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PAPERS OF THE MICHIGAN ACADEMY OF SCIENCE ARTS AND LETTERS

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ERRATUM IN VOLUME IV, PART I

Professor Frank C. Gates requests that the following corrections be made in his paper on *Meteorological Data, Douglas Lake Region*, Michigan, in Volume IV, Part I: In Table VI on page 488 the 1 Season total' under 'White' for the year 1921 should read 1632.7, instead of 1793.6; the 'Rate per day' should be 29.2, instead of 32.0.

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THE INFLUENCE OF JOINTS IN THE FORMATION OF THE ISLANDS AT THE WESTERN END OF LAKE ERIE

CHARLES W. COOK

WHILE carrying on some geological investigations on Pelee Island in Lake Erie, the writer was impressed by the frequency with which lineaments were observed. A straight cliff would appear in one direction, along the extension of a joint plane, and in the opposite direction, along the same line, would appear an island, not infrequently seeming to have a correspondingly straight side. A further investigation of the problem has resulted in an accumulation of data which seem to leave but small doubt that the formation of the islands at the western end of Lake Erie has been very strongly influenced, if not controlled, by joint planes.

The principal joint directions as determined on Pelee Island fall into three sets, approximately, N. 45° E. and N. 45° W., N. 15° E. and N. 75° W., and N. 75° E. and N. 15° W. An examination of Figure 13, which is based upon data taken from the Coast and Geodetic Survey chart, shows that many of the larger features of the islands and the basin of Lake Erie surrounding them present a striking parallelism with these joint directions. This is especially true if the nature of Pelee Island itself is considered. Pelee Island is made up of a number of 'rock islands' joined together by unconsolidated materials. The location of these 'rock islands' is shown on Figure 13 by the dotted lines. Attention is called to the way in which they line up with one another and with the other islands in the principal joint directions. Also the general trend of many of the contour lines and depressions in the basin floor in relation to the joint directions is to be noted. Unfortunately the data from the Lake Survey chart are not sufficiently complete to enable us to distinguish in most instances whether hard rock or loose material is found on the bottom of the lake at various points. However, it seems to the writer, that the parallelism of these features with certain definite directions is too striking to be due merely to coincidence and it is his belief that any unconsolidated material on the lake bottom would tend to obscure rather than to emphasize these features.

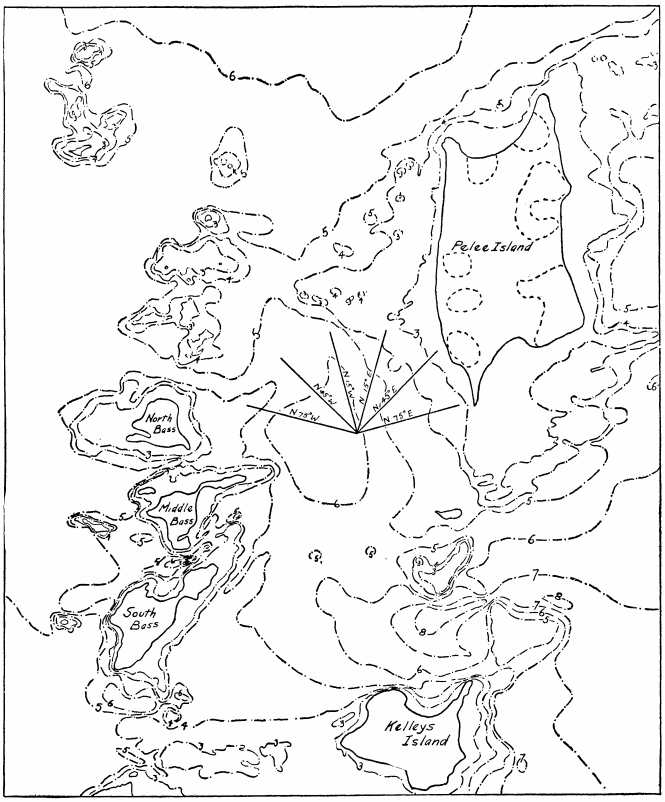

FIG. 13, showing the Parallelism between Topographic Features and Principal Joint Directions

If detailed instead of general relationships are studied, the parallelism is even more striking as may be seen by an examination of Figures 14 and 15. In Figure 14 the twenty-one foot depth-line of Pelee Island has been traced and around it have been drawn straight lines parallel to the principal joint directions. The parallelism seems altogether too pronounced not to be due to some definite cause. Further attention is called to the very striking parallelism of the indentations at the southern and southeastern parts of the island. It should perhaps be stated that the twenty-one foot depth-line was chosen rather than the shore-line in order to avoid, so far as possible, modifications of the shore-line due to wave action.

Figure 15 is a representation of North Bass, Middle Bass and South Bass islands treated in the same way. The parallelism of the twenty-one foot depth-line and the principal joint directions is perhaps even more strikingly shown here than in the case of Pelee Island. It should be recalled that the joint directions employed are the ones found on Pelee Island. Whether or not they are the same as those which would be found on the Bass islands is unknown to the writer. However, the apparent relationships shown in Figure 15 suggest not only that these would be found to be the principal joint directions there, but also that they are the controlling joint directions for the area, irrespective of what joint directions might be determined locally.

If the foregoing data are sufficient, as the writer believes they are, to establish the control by joints, the question then becomes: What is the agent (or agents) involved in the formation of the islands? Although the literature contains many papers upon the Erie basin, only one direct reference to the formation of the islands has been found. Newberry[1] in 1874, after stating that the Laurentian Lakes occupy basins excavated in the plateau skirting the edge of the Canadian Highlands, the outlines of which have been “partially determined by upheaveal" and "at least partly excavated by a mass of moving ice,' says: "The islands at the western end of the lake (Erie) are remnants of hard Corniferous limestone beds raised in the lime of the great Cincinnati anticlinal. These interposed considerable resistance to the action of the glacier and portions of them were left forming islands."

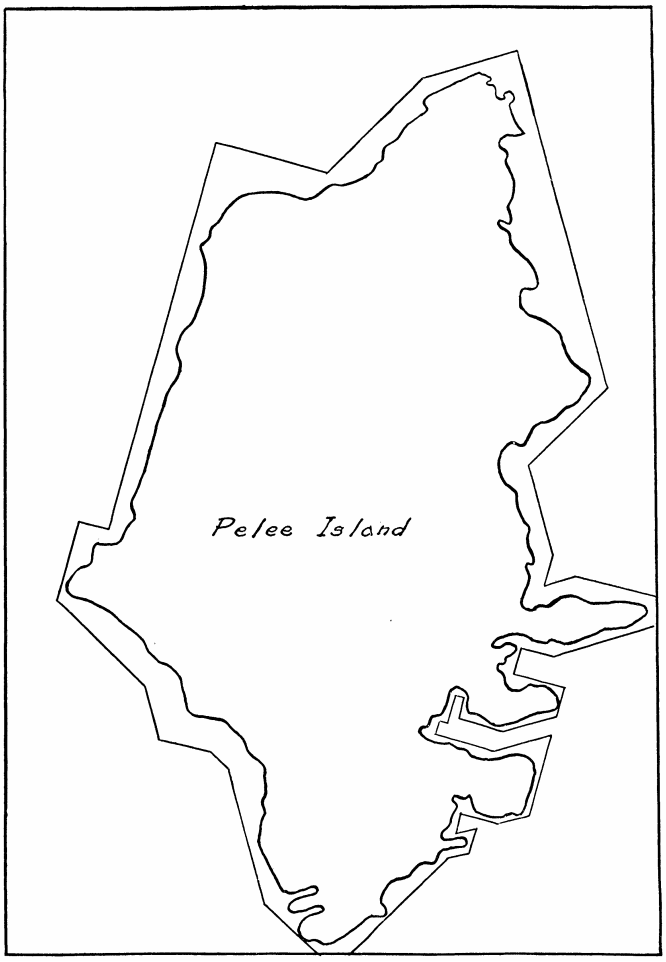

FIG. 14, showing the 21-foot Depth-Line around Pelee Island

Any other ideas as to the origin of these islands must be inferred from statements regarding the origin of the Lake Erie basin. Thus, Lesley[2] in 1881, in discussing a paper presented by Newberry, stated that the glacier protected the Erie basin from erosion while it scratched the islands at the western end of the lake, thereby implying that the islands antedated the glacial period. In the same year, Claypole,[3] after attacking the glacial erosion theory, presented the river-erosion theory.

Also in the same year, Spencer[4] stated that three theories of the origin of the Laurentian Lake Basins had been advanced: "(1) the basins of the lakes are geological valleys; (2) the basins were excavated wholly or partly by glacier-action; (3) the basins were excavated by atmospheric and fluviatile erosion." He concludes with the statement: "The lake basins are valleys of subaerial and fluviatile erosion."

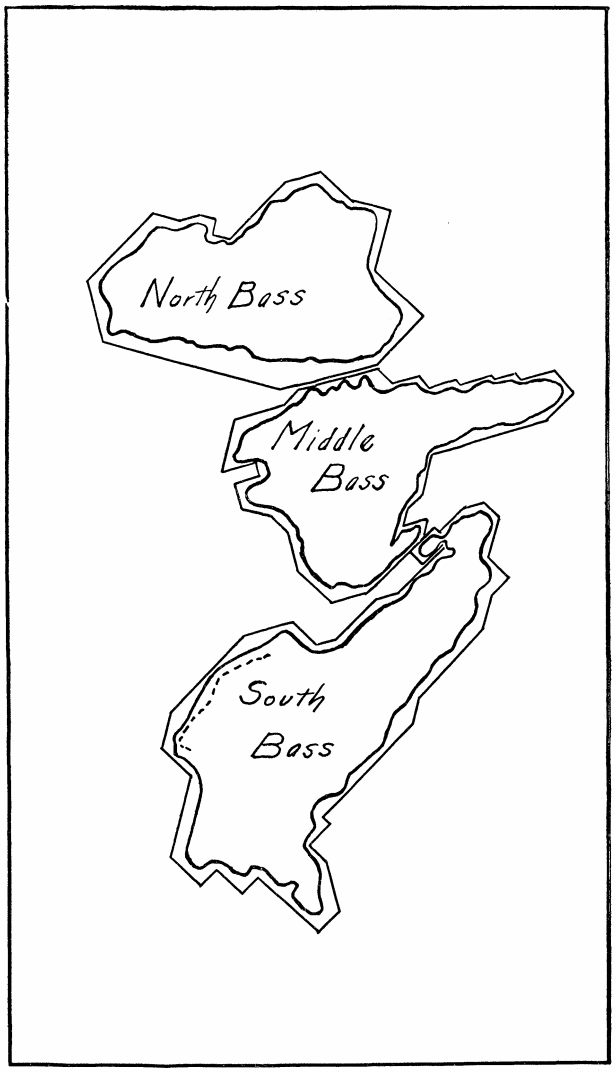

FIG. 15, showing the 21-foot Depth-Line around North Bass, Middle Bass and South Bass Islands

Later, Spencer[5] presented an elaboration of these views before the Geological Society of London. In commenting upon the paper Professor Seeley[6] said that he did not think that the ancient valleys had been excavated any more by rivers than by ice, but that the Laurentian Lakes followed the outcrops of the strata sufficiently to suggest that the lakes were originated by earth movements and that he believed that the main work of excavation was attributable to marine denudation.

