kamchatka, Hokaido, and Formosa. Another line less clearly defined begins in the Marshall Islands, and appears to curve gradually around through New Zealand, the Phœnix, Tokelau, Samoan, Friendly, and Kermadec Islands. North of New Zealand there appears to be a line of narrow ocean deeps close along the east side of a submarine escarpment running from East Cape, New Zealand, to the Friendly Islands. This escarpment indicates folding from the west on the line of New Zealand produced, and it shows clearly that it is the Marshall-Samoa-Friendly line and not the Caroline-Gilbert-Fiji line which connects toward the south with New Zealand. New Zealand itself seems to owe its pronounced development to the junction of important lines, at least one to the northwest from the north island and one to the southeast from the south island.

The Hawaiian Islands, though so far away, appear to have a distinct affinity for the Australian lines southwest of them, and they appear to be just as distinctly independent of Asia and the Americas. The Washington-Christmas line lies farther south, with the same trend. The Samao-Society and Fiji-Cook-Austral lines run east-southeast, while the Taumotu and the Marquesas, on lines still farther east, trend to the southeast. They seem to show some affinity for Australia and at the same time are somewhat independent. Samao, like Fiji, seems to be a point of intersection for lines from the north and the east. These eastern lines seem to show no affinity for South America and very little for Australia, but are perhaps related more closely to a submerged crustal sheet lying to the south.

BORNEO, CELEBES, AND HALMAHERA

The peculiar mountain plans of these three islands have attracted the attention of geologists for more than a century, and the explanation of them has remained a puzzle. Their forms are shown in some detail in figure 8, but their relations to the trend-lines of the peripheral ranges are better shown in figure 2.

It will suffice for the present to point to the fact that they occur just where the advancing folds of Asia and Australia came into conflict (see figure 2). In each of these islands we seem to see a fold belonging to the southeast part of the Malay lobe advancing broadside against the end of one or more Australian folds, and both sets of folds are affected by the encounter. Celebes seems to show the simplest relations. The Malay fold appears to have been retarded and its trend-line indented by the Australian fold, while the Australian appears to be broken and reflected back. The mechanics of these forms, however, are not yet clearly understood.

The plan of Borneo strongly resembles that of Celebes, but it has been elevated so that its platform is above the sea. Halmahera is also a miniature of the same type.

Another point illustrated here is that where the Tertiary belt has several ranges, not only were the back ranges made first, but during the later folding of the front ranges the back ranges were subjected to a movement of elevation without further folding. Borneo is largest and highest, Celebes smaller and lower, and Halmahera still more reduced. We seem to see also a dying out of intensity from Borneo to Halmahera. Is it not significant that these strange forms occur just here at the point of conflict between the Tertiary mountain belts of Asia and Australia?

Suess calls these forms "chiragratic," and places Chalcidyce and Morea of the Dinaro-Tauric arc in the same class (I, 506). The latter are peculiar, but they are not the same as the Malay forms, and were not produced in the same way—that is, by a broadside-to-end conflict of folded ranges.

SOUTH AMERICA

In the present state of knowledge there is not much to say about this continent, for it is decidedly the most abnormal of any that were affected

