PHYSICAL STUDIES OF LAKE TAHOE.—III. *(Concluded.)*

Rhythmical Variations of Level in Lakes: or "Seiches."—As might be expected, the waters of Lake Tahoe are subject to fluctuations of level, depending upon the variable supplies furnished by its numerous affluents. In mid-winter, when these streams are bound in icy fetters, the level falls; while in the months of May and June, when the snows of the amphitheatre of mountain-slopes are melting most rapidly, the level of the lake rises, and a maximum amount of water escapes through its outlet. According to the observations of Capt. John McKinney, made at his residence on the western shore of this lake, the average seasonal fluctuation of level is about 0.61 of a meter; but in extreme seasons it sometimes amounts to 1.37 metres. The Lake of Geneva, in like manner, is liable to fluctuations of level amounting to from 1.95 to 2.60 meters, from the melting of the Alpine snows.

But besides these variations of level due to the variable quantities of water discharged into them by their affluents, many lakes of moderate dimensions are liable to rhythmical oscillations of level of short duration, which are, obviously, not produced by fluctuations in the supply of water. It is to this kind or species of variation of level, that our attention will be directed in the sequel.

This interesting phenomenon was first recognized in the Lake of Geneva; but was subsequently found to be common to all the Swiss lakes, as well as to those of Scotland. It is, therefore, a general phenomenon, which may be observed in all lakes of moderate dimensions. The inhabitants of the shores of the Lake of Geneva have long designated this rhythmical oscillation of the level of the water by the term "Seiche"; and this designation has been adopted by scientific writers.

These "Seiches" were first signalized in the Lake of Geneva in 1730, by Fatio de Duillier, who ascribed them to the checking of the flow of the waters of the Rhone on the shoal near Geneva by the force of the wind at mid-day. Addison and Jallabert, in 1742, supposed them to be caused by sudden increments in the discharge of the affluents, due to the augmentation in the amount of snow melted after mid-day; or to the sudden increase in the flow of the Arve, checking the outflow of water by the Rhone. Bertrand supposed that electrified clouds might locally attract and elevate the waters of the lake, and thus produce oscillations of level. H. B. de Saussure, in 1799, attributed the phenomenon to rapid local variations of atmospheric pressure on different parts of the lake. J. P. E. Vaucher, in 1802 and 1804, adopted de Saussure's explanation, and confirmed it by many excellent observations. He, moreover, established that Seiches, more or less considerable, occur in all the Swiss lakes; and that they take place at all seasons of the year, and at all times of the day; but, in general, more frequently in Spring and Autumn. As regards the cause of the phenomenon, Vaucher shows how rapid local alterations of atmospheric pressure would produce oscillations in the level of the lake, and compares them to the vibrations of a liquid in a recurved tube or siphon. Finally, Arago maintained that Seiches may arise from various causes, and traced the analogy between them and certain remarkable oscillations of the sea, including those arising from earthquakes.

But physical science is indebted to Professor F. A. Forel, of Lausanne, for the most complete and exhaustive investigation in relation to the phenomena of Seiches. This accomplished physicist began his researches in 1869, and has continued them up to the present time. He has been able to demonstrate that these rhythmical oscillations occur in nearly all of the Swiss Lakes, (he studied the phenomena in nine of them),

and that they follow in all cases the same general laws. Those of the Lake of Geneva have received the most elaborate and prolonged investigation. In March, 1876, Forel established a self-registering tide-gauge ("*limnimètre enregistreur*") on the northern shore of this lake, at Morges; and, with the coöperation of P. Plantamour, another one was installed in June, 1877, at Sécheron, near the city of Geneva, at the southern extremity. Since these dates, these two instruments have, respectively, been registering the oscillations of the level of the water of the Lake of Geneva; and they are so sensitive as to indicate the waves generated by a steamer navigating the lake at a distance of ten or fifteen kilometres.

From a most searching investigation of all the phenomena presented by the Seiches in the Swiss Lakes, Forel deduces the conclusion that they are really movements of steady uninodal oscillation (balanced undulations), in which the whole mass of water in the lake rhythmically swings from shore to shore. And, moreover, he shows that the water oscillates according to the two principal dimensions of the lake; thus, giving rise to longitudinal Seiches and transverse Seiches. They occur in series of tautochronous oscillations of decreasing amplitude; the first wave produced by the action of a given cause having a maximum amplitude.