Of the four theories of the origin of the lake basins suggested, one, namely, that they are geological valleys, can scarcely be thought to apply to the origin of the Erie Basin. The other three involve erosion, either by ice, running water or waves, and, although definitely stated

only by Newberry, would imply that the islands at the western end of Lake Erie had been formed by some one of the agents. The consensus of opinion seems to be that stream erosion has played the most important part in the formation of the Erie Basin and therefore of the islands. The writer would like to suggest another possible origin for the islands, namely, faulting.

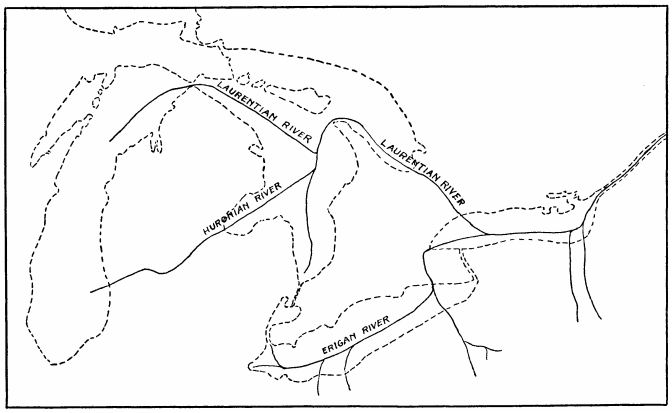

FIG. 16, showing Preglacial Drainage Lines (after Spencer)

Let us then consider the evidence in favor of each of these two theories.

Spencer[7] worked out a system of preglacial drainage lines (Fig. 16) for the area of the Great Lakes and subsequently a somewhat different system was worked out by Grabau[8] (Fig. 17). A comparison of these drainage plans with the joint directions observed on Pelee Island is interesting. It is to be noted that in both instances there is a decided parallelism with some of these joint directions, although the drainage is quite different in the two plans.

Spencer does not give any reason for the drainage plan which he presents. Grabau, however, believes that the main streams, which trend approximately N. 45° E., are consequent streams formed on a southwesterly sloping, Tertiary peneplain and that the subsequent branch streams which developed at right angles had their position fixed by the strike of the southwestward dipping strata. These Streams, therefore, had a general N. 45° W. trend.

It seems to the writer that these directions of the streams may have been determined, at least in part, by the principal joint directions or even by faults. The drainage plan of Spencer, particularly at the eastern end of Lake Erie, is especially suggestive of this. Even stronger evidence of joint or fault control of these preglacial streams is suggested by papers by Hobbs[9] and Pirsson,[10] both of which show that the present drainage lines in Ontario exhibit predominantly the N. 45° E. and N. 45° W. trend, which they assign to joint or fault control. This parallelism of the present and preglacial drainage is suggestive of the same control in both instances.

In support of the idea that faulting may have played a part in the formation of the islands at the western end of Lake Erie, the evidence must be largely circumstantial as no actual displacement of the beds has been observed. There are, however, several lines of evidence strongly suggestive of faulting. Coste[11] has stated that in the Gosfield gas field on the main land northwest of Pelee Island there is a fault trending west-northwest and another at right angles to it. These directions would correspond to the N. 70° W. and N. 15° E. set of joints.

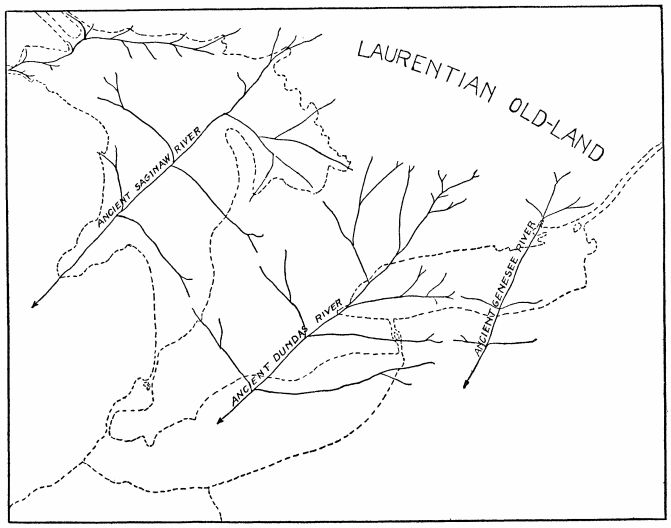

FIG. 17, showing Preglacial Drainage Lines (after Grabau)

Additional evidence of faulting is possibly afforded by the correlation of the unsatisfactory well logs available. Thus it is found that in one of the wells drilled on one of the 'rock islands' to the south, gypsum appears at 660 feet and is absent below 740 feet; whereas in a well recently drilled between the 'rock islands' and where solid rock was not encountered until a depth of 125 feet had been reached, gypsum makes its first appearance at 890 feet.

In conclusion it must be stated that at present the evidence is insufficient to determine the agent of formation with reasonable certainty. The writer believes, however, that the evidence is amply sufficient to indicate the strong influence of joints, irrespective of the agent.

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[1] J. S. Newberry, *Proc. Lyc. Nat. His. Soc., N. Y., Second Ser*., 1874, pp. 136-138.

[2] J. P. Lesley, *Proc. Am. Phil. Soc*., XX (1881): 100.

[3] E. W. Claypole, *Proc. Am. Assoc. Adv. Sci*., XXV (1881): 157.

[4] J. W. Spencer, *ibid*., p. 131.

[5] *Quart. Journ. Geol. Soc. Low*., 46 (1890): 525.

[6] *Ibid*., p. 533.

[7] J. W. Spencer, *Am. Geologist*, VII (1891): 78.

[8] A. W. Grabau, *Bull. N. Y. State Mus*., 45: (1901): 44.

[9] Wm. H. Hobbs, *Wis. Acad, Sci., Arts and Letters*, Vol. 15 (1905), Plate III. Also, Bull. Geol Soc. Am., Vol. 22 (1910), Figs. 25 and 26.

[10] L. V. Pirsson, *Am. Journ. Sci.*, Vol. XXX (1910), Fig. 1, p. 26.

[11] Eugene Coste, *Journ. Can. Min. Inst*., 3: 74.

A "LACCOLITE IN THE AIR"

LAURENCE M. GOULD

AFTER pointing out in his memorable monograph on the Henry Mountains that there are two zones of laccolites in these mountains, Gilbert[1] speculates upon the possibility of the southern mountains, which represent the lower zone, having formerly possessed laccolites of the upper zone. He shows that if superior laccolites had existed, their removal by erosion would have been sure to leave behind them a record of the conduits through which their lava was injected. Naturally the discovery of such conduits, as for instance dikes, cannot be regarded as absolute proof of the former existence of a superior laccolite, but it demonstrates the possibility of such structures. The summits and flanks of Mounts Holmes and Ellsworth have many dikes which have been regarded as subsidiary features of the laccolites beneath them, but Gilbert points out that it is quite possible that any one of them may formerly have led to another laccolite above. But Gilbert finally concludes: "Upon such uncertain evidence no positive conclusion can be based, and it is vain to build laccolites in the air."

In his studies in the La Sal Mountains of southeastern Utah, which lie about 85 miles north of east from the Henry Mountains, the writer has found what seems to be the exact structure which Gilbert had in mind by his "laccolite in the air."

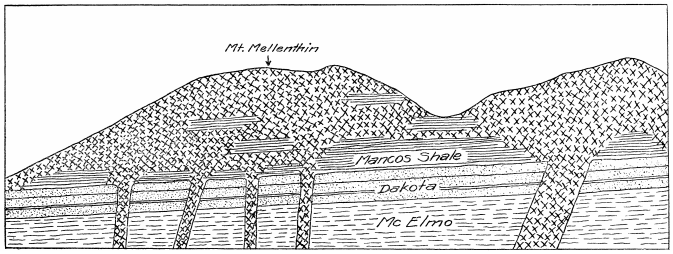

FIG. 18. Diagrammatic Sketch to show the Structural Relationships at the head of Horse Canyon

The La Sal Mountains are divided into three groups separated by sedimentary saddles. The structure of the end-groups is fairly simple. The magma was intruded into the Cutler or perhaps between the Cutler and the Rico, and the overlying beds were upturned. A great force and perhaps the major one in the doming of the strata over these end-groups was orogenic stresses in the nature of folding, for both these groups are intimately associated with anticlinal structures of the plateau country. In the central group there is no evidence that the intrusion was influenced by orogenic stresses and the structural features are more complex than in the end-groups. Here there seem to have been two horizons of intrusion, one above the other. The sediments are found to dip away from the center of this group at an angle of about 5 degrees. When these dipping beds are followed to the igneous cores it is found that the main part of the igneous masses are above these strata. Wherefore it appears that the doming of these strata has been induced by an intrusion not exposed. In case of Mt. Mellenthin of this group this suggestive relationship is clearly displayed. One can stand on the west side of Horse Canyon which heads against the west side of this mountain, and look across the canyon to the east to a surprisingly perfect section of a "laccolite in the air." The dike feeders through which the magma rose are clearly exposed and can plainly be seen cutting upward through the McElmo and Dakota formations into the Mancos shales where the magma spread laterally and also domed up the superior beds. The presence of masses of shale in the porphyry and the nature of the injection of the porphyry into the shales, together with a consideration of the attitude of some outcrops of this shale north of the mountains, indicate that the Mancos formerly constituted the cover of the mountain and may also have possessed small interbedded sheets of porphyry, which have since been eroded away. Figure 18 is traced from a series of photographs taken from the side of Horse Canyon opposite Mt. Mellenthin. It not only shows the genetic relationships between the dikes and the main mountain mass, but it also shows how the floor of the mountain is dipping up toward the south. A careful study of the structure of this entire group indicates the probable existence of a buried laccolitic body below those now exposed. The thickest portion of this buried mass lies near the center of the group or to the south of Mt. Mellenthin; hence the attitude of the beds exposed below the base of this mountain. A general survey of the structure of this group suggests that there are two horizons of intrusions — two zones of laccolites, one above the other after the fashion which Gilbert suggested may have formerly obtained in the southern laccolites of the Henry Mountains.