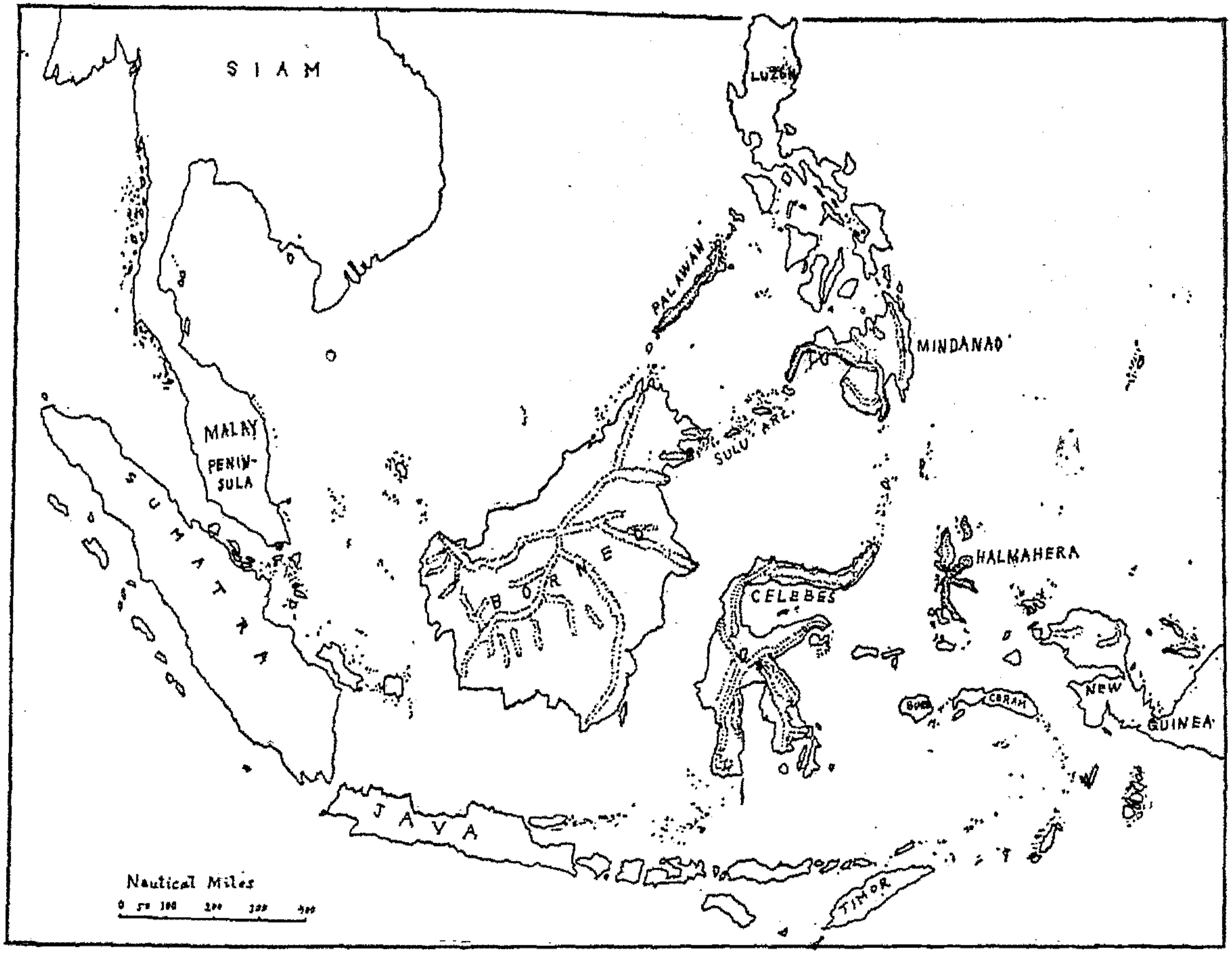


FIGURE 8.—*East Indian Archipelago*

Showing the peculiar mountain plans of Borneo, Celebes, and Halmahera, and their relations to the fold-lines of Asia and Australia.

by the Tertiary tangential movements. Its crustal movement was deflected to the west even more strongly than was that of North America—more strongly than any other continent, unless it be the New Zealand part of the Australian sheet (see figure 7). Only in the extreme northern part was the movement northward. A part of its Tertiary chains in Peru and Bolivia trending northwest and southeast were thrust from the northeast, and have therefore been deflected more than 90 degrees from the normal south-to-north direction, and the same is the case with New Zealand. The great arc of the northern Andes, extending from Venezuela to northern Chile, is convex toward the west—that is, toward the Pacific.

