# CHAPTER IX.

## CHANGES IN THE LEVELS OF THE BEACHES.

### THE NORTHWARD ASCENT OF THE WESTERN SHORE-LINES.

The successive shore-lines of Lake Agassiz are not parallel with each other and with the present levels of the sea and of Lakes Winnipeg and Manitoba, but have a gradual ascent from south to north, which is greatest in the earlier and higher beaches and slowly diminishes through the lower stages of the lake, being at last only slightly different from the level of the present time. On the west side of Lake Agassiz the elevations of its beaches have been determined by my continuous leveling, referred to sea-level by railway surveys, through a distance of more than 300 miles from its mouth at Lake Traverse northward to near Riding Mountain in Manitoba; and the accompanying table, on page 476, shows approximately the stages of the lake during the formation of these shore-lines in their relations to each other and to the present level. These stages of the water surface have been assumed to coincide generally with the foot of the lakeward slope of the beach ridges, and with the base of the eroded shore escarpments, the crests of the beaches having had a variable height from 5 to 15 feet above the lake, corresponding with their less or more massive development, while the escarpments rose from the water's edge 10, 20, or rarely 30 feet.

In this table the estimated stages of the lake are noted for comparison at its mouth, where it outflowed by the River Warren at the north end of Lake Traverse, and on four lines of latitude which are nearly equidistant from each other, passing through Fargo, Grand Forks, Emerson, and Gladstone, respectively 75, 150, 224, and 308 miles north of Lake Traverse. Though the fourth of these intervals is somewhat greater than the others, it may still be considered equivalent to them in the observed elevations and northward ascent of the lake shores, because, as will appear further on, the northward rise of the land and subsidence of the lake had their maximum increase from south-southwest to north-northeast or nearly in that direction. Therefore the more western course of these beaches in the northern part of the area examined compensates approximately for the additional distance between the third and fourth of these groups of observations.

The letters *a b c d* represent successive beaches along the northern part of Lake Agassiz, which are merged in a single beach toward its south end. Several of the beaches thus noted in a preliminary report[1] are found to become double in some parts of their northward extent, and a correspondence in notation is here preserved by designating subordinate stages by double letters, as *aa*, *bb*. There are also added the two stages of the Tintah beaches which were discovered after the publication of that report.

The lake shore belonging to the highest or Herman stage *a* has now a northward ascent of about 35 feet in the first 75 miles north from Lake Traverse, about 60 feet in the second 75 miles, and about 80 feet in the third distance of 74 miles to the international boundary. Its whole ascent thus in 224 miles is 175 feet by a slope which increases from slightly less than a half of a foot per mile in its southern third to slightly more than 1 foot per mile in its northern third. Through six lower stages represented by separate beaches northward, which seem to be united in the single Herman beach along the southern third of the lake, the northward ascent is gradually diminished to approximately 30, 40, 60, and 70 feet in the four portions of the observed course of these shore-lines, amounting thus to 200 feet in about 300 miles. On the international boundary the lowest Herman stage, *dd*, is about 55 feet below the Herman stage *a*, while the probable erosion of the outlet and consequent lowering of the south end of the lake between these stages appears not to have exceeded 10 feet.

Between the series of Herman beaches and the series of Norcross beaches the River Warren eroded its channel about 15 feet; and the upper Norcross shore ascends northward in these successive distances about 25, 35, 55, and 70 feet, amounting to 185 feet in the entire distance of 308 miles. In the most southern quarter its ascent is a third of a foot per mile, and this gradually increases to nearly 1 foot per mile in the most

[1] U. S. Geol. Survey, Bulletin No. 39, p. 20.

*Stages of the glacial Lake Agassiz, western shore.*

| Stages | Beaches. | | Numerical order. | Mouth of Lake Agassiz outflowing by the River Warren, at the north end of Lake Traverse. | On the latitude of Fargo and Wheatland, N. Dak., 75 miles north of Lake Traverse. | | On the latitude of Grand Forks and Larimore, N. Dak., 150 miles north of Lake Traverse. | | On the international boundary, 224 miles north of Lake Traverse. | | On the latitude of Gladstone, Arden, and Neepawa, Manitoba, 308 miles north of Lake Traverse. | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | Feet above the sea. | Feet above the sea. | North ascent from Lake Traverse. | Feet above the sea. | North ascent from Lake Traverse. | Feet above the sea. | North ascent from Lake Traverse. | Feet above the sea. | North ascent from Lake Traverse. |
| Stages during outflow southward. | Herman beaches | *a* | 1 | 1,055 | 1,090 | 35 | 1,150 | 95 | 1,230 | 175 | ....... | ....... |
| | | *aa* | 2 | 1,055 | 1,090 | 35 | 1,145 | 90 | 1,222 | 167 | ....... | ....... |
| | | *b* | 3 | 1,050 | 1,085 | 35 | 1,135 | 85 | 1,212 | 162 | 1,315 | 265 |
| | | *bb* | 4 | 1,050 | 1,085 | 35 | 1,132 | 82 | 1,205 | 155 | 1,295 | 245 |
| | | *c* | 5 | 1,045 | 1,080 | 35 | 1,125 | 80 | 1,190 | 145 | 1,275 | 230 |
| | | *d* | 6 | 1,045 | 1,075 | 30 | 1,117 | 72 | 1,180 | 135 | 1,255 | 210 |
| | | *dd* | 7 | 1,045 | 1,075 | 30 | 1,115 | 70 | 1,175 | 130 | 1,245 | 200 |
| | Norcross beaches | *a* | 8 | 1,030 | 1,055 | 25 | 1,090 | 60 | 1,145 | 115 | 1,215 | 185 |
| | | *b* | 9 | 1,025 | 1,050 | 25 | 1,080 | 55 | 1,130 | 105 | 1,185 | 160 |
| | Tintah beaches | *a* | 10 | 1,015 | 1,035 | 20 | 1,065 | 50 | 1,105 | 90 | 1,150 | 135 |
| | | *b* | 11 | 1,000 | 1,017 | 17 | 1,045 | 45 | 1,080 | 80 | 1,120 | 120 |
| | Campbell beaches | *a* | 12 | 990 | 1,000 | 10 | 1,015 | 25 | 1,045 | 55 | 1,080 | 90 |
| | | *aa* | 13 | 985 | 995 | 10 | 1,010 | 25 | 1,035 | 50 | 1,070 | 85 |
| | | *b* | 14 | 980 | 988 | 8 | 1,000 | 20 | 1,022 | 42 | 1,055 | 75 |
| | McCauleyville beaches | *a* | 15 | 970 | 977 | 7 | 987 | 17 | 1,007 | 37 | 1,035 | 65 |
| | | *aa* | 16 | 965 | 971 | 6 | 981 | 16 | 998 | 33 | 1,023 | 58 |
| | | *b* | 17 | 960 | 965 | 5 | 975 | 15 | 990 | 30 | 1,012 | 52 |
| Stages during outflow northeastward. | Blanchard beaches | *a* | 18 | [1](945) | 950 | (5) | 960 | (15) | 975 | (30) | 995 | (50) |
| | | *b* | 19 | (935) | 940 | (5) | 948 | (13) | 960 | (25) | 980 | (45) |
| | | *c* | 20 | (925) | 928 | (3) | 935 | (10) | 947 | (22) | 965 | (40) |
| | Hillsboro beach | | 21 | (915) | 918 | (3) | 923 | (8) | 935 | (20) | 953 | (38) |
| | Emerado beaches | *a* | 22 | (882) | ....... | ....... | 890 | (8) | 902 | (20) | 920 | (38) |
| | | *b* | 23 | (880) | ....... | ....... | 885 | (5) | 897 | (17) | 915 | (35) |
| | Ojata beaches | *a* | 24 | (870) | ....... | ....... | 875 | (5) | 887 | (17) | 905 | (35) |
| | | *b* | 25 | (860) | ....... | ....... | 865 | (5) | 877 | (17) | 895 | (35) |
| | Gladstone beach | | 26 | (840) | ....... | ....... | 845 | (5) | 857 | (17) | 875 | (35) |
| | Burnside beach | | 27 | (822) | ....... | ....... | 827 | (5) | 837 | (15) | 855 | (33) |
| | Ossowa beach | | 28 | (805) | ....... | ....... | ....... | ....... | 817 | (12) | 835 | (30) |
| | Stonewall beach | | 29 | (795) | ....... | ....... | ....... | ....... | 805 | (10) | 820 | (25) |
| | Niverville beaches | *a* | 30 | (755) | ....... | ....... | ....... | ....... | ....... | ....... | 775 | (20) |
| | | *b* | 31 | (750) | ....... | ....... | ....... | ....... | ....... | ....... | 770 | (20) |

[1] Figures in parentheses in the first column of elevations give approximately the heights which the stages of the lake during its outflow northeastward would have had at Lake Traverse if the land there had been low enough to permit the lake to extend south to its former outlet. From these estimated elevations the northward ascents of these stages, also in parentheses, are obtained, so as to be directly compared with the northward ascents of the beaches that were formed while the lake outflowed southward, showing the changes which were gradually taking place in the levels of the beaches of Lake Agassiz during the whole time of its existence.

*Stages of the glacial Lake Agassiz, western shore.*

[Continued by observations of Mr. J. B. Tyrrell in the region of Riding and Duck mountains and northward.]

| | On Valley River, Manitoba, 375 miles north of Lake Traverse. | | | On Shanty Creek, Manitoba, 395 miles north of Lake Traverse. | | | On Pine, Duck, and Swan rivers, Manitoba, 420 to 440 miles north of Lake Traverse. | | | On Kettle Hill, Manitoba, about 460 miles north of Lake Traverse. | | | On Mossy portage, and at the Grand Rapids of the Saskatchewan River, both in the Province of Saskatchewan, about 510 miles north of Lake Traverse. | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Numerical order. | Feet above the sea. | North ascent from Lake Traverse. | North ascent from latitude of Gladstone. | Feet above the sea. | North ascent from Lake Traverse. | North ascent from latitude of Gladstone. | Feet above the sea. | North ascent from Lake Traverse. | North ascent from latitude of Gladstone. | Feet above the sea. | North ascent from Lake Traverse. | North ascent from latitude of Gladstone. | Feet above the sea. | North ascent from Lake Traverse. | North ascent from latitude of Gladstone. |
| 1 | | | | | | | | | | | | | | | |
| 2 | | | | | | | | | | | | | | | |
| 3 | | | | | | | | | | | | | | | |
| 4 | | | | | | | | | | | | | | | |
| 5 | | | | | | | | | | | | | | | |
| 6 | | | | | | | | | | | | | | | |
| 7 | | | | | | | | | | | | | | | |
| 8 | 1,280 | 250 | 65 | 1,365 | 335 | 150 | 1,440 | 410 | 225 | | | | | | |
| 9 | 1,260 | 235 | 75 | 1,319 | 294 | 134 | | | | | | | | | |
| 10 | 1,220 | 205 | 70 | 1,287 | 272 | 137 | 1,365 | 350 | 215 | | | | | | |
| 11 | | | | 1,235 | 235 | 115 | | | | | | | | | |
| 12 | | | | 1,190 | 200 | 110 | 1,290 | 300 | 210 | | | | | | |
| 13 | 1,135 | 150 | 65 | 1,180 | 195 | 110 | | | | | | | | | |
| 14 | | | | | | | | | | | | | | | |
| 15 | 1,084 | 114 | 49 | [2]1,120 | 150 | 85 | [3]1,201 | 231 | 166 | | | | | | |
| 16 | 1,075 | 110 | 52 | | | | | | | | | | | | |
| 17 | | | | | | | | | | | | | | | |
| 18 | [1]1,040 | 95 | 45 | | | | 1,151 | 206 | 156 | | | | | | |
| 19 | | | | | | | 1,130 | 195 | 150 | | | | | | |
| 20 | | | | | | | [4]1,100 | 175 | 135 | | | | | | |
| 21 | | | | | | | 1,030 | 115 | 77 | 1,070 | 155 | 117 | | | |
| 22 | | | | | | | | | | 1,015 | 133 | 95 | | | |
| 23 | | | | | | | 960 | 80 | 60 | 995 | 115 | 100 | | | |
| 24 | | | | | | | | | | | | | | | |
| 25 | | | | | | | | | | 955 | 95 | 60 | | | |
| 26 | | | | | | | | | | 920 | 80 | 45 | | | |
| 27 | | | | | | | | | | | | | 910 | 88 | 55 |
| 28 | | | | | | | | | | | | | 875 | 70 | 40 |
| 29 | | | | | | | | | | | | | 845 | 50 | 25 |
| 30 | | | | | | | | | | | | | 800 | 45 | 25 |
| 31 | | | | | | | | | | | | | 790 | 40 | 20 |

[1] Estimated from its elevation of 1,025 feet on Ochre River.

[2] Estimated from its elevations on Valley and Pine rivers.

[3] 1,175 on Pine River; 1,201 on Duck River; 1,160 at Square Plain, Swan River.

[4] Estimated approximately for the vicinity of the two preceding; about 1,075 feet at Oak Creek, on the north side of Swan River.

northern quarter. These rates of ascent are slightly reduced in the second Norcross stage, where the total ascent is 160 feet. While the outlet was being eroded probably 5 feet between the Norcross stages, the combined rise of the land and decline of the lake level were about 10 feet on the international boundary and 25 feet on the latitude of Gladstone. The lake shore belonging to the Tintah stage *a* ascends about 20, 30, 40, and 45 feet in the successive distances from south to north, amounting in total to 135 feet; in the same distances the Campbell *a* shore ascends about 10, 15, 30, and 35 feet, in total 90 feet; the McCauleyville *a* shore ascends about 7, 10, 20, and 28 feet, in total 65 feet; and the McCauleyville *b* shore ascends about 5, 10, 15, and 22 feet, in total 52 feet. The erosion of the River Warren from the Norcross *a* stage to the McCauleyville *b* stage, at the end of which the southward outflow ceased, was about 70 feet; but the vertical distance between the shore-lines of these stages on the latitude of Gladstone is about 200 feet, the difference of 130 feet being attributable to the northward rise of the land and the fall of the lake level on account of the diminished attraction of the ice-sheet. The rate of northward ascent is reduced to less than an inch per mile along the southern part of the lowest McCauleyville shore, and to 3 or 4 inches per mile along its northern part, the average being 2 inches.