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[1]Gilbert, G. K., "Report on the Geology of the Henry Mountains," *U. S. Geog. and Geol Survey of the Rocky Mt. Region* (1887), pp. 58-59.

THE CAUSE OF EARTHQUAKES ESPECIALLY THOSE OF THE EASTERN UNITED STATES

WILLIAM HERBERT HOBBS

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PART I. GENERAL

EARLY EARTHQUAKE THEORY

Scriptural doctrine. — The Bible lands were among those racked by earthquake, and the explanation offered in the Bible was one common at the time, namely; that God was displeased with his creatures and was visiting punishment upon them. The imagery of the Old Testament reflects this feeling. "Thou hast made the earth to tremble; Thou hast broken it; heal the breaches thereof for it shaketh," is the description in the sixtieth Psalm. In the one hundred and fourteenth Psalm we read, "Tremble, thou earth, at the presence of the Lord, at the presence of the God of Jacob; which turneth the rock into a standing water, the flint into a fountain of waters;" the fountains of water being a characteristic phenomenon of all earthquakes: and there follows the inevitable, "O God, . . . Thou hast been displeased: O turn Thyself to us again."

Aristotelian view. — The Greek philosophers were familiar with the earthquakes of the Mediterranean region and the view of Aristotle, endorsed as it was by the geographer Strabo, has come down to us, and with some slight modification it has survived in a quite modern theory which until within a score of years was regarded as standard doctrine. Aristotle conceived earthquakes to be brought about by air imprisoned within subterranean cavities, and by its struggles to escape this air caused a shaking of the ground. Regions where there were many caves, such as Achaea, Euboea and Sicily, were, as Aristotle well knew, especially subject to earthquakes.

The Aristotolian idea was well expressed by Shakespeare, who makes Hotspur say to the boastful Glendower:

> O then the earth shook to see the heavens on fire,
> And not in fear of your nativity.
> Diseased nature oftentimes breaks forth
> In strange eruptions; oft the teeming earth
> Is with a kind of colic pinched and vexed
> By the imprisoning of unruly wind
> Within her womb; which, for enlargement striving,
> Shakes the old beldam earth, and topples down
> Steeples and moss-grown towers,

The suggested connection of earthquakes with volcanoes in this passage from *Henry IV* has been common, as is clear from the almost hopeless confusion in most of the early writings which deal with earthquakes and volcanoes.

Von Humboldt's idea of safety-valves. — Alexander von Hum-bolt made the correct observation that although there were earthquakes usually connected with the eruptions of volcanoes, such earthquakes were by comparison with the devastating earthquakes of history relatively weak and insignificant. He conceived the volcanoes to be, therefore, a sort of safety-valve for pent-up gas imprisoned within the earth, which following the Aristotelian view he believed to be the cause of earthquakes.

Modern dress of Aristotle's doctrine, Mallet, 1862. — The ancient view that earthquakes originate within a cavity or focus wherein gases are confined, was given a modern dress as a scientific theory by an Irishman, Robert Mallet, who had invented a new type of mortar and had also made investigations upon the life of guns. These studies had brought him much renown and had been of the greatest service to the Allies during the Crimean War of 1854-1855. When, therefore, in 1857 an earthquake devastated the kingdom of Naples, Mallet applied to the Royal Society for a grant of money for the purpose of making a study of this earthquake. Apparently under the impression that an expert upon explosives was by his training best qualified to study an

earthquake, the Society readily granted his request, and the results of his study were later published in two massive volumes bearing the title *The Neapolitan Earthquake of 1857*. When Mallet undertook this study the science of physics had recently been much advanced by the Dutch physicist Huygens, who had introduced a new method for following the progress of harmonic disturbances travelling through media such as light through glass or sound through air. Mallet adapted this scientific method to a study of the progress of earthquakes through the outer layers of the earth, and he further supplied technical names which have been widely employed even since his theory has been discredited. The supposed cavity or focus within which the shocks were supposed to originate, Mallet called the centrum, and the point upon the earth's surface directly above it he named the epicentrum, at which point the shocks were believed to arrive first and to be of the greatest intensity. This scientific dress applied to Aristotle's theory accounted for its retention by scientists as orthodox doctrine for another fifty years, or until early in the twentieth century.

THE UNIQUE FAULT THEORY

Japanese earthquake of 1891, Kotô, 1893. — Scientists are now well agreed that gases imprisoned within the earth are not the cause of the devastating earthquakes, though they may perhaps in part explain the relatively insignificant shocks which occur in connection with eruptions of certain volcanoes. Students of earthquakes are also in accord in believing that earthquake shocks are in some way connected with the formation of breaks and resulting displacements of the rocks at and near the surface of the earth. This change of viewpoint has come about from studies of earthquakes which have occurred within the last third of a century.

The great earthquake of 1891 in the Neo Valley of Japan was the first to supply striking photographs of changes produced at such times in the surface of the earth, and these photographs came quite generally into the hands of scientists.[1] Though they produced a profound impression they did not immediately discredit the centrum theory. The pictures showed that for many miles across the country a fracture of the ground appeared at the time of the earthquake, and that along this fracture the land upon one side had been raised relatively to that upon the other by as much as eighteen feet at one place; while at other places though neither side had been raised or lowered in reference to the other, the two sides of the displacement had slipped past each other in opposite directions along the surface of the ground a distance of the same order of magnitude as that shown by the vertical displacement. It did not admit of doubt that these scissor-like movements of the ground, whether up or down or along the surface, had been sudden and violent and had, moreover, been connected with the jolting movements to which the term earthquake had been applied.[2]

Hindustan earthquake of 1897, Oldham, 1899. — Six years later occurred the great Assam (Hindustan) earthquake which was also carefully studied.[3] In this case though a small part only of the affected area was examined, there were found no less than three fracture displacements (faults), and the maximum vertical displacement measured was about thirty-five feet. The likelihood is that a number of other faults were produced at the surface, though the localities were riot visited by any representatives of the scientific personnel of the Indian Survey. Stress was, however, laid upon one plane only of fracture and displacement, and this was believed by Oldham to be a thrust on a plane of low angle to the horizon.

THE THEORY OF MOUNTAIN GROWTH, DE MONTESSUS, 1906

Two earthquake girdles. — The late Count de Montessus de Ballore published in 1906 the results of an exhaustive study of the distribution of earthquakes, as a result of which he reached this conclusion:

> The earth's crust quakes almost in equal amounts and almost entirely along two straight zones which lie along two great circles (in the geometric sense) which make an angle with each other of about 67° — the Mediterranean or Alps-Caucasus-Himalaya circle (53.54 per cent of the earthquakes), and the circum-Pacific or Andes-Japan-Malay circle (41.08 per cent of the quakes). These two zones correspond with the two most important lines of relief of the terrestial surface (Fig. 19).

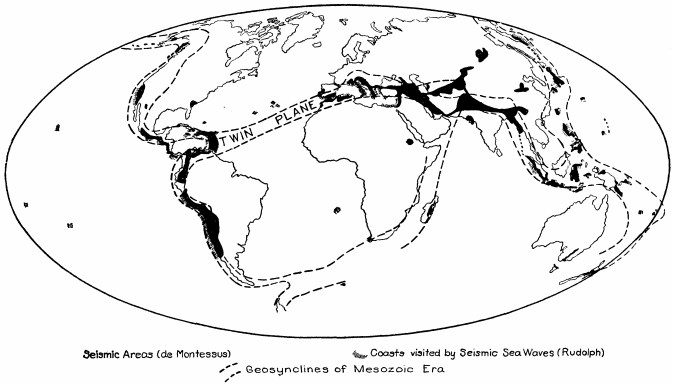

FIG. 19. Map by De Montessus to show the earthquake girdles, but reduced to the Mollweide projection

Mesozoic geosynclines. — Dr. de Montessus furthur concluded:

> The zones, the seismic regions, coincide exactly with the geosynclines of the Secondary epoch.
>
> The geosynclines — the most mobile bands of the earth's surface — where the sediments have been deposited in the greatest thickness, have been energetically folded, dislocated and elevated in the Tertiary epoch, at the time of the formation of the principal existing mountain chains, including within themselves, with two or three doubtful exceptions, nearly all the seismic regions, which in consequence characterize them.
>
> The folded architecture of the geosynclines is unstable, in contrast to the tabular architecture of the continental areas, and this has with much probability been true of all the geological epochs.[4]

We have here, then, a very clear statement that the earth's two zones of earthquake of the present time, including together as they do 94.62 per cent of all recorded earthquakes upon the land areas, are the zones within which the thickest lenses of sediments were deposited during the Mesozoic era, and where also, beginning in late Cretaceous or Tertiary time, ranges of mountains have been in process of erection. It is further pointed out that this zone of folding is much dislocated.

ADJUSTMENTS WITHIN A FAULT MOSAIC AS COROLLARY TO MOUNTAIN GROWTH

Tarr and Martin, 1906. — In 1899 Thoroddsen printed in the Icelandic Language an account of the earthquakes which occurred in Southern Iceland in 1896, and in which five separate earthquakes had shaken in succession each of five contiguous earth blocks.[5] In 1906 Tarr and Martin[6] clearly demonstrated that the earthquake of 1899 along the base of Mt. St. Elias was a renewal of mountain growth along the shore of the Yakutat Bay in which large vertical adjustments measured in ten's of feet took place between the large blocks within a fault mosaic, and that movements of smaller magnitude occurred between smaller blocks which were parts of the larger and composite ones. This study is therefore one of the most important and satisfactory that has ever been made of a great earthquake.