Amplitude of Oscillations.—The amplitude of the oscillations constituting the Seiches is extremely variable. This, doubtless, arises from the fact that the causes producing the disturbances of hydrostatic equilibrium are extremely unequal in intensity, and variable in kind. In some exceptional cases the amplitude of the oscillations has been very large. Thus, there are on record the following extreme fluctuations of the level of the Lake of Geneva:

		Amplitude.
Observed by	Fatio de Duillier, in Sept. 1600	=1.624 m.
" "	de Saussure, " Aug. 1763	=1.481 "
" "	Venié, " Oct. 1841	=2.138 "

By amplitude is meant the difference in height between the maximum and the minimum level of the water in a complete rise and fall. Thus, in Venié's observations, the water rose 1.218 metres above the mean level of the day, and subsequently fell 0.920 metres below the same level; making the amplitude equal 2.138 metres. Hence, we may say that the extreme amplitude of the Seiches at Geneva fluctuates between 0 and 2.14 metres. In ordinary Seiches, however, it varies from 0 to 30 centimetres; or from 0 to 11.81 English inches. At Morges, the self-registering instrument indicated amplitudes within the limits of 0 and 12.5 centimetres, or 0 and 4.92 inches.

Duration of Oscillations.—Like the rhythmical oscillations of a liquid in a siphon, the duration or time of vibration of any series of Seiches at any given place, and originating from a given cause, is independent of the amplitude of the oscillations. In other terms, the time of vibration is approximately the same, whether the fluctuation of level be large or small. But the investigations of Forel clearly prove that the duration of the Seiches depends upon the dimensions of the lake, and upon the mean depth of the water along the axis of oscillation. Thus, in a long lake, the time of oscillation of a longitudinal Seiche will be longer than that of a transverse Seiche; while, on the other hand, in a deep lake, the duration will be shorter than in a shallow one. Hence it follows that every lake has its own period of oscillation for both its longitudinal and transverse Seiches.

Causes.—The disturbances of hydrostatic equilibrium which generate Seiches may be produced by a variety of causes. Among these, the following may be cited: (*a*) Sudden local variations of atmospheric pressure on different parts of the lake. (*b*) A descending wind, striking the surface of the lake over a limited area. (*c*) Thunder-storms, hail-storms, and water-spouts; and especially, when the accompanying winds act vertically. (*d*) The fall of a large avalanche, or of a land-slide into the lake. (*e*) And lastly, earthquakes.

Observations show that the most frequent and evident of these causes are variations of atmospheric pressure and local storms.

With regard to earthquake-shocks as a cause of such fluctuations of level, it is a singular and significant fact that since Forel has established the delicate self-registering apparatus on the shores of the Lake of Geneva, no less than twelve earthquake shocks have been experienced in this portion of Switzerland, and they have had no sensible influence on these sensitive instruments. In fact, a little consideration in relation to the character of such shocks renders it highly improbable that such brief tremors of the earth's crust could have any agency in the generation of rhythmical oscillations of the whole mass of water in the lake. Indeed, it is very questionable whether any earthquake waves are ever produced in the ocean, except when the sea-bottom undergoes a permanent vertical displacement.

Formula for Time of Oscillation of Seiches.—The researches of Forel seem to prove that the Seiches belong to that class of water-waves in which the wave-length bears a large ratio to the mean depth of the water. The mathematical investigations of Sir G. B. Airy and other physicists show that, under these conditions, the time of one semi-oscillation of such a wave is given by the formula:

$$t = \frac{L}{\sqrt{d \times g}} : \text{ in which,}$$

t = Time of semi-oscillation of the Seiche.
L = Length or breadth of lake, according as the Seiche is longitudinal or transverse.
d = Mean depth of lake, along direction of oscillation.
g = Acceleration due to force of gravity.

The preceding formula shows that the duration of Seiches is directly proportional to the length of the lake, and inversely proportional to the square root of its mean depth. Forel has shown that the results obtained by this formula accord, approximately, with the observations of Seiches in the Swiss lakes.[1]

Lake Tahoe.—From inquiries made of the inhabitants of the shores of Lake Tahoe, I was not able to discover that any rhythmical oscillations of the level of its waters have ever been noticed. Some residents declared that they had observed sudden fluctuations of level, which, from their suddenness, they were disposed to ascribe to disturbances of the bottom of the lake due to volcanic agencies, although they were unable to coördinate such oscillations with any earthquake manifestations on the adjacent shores.