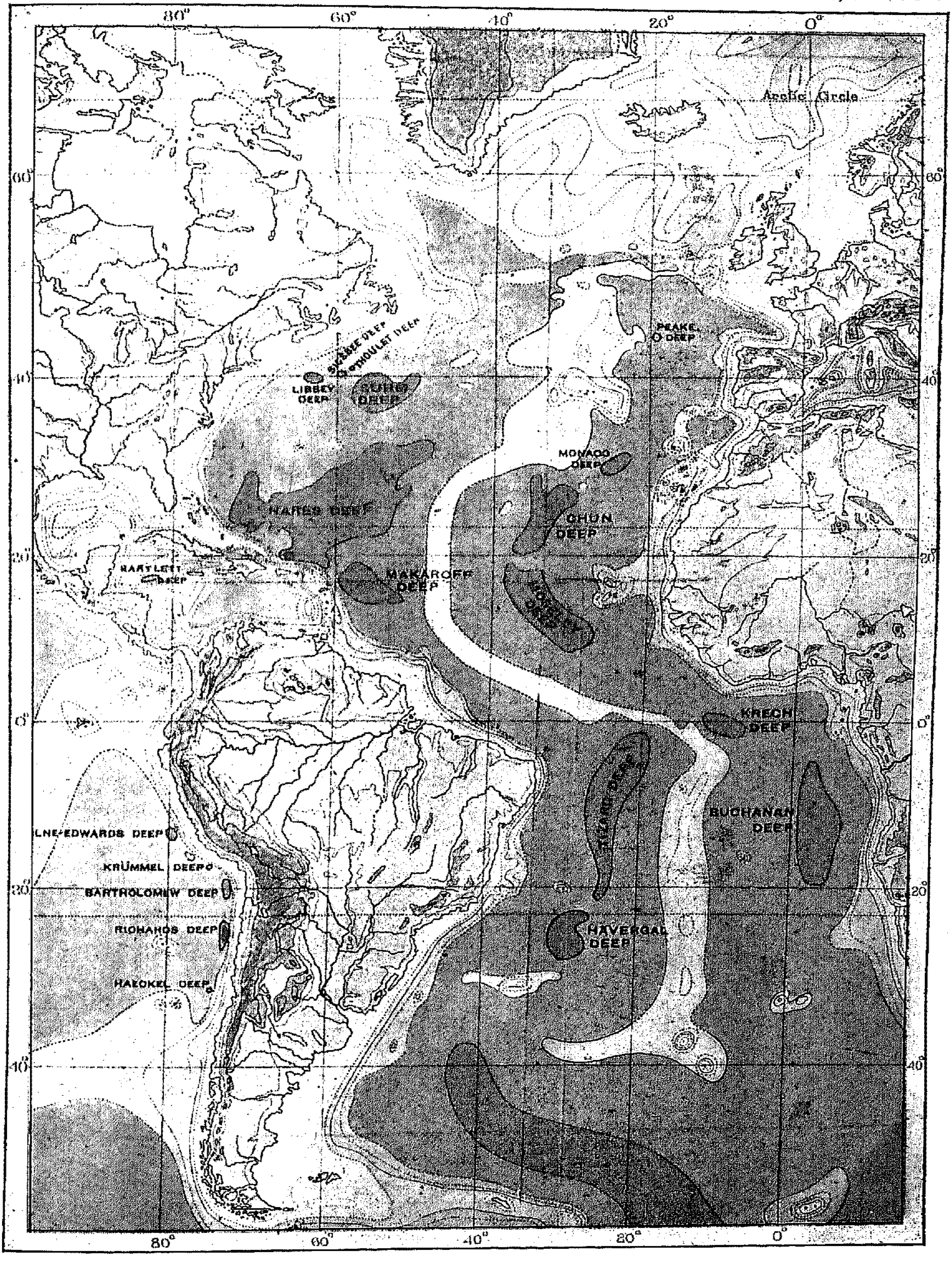
Here again the Cuzco knot of the Andes, one of the most remarkable mountain knots in the world, is somewhat interlobate in character—that is, it is in a re-entrant angle, where the crustal movements were slightly convergent, though less so than in Alaska. The Alps of New Zealand appear also to be at an angle of convergence or intersection.

The most peculiar character in South America, however, is the curvature of its Cordillera to the east at the southern extremity. It is as though the folds of the main Cordillera, being pushed toward the west, had lagged or dragged behind the rest at the extreme southern end. If this be true, it appears to indicate a minimum movement of 400 or 500 miles, which compares favorably with the movement of North America, as indicated by the rift of the Labrador Sea.

The curved ranges of the Antilles lie in the region of conflict between the two Americas, just as the irregular ranges of Europe lie between Europe and Africa and the peculiar mountain forms of Borneo, Celebes, and Halmahera lie between Asia and Australia. But the movements of the two Americas did not meet squarely, nor was one much more vigorous than the other. Both being relatively weak, there was an easier adjustment on curves of broader sweep. Nevertheless, the magnificent curve of the lesser Antilles reminds one of the sharper curves in Europe—the Roumanian, Alpine, and Betic arcs—and still more of the sharp curves of the Java and Timor lines, where they turn in such remarkable curves from east to north and back to the west to the island of Ceram (see figure 2). Even if the explanation of the plan of these ranges be regarded as still problematical, it is easy to see that they all occur in regions where there was a conflict of crustal movements and a tendency to a tangling and complication of folds.