Hobbs, 1907. — In 1905 the writer carried out a comprehensive study of the great Calabrian earthquake of that year with the result of showing that even where actual faults are not disclosed by escarpments or other displacements at the surface of the ground, their course may be followed often in great numbers as *seismotectonic lines* — lines of heavy shock.[7] These lines, as the examination of earlier earthquakes within this much-racked province clearly showed, have been repeatedly the seats of movement. In the same year the writer pointed out in a discussion of seismic sea-waves that these indicate a deepening of trenches on the sea floor at the time of such waves, when the neighboring coasts are usually elevated. To cite:

> Such depressions of the deeps and uplifts of the neighboring shores probably stand in some sort of balance, and both alike call for an initial recession of the water from all near-lying shores toward the area of depression at that instant when the movement occurs. Such a mass of water as would pile up over the depressed area of the sea-floor as a result of the inrush of water from all sides, should be later spread in all directions and roll in to inundate the shores.[8]

At the time it was written this explanation seemed to call for mass movements upon the floor of the sea too large for ready acceptance by geologists, and the view appeared to find little support. Sixteen years later, nothing daunted, the writer had the temerity to state his belief that "the floor of the ocean has undergone sudden changes of elevation measured not in tens of feet, as have the zones of unrest upon the continents, but rather in hundreds and even thousands of feet."[9] Within a few months came the great Japanese earthquake in connection with which there occurred a seismic sea-wave, an elevated coast, and a sudden adjustment of the floor of Sagami Bay off the coast. The volume of the area dropped measured some 50 cubic kilometers and the amount of the drop measured over large areas 50 fathoms or more (300 feet).[10]

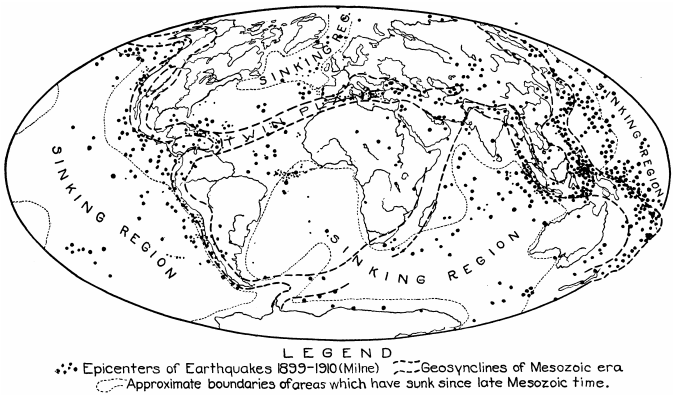

FIG. 20. World map of earthquake distribution for the period 1899-1910, made from data assembled by the British Association, but transferrred to the Mollweide projection

Willard D. Johnson, 1907-1910. — In the early spring of 1907 at the writer's suggestion Mr. Willard D. Johnson undertook a field-study of the scene of the Owens Valley earthquake of 1872. This occurred within a desert region of California in which the dislocations had suffered little change in aspect within the subsequent thirty-eight years. For the first time in history an accurate map was prepared of a fault network which had suffered a mosaic-like adjustment at the time of an earthquake.[11]

Seismic World Map, 1915. — The map of the unstable regions of the earth's outer shell which had been issued by De Montessus in 1906, reveals two narrow great-circle girdles (see p. 262, Fig. 19). The introduction of instrumental methods with use of the modern seismograph has enabled seismologists to extend their studies to the floor of the oceans. The Seismological Committee of the British Association published in 1916 a comprehensive world map of great earthquakes instrumentally located for a ten-year period (1899-1910).[12] This map (Fig. 20) upon a quite different basis confirmed that of De Montessus concerning the twin girdles, but showed that these zones extend outward from the margins of the continents into the sea and include the trough-deeps upon the sea floor. The zone of maximum instability, moreover, corresponds to the steep slope which joins the mountain arcs of the coasts and islands to the deeps which lie parallel to them. The identity of these special earthquake girdles with belts of mountain growth — of wrinkled formations upon the earth's surface — seems thus to be confirmed from a new quarter.

Magma Pocket below and vent above earth-wrinkles. — Geologists no longer generally believe, as formerly they did, that the earth's interior is molten. The source of the

.molten rock (magma or lava) which issues from active volcanoes is now believed to come from reservoirs which are relatively small. There are grounds for believing that these reservoirs are located beneath the arches of the mountains. Though the earth's interior is believed to be hot enough to melt the rock were it at the surface of the earth and under air pressure only, the rock is believed to be kept rigid by the load upon it. The formation of the wrinkle at the surface of the earth lifts this load and thus permits a magma reservoir to form beneath it, and above this reservoir the volcanoes naturally develop.[13]

Omori's law of geographical succession of earthquakes within girdles. — The late Professor Omori, distinguished Japanese seismologist, has given his adhesion to the view that the earthquakes within the great girdles of the earth are connected with mountain growth. It was in 1907 in his report upon the California earthquake that he called attention to the geographical order of succession of earthquakes within the earthquake girdles. An earthquake which occurs within any section of one of the girdles may be regarded as relieving the strain by transforming potential into actual energy, this relief being partial only beyond the area characterized by heavy shocks. The greatest probability of an impending earthquake applies, therefore, to those sections of the girdle which are farthest removed from regions of recent relief.

Earthquake prediction. — Upon this assumption after the California earthquake in 1906, Professor Omori predicted on August 4, 1906, just before he sailed for Japan that the next earthquakes within the circum-Pacific girdle would probably occur south of the equator — in South America. Before his ship had reached Japan occurred the great Valparaiso (Chile) earthquake of August 17, and upon the same day the great Aleutian (Alaska) earthquake.[14]

Utilizing the Omori suggestion, the writer in 1909 predicted that "the zone in which the probability of heavy shocks is now most imminent, are the Japan-Kamchatka segment, the Peru-Bolivia segment, and the archipelago region to the southeast of Asia."[15] (See Fig. 21.)

The mountain range does not, so far as our knowledge goes, appear to be forming throughout the circuit of the great circle hemming in the Pacific, but terminates in West Antartica and in New Zealand. It is in the New Zealand region, particularly, that future shocks may be looked for. Tokyo was largely destroyed by earthquake in 1855 and again in 1923. A heavy earthquake visited the vicinity of Wellington, New Zealand, in 1855, producing a fault scarp which may still be followed at the surface, and it is reasonable to suppose that a recurrence of movement in this neighborhood will take place in the not distant future.

After the meetings of the Second Pan-Pacific Science Congress held in Australia in 1923 and just before his lamented death, Professor Omori travelled in the writer's company from Sydney to Honolulu. Referring to the great Tokyo earthquake which had occurred less than a fortnight before, Professor Omori told the writer that he had fully expected this earthquake to take place within the Tokyo region, though not for another fifty years. This statement of his illustrates well the possibilities of a fair prediction of earthquakes as to their general locality, at the same time that it exposes our limitations with respect to the time of arrival of these devastating visitations.

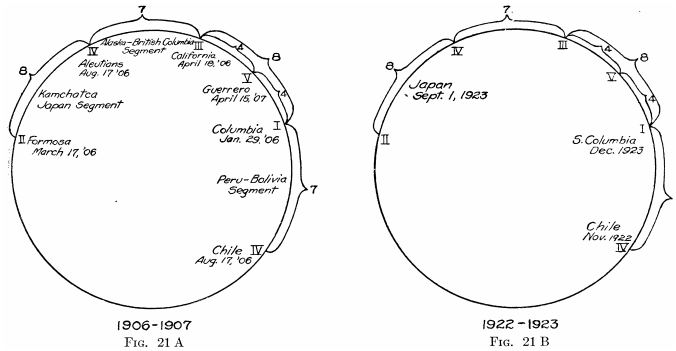

FIG. 21A. Reproduction of the writer's map published in 1909 to show the sequence of recent earthquakes at that time

FIG. 21B. Map showing positions of subsequent large earthquakes

ELASTIC REBOUND THEORY OF REID, 1910

Theory stated. — When in 1906 America was first awakened to the understanding that an earthquake peril exists upon its Pacific Coast, it had few scientists who possessed a background of earthquake lore, as had, for example, the Mediterranean countries of Europe and Japan. It is unfortunate, therefore, that those who came to be charged with the investigation of this earthquake did not endeavor to study the literature of the subject before writing the report and supplying a theory of cause.[16] Reid's theory of elastic rebound is based upon the assumption that there was a single line of dislocation — the visible San Andreas rift or fault — and that the displacement along this plane was entirely in a horizontal direction, the area to the westward being supposed to shear upon that to the eastward. This shearing strain, generated, according to the assumption, as the result of a current or of currents within the subcrustal region on directions parallel to the San Andreas rift, dragged, it was believed, the overlying crust along with them. The strain so set up was believed to be relieved through rebound on the fault plane at the instant of the earthquake.[17] This theory has been further developed by Lawson under the name "crustal creep and elastic rebound" theory.[18]

Its inadequacy. — As already pointed out, the elastic rebound theory of earthquakes is a reversion to the notion that within any district an earthquake is the result of a slip on a unique plane of faulting, and this new theory was set up without any apparent attempt to fit it to other earthquakes. Evidence of vertical, as well as horizontal, displacement along the San Andreas rift was, however, to be noted especially at Skinner's Range

where the writer among many others examined it. It is perhaps true that the revealed displacements upon the San Andreas rift were proportionately more largely horizontal than in the case of many other earthquakes; but lateral displacements of the same order of magnitude combined with large vertical displacements were measured, for example, in connection with the Japanese earthquake of 1891 and the Owens Valley earthquake of 1872. One of the most striking things about earthquakes is the almost monotonous uniformity observed in the nature of the phenomena which accompany them.

Now that geodetic observations have been completed over a sufficient area of the southwestern United States to determine changes of position of triangulation stations since the locations made before the earthquake of 1906, it has been learned that these movements have been quite different from those claimed in the California report to have taken place. The maximum movement recorded is now found to be, moreover, not even within the region of the San Andreas rift. Thus the elastic rebound theory of earthquakes, far from explaining earthquakes generally, cannot be made to fit the facts for the one earthquake to which it was originally applied.[19]

Sekiya's wires. — Many years ago Professor S. Sekiya undertook to represent the sequence of directions of shock received at his earthquake station during a single earthquake with the result of showing that so complex are these motions that to represent their directions and successions by a bent wire, it was necessary to employ three complicated snarls of wire in order to cover a minute only of time. Such a result favors strongly the view that not one fault slip but very many on differently placed surfaces are the cause of the earthquake phenomena.[20]

GENERAL STATEMENT OF PROBABLE CAUSE OF EARTHQUAKES

Proximate cause. — The proximate cause, or in common language the occasion, of earthquakes, so far as they occur within the earthquake girdles of the earth, would seem to be the formation of a fold or flexure within near-surface earth strata; such flexure being incident to the erection of a range of growing mountains of scalloped pattern accompanied by a series of parallel deep-troughs. Such elevation of a mountain range is accompanied as a natural consequence by pockets of lava beneath the arch, and above these are formed a series of vents for the escape of the volcanic materials, both molten rock and gases.

If we omit the special characteristics, the proximate cause of earthquakes may be stated to be adjustments which take place in position or inclination of portions of the outer shell of the earth, and this broad general statement may be applied outside as well as inside the earth's earthquake girdles. Such adjustment on the basis of many observations implies many individual movements among blocks composing a fault-mosaic.

Ultimate cause. — The ultimate cause of earthquakes, the deep-seated reason for the changes brought about in the configuration of the earth's surface, is by geologists generally believed to be the continuous loss into surrounding space of the heat from the earth's interior portions. This loss of heat is accompanied by a reduction of volume, a shrinking of the interior core of the earth; and the outer shell of rock being already cooled to a relatively stable condition must wrinkle as it adjusts itself. The old illustration of an apple in late winter which wrinkles from the loss of water and consequent reduction of volume of its interior portion, may still serve well at the present time.