From the time of this lowest beach, formed during the southward outflow of Lake Agassiz, to the time of the first beach, formed during its northeastward outflow, the lake fell only about 15 feet. Thence there is now a descent, on the latitude of Gladstone, of about 220 feet to the Niverville beach, below which Lake Agassiz, while its northern barrier of ice remained, fell about 45 feet more before it was reduced to Lake Winnipeg. The northward ascent of these shore-lines of northeastward outlet decreases only slightly in the distance of 75 or 80 miles examined north of the international boundary, the change being approximately from 20 feet to 15 feet or less—that is, to the rate of about 2 inches per mile. If these stages of the lake had reached south to Lake Traverse, they would probably show a decrease from about 50 to 25 feet, or to 20 feet, in their total northward ascent above the level of the present time along the distance of more than 300 miles from Lake Traverse to the south ends of Lakes Manitoba and Winnipeg. The whole descent, on the latitude of Gladstone, between the lowest McCauleyville beach, where Lake Agassiz ceased to outflow southward, and the original level of Lake Winnipeg, about 20 feet above the present surface of that lake, is about 280 feet, of which probably 25 or 30 feet may be due to the northward rise of the land and diminution of gravitation toward the ice-sheet, while about 250 feet are due to the gradual lowering of Lake Agassiz by its successive northeastern outlets.

The depth of Lake Agassiz above the present surface of the south end of Lake Winnipeg was about 600 feet during its higher Herman stages, 500 feet at the upper Norcross stage, 440 feet at the upper Tintah stage, 370 feet at the upper Campbell stage, and 325 and 300 feet in the upper and lower McCauleyville stages, being thus reduced to half of its earlier depth before it ceased to flow to the south. During the lower stages of outflow to the northeast the depth of Lake Agassiz above Lake Winnipeg decreased to 285 feet at the upper Blanchard stage, about 240 feet at the time of the Hillsboro beach, 210 feet in the Emerado stage, and successively about 185, 165, 145, 130, 110, and 65 feet in the Ojata, Gladstone, Burnside, Ossowa, Stonewall, and Niverville stages.

The greatest expansion of Lake Agassiz was perhaps reached before the Herman series of beaches was completed, and it apparently was maintained during the greater part of the time of outflow by the River Warren; but through the successive stages of outflow northeastward the lake was diminished in area by nearly proportionate gradations as its depth decreased. When it began to flow in this direction it probably still occupied about half of its area that was attained during the formation of the Herman and Norcross beaches; but, in compensation for loss on its western and southern borders, it may have received meanwhile as great addition by growth toward the north and northeast, thus retaining, until it ceased to outflow at Lake Traverse, nearly its maximum extent.

Beyond the limits of my leveling, portions of nearly all the shore-lines of Lake Agassiz below those of the Herman series have been observed by Mr. J. B. Tyrrell, of the Canadian Geological Survey, at localities in northwestern Manitoba and eastern Saskatchewan. From a careful comparison of the elevation of the beaches noted by Mr. Tyrrell with those determined by my survey, I am enabled to correlate very satisfactorily the two sets of shore-lines. The northern continuations of the successive lake levels from the upper Norcross stage to the Niverville stages, inclusive, are thus identified upon a region lying 50 to 200 miles beyond the area examined by me. This correlation has been tabularly presented on page 477, in juxtaposition with the table showing how the shore-lines ascend along their extent from Lake Traverse to Gladstone.

In the southern area of my exploration nearly equal distances divide the several sections across the shore-lines which are compared together; but upon the country described by Mr. Tyrrell the spaces dividing successive sections are of various lengths. Between the latitude of Gladstone and the Valley River is a distance of 67 miles. Thence to Shanty Creek, the next locality of numerous observations, there is an interval of only 20 miles. Notations of the heights of nine beaches near the Pine, Duck, and Swan rivers are upon an area 25 to 45 miles farther north. In this group the observations in the valley of the Swan River are 20 to 30 miles west of the others, and therefore have, on account of the north-northeastward direction of the ascent of the former lake levels, a nearer equivalence with the elevations of beaches on the Pine River than on the Duck River. The fourth series of beaches recorded is on Kettle Hill, close south of Swan Lake, at a distance of some 20 or 25 miles north from the Duck River and the northern end of Duck Mountain, and about 150 miles north from the latitude of Gladstone. Finally, the fifth series was noted on Mossy portage and at the Grand Rapids of the Saskatchewan, about 50 miles north of the last.

As already stated in Chapters V and VIII, the beaches east and north of Riding and Duck mountains are found to have a more rapid northward ascent than along their southern portion traced by my leveling. It is also very noteworthy that this large amount of differential uplifting was chiefly done after the time of formation of the Campbell beaches, whereas nearly all the uplifting of the area from the southern mouth of Lake Agassiz to Gladstone had taken place earlier. During the first third or half of the period of the entire duration of Lake Agassiz the southern and central part of the lake basin, reaching north to Gladstone, had been raised nearly to its present height. Then followed a time, during the second third of the lake's existence, in which the district that includes Riding and Duck mountains and extends north to the mouth of the Saskatchewan was being rapidly uplifted. But this later northward and northeastward advance of the wave of upheaval had passed beyond the Saskatchewan before Lake Agassiz was reduced to Lake Winnipeg, as is shown by the nearly level Niverville beaches, the latest formed while the ice barrier remained. The rise of the land approximately to its present height is thus known to have followed close upon the glacial recession by which the land was relieved of the ice weight.

The remnants of the ice-sheet adjoining Hudson Bay were not melted away until the Recent or post-Glacial epoch had begun in the northern United States, their departure being possibly even nearer to the present day than to the time of withdrawal of the ice barrier of Lake Agassiz. Moving onward pari passu with the departure of the ice, the uplifting wave of the earth's crust has raised the basin of Hudson Bay 300 to 500 feet since the sea was admitted to it, and the upheaval there is not yet completed. Though doubtless slower than at first, it is still in progress, according to Dr. Bell's observations, at a probable rate of 5 to 7 feet per century.

Three stages of the elevation of this region from its Champlain subsidence are thus indicated by the beaches of Lake Agassiz and the fossiliferous marine beds overlying the till about Hudson Bay, the first extending from Lake Traverse to Gladstone and the south end of Riding Mountain, the second reaching thence probably to the northern and northeastern limits of the area that was occupied by Lake Agassiz, and the third affecting the basin of James and Hudson bays. On the common borders of these contiguous areas the uplifts were of course interblended; but it seems to be clearly shown by the Campbell and Niverville beaches that there was essential rest from the uplifting movement, with a permanence of height nearly as now, upon the southern part of the basin of Lake Agassiz while its northern part was rising, and afterward upon the whole of this basin while the country surrounding Hudson Bay has been elevated. A wave of permanent uplift has advanced from near the southern border of the glaciated area to its central portion, where the ice-sheet was thickest and where it lingered in remnants probably long after its principal mass was melted.[1]

According to my correlation, the highest beach observed by Mr. Tyrrell east of Riding and Duck mountains belongs to the upper Norcross stage of Lake Agassiz, which now has an ascent of 410 feet from its mouth, near Lake Traverse, to Pine River, in a distance of about 420 miles. The rate of ascent of this beach from the latitude of Gladstone to Valley River is about 1 foot per mile, but thence for nearly 50 miles northward to Pine River it somewhat exceeds 3 feet. The same rates of ascent continue, with only slight changes in the Tintah and Campbell beaches, for the distances from the latitude of Gladstone to the Valley and Pine rivers. This portion of the western shore of Lake Agassiz had risen almost uniformly throughout its extent while these beaches were being formed. It had been lifted as a whole to the same amount as its southern part near Gladstone, but it experienced scarcely any differential elevation or tilting until after the formation of the Campbell beaches.

The rate of northward ascent of the upper McCauleyville beach is 9 inches per mile between Gladstone and the Valley River, and thence northward for 55 miles to the Duck River it ascends a little more than 2 feet per mile. In the case of the upper Blanchard beach, the lowest noted near the Valley River, these rates of ascent are respectively 8 inches and 2 feet.

After Lake Agassiz began to outflow northeastward, the differential northward uplifting of this district of the Riding and Duck mountains went on rapidly, amounting probably to 70 feet within the distance of 50 miles next northward from the Valley River during the time between the upper Blanchard beach and the lower Emerado beach. The latter has an ascent of only 60 feet in about 110 miles northward from Gladstone to the Pine River, while in the next 40 miles north to Kettle Hill it rises, like the preceding Hillsboro beach, 1 foot per mile.

Below these shore-lines the later lake levels have been changed comparatively little from their original horizontality. In the distance of 150

[1] Journal of Geology, Vol. II, pp. 383–395, May–June, 1894.

miles northward from the latitude of Gladstone to Kettle Hill the lower Ojata beach and the Gladstone beach ascend, respectively, 60 and 45 feet; and in 200 miles from Gladstone to the Mossy portage and the mouth of the Saskatchewan the successive ascents of the Burnside, Ossowa, and Stonewall beaches are 55, 40, and 25 feet, or only about 3 inches to 1½ inches per mile.

The very regular northward rise of the beaches of this lake throughout all their explored extent, nowhere having any abrupt changes of level, indicates clearly that this region has not experienced violent orogenic disturbance nor faulting since the departure of the ice-sheet. Its changes of level, which have been of large amount, as shown by the tilted planes of the former lake surfaces, took place gradually and continued through the entire duration of the lake. They went forward most rapidly upon the areas which had been latest bared from the retreating ice-sheet, and they were essentially finished, bringing the basin to the same height and attitude as now before the ice barrier was removed from the course of the Nelson River. The continuity of the beaches and the slow and gradual changes in their gradients prove that no faults or dislocations attended the uplifting, tilting, and bending of the subjacent rock formations.

## EASTWARD ASCENT OF THE FORMER LAKE LEVELS.

Exploration of the beaches formed on the east side of Lake Agassiz has been mostly limited to Minnesota, because the eastern part of this lake area in Manitoba is covered by forest and is almost wholly without settlements or roads, so that for the present a survey of the shore-lines there is impracticable. For the same reasons the upper shores in Minnesota have not been exactly traced east of Maple Lake, which lies 20 miles east-southeast of Crookston. Within the prairie area across which the highest eastern shore has been surveyed and its elevation determined by leveling its northward ascent is about 115 feet in 140 miles, from 1,055 feet above the sea at Lake Traverse to 1,170 feet at the north side of Maple Lake. As on the western shore of Lake Agassiz, the rate of ascent gradually increases from south to north, ranging from 6 inches to 1 foot per mile in its southern portion for about 75 miles, and from 1 foot to 16 inches per mile farther north. Before the lake in Minnesota had fallen below its highest eastern beach in the south half of its explored extent the rise of the land and diminution of attraction of the waning ice-sheet had caused a slightly lower parallel beach, three-fourths of a mile to 1½ miles distant, to be formed through the northern third of Clay County; and this secondary beach, sometimes double or triple, is observable at several places along the next 30 miles northward. At the northwest side of Maple Lake definite beach ridges belonging to the Herman stages of Lake Agassiz lie successively about 8, 15, 30, and 45 feet below its highest beach. Yet all these shore-lines were formed while the relative heights of the land and the lake continued stationary or with only slight change, not sufficient for the formation of any secondary beach ridge, along a distance of some 75 miles northward from Lake Traverse and Herman.

The Norcross beaches in Minnesota have been explored and their height measured through the same extent of 140 miles, in which the upper Norcross beach ascends northward about 65 feet by a slope that increases slightly from south to north, averaging nearly 6 inches per mile. In like manner the northward ascents of the Tintah, Campbell, and McCauleyville beaches in Minnesota, and of the lower beaches formed on this east side of the lake during its outflow to the northeast, show a gradual decrease nearly as on the west in North Dakota and Manitoba.

But comparison of the western and eastern shores reveals another very interesting feature of the levels of this glacial lake, namely, an ascent from west to east similar to that from south to north, but of less amount and diminishing in a similar ratio between the successive stages of the lake. On the latitude of Larimore and Grand Forks the ascent of the highest Herman stage of Lake Agassiz above a line now level is approximately 33 feet in about 70 miles from west to east, the rate per mile being very nearly half as much as from south to north; and in the later Herman stages it is diminished to about 30, 25, and 20 feet. On the Norcross shore-lines this ascent toward the east is approximately 10 feet in about 60 miles, and it is reduced in the McCauleyville stages to only 3 or 4 feet in about 50 miles; yet it continues through all these stages approximately half as much per mile as the ascent toward the north. The rate of ascent eastward also increases, like that northward, in proceeding from south to north. At the latitude of Wahpeton and Breckenridge, 35 miles north from the mouth of Lake Agassiz, the ascent of its highest stage is 10 feet from west to east in 45 miles; at the latitude of Fargo and Moorhead, 75 miles north from the outlet, it is 15 feet in 50 miles; and at the latitude of Grand Forks, 150 miles north from the outlet, it is 33 feet in 70 miles.

### RATE OF ASCENT GREATEST TOWARD THE NORTH-NORTHEAST.

These observations that the corresponding beaches are higher on the east than on the west side of the lake, taken in connection with the doubly more rapid northward ascent of the west and east shores, indicate that the changes in the relations of the land and surfaces of level during the existence of Lake Agassiz and through subsequent time have given to the former levels of this glacial lake a maximum ascent from south-southwest to north-northeast, its rate in this direction being somewhat greater than that noted in following the shores in their nearly due-north course. The maximum rates of northward ascent of about 1 foot per mile observed in North Dakota and southern Manitoba, and of 1 foot to 16 inches per mile in Minnesota, therefore belong to a lake level which in its northern portion, within the limits of my exploration, differs from the present level by an ascent of approximately 1½ feet per mile toward the north-northeast. Similar north-northeastward ascent continues through the successive lower stages of the lake, in which its amount in southern Manitoba, between the international boundary and Gladstone, is reduced to about 4 inches per mile at the lowest stage of southward outflow; and it is scarcely 1 inch per mile in the Niverville beaches along their whole observed extent of about 260 miles from Morris, Manitoba, north to the mouth of the Saskatchewan. No more than 20 feet of differential northward uplift has taken place within this distance since the course of the Nelson River was uncovered by the receding ice-sheet.