THE MID-ATLANTIC RIDGE

One of the most remarkable and suggestive objects on the globe is the mid-Atlantic ridge. It is well shown on Sir John Murray's bathymetri-



BATHYMETRICAL CHART OF THE OCEANS

After Sir John Murray

cal chart of the oceans, referred to above, and that part of the chart showing the ridge is reproduced here in plate 4.

The persistence with which this feature maintains a medial position in the ocean bed for nearly 9,000 miles (following its great curves) is very striking, and the position which it takes in passing between South America and Africa is still more remarkable. The ridge is a submerged mountain range of a different type and origin from any other on the earth. It is apparently a sort of horst ridge—a residual ridge along a line of parting or rifting—the earth-crust having moved away from it on both sides. On the chart it is indicated to be mostly less than 2,000 fathoms (12,000 feet) beneath the sea, with some parts less than 9,000 feet and a few volcanic islands which rise 3,000 or 4,000 feet above the sea. Its general height above the surrounding ocean floor is between 3,000 and 6,000 feet, with a few island peaks rising 18,000 or 20,000 feet. Between South America and Africa the ridge runs east-southeast through 40 degrees of longitude (nearly 3,000 miles), and in this part is parallel with the adjacent continental border of South America.

The great westward bulge of Africa north of the equator appears to fit very closely into the westward bend of the mid-Atlantic ridge, suggesting that Africa has drifted eastward from that position. All authorities seem to agree, however, that Africa did not participate in the Tertiary folding, but remained stationary. Hence, if its western margin ever rested on the mid-Atlantic ridge it can hardly have been at a later time than the Carboniferous, for no important or extensive crustal movements appear to have affected Africa since that time. Too little is known of the geology of Africa, however, for settled conclusions now, but the narrow belt of peripheral folds on the southeastern border and also the high plateau of eastern Africa seem to be normal products of a crustal movement from the west-northwest.

At a first glance, the mid-Atlantic ridge appears to favor the torsion hypothesis of Prinz,[8] in which the southern hemisphere is supposed to have been rotated to the east relatively to the northern. The ridge certainly seems to suggest such a movement more definitely and precisely than any other feature yet described, but its form would seem to indicate that the yielding to the torsionary force was confined to a narrow zone near the equator, and that in that zone it had caused a displacement of nearly 3,000 miles. If the ridge ran originally straight north and south, and has been offset by torsion to give it its present form, then a section

[8] Dana's Manual of Geology, 4th ed., pp. 395-396. Also Bulletin of the Geological Society of America, vol. 11, 1899, pp. 93-94.

of it about 1,000 miles long has been stretched to a length of nearly 3,000 miles!

It is probably much nearer the truth to suppose that the mid-Atlantic ridge has remained unmoved, while the two continents on opposite sides of it have crept away in nearly parallel and opposite directions. The Cordillera of South America show that that continent moved a considerable distance toward the west and northwest in the Tertiary diastrophism; the movement of Africa appears to have occurred at a much earlier date, apparently before the Mesozoic era.

There are many bonds of union which show that Africa and South America were formerly united. Their present forms and relations suggest that the force which parted them was one that tended originally to crowd the two parts toward each other—that is, it tended to make Africa move south and South America north. But the release of strain was found by a great diagonal fracture along which the crust divided in two parts that crept away in opposite directions. The mid-Atlantic ridge remained unmoved and marks the original place of that great fracture.

THE ANTARCTIC LAND

This is the great southern horst, just as Greenland is the great northern, but its rôle in the Tertiary movements appears on present knowledge to have been less prominent. The pulling away from the Arctic regions was prodigious, especially toward Asia; only Greenland remained unmoved; whereas the whole of the Antarctic land appears to have held fast, while only Australia and South America pulled away. No doubt great rifts exist, corresponding to the pulling away of these two continents, but they appear to be submerged and obscured much more than those of the north. Perhaps the Jeffreys deep, south of Australia, stands in this relation to that continent, and possibly the Ross deep bears the same relation to South America.