PART II. EARTHQUAKES OF THE EASTERN UNITED STATES

THE REGION A RELATIVELY STABLE ONE

Historical earthquakes of the region. — Northeastern North America lies outside the seismic girdles of the earth (see Fig. 20 p. 265) and at least since its settlement by Europeans it has relatively seldom been vexed by destructive earthquakes. That light shocks have not been infrequent within recent times, or since newspapers and the telegraph have been widely distributed, is, however, evident from compilations made by Rockwood.[21] In the state of Michigan alone within this period some ten earthquakes have been put on record, the latest of which occured February 28, 1925.[22] Contrary to general opinion earthquakes of devastating violence have also visited the region of the eastern United States. These greater earthquakes have seemed to have relation especially to the drainage basin of the Saint Lawrence River and Great Lakes, to the lower Mississippi region of heavy deposition, or to the coastal plain east of the Appalachian Mountains. Accounts made between 1610 and 1791 by the French Jesuit missionaries from within the area reached by canoes about the St. Lawrence River and lakes, show that earthquakes were felt within that region in 1638, 1661, 1663, 1664, 1665, 1668, and 1672; that of February 5, 1663, described in the letters of Jerome Lallemant having been of devastating violence and probably comparable to the greatest earthquakes that are known. The full accounts of the missionaries translated and edited under the direction of the late Reuben G. Thwaites and published in seventy-three volumes by Burrows Brothers of Cleveland, have been searched for earthquake data and the extracted results published by Rev. Father Odenbach of Cleveland.[23]

In 1811 within the lower Mississippi Valley a really great earthquake generally referred to as the New Madrid earthquake was felt over a relatively broad area of the Mississippi Valley. For more than a century the region has now been generally quiet, but the scars of the

disastrous disturbances of 1811 still arrest the attention, and this earthquake must be reckoned among the most severe of any that have been anywhere recorded.[24]

The Charleston earthquake of 1886, while of greatest intensity in the vicinity of that Southern city, was felt as far north as the City of New York.[25] All three of these great disturbances of the eastern United States were within areas far outside the seismic girdles which mark the earth's zones of special instability.

If we look upon the earthquake of the late seventeenth century within and about the St. Lawrence drainage basin as more or less completely relieving the strains which had quietly been accumulating within that area, and much less completely the outside areas characterized by lighter shocks; then the New Madrid earthquake of a century and a half later may be considered to have accomplished a similar result for the large area to the south and west, the valley of the lower Mississippi. Three-quarters of a century now elapse and the residue of the broad area, that to the south and east, finds relief during the earthquake of Charleston in 1886, with some relief also within the outlying areas where no destructive shocks, but only jars and tremors, were felt.

Geological evidence is available from within the destructive area of the New Madrid earthquake, to show that an earthquake of devastating intensity and comparable in this respect with that of 1811, visited the region at least one hundred years earlier. Altogether, then, we have the evidence that at intervals averaging a century or more, this broad region of eastern North America, usually looked upon as especially favored by its stability, has been visited by racking earthquakes of the first importance. It is therefore necessary today to modify in a measure the views which have been generally held concerning earthquake distribution. The fact that the settlement of America by Europeans came so recently, and that of the three great earthquakes known from the region, two belong to the early period of sparse settlement, pioneer scientific method, and imperfect historical record, largely explain the failure to assign proper values to these really great earthquakes.

Epeirogenic earthquakes of De Montessus. — Dr. de Montessus in a magistrate posthumous work which came from the press in 1924, has described a new class of earthquakes for such regions as lie outside the earthquake girdles. These earthquakes he ascribes to epeirogenic movements, up-and-down movements of neighboring sections of the earth's surface layers — and hence block movements which are unassociated with the folding process, as are those which occur within the earthquake girdles.[26] In this he clearly recognized that his two earlier volumes through laying especial stress upon the importance of the two earthquake girdles, ascribed far too little importance to those earthquakes which occur outside.

It is easy to account for the earthquakes of the lower Mississippi Valley through the gradually accumulating load over the delta region and the lower flood-plain of this great river. It has been estimated upon good authority that 513 million tons of suspended matter are carried out each year to tidewater in Louisiana, and this takes no account of the vast load that is laid down within the broad area of the flood-plain in the states of Arkansas, Missouri, Tennessee, Mississippi and Louisiana.

Coastal changes of level, which though extremely slow are yet recorded in the uplifted terraces of wide tread and small rise along the Atlantic coast of the country, may account for the Charleston earthquake of 1886 and the many light earthquakes felt along the Atlantic seaboard. A no less apparent cause for adjustment of the outer shell of the earth relates to the area of the Laurentian Great Lakes, and here fortunately we have a much greater body of evidence at our disposal.

Epeirogenic adjustments within Great Lakes area. — During the latest — and present — geological period, the Pleistocene, continental glaciers of an estimated thickness of between one and two miles, for a portion of the time lay over northern America so as to cover at their culmination the greater part of the area east of the Rocky Mountains and north of the Missouri and Ohio rivers. Such a burden of ice must be conceived to have brought about a depression of the earth's surface within the region, from which recovery would presumably be either wholly or partially obtained when the ice waned and finally disappeared. The evidence is conclusive that since the retirement northward of the latest continental glacier, the Laurentian drainage region has been undergoing an elevation which began toward the southern margin, has increased in amount toward the north, and is still continuing today at a somewhat rapid rate.

There is an extensive literature of the subject[27] as regards the nature of the evidence of uplift, but the explanation of the earthquakes of the region as a consequence of this uplift and uptilt of the land was, so far as he is aware, first made by the writer in two related papers published in 1911.[28]

Summarized for the general reader, the available data which prove the uplift and uptilt of the Laurentian basin relate: (1) to the evidence of already accomplished movement, and (2) to the evidence that this upward movement still continues and so may be invoked to explain the earthquakes within the region.

The evidence of the already accomplished uplift and uptilt is derived from the present positions and inclinations of the now abandoned shore-lines of the system of great ice-dammed lakes which lay along the front of the continental glacier during its retreat. These shore-lines, which were of course horizontal when first formed, are now tilted upward toward the north at angles which increase rather rapidly as one proceeds north. The uptilt has been likened to that of a trapdoor in the floor rotating upon its hinge, the hinge-line for the

Laurentian region taking an average direction in the neighborhood of the Great Lakes of about 15° to the north of west. The case is, however, not quite so simple as this, for the main hinge-line of the region has itself migrated northward since the beginning of the uptilt, and secondary hinge-lines within the trapdoor itself appear also to have functioned. One may liken the complex movement in its main lines to that of a trapdoor made up of several planks all parallel to the main hinge and each hinged to its neighbors, all hinges being or having been in action (Fig. 22).

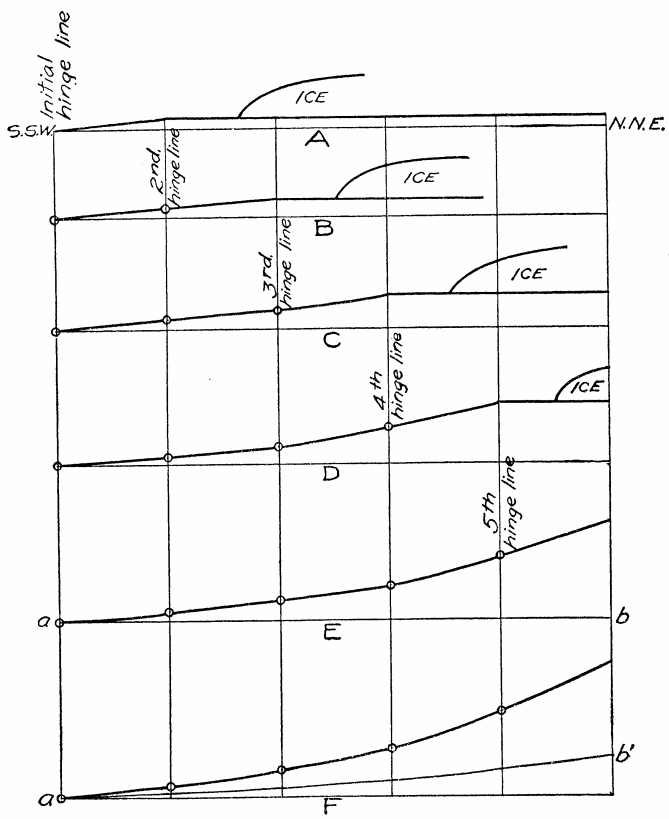

FIG. 22. Diagram to show the nature of the Laurentian region as the continental glacier retired northward

We are now chiefly concerned, however, with the evidence that uptilt of the land is still going on, and may therefore be responsible for the earthquakes of the region. The earliest clear recognition of such present-day uptilt was made by a land surveyor of Wisconsin, Mr. G. K. Stuntz, who in 1870 published a brief paper on observations made by him in the years 1852 and 1853 about Lake Superior.[29] Stuntz had noticed that on the northern shore of Lake Superior there were evidences that the land had recently risen, whereas on the south shore there were as clear signs of recent overflow. It was as though one were to take in the hands a partly filled basin of water and by tilting it cause the water to withdraw from one side, where in consequence the bottom of the basin rises out of the water; and to flood the opposite side. Additional observations from Lake Superior which confirmed these observations by Stuntz were made by Lawson in 1891.[30] The attention of geologists was first strongly directed to this tilting by Gilbert in 1898, when he investigated the series of records of the several gauging stations about the Great Lakes and found additional confirmation of the uptilt.[31]

Upon the south side of Lake Superior in Michigan the evidences are especially easy to read. The rivers of this coast have estuaries especially marked in the stretch from Ontonagon westward. At some points in the Porcupine Mountain district the trees along the shore of the lake stand six to eight feet out from the shore in six to eight inches of water. At other points where the trees are at the shores, the waves are beating against them and removing the bark. Here the lake has already encroached upon roads so that they have had to be abandoned.[32]

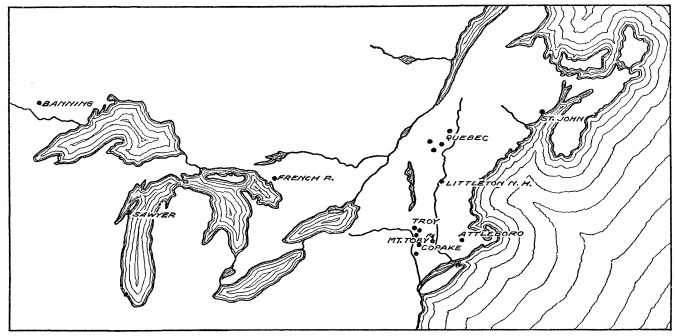

FIG. 23. Sketch map to show where post-glacial faults have been observed within the glaciated region of North America. Of those from the province of Quebec only a few have been entered.