Preliminary descriptions and discussions of the uplifting of this basin which have been given in the chapter on the history of Lake Agassiz showed that the movement of elevation of the country at Lake Traverse after the ice above was melted probably did not exceed 90 feet; that thence northward the rise of the land and sinking of the geoid level, as affected by ice attraction, increased to a combined value of about 350 feet at Gladstone and nearly 500 feet in the district of the northern part of Duck Mountain, where, as in North Dakota and Minnesota, the maximum rate of ascent of the beach planes is toward the north-northeast; and that probably thence north to the Saskatchewan and the Churchill, northeast to Hudson Bay, and east to James Bay, the Ottawa basin, and Montreal, the amount of uplift, since the departure of the ice, of a very large central part of the area which it had covered was somewhat uniformly 500 to 600 feet. It has been also shown from Mr. Tyrrell's observations in the district of Riding and Duck mountains that after the southern half of the lake area had been raised almost to its present height, and while that country north to Gladstone lay nearly undisturbed, a great uplift of later date took place in the next 100 miles to the north; and that, after both these movements, the region of Hudson and James bays was still later raised, probably from its maximum depression to its present height. Throughout the area of my survey of the Lake Agassiz shore-lines, and northward along the Riding and Duck mountains, the epeirogenic movement was a tilting with ascent to the north-northeast, toward the region where the ice-sheet had its greatest thickness; but the more northern and northeastern part of this lake bed, with a great adjoining central portion of the vast expanse which had been ice-enveloped, were elevated to an approximately uniform amount. The elevation progressed from south to north and northeast like a wave, permanently uplifting successive areas, excepting so far as the borders of each necessarily shared in the movements of the contiguous tracts earlier or later uplifted.

## CHANGES OF LEVELS NEARLY COMPLETED DURING THE EXISTENCE OF LAKE AGASSIZ.

Nearly the entire amount of the changes in the levels of the beaches of Lake Agassiz was evidently contemporaneous with the existence of this lake, taking place gradually, but apparently progressing comparatively fast between the stages marked by the formation of definite beaches, which doubtless belong to times when these changes advanced very slowly or were interrupted by intervals of repose. Great as were the combined epeirogenic uplift and modification of the geoid surface of level, producing a differential rise of the highest western shore of the lake in Manitoba to the extent of 175 feet at the international boundary, 265 feet at the latitude of Gladstone, and about 400 feet at the latitude of 51° 52′ north on the east side of Duck Mountain, 200 miles north of the international boundary, in the relation of the land to the water level, as compared with the vicinity of Lake Traverse, they were yet almost or perhaps quite completed before the ice-sheet was so far withdrawn that it was no longer a barrier to prevent free drainage from the basin of the Red River and Lake Winnipeg.

During the subsequent postglacial period, to the present time, only very slight changes have taken place in the relative elevations of the part of this area where the heights of the beaches of Lake Agassiz have been determined in Minnesota, North Dakota, and Manitoba; and these small changes of level, shown by the Niverville beaches, have been merely a continuation of the movements which accompanied the recession of the ice-sheet and are recorded by the successive shore-lines of this lake.

## CAUSES OF THE CHANGES OF LEVELS.

In attempting to discern the causes of the changes of levels shown by the shore-lines of Lake Agassiz, three diverse agencies, which certainly must have been factors working together to produce the observed results, are to be studied with respect to the proportion contributed by each. They are considered in the following order: (1) Gravitation of the water of Lake Agassiz toward the ice-sheet; (2) changes in the temperature of the earth's crust due to the ice-sheet, or, in other words, to the cold of the Glacial period and the return of the warmer climate now enjoyed; (3) epeirogenic movements, or downward and upward bending, often more or less accompanied with the formation of faults, affecting large areas of the earth's surface, which may be due (*a*) to the imposed weight of the ice-sheet and to its removal, or (*b*) to conditions and stresses of the earth's crust and interior originating otherwise, as by secular cooling and contraction.

The order in which we shall thus examine these several parts of the complex causation of the changes of levels is not, however, the order of their importance or several shares in the work. The third agency, manifested in obedience to the pressure of the ice and in resilience when relieved from it, is found to have been the principal factor, producing far the greater part of the changes of levels. Its manifestation within the area of Lake Agassiz during the Glacial and Recent periods on account of the other conditions and stresses mentioned appears to be only a small element in the problem; though, when thus originating, it is seen to have had great importance in causing such changes in other parts of the world, and even in parts of North America, contemporaneously with the uplifting of the basin of this lake. The first agency noted is found to be a considerable factor, working in the same directions as the epeirogenic effects of the transient ice weight, and contributing perhaps a fifth or a fourth as much toward the changed relations of the water level and the land area. But the second agency, upon investigation, proves to have been slight in its effect, and within the basin of Lake Agassiz, so far as it availed, it was opposed to the other two.

### GRAVITATION TOWARD THE ICE-SHEET.

Consideration of the character of the changes in the levels of the beaches, resulting in a greater ascent upon the northern part of the area examined than farther south, and gradually approximating, through the successive stages of the lake, to parallelism with the present geoid surface of level, led me in my earlier studies to attribute these changes almost wholly to gravitation of the water of the lake toward the ice-sheet. The cause of the present relations of the old shore-lines seemed to be discovered in the explanation that at first this attraction had a large effect upon the lake level because of the nearness of a great depth of ice on the east in northern Minnesota and on the north in British America, but that afterward it was gradually diminished to a comparatively small influence when the southern portion of the ice-sheet had been melted and the attracting force proceeded from the region far north between Lake Winnipeg and Hudson Bay.[1] Under this view the earth's crust was believed to be so

[1] Geol. and Nat. Hist. Survey of Minnesota, Eleventh Annual Report, p. 152; U. S. Geol. Survey, Bulletin No. 39, p. 18.

rigid that it was not depressed by the vast weight of the ice nor raised when relieved of that weight, and the changes were believed to consist chiefly in the differential subsidence of the lake level, not in the differential elevation of the land basin.[1] The general uniformity of these changes in their direction and extent, and their probable completion during the departure of the ice-sheet, seemed to accord with this hypothesis. The exact comparison of the shore-lines surveyed by me, with leveling, on both the east and west sides of the lake, extending for its upper stages 140 miles from south to north in Minnesota and more than 300 miles from south to north in North Dakota and southern Manitoba, shows no considerable irregularity in the rates of northward and eastward ascent—that is, of north-northeastward ascent—of the former lake levels, which thus seem to be attributable to gravitation toward the waning ice-sheet, rather than to a progressive elevation of the land, for that would be expected to present noteworthy irregularities upon so large an area. It is probable, however, that close scrutiny of the shore-lines will disclose small divergences, within limits of a few feet, from the uniformity of slopes which they should have for agreement with this explanation; and it is to be noticed that the highest shores in the vicinity of Treherne, Brandon, and Neepawa, Manitoba, have more nearly a northward than north-northeastward ascent; also that a slightly disproportionate increase in the ascent of the highest Minnesota shore-line in the next 10 or 15 miles north of the Buffalo River was ascribed to the proximity of a portion of the ice-sheet on the east, where it was forming the Fergus Falls and Leaf Hills moraines. Though it now appears true that the greater part of these changes of level are due to the differential rise of the land, the gravitation of the lake toward the ice-sheet certainly operated in conjunction with that cause, contributing to the full extent of its competency in producing the results observed.

Mr. R. S. Woodward, of the United States Geological Survey, has worked out the mathematical problem of determining the effect of any

[1] Similar oscillations in the relative heights of sea and land, associated with glaciation, have been thus ascribed to ice attraction by Adhemar, in Révolutions de la Mer, 1840; by Croll, in Climate and Time, 1875; and by Penck, in Schwankungen des Meeresspiegels, Jahrbuch der Geographischen Gesellschaft zu München, bd. VII, 1882.

added mass, as an ice-sheet, upon the earth's surface, to disturb the levels of the sea and of lakes.[1] Assuming an ice-sheet with a radial extent of 38°, or about 2,600 miles, and a central depth of 10,000 feet, from which the depth decreases at first slowly and then more rapidly to its border, he finds that the average slope within 1 degree of the border of the ice would be about 5 inches per mile, or less than one-third of the north-northeastward ascent of the highest shore-lines of Lake Agassiz in the north part of the area where they have been traced with leveling. If we compare the premises in this problem with the probable conditions affecting this glacial lake, it seems sure that the North American ice-sheet in its maximum extent covered not more than about one-fourth so great an area, its extent being equivalent to a spherical circle with a radius of 1,200 or 1,300 miles; but, on the other hand, it is probable that the maximum depth of this ice-sheet somewhat exceeded 10,000 feet, and that the area of this great depth was a belt extending eastward from a few hundred miles north or northeast of the south part of Lake Agassiz to a distance of about 1,000 miles east-northeast, lying thus much nearer than in the assumed case of Mr. Woodward's investigation. The smaller area and less total mass of the ice-sheet attracting Lake Agassiz may have been offset by the nearer position of a large part of its mass than in the assumption of the problem, so that possibly its influence might be as great in producing an ascent of the lake level above the level of the present time; but, if this mathematical investigation is reliable, gravitation of the lake toward its ice barrier could not give to its highest shore a northward ascent of more than a few inches per mile, at the most not so much as half a foot, whereas its observed ascent within the area of my leveling attains a maximum rate of 1 foot to 16 inches per mile, and this belongs to a north-northeastward ascent of fully 1½ feet per mile. A quarter part, or probably less, of the changes in the levels of these beaches is therefore referable to ice attraction, while the

[1] U. S. Geol. Survey, Sixth Annual Report, for 1884–85, pp. 291–300; and Bulletin No. 48, "On the form and position of the sea level," 1888, p. 88. Compare also Prof. Edward Hull's computations, "On the effect of continental lands in altering the level of the adjoining oceans," Geol. Magazine (3), Vol. V, pp. 113–115, March, 1888; "Polar ice-caps and their influence in changing sea levels," by Sir William Thomson, Trans., Geol. Society of Glasgow, Vol. VIII, 1888, pp. 322–340; and "The study of the earth's figure by means of the pendulum," by E. D. Preston, Am. Jour. Sci. (3), Vol. XLI, pp. 445–460, June, 1891.

remaining three-quarters, or a larger part, amounting at least to about 130 to 300 feet, from south to north, in southwestern Manitoba, belongs to a differential elevation of the land.

CHANGES IN THE TEMPERATURE OF THE EARTH'S CRUST.

Among the conditions producing changes in the height and slopes of the land on which Lake Agassiz lay are the cooling and contraction of the earth's crust by the ice-sheet and glacial waters, and the subsequent warming and expansion owing to the amelioration of the climate. The superficial portion of the earth's crust in the Red River Valley has a temperature of 47° to 42° F., as shown by the water of artesian wells situated respectively at Ada and Donaldson, Minn.[1] But during the time when this district was covered by the ice-sheet the temperature of the underlying land surface was reduced to the freezing point, 32° F., and a similar lowering of temperature may have affected the crust to a considerable depth, largely through the influence of percolating water, causing a slight depression of the isogeotherms, with consequent contraction of the rocks and lowering of the land surface. By comparison with the present mean annual temperature of the Red River Valley, ranging approximately from 41° at Lake Traverse to 33° at Winnipeg,[2] it is evident that the artesian waters before noted receive part of their heat from the earth's interior. In like manner probably the interior heat kept the superficial portion of the earth's crust beneath the ice-sheet as warm as 32°, at which temperature the earth's heat would be continually melting the ice, though certainly at a very slow rate.

The differences in the temperatures of the earth's crust, due to the ice-sheet and to water permeating downward from it, would not, therefore, probably exceed 15° from that of the present time in the southern part of the basin of Lake Agassiz, and would decrease to 10° at Donaldson, in Kittson County, the most northwestern in Minnesota, and to even a less amount at Winnipeg. The extent to which these slight changes in the

[1] Geol. and Nat. Hist. Survey of Minnesota, Eleventh Annual Report, pp. 147, 148. Detailed descriptions of these wells are given in the next chapter.

[2] C. A. Schott in Smithsonian Contributions to Knowledge, Vol. XXI, 1876; Atlas of the Tenth Census of the United States; Report of the Department of Agriculture and Statistics of Manitoba for 1882, p. 318. Also see Chapter XI for statements of the monthly and mean annual temperature of this district.

crustal temperatures would depress the land while it was ice-covered and raise it when the ice was withdrawn depends on the ratios of contraction and expansion of the underlying rocks. These ratios have been experimentally determined in the case of various building stones, and computations therefrom indicate that only a very small amount of subsidence and elevation of the land could be caused in this way.[1] The total elevation so produced was probably not more than 50 feet in the southern part of the Red River Valley, and not more than 30 feet at Winnipeg; and its slight differential effect would be in the opposite direction to that which has given to the beaches of Lake Agassiz their northward ascent. This element in the causation of the changes of elevation appears to be comparatively insignificant in itself, and its small component in the oscillation of the shore-lines would be opposed to that for which we are seeking an explanation.

### EPEIROGENIC MOVEMENTS APPARENTLY DEPENDENT ON GLACIATION.

It seems to be very clearly indicated by the gradual diminution in the northward ascent of the beaches, until the lowest and latest have nearly the level of the present time, that these progressive changes of elevation were directly dependent upon the departure of the ice-sheet, with which great geologic event they were contemporaneous. As already noted in Chapter V and on a foregoing page of this chapter, these changes were so directly proportionate with the glacial recession that the northward ascents of the successive beaches were at first referred to the diminishing gravitation of the lake toward the ice-sheet; but, apart from the inadequacy of this cause, determined by Mr. Woodward's investigations, the great extent of the highest beach and its relation to terminal moraines marking stages in the glacial recession sufficiently demonstrate that other causes contributed even more than ice attraction to produce the changes observed in the levels of the beaches.