THE SOUTHERN HEMISPHERE THE COMPLEMENT OF THE NORTHERN IN TERTIARY CRUSTAL MOVEMENTS

Although the facts are fewer and perhaps not so clear in their import, there seems still to be ample evidence that, excepting the southern part of the Malay arc, those parts of the Tertiary mountain belt which fall within the southern hemisphere were produced by crustal movements which were directed in general from south to north or in the opposite direction from those of the northern hemisphere.

The abstract statement made above may now be extended so as to include the whole earth, thus: In the Tertiary mountain making the crustal sheets moved in general from high toward low latitudes in both hemispheres—that is, both polar areas were regions of crustal dispersion or spreading, and the continental sheets, excepting Africa, all crept toward the equatorial zone. Hence the general order or plan of deformation was the same for both hemispheres, and the two complementary halves taken together make a symmetrical whole.

Distribution of the deforming Force

If the foregoing conception of the manner of production of the Tertiary mountain ranges be erroneous it is, of course, useless to seek an explanation of the earth's plan by this means. It may be said, however, for this conception that it is built upon a foundation consisting solely of observed facts, without any dependence upon a preconceived idea of the cause of the crustal movements, and yet it reveals, in the distribution of the Tertiary mountain belt and in characters which show the relations of the several parts of that belt to the continental crustal sheets, a degree of systematic order and unity not reached by other methods, and this alone seems to justify further consideration.

It is worthy of note that no other great crustal movements than those described above appear to have occurred in the Tertiary diastrophism. Indo-Africa was not affected by tangential movement. If it was affected at all it moved only radially—that is, either up or down. There appear to be conflicting evidences on this point, but the great rift valleys of the lake region in Africa suggest moderate uplift. These valleys are roughly meridional and suggest a slight girth-expansion of the earth. This effect, however, is relatively small, and for the present purpose is negligible. The tangential movements affecting the other continents may therefore be taken as a substantially complete inventory of Tertiary deformation.

The facts of distribution seem to show plainly that the deforming forces were in some way conditioned by latitude, for vast crustal sheets moved toward lower latitudes from both poles, and these movements appear to have satisfied largely the stresses caused by the deforming forces. The effect appears to be the same as if the deforming forces had operated to flatten the earth at the poles. If Africa were slightly uplifted without tangential movement, this uplift and the meridional rifting may be an effect of equatorial bulging or girth-expansion. But whether Africa shows equatorial expansion or not, the remainder of the continents surely show polar flattening and crustal dispersion. The deforming force appears to have acted with maximum power in high latitudes, for the mountain ranges produced by the Tertiary crustal movements are found mainly in middle and low latitudes—that is, along the lower margins of the crustal sheets.

Relation of the Tertiary crustal Movements to the Earth's Plan

Enough has been said in the preceding pages to show how the present plan of the earth has been affected by the Tertiary crustal movements. All the continents excepting Indo-Africa were affected and modified by them. As Suess observes, all the older parts of the continents were subjected to folding before the Tertiary, and yet it is certainly true that the Tertiary movements dominate largely in the earth's present plan and have given all the continents the larger part of their present outlines, excepting Indo-Africa.

One of the most remarkable things in the earth's plan is the fact that so much land appears to be clustered around the north pole and so little around the south pole. The northern hemisphere is largely continental, while the southern is mainly oceanic. In the northern hemisphere, however, Greenland is the only large remnant of the original north polar continent and most of the polar region is open sea, much of it deep, while in the southern the pole and the polar regions generally are occupied by the Antarctic continent, which is many times larger than Greenland. These peculiarities have not been explained, but if flattening of the poles with crustal dispersion characterized the Tertiary deformation as described above, then a simple explanation seems available.

Suppose the earth to have been originally a perfect sphere, and then to have been subjected to polar flattening, like that described above and suggested by Suess himself in one of his later works. This would change the earth to an oblate spheroid. The polar flattening, with a tendency to crustal dispersion, may be supposed to affect both poles at once and at first equally.

Now the first pole to undergo a crustal movement toward lower latitudes on a large scale would manifestly cause a slight shifting of the earth's center of gravity toward the other pole. Suppose the first large movement to have been from the north pole, then the earth's center of gravity would be shifted slightly toward the south pole. This would leave the remaining north polar lands under slightly greater strain than before, while the strain tending to dispersion of south polar lands would be proportionally diminished.