Evidences of a somewhat similar nature to those found characteristic of Lake Superior belong also to Lake Erie. They show that here also the tilt of the land is upward toward the north. From the rate of flooding of the shores of Sandusky Bay Moseley has estimated that the rate of submergence on this shore is 2.14 feet per century.[33]

Lake Michigan-Huron, for this is a single body of water, has its outlet at Port Huron far to the south and now to the southward of the hinge-line of uptilt. Were this not the case flooding of the Chicago shore of Lake Michigan and of Bay City shore of Saginaw Bay would be going on.

Post-glacial faults. — Evidence is at hand that faults have been an accompaniment of the epeirogenic movements which have been going on within this region. The continental glaciers which in the yesterday of geology covered the region, planed the rock surfaces to a fresh polished condition upon which any subsequent displacement, even though of small measure, must be revealed whenever diligently sought for. No such search has been generally made, but already a considerable number of observations widely scattered through the region have been put on record (Fig. 23).

Such post-glacial faults appear to have been first noticed by Mather[34] at Copake, N. Y. near the common corner of Massachusetts and Connecticut. Similar faults have

since been described by Matthew[35] from St. John, New Brunswick; by Chalmers[36] from many localities in the province of Quebec; by C. H. Hitchcock[37] from Littleton, N.H.; by Woodworth[38] from many localities in eastern New York and Massachusetts; by Lawson[39] from Banning in Western Ontario; by Hobbs from Sawyer, Wisconsin,[40] and the French River in Central Ontario;[41] and by Loomis[42] from Mt. Toby, Massachusetts. While these faults are generally small individually they are numerous and they grow large in the aggregate.

The faults of eastern New York have been found chiefly along the lineament which follows the Hudson River and its continuation northward. The lineaments of the northeastern United States in their relation to the recorded earthquakes of the district as the data have been assembled by De Montessus have already been put upon record.[43]

CONCLUSION

The earthquake of February 28, 1925, was felt throughout the glaciated area of North America and at relatively few places outside. It was peculiarly an earthquake of this Laurentian area, and it is best explained as due to epeirogenic block movements as a result of continued uptilt of the area depressed during the periods of glaciation. The earthquake history of the region affords no warrant for the belief that the region of the northeastern United States is to remain immune from destructive earthquakes. Such visitations, it may be assumed, will be far less frequent than earthquakes which occur within the great girdles where mountain growth is proceeding lustily, but there is every reason to suppose that the future will bring to the Laurentian region earthquakes which are comparable in intensity with those of 1663 and 1811. So long as light shocks continue within the region, there is reason to believe that at least a partial relief from earth strain is being secured, and the date of the next destructive shocks is correspondingly removed farther into the future. Paradoxical as it may appear, the time for alarm will come whenever the region becomes abnormally quiescent.

UNIVERSITY OF MICHIGAN
April, 1925

[1] John Milne and W. K. Burton, Professors in the Imperial University, *The Great Earthquake in Japan*, 1891, 30 photogravures, plates, and map with descriptions. Lane, Crawford and Co., Yokohama (no date).

[2] B. Kotô, "On the Cause of the Great Earthquake in Central Japan, 1891,"*Journ. College Sci. Imp. Univ*., Tokyo, vol. 5, 1893, pp. 295-355, pis. 28-35.

[3] R. D. Oldham, "Report on the Great Earthquake of 12th June, 1897," *Mem. Geol. Surv. India*, Calcutta, vol. 29, 1899, pp. 379, pls. 42, maps.

[4] F. de Montessus de Ballore, "Les Tremblements de Terre," *Géographic Séismologique*, Colin, Paris, 1906, pp. 24-25.

[5] A German abstract of Th. Thoroddsen's paper appeared in vol. 47 (1901) of Petermann's *Mitteilungen*.

[6] R. S. Tarr and L. Martin, "Recent Changes of Level in the Yakutat Bay Region, Alaska," *Bull. Geol. Soc. Am*., vol. 17, May, 1906, pp. 29-64, pls. 12-23.

[7] William Herbert Hobbs, "On Some Principles of Seismic Geology, with an Introduction by Eduard Suess," *Gerlands Beiträge zur Geophysik*, Leipzig, vol. 8, 1907, pp. 217-292, pl. 1 and 10 figs. "The Geotectonic and Geodynamic Aspects of Calabria and Northeastern Sicily, a Study in Orientation, with an Introduction by the Count de Montessus de Ballore," *ibid*., pp. 293-362, 10 pls. and 3 figs.

[8] W. H. Hobbs*, Earthquakes, an Introduction to Seismic Geology*, Appleton, 1907, chap. XV, especially pp. 253-254.

[9] "The Rate of Movement in Vertical Earth Adjustments Connected with the Growth of Mountains," *Proc. Am. Phil Soc*., vol. 62, 1923, p. 70.

[10] A. Imamura, "Preliminary Note on the Great Earthquake of S. E. Japan on Sept. 1, 1923," *Seismological Notes*, No. 6, Imp. Earthq. Invest. Comm., Tokyo, July, 1924, p. 16, pl. 4. T. Kato, " Preliminary Notes on the Kwanto Earthquake in Japan, September 1, 1923," *Journ. Geol. Soc. Tokyo*, vol. 30, No. 361, p. 8.

[11] W. H. Hobbs, "The Earthquake of 1872 in the Owens Valley, California," *Gerlands Beitrdäe zur Geophysik*, vol. 10, Leipzig, 1910, pp. 351-384, pls. X-XXIII (Read before the Association of American Geographers at Chicago, December, 1907).

[12] H. H. Turner, and others, *20th Rept. Seismol. Comm., Rept. Brit. Asso*., Manchester meeting (1915) 1916, pp. 52-79, pl. 1.

[13] *Earth Evolution and Its Facial Expression*, 1921, chaps. 3-5.

[14] F. Omori, "Preliminary Note on the Cause of the San Francisco Earthquake of April 18, 1906, "*Bull. Imp. Earthq. Inves. Comm*., vol. 1, no. 1, Jan., 1907, pp. 21-25. For later expression of this view see "Earthquake Zones in and around the Pacific," *ibid*., vol. 11, no. 1, 1923, pp. 28-32.

[15] "The Evolution and the Outlook of Seismic Geology," *Proc. Am. Phil. Soc*., vol. 48, July 6, 1909, p. 32.

[16] See *Bull. Geol. Soc. Am*., vol. 32, 1921, p. 45.

[17] H. F. Reid, "On Mass Movements in Tectonic Earthquakes and the Depth of the Focus," *Gerlands Beitr. z. Geophysik*, Leipzig, vol. 10, 1910, pp. 318-351; also, *Rept. State Earthq. Invest. Comm*. (Carneg. Inst., Wash.), vol. 2, 1910; also, "The Elastic Rebound Theory of Earthquakes," *Bull. Dept. Geol. Univ. Calif. Pub.*, vol. 6, 1911, pp. 413-444.

[18] A. C. Lawson, "The Mobility of the Coast Ranges of California, an Exploitation of the Elastic Rebound Theory," *Bull. Dept. Geol., Univ. Calif. Pub*., vol. 12, no. 7, 1921, pp. 431-473, 19 text-figs.

[19] Arthur L. Day, "The Study of Earth Movements in California," Address of the President of the Washington Academy of Science, Jan. 13, 1925, *Science*, vol. 71, no. 1578, March 27, 1925, p. 325.

[20] S. Sekiya, "A Model to Show the Motion of an Earth Particle during an Earthquake," *Trans. Seis. Soc. Japan*, vol. 11, 1887, pp. 175-177, pls. 1-2.

[21] C. G. Rockwood, fourteen articles in *Am. Journ. Sci*., from 1872 to 1885.

[22] W. H. Hobbs, "Earthquakes in Michigan," Pub. 5 (*Geol. Ser*. 3), Mich. Geol. and Biol. Surv., Lansing, 1911, pp. 69-87, 2 pls.

[23] *Twelfth Ann. Rept. Meteorol. Observ*., Coll. St. Ignatius at Cleveland, Ohio, 1906-1907, pp. 7-15. For an abridged summary see the author's Earthquakes, Appleton, 1907, pp. 315-320. Lawson seems to be quite unaware of this earthquake (*Bull. Seis. Soc. Am*., p. 139, — reprints indicate no volume or date).

[24] Myron L. Fuller, "The New Madrid Earthquake," Bull 494, *U.S. Geol. Surv*., 1912, pp. 119, pls. 10, figs. 18.

[25] C. E. Dutton, "The Charleston Earthquake of August 31, 1896," *Ninth Ann. Rept. U. S. Geol. Surv*., 1889, pp. 203-528.

[26] F. de Montessus de Ballore, *La Géologie Sismologique, les Tremblements de Terre*, Colin, Paris, 1924, chap. I.

[27] The more important series of papers are by Gilbert, Leverett, Taylor and Goldthwait.

[28] "The Later Glacial and Post Glacial Uplift of the Michigan Basin; Earthquakes in Michigan," *Mich. Geol. and Biol. Surv*., Pub. 5 (Geol. Ser. 3), Lansing, 1911, pp. 87, pls. 2 and 3, and figs. 48 and 5.

[29] G. K. Stuntz, "On Some Recent Geological Changes in Northeastern Wisconsin," *Proc. Am. Assoc. Adv. Sci*., vol. 18, 1870, pp. 206-207.

[30] A. C. Lawson, "Sketch of the Coastal Topography of the North Side of Lake Superior with Special Reference to the Abandoned Strands of Lake Warren [Lakes Nipissing and Algonquin, W. H. H.,] *20th Ann. Rept. Geol. and Nat. Hist. Surv. Minn*., 1893, pp. 181-289.

[31] G. K. Gilbert, "Recent Earth Movement in the Great Lakes Region," *18th Ann. Rept. U. S. Geol. Surv*., 1898, pt. 2, pp. 595-647.

[32] F. E. Wright, "Report on the Progress Made by the Porcupine Mountain Party during the Summer of 1903," *Rept. Geol. Surv. Mich. for 1903* (1905), p. 37.

[33] This is notwithstanding the fact that the present hinge-line of tilting now crosses the northeastern half of the lake. Gilbert's earlier estimate of the rate of uptilt (*18th Ann. Rept. U. S. Geol. Surv.*, 1898, pt. 2, p. 637), even as corrected by Lane (*Geol. Surv. Mich*., vol. 7, 1900, pp. 36-39), is in error and much too large; since he conceived the entire area about the lakes to be tilting like a plane without recognizing the positions and the migrations of the hinge-lines (*Mich. Geol. and Biol. Surv*., Pub. 5, 1911, pp. 40-41).