There remain to be considered, as probable causes, first, the relationship between the earth's crust and its interior which may have permitted a

[1] T. C. Chamberlin in Sixth Annual Report, U. S. Geol. Survey, p. 302, and in paper read before the Philosophical Society, Washington, March 13, 1886; G. K. Gilbert in Am. Jour. Sci. (3), Vol. XXXI, p. 297, April, 1886, and in U. S. Geol. Survey, Monograph I, "Lake Bonneville," pp. 377, 378.

sinking of the crust beneath the vast weight of the ice-sheet and a reelevation when that weight was removed, and, second, oscillations which may have occurred without dependence on the glaciation. For the discrimination of these movements it will be very instructive to notice the changes of elevation that have been going forward at the same time in other parts of the North American and European glaciated regions, and also in various areas which were never thus ice-laden. If Lake Agassiz is found to be an instance where nearly all these changes are apparently referable to glaciation, there will be no lack of opportunity for comparing it with other regions where the effects due to glaciation are combined with independent crustal movements.

*Discussion of the relationship of the earth's crust to the interior.*—My former reference of the northward ascent of the beaches of Lake Agassiz to ice attraction, with the assumption that the earth was so rigid that its form would not be changed by the load of the ice-sheet nor by its removal, seemed more probable because of the well-known physical and mathematical researches of Hopkins, Thomson, Pratt, and Prof. G. H. Darwin, who conclude that the earth is probably solid, with not less rigidity than that of glass or of steel. In deference to their investigations, this conclusion is accepted and taught in recent text-books of geology by A. Geikie and Le Conte;[1] but in similarly recent text-books Prestwich and Dana teach that the earth probably consists of a comparatively thin crust, underlain by a molten interior, which may change within a moderate depth to a great nucleal solid mass. Among other geologists and physicists who have discussed the conditions of the earth's interior, King,[2] Shaler,[3] and

[1] Since the publication of Le Conte's Elements of Geology, revised second edition, 1882, this eminent geologist has abandoned the opinion here noted, and now believes "that the general structure of the earth is that of a solid nucleus constituting nearly its whole mass, a solid crust of inconsiderable comparative thickness, and a subcrust liquid layer, either universal or over large areas, separating the one from the other. * * * Also that the crust rests upon the subcrust liquid as a floating body." American Geologist, Vol. IV, pp. 38–44, July, 1889; Am. Jour. Sci. (3), Vol. XXXVIII, pp. 257–263, Oct., 1887; Elements of Geology, third edition, 1891, pp. 84–87, 264.

[2] U. S. Geological Exploration of the Fortieth Parallel, Vol. I, Systematic Geology, 1878, pp. 117, 696–725.

[3] Proc., Boston Soc. Nat. Hist., 1866, Vol. XI, pp. 8–15; 1868, Vol. XII, pp. 128–136; 1874, Vol. XVII, pp. 288–292. Memoirs, Boston Soc. Nat. Hist., 1874, Vol. II, pp. 320–340. Scribner's Magazine, Vol. III, pp. 201–226, Feb., 1888.

Reade[1] believe it to be solid, while Whitney,[2] Dutton,[3] Powell,[4] Wadsworth,[5] Crosby,[6] Claypole,[7] Phillips,[8] Airy,[9] Fisher,[10] and Jamieson[11] believe that it is molten, or at least is surrounded by a molten layer, and that the earth's crust floats in a condition of isostasy[12] or gravitational equilibrium upon the heavier liquid or viscous mobile interior or layer enveloping the interior, subject, however, to stresses and resulting deformation because of the earth's contraction. The thickness of the crust, according to this hypothesis, is variously estimated to be from 20 to 50 miles, or possibly 100 miles or more.

Another statement of the probable relationship of the earth's crust to the interior, which seems to come between these diverse opinions and in some measure to express the important features of each, is given as follows by Gilbert, in his discussion of faults and displacements of the Wasatch range and the area of Lake Bonneville:

> We are forced to conclude that the mountain ranges of the Bonneville basin and the valleys between them do not, with reference to each other, obey the law of flotation.
>
> It follows with equal cogency that the faults do not penetrate to a layer characterized by fluidity or semi-fluidity, implying by these terms the power to flow under small shearing strain, but terminate in a region of rigidity, implying by that term the ability to withstand relatively large shearing strain. I conceive them to terminate at the upper limit of the region of plasticity by pressure, implying by that phrase that at and below a certain depth the rocks of the crust, however rigid, are

[1] The Origin of Mountain Ranges, 1886, pp. 6, 7, 256, 267, 270, etc. Philosophical Magazine, June, 1891 (also in Am. Geologist, Nov., 1891).

[2] Earthquakes, Volcanoes, and Mountain Building, 1871, pp. 77–87.

[3] Penn Monthly, Vol. VII, pp. 364–378, and 417–431, May and June, 1876. U. S. Geol. Survey, Fourth Annual Report, pp. 183–198; Sixth Annual Report, pp. 195–198.

[4] Science, Vol. III, pp. 480–482, April 18, 1884. The Forum, Vol. II, pp. 370–391, Dec., 1886.

[5] Am. Naturalist, Vol. XVIII, June, July, and August, 1884.

[6] Proc., Boston Soc. Nat. Hist., 1883, Vol. XXII, pp. 443–485. Geol. Magazine (2), Vol. X, 1883, pp. 241–252.

[7] Am. Naturalist, Vol. XIX, pp. 257–268, March, 1885. Am. Geologist, Vol. I, pp. 382–386, and Vol. II, pp. 28–35, June and July, 1888.

[8] Vesuvius, 1869, pp. 324, 329.

[9] Nature, Vol. XVIII, pp. 41–44, May 9, 1878.

[10] Physics of the Earth's Crust, 1881, pp. 223, 270, etc.

[11] Geol. Magazine (3), Vol. IV, 1887, pp. 344–348.

[12] A term proposed by Capt. C. E. Dutton in a paper "On some of the greater problems of physical geology," Bulletin of the Philosophical Society of Washington, Vol. XI, pp. 51–64, April 27, 1889. See also an important discussion of this condition of the earth's crust, "The Gulf of Mexico as a measure of isostasy," by W J McGee, in Am. Jour. Sci. (3), Vol. XLIV, pp. 177–192, Sept., 1892.

subject to such pressure that their yielding under shearing strains exceeding the elastic limit is not by fracture, but by flow. I conceive the orogenic blocks as confluent with the subjacent layer, excepting such as may wedge out by the convergence of fault planes.[1]

This view is closely allied with that which regards the interior as solid, and, indeed, if I understand the authors holding the doctrine of solidity, forms a necessary postulate of their explanation of orogenic and epeirogenic movements. It is again well stated by Becker, who regards the earth "as a solid mass of extremely high viscosity which would yield slowly to relatively moderate forces of constant terrestrial direction and long duration, but which would probably yield almost imperceptibly to any force of brief duration or rapidly changing direction."[2] For such a condition, however, which seems to me probably or possibly true for all the earth excepting its volcanic areas, I should prefer, as more intelligible to ordinary readers, to speak of the interior as plastic rather than as either solid or liquid, though in its rigidity or resistance to change of form it may equal or surpass the hardest rocks of the earth's surface.

In the present state of our knowledge, the elevation of the area of Lake Agassiz, increasing in amount from south to north, during the departure of the ice-sheet, seems most clearly intelligible by supposing it to have been an uplifting of the crust by the inflow of plastic if not perfectly molten rock from districts outside the glaciated area, occurring probably between the depths of 20 and 100 miles, in obedience to gravitation, which, to preserve the condition of isostasy, would cause the crust, when loaded by the ice-sheet, to sink and displace part of the plastic interior, and when the ice-sheet was removed would cause the plastic rock to flow back and raise the crust approximately to its former height.

It must be confessed that we have only a very inadequate knowledge of the conditions which would result from the enormous pressure and high temperature of the earth's interior; and wide diversity in speculations on this subject will probably long continue. Professor Shaler, while holding that the earth is mainly solid throughout, perhaps having in its most mobile layer beneath the crust "a rigidity such as belongs to the metals of average

[1] U. S. Geol. Survey, Monograph I, Lake Bonneville, 1890, pp. 358, 359.
[2] Bulletin, G. S. A., Vol. II, 1891, p. 70.

resistance to compression," yet is one of the earliest and most decided advocates of the opinion that the weight of an ice-sheet may depress the area on which it lies, and that the departure of the ice would be attended by reelevation. In comparison, however, with the physical conditions and laws familiar to us upon the earth's surface, the subsidence and elevation of extensive areas, as of nearly all glaciated regions, seem to demonstrate a mobility of the earth's interior as if it were fused rock. The same conclusion is indicated by volcanoes, which are probably the openings of molten passages that communicate downward through the crust to a heavier melted portion of the interior, thence deriving their supply of heat, while their outpoured lavas consist largely or wholly of fused portions of the crust, the phenomena of eruption being caused by the access of water to the upper part of the molten rock, near the volcanic vent. But the great plications of the strata in the formation of mountain chains evidently involve only the upper part of the earth's crust, crumpled into smaller area in adapting itself to the diminishing volume of the lower portion of the same crust, which, with the nucleus, is undergoing contraction on account of the gradual loss of its heat, and perhaps also on account of progressing solidification and compression. There is in this process no dependence on the plastic or perhaps molten condition of the interior, except as that seems to be necessary for distortion of the earth, both of the crust and nucleus or mobile layer enveloping the nucleus, whereby considerable shrinkage of volume can take place before the accumulated stress becomes sufficient for the formation of a mountain chain. At the present time depressions and elevations, probably caused by accumulating stresses, are slowly changing the relations of land and sea upon many parts of the earth's surface. In the same way the downward and upward movements which would be caused by the burden of the ice-sheet and its removal are doubtless in many places complicated by concomitant or subsequent movements thus due to deformation under stresses, by which the elevation attributable to the departure of the ice-sheet may be augmented or partly or wholly counteracted, giving much irregularity to the glacial and postglacial oscillations of the land.

The area of Lake Bonneville has experienced changes of level since the formation of its highest shore-line, which Mr. Gilbert finds to be in harmony with the explanation that they were due to the evaporation of the lake and the consequent partial restoration of equilibrium by the underflow of plastic rock; but he regards his observations as too incomplete to furnish absolute proof of this hypothesis.[1] A supplementary and more satisfactory test is supplied by this survey of Lake Agassiz. Debarred from referring the northward ascent of the beaches of this glacial lake chiefly to ice attraction, I regard my observations of their increasing rate of ascent in proceeding from south to north, the gradual approximation in the lower beaches toward horizontality, and the probable completion of these changes in relative elevation during the existence of Lake Agassiz and the departure of the ice-sheet, as all strikingly accordant with this explanation, and, indeed, as demonstrative of its truth. These changes in the levels of the beaches of Lake Agassiz, partly pertaining to the lake itself and in larger part to the crust of the earth, are thus believed still to be wholly referable to the influence of the ice-sheet in its recession, with which they show such remarkable correspondence in the direction, character, and gradual decrease of the northward ascent. No irregularities of the differential changes in elevation are found which seem to require other explanation, the rise caused by the removal of the ice-sheet not being combined upon this area, so far as can be determined, with independent earth movements either of elevation or depression.

*History of the doctrine of crust deformation by the ice-sheet.*—Jamieson appears to have been the first, in 1865, to suggest this view, which I receive from him, that the submergence of glaciated lands when they were loaded with ice has been caused directly by this load pressing down the earth's crust upon its fused interior, and that the subsequent reelevation was a hydrostatic (or we may better say isostatic) uplifting of the crust by underflow of the inner mass when the ice was melted away.[2] Two

[1] Am. Jour. Sci. (3), Vol. XXXI, pp. 284–299, April, 1886. U. S. Geol. Survey, Monograph I, Lake Bonneville, 1890, pp. 379–392.

[2] Quart. Jour. Geol. Soc., Vol. XXI, p. 178. Later discussions of this subject by Mr. Jamieson are in the Geological Magazine (2), Vol. IX, pp. 400–407 and 457–466, Sept. and Oct., 1882; and (3), Vol. IV, pp. 344–348, Aug., 1887. In the article last cited he applies this explanation to the changes of the beaches of Lake Agassiz, which up to that time I had attributed mainly to ice attraction. The same principle, however, was brought forward by Sir John Herschel in 1836, and had been advocated by Prof. James Hall, of New York, in 1859, in attributing to the weight of sediments the long-continued subsidence of the areas on which they have been deposited in great thickness.

years later Whittlesey published a similar opinion.[1] In 1868 Shaler referred the subsidence of ice-covered areas to a supposed rise of isogeothermal lines in the subjacent crust, operating, in conjunction with the ice-sheet, to produce downward flexure;[2] but in 1874 and later he regards the depression as due directly to the weight of the ice, and the reelevation as due to its removal.[3] The same view is advanced also by Chamberlin to account for the basins of the Laurentian lakes, where he believes a considerable part of the glacial depression to have been permanent.[4]

*Tardiness in the beginning of the changes of levels of the Lake Agassiz basin.*—That the greater part of the changes of levels upon the area of Lake Agassiz has been due to differential elevation of the earth's crust, instead of ice attraction, seems to be proved by the tardiness of their beginning, as shown by the relationship of the highest beach of Lake Agassiz to the contiguous terminal moraines formed on the adjacent land areas during the recession of the ice-sheet, of which a detailed description has been given in Chapter IV. The highest beach is continuous on the east from Lake Traverse about 140 miles north to Maple Lake, which is as far as exact exploration of it has been carried. On the west this shore-line is unbroken along an extent of about 250 miles from south to north, reaching into Manitoba. Now the adjacent Dovre, Fergus Falls, Leaf Hills, and Itasca moraines appear to have been successively accumulated during the time of formation of this single highest beach, which marks, through so great distances and so large a portion of the glacial recession, a nearly or quite unvarying stage of the lake and undisturbed repose of the earth's crust. If diminishing gravitation of the water of the lake toward the ice-sheet had been the chief cause, or even an element of large importance among component causes, of the changes of levels of the beaches, the surface of the lake must have fallen considerably in its northern portion

[1]Proc., A. A. A. S., Vol. XVI, pp. 92–97.

[2]Proc., Boston Soc. Nat. Hist., Vol. XII, pp. 128–136.