Such a change would, of course, increase the chances of further movements from the north pole and decrease those from the south pole. Thus the pole from which the first great movement occurred would take the lead in crustal movements, and would continue henceforth to be the one from which the greatest movements would take place. The ocean would follow the shifting center of gravity, and thus would tend to draw away slightly from the north polar regions and rise slightly upon the south polar regions. Both of these effects tend to a concentration of land around the north pole and of water around the south pole. The stronger crustal creep from the north pole appears to have carried the land away from the immediate vicinity of that pole, while the feebler dispersion from the south pole has left a high, extensive land-mass in that region.

The southward tapering of the continents may also be related in some way to the dominance of crustal movements from the north pole. The strong dispersion from this pole and the drawing away of the water has left a girdle of land near the Arctic circle which is continuous, except for the narrow Bering Strait and the wider rifts on the east and west sides of Greenland. Even if the entire surface of the globe north of the 45th parallel of north latitude had been land at the beginning of the Tertiary movements, and if all the crust of this area had crept away southward into latitudes lower than the 45th parallel, it could not have filled the space south of this parallel with land, because of the great increase of area. At the same time, the north polar flattening appears to have been confined almost wholly to the area north of the 45th parallel. Hence, in moving southward there was a diminishing power of the deforming force and at the same time a very large increase of surface area. In these two circumstances there are elements which necessarily imposed limitations upon the southward extension of the continents, but they seem to suggest broad lobate forms like Asia and Australia, rather than tapering, pointed forms like North and South America. But the American and African forms may have arisen from the influence of preexistent meridional faults or lines of weakness which drew the crustal movements to one side.

Suess on the Cause of Deformation of Strand-lines

It does not fall within the scope of this paper to attempt any discussion of the ultimate causes of the Tertiary mountain making, nor of the more recent displacement of the strand-lines, but any suggestion by Suess upon these points is worthy of the most careful consideration. Because he has reviewed the field more extensively and more thoroughly than any other living man, we are naturally inclined to look to him more than to any one else for an explanation of the causes of displacement of strand-lines and of mountain making. But Suess does not undertake to explain. He is content to make only very brief and apparently tentative suggestions concerning the nature of the causes.

It is interesting to observe that after relying upon eustatic negative movements through nearly all of part III of "The Face of the Earth" to account for displaced strand-lines, Suess turns in the closing pages of that part to a very different cause, where he says:

"Movements like these, which present themselves as oscillations, and extend around all coasts and under every latitude in complete independence of the structure of the continents, can not possibly be explained by elevation or subsidence of the land. Even as the transgressions of the ancient periods are much too extensive and uniform to have been produced by movements of the lithosphere, so, too, are the displacements of the strand-line in the immediate past" (II, 550).

After rejecting Adhémar's suggestion of an alternating accumulation of water at each of the poles, he observes:

"As far as we are in a position to judge, it appears much more as if that which characterized the more recent movement was an accumulation of water toward the equator, a diminution toward the poles, and as though this last movement were only one of the many oscillations which succeed each other with the same tendency—that is, with a positive excess at the equator, a negative excess at the poles.

"Negative traces are to be seen in all latitudes. We may attempt to explain them by means of eustatic negative processes—that is, by great subsidences; but this would presuppose a uniform sinking of the sealevel to the extent of more than 1,000 feet in quite recent times. It is much more probable that the negative traces at considerable altitudes in the tropics are not of the same age as those in high latitudes, and that an accumulation of water occurs alternately at the poles and the equator. Among these traces there may be one or more of a eustatic negative origin, but if so, we have not yet learned how to distinguish them" (II, 551).

Thus, although he had relied in earlier chapters almost exclusively upon subsidence as the one great agency of change in the earth's history, Suess seems constrained to admit in the last analysis that most of the displaced strand-lines appear to have been caused by an independent oscillatory movement of the ocean. Suess calls this movement an oscillation; but what kind of an oscillation is it? He answers this question clearly enough, where he says that "an accumulation of water occurs alternately at the poles and the equator."