[34] W. W. Mather, *Geology of New York, Report on First District*, 1843, pp. 156-157.

[35] G. F. Matthew, "Movements of the Earth's Crust at St. John, N. B. in Post-Glacial Times," *Bull. Nat. Hist. Soc. New Brunswick*, no. 12, 1894, pp. 34-42.

[36] R. Chalmers, "Report on the Surface Geology and the Auriferous Deposits of South-Eastern Quebec," *Geol. Surv. Can., Ann. Rept*., vol. 10, 1897, pt. J, pp. 10-12.

[37] C. H. Hitchcock, "The Geology of Littleton," in *History of Littleton*, 1905, pp. 28-29.

[38] J. B. Woodworth, "Post-Glacial Faults of Eastern New York," *Bull. 107 N. Y. State Museum*, 1907, pp. 4-28.

[39] A. C. Lawson, "On Some Post-Glacial Faults near Banning, Ontario," *Bull. Seismol. Soc. Am*., vol. 1, pp. 159-166.

[40] W. H. Hobbs, "The Late Glacial and Post-Glacial Uplift of the Michigan Basin," *Mich. Geol and Biol. Surv*., Pub. 5, 1911, p. 45.

[41] W. H. Hobbs, "Post-Glacial Faulting in the French River District of Ontario," *Am. Journ. Sci*., vol. 1, 1921, pp. 507-509.

[42] F. B. Loomis, "Post-Glacial Faulting about Mt. Toby, Massachusetts," *Bull. Geol. Soc. Am*., vol. 32, 1921, pp. 75-80.

[43] *Beiträge zur Geophysik*, vol. 8, 1907, pl. 2.

HEMATITE INCLUSIONS IN THE LAKE SUPERIOR AMETHYST

† EDWARD F. HOLDEN

DURING the course of an investigation on the nature of the pigment of amethyst,[1] a number of specimens from the Thunder Bay district were examined. This locality is on the northern shore of Lake Superior.

The amethysts from Thunder Bay frequently contain abundant reddish-brown spots. They are quite small, with a diameter generally less than one millimeter. The inclusions are of interest both because of their form and because of their relation to the color of amethyst. They were identified as hematite, since:

(1) They have a red streak, and color the powdered amethyst a pale brick-red.

(2) Analyses showed the spotted amethyst to contain comparatively large amounts of iron. One specimen contained 0.35 per cent Fe_2O_3, which was largely due to the inclusions, though a few hundredths of a per cent must have been contributed by the ferric compound found to be the pigment of amethyst.

(3) The inclusions are entirely soluble in hydrochloric acid.

The hematite inclusions are distributed in definite planes parallel to and generally very near the surface of the crystals. In form they are circular, having the appearance of the cross-section of an oölite. They are not spherical, however, but are disk-shaped. If a fragment containing some inclusions is tipped up, under the microscope, the hematite particles can be looked at edge on, and their thin, flat character is apparent. A microphotograph of a typical group of inclusions is given in Figure 24. The specimens in which they occur have a pronounced lamellar structure, parallel to the rhombohedron faces. It seems probable that iron-bearing waters were included in the spaces between the lamellae, and on gradually evaporating they left the inclusions in the form just decribed.

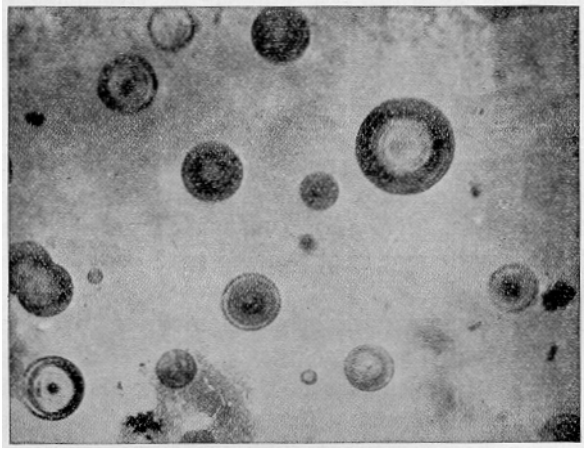

FIG. 24. Microphotograph of Hematite Inclusions in Lake Superior Amethyst

The investigation of a large number of amethyst specimens has shown that its pigment is very probably a compound of ferric iron. The distribution of the hematite inclusions in the Thunder Bay amethyst confirms this hypothesis. In these crystals the violet color was deepest for several millimeters below the thin layers of hematite inclusions, the rest of the crystals being white or colorless. In most crystals there appears to be but one zone of hematite inclusions, but sometimes two or more layers are present. In a crystal with two zones of

hematite particles the intervening layer of quartz was so dark a violet as to appear almost black. The hematite inclusions are very close to the surface of most of the crystals. These relations indicate that violet quartz began to be deposited when a sufficient concentration of iron was attained in the mineral solutions, the quartz previously formed being colorless. As the amount of iron increased, the color became darker, and finally the deposition of hematite took place. There is, therefore, a correlation between the abundance of iron and the violet coloration.

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†The writer of this paper, Dr. Edward F. Holden, met his death by drowning on August 5, 1925, at North Deer Isle, Maine. He was born on August 29, 1901, at Woonsocket, Rhode Island. He had been a member of the staff of the Department of Mineralogy of the University of Michigan since 1921 and of the Michigan Academy of Science since 1922. He was particularly interested in the cause of color in minerals and his investigations on the color of rose quartz, amethyst and smoky quartz have appeared in recent issues of *The American Mineralogist*. Dr. Holden was also one of the assistant editors of *Chemical Abstracts* and an associate editor of *The American Mineralogist*. His death removes from our membership one of the most promising of the younger scientists. — EDITORS' NOTE.

[1] Reported before the Section of Geology and Mineralogy under the title "The Pigments of Amethyst and Smoky Quartz," April 2, 1925. The present paper is a portion of the longer and more general paper then given.

GEOLOGY AS A FACTOR IN SOIL CLASSIFICATION

J. O. VEATCH

SOIL is an object of nature in which differences exist and wherever man is able to perceive differences, he makes comparisons and begins a classification although it may be unconsciously. The classification may be crude, illogical, artificial when viewed in the light of later knowledge, but schemes change, undergo evolution and become more perfected as knowledge of the object to be classified accrues. Ever since man became civilized and drew a great part of his sustenance from the cultivation of soils, he has made comparisons or has attempted to classify them.

In the United States early comparisons or classifications have been purely local or provincial, never comprehensive or universal in their application. Environmental or external factors, more often than intrinsic properties, other than perhaps a single peculiarity, have been made the basis of comparison and rarely were distinctions made between land and soil. Pioneer settlers, farmers, agriculturists and naturalists made comparisons upon the basis of topography and drainage, natural vegetation, soil color, underlying rocks, agricultural use, and in various parts of the country we had upland and bottom land, hill land and level land, prairies and forest land, pine land and hardwood land, black lands and red lands, cotton land and tobacco land, granite soils, limestone soils, etc. As the need for more exact comparisons and classifications became appreciated, workers in the sciences of chemistry, physics and geology felt called upon to apply some of their knowledge and laws to the study of the soil. We began to accumulate more exact or scientific comparisons and knowledge in place of the utilitarian, spontaneous and more or less obvious comparisons. The chemist contributed essential knowledge concerning the soil, but as we all know, his analysis was utterly impracticable as a basis of soil classification. The physicist provided facts quite as fundamental in relation to plant growth as those of the chemist, but physics could give us no basis for a universal system of soil classification. The agronomist viewed soils purely in relation to crop productivity and farming and, therefore, could evolve no comprehensive systematic scheme of classification.

The geologist, however, was able to provide a scheme which promised to have a universal application and serve as a basis for the actual mapping of soils. Soils were to be classified according to their geologic origin: sedentary and transported, residual, alluvial, cumulose, etc., while a close correlation was assumed between the soil and kind of rock from which it was derived. The geologic conception of soils has been pretty generally adopted and has exerted a strong influence in soil studies.

The early system of classification initiated by Dr. Milton Whitney and the U. S. Bureau of Soils about twenty-five years ago, was essentially geologic, since soil provinces were either geologic or physiographic, while origin and source of material were controlling factors in determining the series and types, in conjunction with texture, color and structure of the soil.

But now a new conception of soils, in their genetic and taxonomic relationships, is beginning to gain acceptance among soil scientists in this country. The two men who are chiefly credited with having evolved the new conception, or with greatly modifying old views, are K. Glinka, the Russian pedologist, and Dr. C. F. Marbut of the U. S. Bureau of Soils. Glinka published a book in German in 1914, *Die Typen der Bodenbildung*, in which his scheme of universal soil classification is presented and his theories of soil formation are outlined in a comprehensive and masterly manner. Dr. Marbut was quick to appreciate the basic worth of Glinka's book, but without accepting all of the conclusions, and began to disseminate, in a quiet way, the Glinka conception of soil, which is in brief: Climate, not geology, is the primary or controlling basis of soil classification; the moisture, or drainage, and temperature conditions are the main controlling factors in soil development; the nature of the soil profile, the result of the action of chemical, physical and biotic agencies, differs in different climatic belts; and the age of the soil — the maturity or on the other hand incompleteness of the profile — is an important consideration.

Dr. Marbut[1] has defined the soil unit and named the criteria, or factors, which can be used in its differentiation. He has established a principle which will have a far-reaching effect upon the work of the pedologist or scientist in soil classification. This principle is: The divisions and units of the soil classification must be differentiated on the basis of *intrinsic* characteristics of the soil itself. There is nothing illogical or radical in insisting upon the soundness of this point of view. If one were to make a proposal to botanists that trees be classified upon the basis of the soil in which they grew, the proposal would be rightly treated as nonsense; the mineralogist bases his classification of minerals upon their own intrinsic chemical and physical peculiarities, not upon occurrence in a certain geologic formation or in a certain physiographic province. Then is it not logical since plants, animals, rocks and minerals and other objects of nature are classified on a natural basis, the basis of intrinsic peculiarities and properties, that soil also should be classified on this basis and not upon the basis of external and associated things, whether geology, climate or agriculture?

In the full acceptance of the foregoing viewpoints there may be a tendency at first to subordinate and ignore the geological factor too far. Geology, however, remains an important factor and it is the duty of the soil scientist, or more particularly the pedologist, to evaluate it in each particular region or locality that he studies. But, to state the matter rather bluntly, geologic origin and source of material are no longer to be regarded as the primary and controlling basis of the soil classification. Climate admittedly transcends geology in importance as a cause of differences between the larger orders of the soil classification. To give a familiar illustration, the broad differences between the soils of the northern regions, the podsols, and those of the sub-humid treeless regions, the tschernosems, are a function of climate; the geologic source of material is entirely a subordinate factor. In smaller subdivisions the moisture conditions under which the soil has developed, the age of the soil, and the degree to which the processes of *eluviation* and *illuviation*, leaching and concentration, have operated may be controlling factors, but here geology generally appears as a modifying factor.