[3]Proc., Boston Soc. Nat. Hist., Vol. XVII, pp. 288–292; Memoirs, Boston Soc. Nat. Hist., Vol. II, pp. 335–340. Am. Jour. Sci. (3), Vol. XXXIII, pp. 220, 221, March, 1887. Scribner's Magazine, Vol. I, p. 259, March, 1887.

[4]Geology of Wisconsin, Vol. I, 1883, p. 290; Proc., A. A. A. S., Vol. XXXII, 1883, p. 212. The problems of ice attraction and of deformation of the earth's crust have been further discussed by Professor Chamberlin before the Philosophical Society of Washington, March 13, 1886; and, jointly with Professor Salisbury, in the Sixth Annual Report, U. S. Geol. Survey, pp. 291–304.

because of the decreasing attraction of the ice during the stages of its retreat between these moraines. But the extent of the highest beach shows that no appreciable changes of level took place while the ice-sheet was being melted back 250 miles or more and was probably much reduced in thickness upon a large area farther north, meanwhile, at times of halt in its recession, or perhaps of some readvance, accumulating the most massive morainic deposits of this region. The stability of the crust had been maintained during this great reduction of the ice pressure; and when at length an uplift ensued, the process was slow and marked by no paroxysmal action, but progressed in a gradual manner, though yet with pauses, as was also doubtless the method of the continued retreat of the ice.

*Pauses in the crustal uplift recorded by the series of beaches.*—The successive beaches of Lake Agassiz, numbering seventeen in its northern part while the lake outflowed southward by the river Warren, and fourteen while it outflowed northeastward, appear to have been formed during pauses in the differential elevation of this area. Between the times of formation of the beaches the uplift of the land was too rapid to be recorded by wave erosion and beach deposits, and the definitely marked shore-lines belong to stages of interruption or slower progress of this crustal uplift.

At the southern end of the lake each of the beaches, into which several in their course from north to south become merged, may belong to a slowly sinking lake surface, with change of 5 feet, or in some cases 10 feet, during the accumulation of the single beach ridge; and the intervals of 10 or 15 feet between the levels held by the mouth of the lake while the beaches of its southern part were being formed appear to represent times of exceptionally rapid erosion because of comparatively fast elevation of that area and of the country crossed by the River Warren. Along the course of this stream, the present valley of the Minnesota River, no outcropping rocks are found at so high levels that they would be touched by the continuation of the planes of the upper beaches of Lake Agassiz, having in their southern part a descent to the south of about a half of a foot per mile. The River Warren cut its channel wholly in glacial drift, until during the McCauleyville stages of the lake it reached the ledges of granitoid gneiss which outcrop in the bottom of the valley along a distance of several miles next below Big Stone Lake.

*Changes in levels of the beaches only a partial measure of the ice weight.*—If the thickness of the ice-sheet upon the area of Lake Agassiz was a half mile to 1½ miles, as seems probable, increasing from south to north and northeast, the crustal uplift measuring the inflow to this area of an equal weight of plastic or molten rock would range from 880 feet, or a sixth of a mile, at Lake Traverse, on the south, to 2,640 feet, or a half mile, at the north end of Lake Winnipeg, on the assumption that the density of the inflowing rock or magma were that of the upper portion of the earth's crust. The density of ice is taken as 0.9, water being 1.0; and that of the rocks forming the earth's surface is assumed to average 2.7, the earth's mean density, determined by three independent methods with closely accordant results, being about 5.5. But the mobile stratum next beneath the solid crust is surely somewhat heavier than the crust. Comparison of the earth's superficial and mean densities indicates for this magma a probable density of 3.5 or more, which would reduce the computed uplift to 680 feet at the south, with increase of about 2 feet per mile northward to 2,040 feet, in round numbers 2,000 feet, at the mouth of Lake Winnipeg and along the Nelson River, or less than these amounts if the density of the uplifting magma was greater than 3.5. It is very probable that the subsidence caused by the ice-sheet, depressing the crust below its preglacial height, was more than would be thus strictly proportionate to the weight added by the ice accumulation; but on the other hand it seems probable, as shown by the northward ascent of the beaches of Lake Agassiz, that only a minor fraction, perhaps nowhere within this basin exceeding one-fourth, of the weight of ice removed was compensated by the differential uplift of the land.

But could we well explain the facts of glacial striation and drift transportation by assuming for the ice-sheet a less thickness, as one-third of a mile to 1 mile from south to north upon the lacustrine area, which may, indeed, be nearer the truth, the rate of ascent of the shore-lines within the area of my survey, resulting apparently from the departure of the ice, would be closely in accordance with the hypothesis that the earth's crust is floating in isostatic equilibrium upon a plastic or molten interior, though the vertical extent of elevation of the whole basin is probably several hundred feet less than would be expected as a full measure of the weight removed. Even with the presumption that the uplift in its rate of increase toward the north is only approximately half, and in its aggregate amount only a quarter part, or less, of what computation would require, this hypothesis still seems to afford the best explanation that we are able to offer for the northward ascent of these beaches, beyond such small portion as can be referred to ice attraction. And it is to be observed that glaciated areas generally show by their fjords that part of their depression by the ice-sheet continues to the present time, not having been equaled by the crustal elevation when the ice-sheet was dissolved.

## REVIEW OF PLEISTOCENE OSCILLATIONS OF LAND AND SEA.

Having thus examined the probable causes of the changes in relative elevations within the area of Lake Agassiz, we shall gain much further knowledge of the evidence supporting the hypothesis concerning the earth's crust and interior, to which it has led us, by reviewing the oscillations that have affected various other parts of the world contemporaneously with the accumulation and disappearance of the Pleistocene ice-sheets. Fjords, fossiliferous marine deposits, and migrations of animals and plants bear important testimony of these vicissitudes of land and sea. It will be well first to consider our own continent, and afterward to inquire whether South America and Europe fared similarly.

### PREGLACIAL ELEVATION OF NORTH AMERICA SHOWN BY FJORDS AND SUBMARINE RIVER VALLEYS.

One of the most interesting fjords of North America is that of the Saguenay, tributary to the St. Lawrence. Along a distance of about 50 miles the Saguenay is from 300 to 840 feet deep below the sea-level; its adjoining cliffs rise abruptly in some places 1,500 feet above the water; and the width of its wonderfully sublime and picturesque gorge varies from about a mile to 1½ miles.[1] This fjord, like the many which indent our

[1] J. W. Dawson, Notes on the Postpliocene Geology of Canada, 1872, p. 41.

eastern coast from Maine to Labrador and Greenland, and our western coast from Puget Sound to the Arctic Ocean, was eroded by a stream that flowed along the bottom of the gorge when it was above the sea; and this erosion was probably going forward in the epoch immediately preceding the Ice age, for earlier subsidence during any period of much length, geologically speaking, would have caused the submerged valley to be filled with sediments. The preglacial elevation of the Saguenay region therefore appears to have been at least about 1,000 feet greater than now.

Similarly it is proved by the fjords of Maine, the eastern Canadian provinces, and Newfoundland, of Labrador and Greenland, of the Arctic coasts of North America, and the archipelago west of Baffin Bay, and of the Pacific coast from Alaska to Oregon, that the entire extent of the North American glaciated area was considerably higher before than after glaciation.

But the preglacial altitude of this area was much greater than the depth of the fjords which indent its shores. It is more nearly, but probably still only partially, measured by river valleys and fjords which are now entirely submerged beneath the ocean. The submarine border of the continental plateau to depths of more than 3,000 feet is cut by valleys or channels which if raised above the sea-level would be fjords or canyons. These can be no other than river courses eroded while the land stood much higher than now; and its subsidence evidently took place in a late geologic period, else the deposition of silt must have obliterated the channels. For this continent a most impressive review of the evidences of its lately far greater height, as shown by these submerged river courses, has been given by Prof. J. W. Spencer.[1]

According to the United States Coast Survey charts, as noted by Spencer, the bottom of a submerged valley just outside the delta of the Mississippi is found by soundings at the depth of 3,000 feet. This valley is a few miles wide and is bounded by a plain of the sea bed from 900 to 1,200 feet above its floor. It thus appears that the country north of the Gulf of Mexico has been raised for a short time to a height of not less than

[1] "The high continental elevation preceding the Pleistocene period," Bulletin, G. S. A., Vol. I, 1890, pp. 65–70; also in the Geol. Magazine (3), Vol. VII, pp. 208–213, May, 1890.

3,000 feet; and it is important to note in passing that an equal uplift would wholly close the Strait of Florida, 2,064 to 3,000 feet deep, through which the Gulf Stream now pours into the North Atlantic.

The continuation of the Hudson River Valley has been traced by detailed hydrographic surveys to the edge of the steep continental slope at a distance of about 105 miles from Sandy Hook. Its outermost 25 miles are a submarine fjord 3 miles wide and from 900 to 2,250 feet in vertical depth, measured from the crests of its banks, which, with the adjoining flat area, decline from 300 to 600 feet below the present sea-level. The deepest sounding in this fjord is 2,844 feet.[1]

In a similar position, just inside the bathymetric line of 100 fathoms on the submerged margin of the continental plateau off the mouth of Delaware Bay, the Coast Survey soundings reveal a short fjord which has a depth of 396 fathoms, or 2,376 feet.[2]

Again, the United States Coast Survey and British Admiralty charts, as Spencer states, record submerged fjord outlets from the Gulf of Maine, the Gulf of St. Lawrence, and Hudson Bay, respectively, 2,664 feet, 3,666 feet, and 2,040 feet below sea-level. The bed of the old Laurentian River from the outer boundary of the Fishing Banks to the mouth of the Saguenay, a distance of more than 800 miles, shown by Professor Spencer's map, is reached by soundings 1,878 to 1,104 feet in depth.

Greenland is divided from the contiguous North American continent and archipelago by a great valley of erosion which is estimated from soundings and tidal records to have a mean depth of 2,510 feet below sea-level for 680 miles through Davis Strait, 2,095 feet for 770 miles next northward through Baffin Bay, and 1,663 feet for the next 55 miles north through Smith Strait.[3]

On the Pacific coast of the United States Prof. Joseph Le Conte has shown that the islands south of Santa Barbara and Los Angeles, now separated from the mainland and from each other by channels 20 to 30 miles

[1] A. Lindenkohl, Report of U. S. Coast and Geodetic Survey, for 1884, pp. 435–438; Am. Jour. Sci. (3), Vol. XXIX, pp. 475–480, June, 1885, and Vol. XLI, pp. 489–499, with map, June, 1891. J. D. Dana, Am. Jour. Sci. (3), Vol. XL, pp. 425–437, Dec., 1890, with map reduced from U. S. Coast Survey chart.

[2] A. Lindenkohl, Am. Jour. Sci. (3), Vol, XLI, p. 498.

[3] Smithsonian Contributions to Knowledge, Vol. XV, pp. 163, 164.

wide and 600 to 1,000 feet deep, were still a part of the mainland during the late Pliocene and early Pleistocene periods.[1]

In northern California Prof. George Davidson, of the United States Coast Survey, as cited by Spencer, reports three submarine valleys about 25, 12, and 6 miles south of Cape Mendocino, sinking respectively 2,400, 3,120 and 2,700 feet below the sea-level where they cross the 100-fathom line of the marginal plateau.[2] If the land here were to rise 1,000 feet, these valleys would be fjords with sides towering high above the water, but still descending beneath it to profound depths. The time of great elevation permitting erosion of these and a large number of other submerged valleys of the Californian coast is shown by Le Conte to have been the Pliocene period, with culmination of the uplift in the early part of the Pleistocene.[3]

Farther to the north, Puget Sound and the series of sheltered channels and sounds through which the steamboat passage is made to Glacier Bay, Alaska, are submerged valleys of erosion, now filled by the sea, but separated from the open ocean by thousands of islands, the continuation of the Coast Range of mountains. From the depths of the channels and fjords Dr. G. M. Dawson concludes that this area had a preglacial elevation at least about 900 feet above the present sea-level during part or the whole of the Pliocene period.[4]

The general absence of Pliocene formations along both the Atlantic and Pacific coasts of North America indicates, as pointed out by Prof. C. H. Hitchcock, that during this long period all of the continent north of the Gulf of Mexico held a greater altitude, which from the evidence of these submarine valleys is known to have culminated in an elevation at least 3,000 feet higher than that of the present time. Such plateau-like uplift of the continent appears to have exerted so great influence on its meteorologic conditions, bringing a cooler climate throughout the year, that it finally became enveloped by ice-sheets to the southern limit of the glacial striæ, till, and moraines, stretching from Nantucket and Cape Cod to New York City, Cincinnati, St. Louis, Bismarck, and thence westward to the

[1] Bulletin of the California Academy of Sciences, Vol. II, 1887, pp. 515–520.
[2] Ibid., Vol. II, pp. 265–268.
[3] Bulletin, G. S. A., Vol. II, 1891, pp. 323–330.
[4] Canadian Naturalist, new series, Vol. VIII, pp. 241–248, April, 1877.

Pacific somewhat south of Vancouver Island and Puget Sound. The thickness of the ice in the region of the White Mountains and Adirondacks was about 1 mile; and Dana has shown, from the directions of striation and transportation of the drift, that its central portion over the Laurentide highlands between Montreal and Hudson Bay had probably a thickness of fully 2 miles. In British Columbia, according to Dr. G. M. Dawson's observations, it covered mountain summits 5,000 to 7,640 feet above the sea.[1]

### LATE GLACIAL OR CHAMPLAIN SUBMERGENCE SHOWN BY FOSSILIFEROUS MARINE BEDS OVERLYING THE TILL.

While thus heavily ice-laden, nearly the whole glaciated area of North America sank below its present level, but for the most part only to a slight amount in comparison with its previous elevation. Beginning at or near a line drawn northeastward through New York City, Boston, and Nova Scotia, the extent of the submergence of the land by the sea at the time of the recession of the ice-sheet, as shown by fossiliferous marine deposits overlying the till, increased from 150 feet in southeastern New Hampshire, and 200 to 300 feet on the coast of Maine and New Brunswick, to 375 feet on the St. Lawrence opposite to the mouth of the Saguenay, and 560 feet at Montreal. It was 300 to 400 feet, increasing from south to north, in the basin of Lake Champlain; about 275 feet at Ogdensburg, and 450 feet near the city of Ottawa; and 300 to 500 feet, likewise increasing northward, on the country southwest of James Bay.[2] In Labrador the submergence was of small amount at the south, adjacent to the Gulf of St. Lawrence and Newfoundland; but was about 1,500 feet at Nachvak, near latitude 59° N., according to Dr. Robert Bell;[3] and in northern Greenland and in

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[1] Geol. Magazine (3), Vol. VI, 1889, pp. 350–352. Transactions, Royal Society of Canada, Vol. VIII, Sec. IV, 1890, pp. 31, 32.