The present figure of the ocean is that of an oblate spheroid—a spheroid having a certain degree of oblateness which is roughly expressed by the fact that the polar diameter of the globe is 26 miles shorter than the equatorial diameter. If the present phase of oscillation is one in which, as Suess says, there is an accumulation or positive excess of water at the equator and a negative excess at the poles, then the climax of the next preceding phase was one in which the positive excess was at the poles and the negative at the equator, and the degree of oblateness was less than it is now. Suess does not give a name to the oscillation which he describes, but he might as well have done so, for obviously it is merely an oscillation of the oblate figure—that is, a change from one degree of oblateness to another and back again, repeated time after time. The latest change, according to Suess, was an increase of oblateness.

The case could not be more clearly or forcefully stated than it is by Suess, so far as relates to the ocean. But he stops there. Yet, how is it possible to confine a force which changed the figure of the sea to the sea alone? The same force must have been exerted at the same time and with the same power upon the land—that is, on the lithosphere or solid globe. And if it were, what would be the nature of the stresses set up and what movements might be expected when those stresses were relieved?

Manifestly, on Suess' idea the present surface of the ocean is lower in the polar regions than it was some time in the relatively recent past and higher at the equator. The new figure intersects the old on a parallel a little below the 45th in both hemispheres. The lands in the far north therefore stand relatively higher above the sea, or rather above the ideal mean surface plane of the solid globe,[9] than before and at a slightly different angle to this plane at all points, excepting at the poles and the equator. In middle latitudes there is a slight change of angle, but no appreciable change of altitude.

Any imaginary plane or surface which before the change lay parallel with the surface of the sea in northern latitudes would now have the appearance of slanting slightly downward toward the south. It would seem certain that such a change as this would be fraught with tremendous consequences to the solid globe, for the relative increase in altitude of all lands in high latitudes would disturb the preexisting equilibrium and increase the stresses in those lands tending to subsidence. But the earth being solid from its surface to its center, and more rigid than the hardest steel, the tendency to sink directly toward the center could not be realized. The more rigid central body would resist effectively, and the forces would consequently be deflected from inward radial to tangential forces radiating from the pole and affecting only a relatively

[9] Estimated by Gilbert, on data collected by Sir John Murray, to be about 9,000 feet below sealevel. In his International Geography, H. R. Mill puts it at about 7,500 feet.

thin crust. These forces would tend to cause the crust to creep away on lines of dispersion from the pole.

An imaginary plane, like that mentioned above, gently sloping toward lower latitudes and situated beneath the earth's crust just within the zone of rock flowage, would seem to afford a basal slope down which the crustal sheets might move, and the tangential thrust forces exerted in the crust toward lower latitudes would tend to give the crust the requisite impulse to move.

We may thus enumerate, in part, the conditions and the tendencies to earth-movements which might be expected to affect the lithosphere on the supposition of a flattening of the poles, like that postulated by Suess in explanation of displaced strand-lines.

Conclusion

The displacement of strand-lines by eustatic negative movements is a very different thing from displacement by oceanic oscillations. As was pointed out above, it is only at the end of his exhaustive review of the whole subject that Suess recognizes and accepts the principle of oceanic oscillation. After accepting this principle in explanation of the strand-lines, it seems a little strange that Suess should have made no mention in "The Face of the Earth" of the possibility that the same force which caused oscillation of the ocean might be a cause of crustal movements also; but there appears to be no suggestion of this idea, at least not in the first four parts.[10]

In a later work, however, Suess seems to see the possibility of deformation of the lithosphere by a force that flattens the poles in the same manner as he supposes oscillations of the ocean to do for the strand-lines. He says: "One is inclined to suspect that the formation of the curved chains in Asia, open to the north, stands in some connection or other with the outflow of superfluous earth-mass from the pole—that is, with a flattening of the same."[11]

Perhaps these words are not sufficiently explicit to enable one to say that Suess accepts the idea that the forces associated with an increased oblateness of the earth's figure are the cause of polar flattening of the lithosphere, but it is hard to see how he could have had any other cause

[10] Volume IV, containing Part V of Suess' "Face of the Earth," reached the writer a few days before the proof of this paper. A hasty examination disclosed nothing that suggests any important change in the conclusions reached. Chapters VII, IX, X, XI, XIV, XVI, and XVII are of particular interest in connection with this paper.