A close correlation between geology and soils, between a geologic map and a soil map, will depend upon whether the geologic divisions and the soil divisions are of the same order, even were there no other causes for a lack of unity. In general no correlation between a geologic formation and a single soil type could be expected, because the two divisions are rarely of the same order. And again it is patently futile to attempt to establish any significant relationships where a geologic formation or group of rocks has a distribution in two or more climatic divisions. To give an extreme illustration, the soils from a Carboniferous limestone in Alabama and Georgia and one from a Carboniferous limestone on the arid plains of New Mexico would be quite dissimilar, even were the rocks identical in every respect. Locally, a relation between texture and chemical and physical characteristics of a soil type may be close or on the other hand almost nonexistent, accordingly as geologic subdivisions are made purely on a lithologic basis, or on the other hand, on the basis of age or fossil life forms, or in the case of glacial deposits on the basis of manner of deposition and topographic expression.

It should be understood, however, that this relationship is not everywhere simple and that a mere statement of the kind of rock and source of material is not equivalent to a description of the soil. We know from extensive observation that the climax soil, the final product of the operation of soil-forming processes, may bear only a remote resemblance to the lithologic and physical aspect of the subjacent rock. This is particularly true under extremes of climate. Even in a region like Michigan, where the surface formations are glacial deposits and the land surface is relatively youthful, the structural and other resemblance between horizons of the soil profile and the underlying geologic deposit may be almost entirely obliterated, as for example in certain types of the Fox and Waukesha where the B horizon may be highly compact, clayey and acid while the parent deposit is coarse, pervious, unconsolidated and calcareous. Close consanguinity between the rock and the soil may exist, but it can be traced only by intricate microscopic, chemical and geologic study of both the soil and the rock, while the relationships must be worked out for each separate horizon of the soil profile, since in each there is a different expression of the relationship. In one instance the relationship may be marked in texture, in another in color, in another in chemical nature. Only the very broadest generalizations, exceedingly difficult to formulate, can be made for universal application. We cannot even state that universally a 'parent' formation of sand will produce a soil uniformly sand in textural class throughout. In general, relationships are purely local in value. Extremely scant information is conveyed about the actual nature of the soil itself merely to state that it is a 'limestone' soil or a 'granite' soil, etc., unless the influence of the rock is interpreted in soil terms which is a task requiring laborious study and mental effort if it is to be done in more than a superficial manner. If the object be a soil map, a more logical, a simpler and more direct method is to work out the soil classification on the basis of the soil itself. When this is done, comparisons and relationships to rocks, vegetation, climate and agriculture may be made, and one may make whatever use of the relationships their worth may merit.

Again a close parallelism between the distribution of soil types and geologic formation depends upon the uniformity of drainage conditions, since if the drainage conditions vary throughout the geological terrane, it is quite probable that there will be as many soil types as there are drainage types. In a region like peninsular Florida where climatic conditions have tended to make all the mature soils uniform lithologically, that is dominantly siliceous sand, regardless of the nature of the geologic formation underlying, the important surface

soil differences are due almost entirely to the drainage or moisture conditions under which the soils have developed. But even here, however, as elsewhere, the geologic substratum may be an important factor in the soil differentiation where it lies at a shallow depth and within reach of plant roots.

It is seldom that a geologic map can be interpreted directly in terms of plant growth or seldom that it has a direct application to agriculture; its relation to soil must first be worked out and thence through the medium of soil we may state the relation to plant growth and to agriculture. A near equivalency of the surface part of a geologic formation, or deposit, and a soil may exist in the case of very recent alluvium, recent volcanic deposits, recent beach deposits, recent dunes, some peat deposits — land so new that soil-forming agencies have not had time to produce visible results. Under such conditions the soil profile is immature and incomplete, and the pedologist simply describes the surface part of the deposit in soil terminology.

In connection with the discussion of the completeness and incompleteness of soil profiles, the postulation is here made that all soils are residual. Differences appear merely in the degree of alteration of the associated geologic formation. This applies regardless of the geologic origin and age of the rock whether pre-Cambrian granite of the Piedmont plateau, Tertiary sand or marl of the Atlantic Coastal plain; the deposits of Wisconsin glaciation; or a recent peat deposit. The sand dunes on the east side of Lake Michigan, which are geologically very recent, exhibit incipient soil profiles and in fact in places a marked alteration of the sand appears. Again cumulose or peat deposits may be divided into groups, or organic soil types, on the basis of degree of surface alteration of the parent organic deposit, or stated in another way, upon the basis of the relative age of the soil and completeness or incompleteness of the soil profile. One of the principal reasons why the classification of regolith given by Merrill[2] fails when applied to soils is that all soils are in a strict sense residual.

The foregoing statements have not been made with a conscious purpose to belittle or to derogate the importance of geology in soil study. On the contrary I regard a knowledge of geology and physiography as a part of the essential equipment of the pedologist. A knowledge of the geology and history of a land surface has a high value in working out academic relationships, facts of broad scientific interest; it constitutes a factor in the speculative study of soil, in deciphering the history of a soil, in tracing its evolution, in speculative studies upon the absolute age of a soil and the time required for the development of a profile under different geologic and climatic conditions; the causes for the alteration and degradation of soils; in distinguishing between acquired and inherited characteristics; in determining the causes for distribution of a soil type within the limits of a soil province; a detailed knowledge of the lithology of the geologic formation which has had an influence upon a soil, greatly facilitates theoretic explanation of some of the chemical and physical phenomena of horizons of the soil profile. In a strictly technical sense, the substratum constitutes a part of the complete soil profile, its C horizon, and, therefore, a consideration of its nature is important in the taxonomic study of the soil.

Some observations on the relationships of soil and geology with particular reference to Michigan may be given here. A very excellent map of the surface formations of Michigan has been made by Leverett,[3] while recent soil surveys have been made of eighteen counties and in addition extensive reconnaissance studies of the soils, have been made during the past four years. When the geologic divisions and soil divisions are compared we find that in association with: *moraines*, twelve soil series have been differentiated exclusive of mucks which may number three or four additional types; *clay till plains*, fourteen soils exclusive of mucks; *outwash plains*, nine soils, exclusive of mucks; *lake clay*, nine soils exclusive of mucks; *sandy lake beds*, fifteen soils exclusive of mucks; river deltas, four soils. It is, therefore, evident that no consistent relation, over a large area, between the geologic division and the soil series or type exists. The causes for this lack of close relationship are fundamental. The mature soil and the geologic formation underlying are never entirely synonymous, because of alteration of the underlying rock by weathering and soil-forming agencies. The accompanying Table illustrates some of the changes which have taken place in geologically recent glacial deposits in Michigan in their transformation of soil.

PARENT GLACIAL DEPOSIT AND SOIL

Parent *		Soil		Parent †		Soil	
	Clay percentage	A_0, A_1 horizon	Clay percentage	Lacustrine	CaO–MgO	A_0, A_1 horizon	CaO–MgO
Reddish till clay	28.2	A_2 horizon	6.6	Clay	22.23	A_2 horizon	3.10
	28.2	A_3 horizon	11.7		22.23	A_3 horizon	5.28
	28.2	B horizon	22.5		22.23	B horizon	9.10
	28.2	C horizon	28.2		22.23	C horizon	22.23

* Ogemaw Co., Kewaunee loam soil type, mechanical analysis, U. S. Bureau of soils.
† Alcona County, Ontonagon silt loam, analysis from "Soil Profile Studies in Michigan" by M. M. McCool, J. O. Veatch and C. H. Spurway, in *Soil Sci.*, Vol. XVI, No. 2, Aug. 1923.

Again, equivalency does not exist, because in general the peculiarities of soil types which are inherited from the subjacent formation are related almost wholly to lithologic character rather than to origin, geologic age and manner of deposition. If the geologist would further minutely subdivide the moraines and other divisions upon the basis of lithologic variations in the surface exposures, and after this is done were a still further subdivision made upon the basis of differences in drainage conditions, then the geologist's map and the soil map would doubtless reveal a closer parallelism, provided recognition were given to climatic differences. Our soil studies in Michigan have strongly suggested

that the generalized profiles in the northern part of the State are sufficiently different from those in the southern part to warrant the establishment of two broad soil divisions or provincial orders, and that these differences are climatic in origin. True podsols occur in the northern part of the State, while in the southern part of the southern peninsula brown forest soils and degraded podsols are present.

In a glaciated region like Michigan, where the land surface is *youthful*, where there has been but little or no alteration of the constructional topographic forms, inherited soil characteristics are more closely associated with the subjacent formation than in an old non-glaciated eroded region. A geologic map therefore, such as that made by Leverett, has a great value in pedologic investigations. It is hardly to be expected that an outwash plain or a moraine or any of the other divisions of the same order would have the same meaning in soil terms throughout the whole State, because of the variations in lithologic character and in drainage. However, when local interpretations are made, soil group-relationships may be established, particularly textural groups, and hence, the geologic map may be very useful in reconnaisance soil-mapping and in working out problems of soil origin and geographic distribution.

If detailed petrologic descriptions of the drift were available, a quantitative estimate of the different kinds of rock in the moraines, outwash plains and till plains in different localities, together with chemical and mechanical analyses of the unaltered drift, the value of geology as a factor in the soil classification in the State would be greatly increased. Additional knowledge would be available which would be an important aid in our efforts to explain many of the chemical and physical phenomena of the soil profile. But, however detailed a geologic map may be, however minute the description of the rock or formation, the map cannot be regarded as the equivalent of the soil map, because drainage or moisture conditions under which the soil has developed, the relative age of the soil, the number and arrangement of soil horizons, their thickness; their color, texture, structure, their colloidal content, their reaction; their organic matter; their moisture relationships; their relative amounts of plant food elements are not a part of the geologist's criteria of differentiation. The consideration of these things or soil taxonomy and profile analysis in conjunction with the origin, evolution and geographic distribution of soils constitutes a new science — pedology.

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[1] Marbut, C. F., "Contributions of Soil Surveys to Science," *Proceedings, 41st Annual Meeting, Society for the Promotion of Agricultural Science*, 1920, pp. 116-142. Also Bull. III, pp. 24-34, *Report, Second Annual Meeting, American Soil Survey Association,* Feb., 1922.

[2] George P. Merrill, *Rocks, Rock Weathering and Soils* (Macmillan Co., 1913), p. 288.

[3] Frank Leverett, "Surface Geology of Michigan," Pub. 25, *Michigan Geological and Biological Survey*, 1917.