[2] A. S. Packard, jr., Memoirs, Boston Soc. Nat. Hist., Vol. I, pp. 231–262. J. W. Dawson, Notes on the Postpliocene Geology of Canada; and Am. Jour. Sci. (3), Vol. XXV, 1883, pp. 200–202. C. H. Hitchcock, Proc., A. A. A. S., Vol. XXII, 1873, pp. 169–175; Geology of New Hampshire, Vol. III, pp. 279–282; and Geol. Magazine (2), Vol. VI, 1879, pp. 248–250. G. H. Stone, Am. Jour. Sci. (3), Vol. XL, pp. 122–144, Aug., 1890. R. Chalmers, Transactions of the Royal Society of Canada, Sec. IV, 1886, pp. 139–145. Baron Gerard de Geer, Am. Geologist, Vol. IX, pp. 247–249, April, 1892; and Proc., Boston Soc. Nat. Hist., Vol. XXV, 1892, pp. 454–477. Warren Upham, Proc., Boston Soc. Nat. Hist., Vol. XXIV, pp. 127-141, Dec., 1888; Am. Jour. Sci., May, 1889.

[3] Bulletin, G. S. A., Vol. I, 1890, p. 308.

Grinnell Land it was from 1,000 to 2,000 feet, as shown by raised beach deposits containing marine shells.[1]

That the land northward from Boston was so much lower while the ice-sheet was being melted away is proved by the occurrence of fossil shells of far northern range, including *Yoldia* (*Leda*) *arctica* Gray, now found living only in arctic seas where they receive muddy streams from existing glaciers and from the Greenland ice-sheet. This species is plentiful in the stratified clays resting on the till in the basin of James Bay, in the St. Lawrence Valley, and in New Brunswick and Maine, extending south to Portsmouth, N. H.

Scantier but yet conclusive proofs of the depression of British Columbia under the ice load are found in the valley of the Fraser River and on the Pacific coast, in Vancouver Island and the Queen Charlotte Islands. Lamplugh has observed recent marine shells in a railway cutting on the west bank of the Harrison River, near its junction with the Fraser, at an elevation not less than 100 feet above the sea.[2] At New Westminster, on the Frazer, near its mouth, raised beaches inclosing fragments of marine shells are reported by Bauerman about 30 feet above the river.[3] Fossiliferous marine deposits found in the vicinity of Victoria and Nanaimo, in the southeast part of Vancouver Island, at small elevations above the sea, are believed by Dr. G. M. Dawson to have been formed at or near the wasting edge of the ice-sheet;[4] and near the middle of the northeast side of this island two distinct deposits of till occur, with intervening beds of loess-like silts, from which this author infers two times of glaciation, separated by an interval during which the land was submerged from 100 to 200 feet.[5] Again, in the northeast part of the Queen Charlotte Islands Dr. Dawson

[1] Quart. Jour. Geol. Soc., Vol. XXXIV, 1878, pp. 66, 566. Geol. Magazine (3), Vol. I, 1884, p. 522. A. W. Greely, Report on the U. S. Expedition to Lady Franklin Bay, Grinnell Land, Vol. II, 1888, p. 57.

[2] Quart. Jour. Geol. Soc., Vol. XLII, 1886, pp. 284, 285.

[3] Geol. and Nat. Hist. Survey of Canada, Report of Progress for 1882–83–84, p. 33 B.

[4] Geol. and Nat. Hist. Survey of Canada, Annual Report, new series, Vol. II, for 1886, p. 99 B; Quart. Jour. Geol. Soc., Vol. XXXIV, 1878, pp. 97, 98, and Vol. XXXVII, 1881, p. 279. Compare also Mr. G. W. Lamplugh's observations of glacial shell beds at Esquimault, near Victoria, Quart. Jour. Geol. Soc., Vol. XLII, 1886, pp. 276–284.

[5] Geol. and Nat. Hist. Survey of Canada, Annual Report, new series, Vol. II, p. 105 B.

finds evidence of submergence to the amount of 200 or 300 feet, while the glacial conditions still endured.[1]

### REELEVATION CLOSELY FOLLOWING THE DEPARTURE OF THE ICE-SHEET.

From the Champlain submergence this continent, since the ice weight depressing it was removed, has been uplifted to its present height. The changes in the levels of the beaches of Lake Agassiz prove that in the interior of the continent this movement closely followed the recession of the ice; but on the shores of Hudson Bay the reelevation is still in progress, indicating that no long time has passed since large remnants of the ice in that region melted away. On the Atlantic coast we have different evidence of the rise of the land soon after the ice-sheet disappeared, and the movement there, as also on the coast of British Columbia, resulted in an elevation somewhat higher than now, so that the latest oscillation of these regions has been a subsidence, which is still very slowly continuing.

The recent depression of the eastern seaboard is shown by submarine stumps of trees, rooted where they grew, and by submerged peat bogs, which prove that the whole coast from New Jersey to southern Greenland has lately sunk to a moderate extent. The maximum known by these observations is about 80 feet, at which depth a peat bed occurs under the Tantramar salt marsh at the head of the Bay of Fundy.[2] After the land had recovered from the Champlain depression to its present level, or perhaps to the higher stage noted, the temperature of the North Atlantic was for a time somewhat warmer than now. Southern species of marine mollusks were then able to extend northward to the Gulf of St. Lawrence; but they have since become exterminated by a considerable refrigeration of

[1] Geol. and Nat. Hist. Survey of Canada, Report of Progress for 1878–79, p. 95 B. Trans., Royal Society of Canada, Vol. VIII. Sec. IV, 1890, pp. 3–74. Important notes of recent changes in level of the coast of British Columbia, of the State of Washington, and of southern Alaska, are given by Dr. Dawson in the Canadian Naturalist, new series, Vol. VIII, pp. 241–248, April, 1877. He concludes that this area had a preglacial elevation at least about 900 feet above the present sea-level during part or the whole of the Pliocene period, this being indicated by the fjords; that it was much depressed during the Glacial period; and that in Postglacial time it has been reelevated to a height probably 200 or 300 feet greater than now, followed by subsidence to the present level, the latest part of this oscillation being a somewhat rapid depression of perhaps 10 or 15 feet during the latter part of the last century—a movement which may still be slowly going on.

[2] Geol. and Nat. Hist. Survey of Canada, Annual Report, new series, Vol. IV, for 1888–89, pp. 42 A and 10 N.

the sea along the coast north of Cape Cod, excepting isolated colonies.[1] The coast had been reelevated soon after the retreat of the ice-sheet and before the southern mollusks migrated northward, for in the extensive lists of the fossil fauna of the Champlain beds, also denominated in their two principal phases the Leda clays and Saxicava sands, none of the southern species is included, excepting perhaps the oyster in southwestern Maine.[2]

Postglacial elevation of the country along the East Main coast of Hudson Bay and on Hudson Strait is shown by conspicuous raised beaches, according to Dr. Robert Bell, up to heights of at least 300 feet, while probably others much higher exist farther inland.[3] In the region draining from the southwest to James Bay Dr. Bell reports marine shells in stratified beds overlying the glacial drift along the Moose, Mattagami, and Missinaibi rivers up to about 300 feet above the sea;[4] along the Albany and Kenogami rivers up to a height of about 450 feet;[5] and on the Attawapishkat to about 500 feet above the sea.[6] It is also evident that the shores of Hudson and James bays are still undergoing elevation, this being proved by the fresh appearance of the raised beaches, by driftwood far above the limit of the highest waves in storms, and by the gradual shoaling of harbors. The rate of emergence of the eastern coast is estimated by Bell to be between 5 and 10 feet in a century; Outer Digges Island, at the entrance of Hudson Strait, has risen 70 or 80 feet since it was inhabited by Eskimos; and the rise of the mouths of the Churchill, Nelson, and Hayes rivers seems to be similarly rapid, being estimated at about 7 feet in a hundred years.[7]

In British Columbia the reelevation following the Champlain depression was probably completed within a short time, geologically speaking,

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[1] Proc., Boston Soc. Nat. Hist., Vol. XXV, 1891–92, pp. 305–316; also Am. Jour. Sci. (3), Vol. XLIII, pp. 201–209, March, 1892.

[2] C. H. Hitchcock, "The geology of Portland," Proc., A. A. A. S., Vol. XXII, for 1873, pp. 163–175. A. S. Packard, Jr., "Observations on the glacial phenomena of Labrador and Maine," Memoirs of the Boston Society of Natural History, Vol. I, 1865, pp. 210–262. J. W. Dawson, "Notes on the Postpliocene geology of Canada," 1872, pp. 112 (from the Canadian Naturalist, new series, Vol. VI).

[3] Geol. and Nat. Hist. Survey of Canada, Report of Progress for 1877-78, p. 32 C; for 1882–83–84, p. 31 D.

[4] Ibid., Report of Progress for 1875–76, p. 340; for 1877–78, p. 7 C.

[5] Ibid., Report of Progress for 1871–72, p. 112; for 1875–76, p. 340; Annual Report, new series, Vol. II, for 1886, pp. 34 and 38 G.

[6] Ibid., Annual Report, Vol. II, p. 27 G.

[7] Geol. and Nat. Hist. Survey of Canada, Report of Progress for 1877–78, pp. 32 C and 25 CC; for 1878–79, p. 21 C; for 1882–83–84, pp. 26, 30, 32 DD; Annual Report, new series, Vol. I, for 1885, p. 11 DD.

after the continental ice-sheet was removed, for Dawson, as before cited, finds that this region since then has stood higher than now, allowing forests to grow on shores which have very recently become again submerged, as on the eastern side of the continent. During the past hundred years, too, a considerable subsidence has taken place, according to Dall, at a locality known as Sinking Point, in Chalmers Bay, Prince William Sound, on the south coast of Alaska; but all of that country west of the one hundred and fiftieth meridian, to Bering Strait and the adjacent Siberian coast, is stated by this author to be now rising at a somewhat rapid rate. Barnacles are found on St. Michael's Island, Norton Sound, at least 15 feet above high tide, and driftwood at many localities on Norton Bay and Sound is "piled in winrows * * * far above the level which the most severe storms and the highest tides now attain, * * * much decayed, but still preserving its shape."[1]

### OSCILLATIONS ASSOCIATED WITH GLACIATION IN OTHER COUNTRIES.

Two other areas of great extent, namely, Patagonia and northwestern Europe, have been covered by ice-sheets which have disappeared; and a brief consideration of their oscillations attending the ice accumulation and following its departure will be useful in this discussion of the causes of the Pleistocene earth movements of the basin of Lake Agassiz and of the North American glaciated area.

The many intricate and deep fjords, channels, and sounds on the coast of Patagonia, southern Chile, Tierra del Fuego, and the Falkland Islands, prove that this part of the earth's crust has lately stood for a considerable time at a much higher level than now. This stage of elevation was followed by the envelopment of the southern extremity of the continent by an ice-sheet, which, according to the observations of Darwin and Agassiz, spread its drift northward to latitude 42°, while local glaciers extended farther north. When the ice melted away, the land was depressed lower than now, and since then a reelevation has been in progress. Darwin states that "the land from the Rio Plata to Tierra del Fuego, a distance of 1,200 miles, has been raised in mass (and in Patagonia to a height of between 300

[1] Alaska and its Resources, 1870, pp. 465, 466.

and 400 feet) within the period of the now existing shells. The old and weathered shells left on the surface of the upraised plain still partially retain their colors."[1] Another evidence of the recency of the uplift is supplied by the discovery by Agassiz of a saline lakelet about 150 feet above the sea, in which several species of marine mollusks were found living, identical with those of the neighboring seashores.[2]

Northwestern Europe also had a much greater altitude during the later part of the Tertiary era, in which the land suffered vast denudation, with erosion of fjords and channels that are now submerged hundreds and even thousands of feet beneath the sea. About the northern parts of the British Isles the depths of the submarine channels of the old land surface are approximately from 500 to 800 or 1,000 feet.[3] The Skager Rack, between Denmark and Norway, has a depth of 2,580 feet, with a still deeper submerged valley running from it west and north to the abyssal Arctic Ocean.[4] On the coast of Norway the depth of Christiania fjord below the sea-level is 1,380 feet; of Hardanger fjord, 2,624 feet; and of Sogne fjord, the longest in Norway, 4,080 feet.[5] The preglacial altitude of these portions of the European glaciated area was therefore from 1,000 to 4,000 feet higher than now. Probably many of these submarine channels are more or less filled with the glacial drift, so that valleys originally descending continuously toward the margin of the continental plateau have become in some portions changed to inclosed basins. Another and more probable explanation of the much greater depth of some of the fjords in their inland portion than at their mouths is the depression of the country while it was ice-covered, the coast having subsided much less than the interior.

At the close of the Ice age in Europe, as in America, the glaciated areas were mostly depressed somewhat below their present height. The supposed great submergence, however, up to 1,200 or 1,500 feet or more, which has been claimed by British geologists for northern Wales, northwestern England, and a part of Ireland, on the evidence of marine shells

[1] Voyage of the Beagle, Chapter VIII.

[2] Louis Agassiz: His Life and Correspondence, Vol. II, p. 716.

[3] James Geikie, Quart. Jour. Geol. Soc., Vol. XXXIV, 1878, Pl. XXXIII; The Great Ice Age, 2d ed., pp. 279-284, Pls. IX-XII.

[4] Nature, Vol. XXIII, p. 393, with map of submarine contour.