[11] E. Suess: Asymmetry of the Northern Hemisphere. Appendix to the presidential address of B. K. Emerson. Bulletin of the Geological Society of America, vol. 11, 1899, p. 105. Published in German in 1898.

in mind. Whatever the cause may have been, its distributive characters appear to be precisely the same as those which belong to an increase of oblateness of the oceanic figure. Why should we look for two separate causes for two sets of phenomena which appear to require precisely the same kind and distribution of force to produce them?

The first author to suggest oscillations of the figure of the ocean as the cause of displaced strand-lines appears to have been Emmanuel Swedenborg. Suess traces this idea back to him through Robert Chambers and P. Frisi (II, 7, 11, 16, and 21). But whether Suess regards increased oblateness as the cause of crustal movements or not, it seems certain that he would have reached this conclusion long ago if he had held steadfastly to his first conception that the mountain ranges of western North America were folded toward the Pacific, instead of receding from that position in deference to the contrary opinions of certain American and Canadian geologists; for if he had found North America folded toward the Pacific Ocean, he would also have found that the evidence of general crustal creep and dispersion from high toward low latitudes is complete for the northern hemisphere.

All forms of the contraction hypothesis meet with two insurmountable difficulties with reference to the Tertiary period of mountain making. They fail to explain in a satisfactory way the distribution of Tertiary mountain ranges upon the earth's surface, and they do not explain how so great a period of mountain making could have occurred in so recent time. If due to contraction arising from cooling, it is necessary to suppose a very long period of accumulation and storage of mountain-making force before the beginning of the folding movement. The amount of crustal movement which occurred during the Tertiary period seems to be far in excess of the most that can be attributed to cooling and shrinking since the time of the Permo-Mesozoic (Appalachian) folding, even on the most liberal estimate. It is scarcely credible that any considerable mountain-making force derived from cooling before the time of the Permo-Mesozoic folding could have survived that event so as to be an important element in the Tertiary folding.

Referring to the tangential crustal movements in Asia, Willis, in a recent development of the contraction hypothesis based on isostacy, says: "What Suess considers an outward advance, I regard as a retarded superficial layer, beneath which the deeper mass has been squeezed northward into narrower space."[12] Willis supposes subsidence of the earth-segment under the Pacific and Indian Oceans, with northward spreading or un-

[12] Bailey Willis: Research in China, vol. 2, Systematic geology. Carnegie Institution of Washington, 1907, p. 126.

derthrusting of the deep-seated mass beneath Asia. By this hypothesis the crustal sheet in which the folding, overthrusting, etcetera, are produced is not the part in which the principal movement occurs. The crustal sheet is regarded as a passive element, and the mountains of Asia exist only because some other part of the earth than the crust moved horizontally and the crust became involved in that movement. But if the same results in mountain making can be derived from horizontal movements of the crust alone, why postulate a more complicated indirect process?

Even Chamberlin's Planetesimal hypothesis, which has brought so great an advance over the Nebular hypothesis of Laplace with reference to the origin and growth of the earth, meets these same two difficulties, and with no better success.[13]

It seems certain that no man living has ranged so widely over the fields of geology for the entire earth as Eduard Suess. He appears to have made himself familiar with every official report and every important memoir or scientific contribution that has ever been written on the subject. His earlier studies turned his mind along certain lines of interpretation, chiefly depression of oceanic basins and tangential crustal movements overthrusting those basins. This was natural, for every one must arrange his thoughts around some central idea as he goes on working year after year, decade after decade. Indeed, one's thoughts will inevitably crystallize themselves around some uniting principle, whether he will or no. These early principles of interpretation served Suess well throughout the greater part of his life. But is it not deeply significant that after a lifetime of study along the lines of those early principles, Suess at last leans toward a different interpretation, both as to the cause of displaced strand-lines and of deformations of the lithosphere? And is it not still more significant that in both instances his leaning is toward a cause which conforms precisely with increased oblateness of the earth's figure, or with oscillations of the same?

The argument presented in this paper rests at last on the truth of Suess' interpretation of the mountain plan of Asia. The principles which he worked out there have been applied without important modification to the other continents, and the conclusions reached in this way appear to accord very closely with suggestions made by Suess himself in his later writings. For a change in the degree of oblateness, either in oceanic oscillations or in deformations of the lithosphere, one is inclined to reject all internal causes and to look to some form of tidal force as the only possible agency.

[13] Chamberlin and Salisbury: Geology, vol. ii, pp. 82-132.