[5] T. F. Jamieson in Geol. Magazine (3), Vol. VIII, pp. 387-392, Sept., 1891.

and fragments of shells in glacially transported deposits, is shown by Belt, Goodchild, Lewis, Kendall, and others, to be untenable. Indeed, these fossils, not lying in the place where they were living, give no proof of any depression of the land, since they have been brought by currents of the ice-sheet moving across the bed of the Irish Sea. But it is clearly known by other evidence, as raised beaches and fossiliferous marine sediments, that large portions of Great Britain and Ireland were slightly depressed under their burden of ice, and have been since uplifted to a vertical extent ranging probably up to a maximum of about 300 feet.

In Scandinavia the valuable observations and studies of Baron Gerard de Geer, of the Geological Survey of Sweden, have supplied lines of equal depression of the land at the time of the melting away of the ice.[1] This region of greatest thickness of the European ice-sheet is found to have been depressed to an increasing extent from the outer portions toward the interior. The lowest limit of the submergence, at the southern extremity of Sweden, is no more than 70 feet above the present sea-level, and in northeastern Denmark it diminishes to zero; but northward it increases to an observed amount of about 800 feet on the west shore of the Gulf of Bothnia, near latitude 63°. Along the coast of Norway it ranges from 200 feet to nearly 600 feet, excepting far northward, near the North Cape, where it decreases to about 100 feet. In proportion with this observed range of the subsidence on the coasts of Scandinavia, its amount in the center of the country was probably 1,000 feet.

A very interesting history of the postglacial oscillations of southern Sweden has been also ascertained by Baron de Geer, which seems to be closely like the postglacial earth movements of the northeastern border of North America. As on our Atlantic coast, the uplift from the Champlain submergence in that part of Sweden raised the country higher than now. The extent of this uplift appears to have been about 100 feet on the area between Denmark and Sweden, closing the entrance to the Baltic Sea, which became for some time a great fresh-water lake. After this another depression of that region ensued, opening a deeper passage into the Baltic

[1] "Quaternary changes of level in Scandinavia," Bulletin, G. S. A., Vol. III, 1892, pp. 65–68, with map of the late glacial marine area in southern Sweden.

than now, giving to this brackish body of water a considerably higher degree of saltness than at present, with the admission of several marine mollusks, notably *Litorina litorea* Menke, which are found fossil in the beds formed during this second and smaller submergence, but are not living in the Baltic to-day. Thus far the movements of southern Sweden are paralleled by the postglacial oscillations of New England and eastern Canada; but a second uplifting of this part of Sweden is now taking place, whereas no corresponding movement has begun on our Atlantic border. It seems to be suggested, however, that it may yet ensue. The subsidence has ceased or become exceedingly slow in eastern New England, while it still continues at a measurable rate in New Jersey, in Cape Breton Island, and in southern Greenland.

So extensive agreement on opposite sides of the Atlantic, and also in Patagonia, in the oscillations of the land while it was ice-covered and since the departure of the ice-sheets, has probably resulted from similar causes, namely, the pressure of the ice weight and resilience of the earth's crust when it was unburdened. The restoration of isostatic equilibrium in both North America and Europe is attended by minor oscillations, the conditions requisite for repose being overpassed by the early reelevation of outer portions of each of these great glaciated areas.

In view of this harmony in the epeirogenic movements of the two continents during the Glacial and Recent periods, it seems evident that the close of the Ice age was not geologically long ago, for equilibrium of the disturbed areas has not yet been restored. Furthermore, the parallelism in the stages of progress toward repose indicates nearly the same time for the end of the Glacial period on both continents, and approximate synchronism in the pendulum-like series of postglacial oscillations.

### PLEISTOCENE OSCILLATIONS INDEPENDENT OF GLACIATION.

In this class of changes are to be included, wholly or in part, the postglacial elevation of Grinnell Land and the northwestern coast of Greenland, 1,000 to 2,000 feet;[1] post-Pliocene upward movements of 2,000 feet or

[1] Quart. Jour. Geol. Soc., Vol. XXXIV, 1878, pp. 66 and 566. Geol. Mag. (3), Vol. I, 1884, p. 522. A. W. Greely, Report of the U. S. Expedition to Lady Franklin Bay, Grinnell Land, Vol. II, 1888, p. 57.

more in Jamaica and Cuba,[1] and of about 1,100 feet in Barbados;[2] the recent uplift of the coast of Peru at least 2,900 feet,[3] which in diminished amount seems to extend along the whole range of the Andes;[4] its probable connection with the upheaval of the Cordilleras of North America, where Le Conte[5] and Diller[6] believe that the elevatory movements reached their greatest intensity in early Quaternary time, causing a rise of several thousands of feet in the Sierra Nevada; and the apparently correlative subsidence of a great area dotted with coral islands in the Pacific. The Pleistocene uplifts of the Andes and Rocky Mountains and of the West Indies make it nearly certain that the Isthmus of Panama has been similarly elevated during this period. On the line of the Panama Railway the highest land rises only 299 feet above the sea, and the highest on the proposed route of the Nicaragua Canal is about 133 feet; while the Isthmus nowhere attains the height of 1,000 feet.[7] It may be true, therefore, that submergence of this isthmus was one of the causes of the Glacial period, the continuance of the equatorial oceanic current westward into the Pacific having greatly diminished the Gulf Stream, which carries warmth from the tropics to the northern Atlantic and northwestern Europe.

Pleistocene mountain-building is known to have occurred on a most massive scale in Asia, where the Himalayas, stretching 1,500 miles from east to west, and towering 20,000 to 29,000 feet above the sea, are known to have been formed in great part during this latest geologic period,[8] con-

[1] J. G. Sawkins, Reports on the Geology of Jamaica, 1869, pp. 22, 23, 307, 311, 324–329; W. O. Crosby, "On the mountains of eastern Cuba," Appalachia, Vol. III, pp. 129–142. Compare William M. Gabb's memoir, "On the topography and geology of Santo Domingo," Trans., Am. Phil. Soc., Vol. XV, pp. 103–111.

[2] "The geology of Barbados," by A. J. Jukes-Browne and J. B. Harrison, Quart. Jour. Geol. Soc., Vol. XLVII, pp. 197–250, Feb., 1891.

[3] A. Agassiz, Proc., Am. Acad. of Arts and Sciences, Vol. XI, 1876, p. 287; and Bulletin of the Museum of Comparative Zoology at Harvard College, Vol. III, pp. 287–290. Above this height, at which corals are found attached to rocks, recent elevation of much greater amount seems to be indicated by terraces, by saline deposits, and by the presence of eight species of Allorchestes, a marine genus of crustacea, in Lake Titicaca, 12,500 feet above the sea.

[4] Darwin's Voyage of the Beagle, Chapter XVI.

[5] Am. Jour. Sci. (3), Vol. XXXII, pp. 167–181, Sept., 1886; Vol. XXXVIII, pp. 257–263, Oct., 1889.

[6] U. S. Geol. Survey, Eighth Annual Report, for 1886–87, pp, 428–432.

[7] Charles Ricketts, "The cause of the Glacial period, with reference to the British Isles," Geol. Magazine (2), Vol. II, 1875, pp. 573–580. A. R. Wallace, The Geographical Distribution of Animals, Vol. I, p. 40.

[8] Manual of the Geology of India, by H. B. Medlicott and W. T. Blanford; Calcutta, 1879; Part I, pp. lvi, 372; Part II, pp. 569–571, 667–669, 672–681.

temporaneously with the glaciation of North America, Europe, and portions of the southern hemisphere. Within the same time the great table-land of Thibet[1] and much of central and northwestern Asia have been uplifted; the tract extending from the Black and Caspian seas northeast to the Arctic Ocean has risen to form a land surface; and the deep basin of Lake Baikal probably has been formed in connection with these crustal movements. Accompanying the formation of the Himalayas, there has been doubtless much disturbance by faults, local uplifts, and here and there plication of strata along the whole complex east to northwest and west mountain system of Oceanica, Asia, Europe, and northern Africa, from New Guinea, the Sunda Islands, Anam, and Siam, to the Caucasus, Carpathians, Balkans, Apennines, Alps, Pyrenees, and Atlas mountains, stretching quite across the Eastern Hemisphere; but the greater part of the relief from the previously existing deformation of the earth was doubtless along the central part of the belt, in the colossal Himalayan range. In like manner the North American Cordilleras and the Andes, reaching in one continuous mountain system from the Arctic Circle to Cape Horn, have experienced within the same period great disturbances, as already noted, similar to those of the mountains of southern Europe and the adjacent part of Africa. With this American orographic belt is also probably to be associated the mountain system, consisting largely of volcanoes now active, which forms the Aleutian Islands, Kamchatka, the Kurile Islands, Japan, Formosa, the Philippines, Borneo, and Celebes, lying nearly in the same great circle with the Andes and Rocky mountains, and with them continuous in an arc of about 240°. Along two lines transverse to each other, one having an extent of half and the other of two-thirds of the earth's circumference, the great lateral pressures of the earth's crust which probably caused the elevation and glaciation of extensive areas during the Pleistocene period have been relieved by plication, faults, and uplifts in the processes of the formation of mountain ranges.

Asia had no extensive ice-sheet like those of Europe and North America, probably because a sufficient elevation was not attained there until the Himalayas and Thibet were uplifted in the Glacial period. The southern

[1]Ibid., Part II, pp. 585, 586, 669–672.

latitude of the Himalayan range and the position of Thibet and Mongolia in an arid and partly rainless belt, which stretches thence west to the Sahara, forbade their glaciation; but from these recently uplifted Asiatic table-lands and mountains the most extensive Pleistocene stratified deposits in the world have been brought down by rivers and spread in the vast low plains of Siberia, eastern China, and northern India, sloping gently toward the sea, into which the finer part of this alluvium is carried. All the puzzling features of the Chinese loess formation,[1] reaching to great elevations with such thickness and slopes of its surface that it could not be so accumulated as alluvium of flooded streams under the present conditions, seem to be readily explained by referring its deposition to annual floods from immense snow melting during the European and North American Glacial period upon the gradually rising central part of the Asiatic continent, which consists largely of easily erosible strata, and had in pre-Glacial time become extensively disintegrated by weathering under a dry climate.

### EFFECTS OF ICE ACCUMULATION ON THE SEA-LEVEL.

During the Glacial period significant changes of the sea-level were caused, first, by abstraction of water from the ocean and its deposition on the land as snow, which under pressure made the vast ice-sheets; and, second, by ice attraction of the ocean, lowering it still further, except in the vicinity of glaciated lands. An area of about 4,000,000 square miles in North America and another of about 2,000,000 square miles in Europe were covered by ice-sheets, which in their maximum extent had probably an average thickness of a half or two-thirds of a mile, or perhaps even of 1 mile. Disregarding the accumulation of ice-sheets of smaller extent, which probably or possibly existed at the same time in parts of Asia and of the southern hemisphere, as also the glaciers of mountain districts, the lowering of the ocean surface, which covers approximately 145,000,000 square miles, would slightly exceed 100 feet, if the mean depth of the ice accumulation was a half mile. More probably the sea over the whole globe was thus

[1] Baron Richthofen, Geol. Magazine (2), Vol. IX, 1882, pp. 293–305. J. D. Whitney, Am. Naturalist, Vol. XI, pp. 705–713, Dec., 1877. R. Pumpelly, Am. Jour. Sci. (3), Vol. XVII, pp. 133–144, Feb., 1879. E. W. Hilgard, Am. Jour. Sci. (3), Vol. XVIII, pp. 106–112, Aug., 1879.

depressed fully 150 feet, which would correspond to an average of about 3,600 feet of ice on the glaciated areas of North America and Europe.

For the second factor in causing such changes, Mr. Woodward's computations before cited indicate that gravitation toward the ice would further depress the ocean probably 25 to 75 feet within the tropics and in the southern hemisphere, while it would raise the level enough near the borders of the ice-sheets to counterbalance approximately the depression due to the diminution of the ocean's volume, and would lift portions of the North Atlantic and of the Arctic Sea perhaps 200 or 300 feet higher than now. Stream erosion while the sea was lowered to supply the ice of the Glacial period may explain the indentations of the southeastern coast of the United States, as Pamlico and Albemarle sounds, besides similar inlets in many other parts of the world; but the excavation of Chesapeake and Delaware bays seems more probably referable, at least in part, to the time of preglacial elevation, with the channeling of the now submerged Hudson fjord.

#### PROBABLE RELATIONSHIP OF EPEIROGENIC MOVEMENTS THROUGHOUT THE WORLD TO GLACIATION.

In view of the extensive Pleistocene oscillations of land and sea both in glaciated and unglaciated regions, it seems a reasonable conclusion that, while some of these movements, as those affecting the beaches of Lake Agassiz, have resulted directly from the accumulation and dissolution of ice-sheets, more generally, when the whole area of the earth is considered, they have been independent of glaciation. May not such movements of the earth's crust, then, have elevated large portions of continents, as the northern half of North America and the northwestern part of Europe, either together or in alternation, to heights like those of the present snow-lines on mountain ranges, until these plateaus became deeply channeled by fjords and afterward covered by ice-sheets? For the recentness of the Ice age, believed to have ended in the region of Lake Agassiz and the Laurentian lakes not more than 10,000 to 6,000 years ago,[1] forbids our referring the glacial climate to conditions brought about by a period of increased eccentricity of the earth's orbit from 240,000 to 80,000 years ago, which has been

[1] See Chapter V, pp. 238–240.

so ably maintained by Croll and Geikie; and some other adequate cause or causes must be sought for the glaciation of these great continental areas and other districts of smaller extent, both in the northern and southern hemispheres, during the Pleistocene period.

The principal cause of the Ice age seems to the writer to be probably found by the clew supplied in the relations already stated of the earth's crust and interior whereby they become somewhat distorted from the spheroidal form while the process of contraction goes forward, the lateral pressure bearing down some portions of the earth's surface and uplifting other extensive areas. The protuberant plateaus, swept over by moisture-laden winds, would be the gathering grounds of vast ice-sheets. A similar explanation of the Glacial period was long ago proposed by Lyell and Dana, but without referring the elevatory movements to the earth's deformation by contraction and accumulating lateral pressure while approaching an epoch of mountain-building, which fundamental principle was first suggested to me in an article from the pen of Prof. W. O. Crosby on the origin and relations of continents and ocean basins.[1]

During the periods immediately preceding great plications and shortening of segments of the earth's crust involved in the formation of lofty mountain ranges, the broad crustal movements causing glaciation would be most widespread and attain their maximum vertical extent. The accumulation of ice-sheets may have brought about the depression of their areas, with corresponding elevation of other plateaus, which in turn would become ice-covered, so that the epochs of glaciation of the Northern and Southern hemispheres, or of North America and Europe, may have alternated with each other.[2] More probably, however, as shown by the observations and studies of Salisbury, Geikie, Chamberlin, the present writer, and others, the glaciations of North America and Europe were approximately synchronous; and even the successive stages of the Ice age on these two continents

[1] Proc., Boston Soc. Nat. Hist., 1883, Vol. XXII, pp. 455–460.

[2] Compare the opinions of Capt. F. W. Hutton, cited in A. Geikie's Text-book of Geology, 2d ed., p. 912, that the former greater extension of glaciers in New Zealand was caused by an increase in the elevation of the land, and that it belonged to a much earlier time than the Ice age in the northern hemisphere, probably to the Pliocene period.

have a remarkable parallelism, which probably indicates a similar sequence of events on the opposite sides of the North Atlantic.[1]

When the building up of a great range of mountains ensued, which may have been initiated and accelerated by the repeated depressions under ice weight and consequent transfers of the earth's deformation from one region to another, the accumulated stress in the earth's crust with development of immense lateral pressure would be diminished below the limit of its competency to cause glaciation.

It seems probable that the rate of the earth's contraction has been somewhat uniform throughout the vast ages known to us by the researches of geology; but the corrugation of the earth's surface in mountain-building has been much more rapid in some epochs than in others, and between the times of formation of great mountain ranges there have been long intervals of quietude.[2] The slowly progressing contraction of the globe has been uninterrupted, and in some way the cooled outer part of the crust which has not shared in this diminution of volume has been able to accommodate itself to the shrinking inner mass. As stated in previous pages, this has probably resulted in distortion of the earth's form, both of the whole thickness of the crust and of the plastic or molten interior, within moderate limits, during the periods of quiet, until so much lateral pressure has been accumulated as to compress, fold, and uplift the strata of a mountain range.

In attributing the severe climate of the Glacial period to great uplifts of the areas glaciated through such deformation preparatory to the process of mountain-building, it is distinctly implied that Pleistocene time has been at first exceptionally marked by such broad crustal movements and has since gained comparative rest from the lateral stress to which they were due by equally exceptional plication, uplifts, and faults, in the birth and growth of mountains. Further, it is implied also that stress in the earth's crust had been gradually increasing through long previous time, while the processes of mountain-building failed to keep pace with contraction, but

[1] R. D. Salisbury, Am. Jour. Sci. (3), Vol. XXXV, pp. 401–407, May, 1888. James Geikie and T. C. Chamberlin, The Great Ice Age, third ed., 1894; Journal of Geology, Vol. III, pp. 241–277, April–May, 1895. Warren Upham, Am. Naturalist, Vol. XXIX, pp. 235–241, March, 1895; Am. Geologist, Vol. XV, pp. 273–295, May, 1895.

[2] Dana's Manual of Geology, 3d ed., p. 795. Prestwich's Geology, Vol. I, Chapter XVII.

were still sufficient to keep the earth's deformation less than is required to produce glaciation; for no evidences of intense and widely extended glacial conditions are found in the great series of Tertiary and Mesozoic formations, representing the earth's history through probably ten to fifteen million years. And, indeed, these conclusions, drawn from the Pleistocene period and the absence of glaciation through vast eras preceding, accord well with the known age and stages of growth of mountain ranges that have been formed during these eras. No period since the close of Paleozoic time has been more characterized by mountain-building than the comparatively short Pleistocene, whose duration may probably be included within 100,000 or 150,000 years.

Elevation of broad areas, as half of North America and half of Europe, either synchronously or, less probably for these companion continental regions adjoining the North Atlantic, in alternation, to such heights that their precipitation of moisture throughout the year was nearly all snow, gradually forming ice-sheets of great thickness, seems consistent with the conditions of the earth's crust and interior which are indicated by the changes in the levels of the beaches of Lake Agassiz. A plastic interior or molten magma beneath the solid crust accounts for the uplift of the area of this glacial lake, with its gradual increase from south to north, and also appears, in connection with contraction of the earth and the formation of mountain ranges, to afford an adequate explanation of glaciation. It is probable that the great uplifts which are thus supposed to have caused ice accumulation were very slow in their progress, and that their effect upon extensive continental areas was so distributed that the maximum changes in slope on their borders would nowhere exceed 20 or 30 feet or at the most 50 or 75 feet per mile, while perhaps some portions of the uplifted region would receive no change of slope. And the subsidence beneath the weight of accumulated ice was probably slow, though apparently much faster than the processes of preglacial and interglacial elevation, and was similarly distributed, no limited district being greatly changed. Excepting the areas where disturbances of mountain-building or extraordinary rising or sinking of mountain ranges were associated with these movements, the contour of the country, with its valleys, hills, and mountains, remained in general the same from preglacial time, through the Ice age, to the present, with only changes of slope, commonly small in any limited tract, which, in long distances, allowed great upheavals and depressions. The elevation of the central part of glaciated areas, with downward slopes on all sides, favored the outward flow of the ice-sheets and their erosion and transportation of the drift. But mountains and hills jutted upward in ridges and peaks within the moving ice-sheets, as they now stand forth in bold relief above the lowlands; and the ice, with its inclosed drift, was pushed around and over them, some portions being deflected on either side, and usually a larger part being carried upward across their tops.

### EPEIROGENIC MOVEMENTS INDEPENDENT OF GLACIATION OFTEN COMBINED WITH OTHERS DUE TO THE ICE WEIGHT AND TO ITS REMOVAL.

The foregoing review of the Pleistocene epeirogenic movements of various parts of the world shows that many of them have affected countries which never were glaciated. In these areas they have been mostly or wholly without any demonstrable relationship to glaciation. Again, in countries which have become ice-covered, we learn from fjords and submerged river valleys that great epeirogenic elevation of the land preceded the accumulation of the ice-sheets. These movements also were evidently independent of glaciation, not being caused by it, though, on the other hand, the writer believes that they were the cause of the ice accumulation and of its resulting drift deposits. The more extended epeirogenic movements of the earth within the Pleistocene period have probably arisen from the relationship of the earth's crust and interior, and in areas of sufficiently high latitudes, and in mountain districts, they have here and there produced epochs of glaciation.

While so widespread earth movements not due to glaciation have been taking place throughout this period, it is evident that some of them would probably be in progress in glaciated countries at the same time with the ice accumulation and after the departure of the ice-sheets, being combined in their effects with other crustal movements due to the weighting of the crust by the ice-load, and to its relief by the ice-melting. Thus, for example, while we may refer the rise of the greater part of North America from the

Late Glacial or Champlain subsidence to the resilience of the earth's crust on account of the departure of the ice, the uplifting of northern Labrador and of northern Greenland and Grinnell Land has been too great in vertical extent to be proportionate with the probable thickness of the ice-sheet on those areas. Their uplifting has been in its greater part probably due to a movement independent of glaciation.

Epeirogenic movements of regions which have not been ice-covered seem in some instances referable to a transfer of disturbances from glaciated districts. Accompanying the subsidence of ice-loaded tracts, there were doubtless uplifts of contiguous regions, perhaps sometimes including outer portions of the country glaciated. For example, the upheaval of the St. Elias range and of its foothills, found by Russell to have taken place subsequent to a long and severe glaciation of that region,[1] may very probably have been correlative with the Champlain subsidence ending the Glacial period in the northern United States.

### UPLIFT OF THE BASIN OF LAKE AGASSIZ APPARENTLY ATTRIBUTABLE WHOLLY TO THE DEPARTURE OF THE ICE-SHEET.

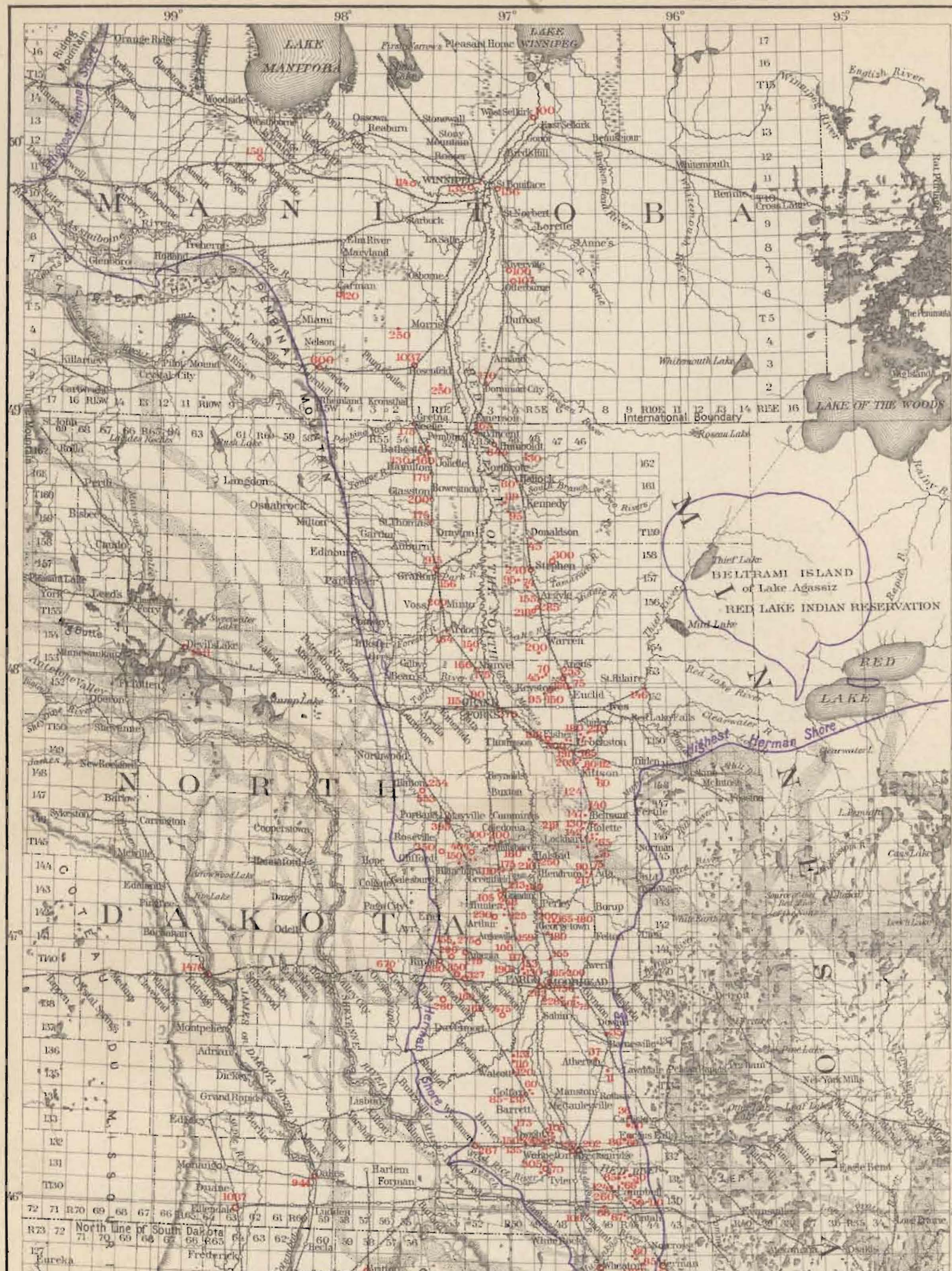
Within the basin of the glacial Lake Agassiz I believe that high preglacial altitude, affecting likewise all the North American glaciated area, was terminated by the depression of the land while it was ice-burdened. All the movements which this basin has since experienced, as recorded by the changes of levels of the beaches, seem to have resulted from the tendency of the earth's crust to regain equilibrium, after the ice melted away, by a moderate uplift, with inflow of the plastic or molten magma beneath. The very regular gradation in the differential uplifting of the old shorelines, and its progress almost to completion while this lake was still held by an ice barrier, accord well with this explanation. No element of epeirogenic disturbance is known here which is not readily accounted for by this hypothesis. The explanation is found to be adequate and applicable to all the features of the progressive changes in the levels of the beaches. The very small component which could be ascribed to postglacial change in the

[1] "Mount St. Elias and its glaciers," Am. Jour. Sci. (3), Vol. XLIII, pp. 169-182, with map, March, 1892.

temperature of this part of the earth's crust on account of the departure of the ice would be practically insignificant in comparison with the direct effects of the removal of the ice weight; and its small proportion in the whole result would be to diminish instead of to increase its amount. Upon this district, therefore, it seems well-nigh certain that no other important movement of elevation or of depression has taken place in connection with that dependent on relief from the previously existing ice load.

But a fraction of the changes in the levels of this basin was due to the diminution and final cessation of the ice attraction in its effect to draw water surfaces and the geoid level upward in the direction of the ice mass. The proportion of this element may apparently have been as large as a sixth or a quarter of the measured changes of levels; but its supposed amount, so far as I am able to indicate it, is derived from estimates of the volume of the ice-sheet, rather than from a discrimination of this part from that due to elevation of the land. The two agencies of change were nearly synchronous in their action upon the levels of the old shores, their effects were distributed in the same manner in their relationship to time and space, and both had almost ceased within this basin when the ice barrier of the glacial lake was melted away.

After progressively uplifting the area of Lake Agassiz, first chiefly in its southern half and afterward mostly at the north, but nearly ending their work here while the glacial lake yet existed, these agencies have since been elevating the basin of Hudson and James bays. The latter part of their labor remains unfinished, but during each century approaches considerably toward its completion, which will fully restore equilibrium or isostasy to this portion of the earth's crust.

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MAP SHOWING THE DISTRIBUTION AND DEPTHS OF ARTESIAN WELLS IN THE RED RIVER VALLEY.

Scale, about 42 miles to an inch.

Artesian Wells wholly in the Drift. Artesian Wells and other Borings reaching to the Bed Rocks

*Depths are noted in feet below the surface. For their relationship to the sea level, see Plate X.*