It is evident, however, that until arrangements are consummated for recording systematic observations on the variations of the level of this lake, we cannot expect that its Seiches will be detected. Of course, self-registering gauges would give the most satisfactory results; but any graduated gauge, systematically observed, would soon furnish evidence of the phenomenon. For the longitudinal Seiches, "Hot Springs," at the northern extremity of the lake, or "Lake House," at the southern end, would be eligible stations for gauges; and for the transverse Seiches, Glenbrook, on the eastern shore, or Capt. McKinney's on the western margin, would afford good stations.

As far as I am aware, true Seiches have never been observed in any of the American lakes. This fact is the more remarkable from the circumstance that long-continued and careful observations have been made on the fluctuations of level of several of the large Canadian lakes, with the view of testing the possible existence of lunar tides. Perhaps these lakes may be too large to manifest the uninodal rhythmical oscillations which have been so successfully studied by Forel in the smaller lakes of Switzerland.[2]

[1] Forel's Monographs on the Seiches of the Swiss lakes may be found in the several volumes of the "*Archives des Sci. Phys. et Nat.*" from 1874 to 1880. We cite the following: Tome 49, p. 24, *et seq.*; tome 53, p. 281, *et seq.*; tome 57, p. 278, *et seq.*; tome 59, p. 50, *et seq.*; tome 63, pp. 113, 189, *et seq.*

[2] It is proper to add that "Fluctuations of level in the North American lakes" have been noticed by various observers, from the time of the Jesuit Fathers of the period of Marquette, in 1673, down to the present epoch. Among those who have discussed this problem, may be mentioned in chronological order:

Fra Marquette	in 1673
Baron La Hontan	" 1689
Charlevoix	" 1721
Carver	" 1766
Weld	" 1796
Major S. A. Storrow	" 1817
Capt. Henry Whiting	" 1819
H. R. Schoolcraft	" 1820
Gen. Dearborn	" 1826-29

Be this as it may, there can be no doubt that Lake Tahoe is a body of water in all respects adapted for the manifestation of this species of oscillation; and that, like the Swiss lakes, it is subject to Seiches. Indeed, the far greater simplicity in the configuration of the basin of Lake Tahoe than that of the Lake of Geneva must render the phenomena much less complicated in the former than in the latter.

In advance of any observations, it may be interesting to put on record the probable duration, or period of oscillation, of the Seiches of Lake Tahoe. Such theoretical previsions or anticipations may be verified or disproved by future observations; and, in order to apply such tests, it is convenient to have numerical results presented to the observer. In the formula previously given, expressing the time of one semi-oscillation of the Seiche, all the factors can be readily determined in relation to Lake Tahoe, excepting the mean depth, or *d*. For this lake, we have the quantities indicated in the formula, as below:

L. (longitudinal) = 21.5 English miles = 34,600 meters.
L. (transverse) = 12 " " = 19,313 "
g. (at Lat. 39° and 1904 meters above sea-level) ..... = 9.794,808 " per second.

The following table has been calculated by means of the formula, by assuming the several mean depths indicated in the table. The duration of one complete oscillation [2*t*] is given in the table (instead of the value of one semi-oscillation [*t*]), for both longitudinal and transverse Seiches in Lake Tahoe.

		Longitudinal Seiches.		Transverse Seiches.		
	d in Meters.	2t in Seconds.	2t in Minutes	d in Meters.	2t in Seconds.	2t in Minutes
	450	1042	17.4	450	582	9.7
	425	1073	17.9	425	599	10.0
	400	1106	18.4	400	617	10.3
	375	1142	19.0	375	637	10.6
	350	1182	19.7	350	660	11.0
	325	1226	20.4	325	685	11.4
	300	1277	21.3	300	713	11.9
	275	1333	22.2	275	744	12.4
	250	1398	23.3	250	781	13.0
	225	1474	24.6	225	823	13.7
	200	1563	26.1	200	873	14.5
	175	1672	27.9	175	933	15.5
	150	1805	30.1	150	1008	16.8
	125	1978	33.0	125	1104	18.4
	100	2211	36.8	100	1234	20.6

Gov. L. Cass ..... in 1828
Prof. C. Dewey ..... " 1845
" W. W. Mather ..... " 1847
Major R. Lachlan ..... " 1854
Col. Charles Whittlesey ..... " 1856
" " " ..... " 1873

It seems that pendulum-like pulsations were observed by Prof. Dewey in Lake Ontario in 1845, by Prof. Mather in Lake Superior, at Copper Harbor, in July, 1847, and by Colonel Whittlesey at Eagle River, twenty miles west on the same coast of the latter lake, in 1854 and 1856. According to the last-named observer, the period of oscillations varied from 3.1 minutes to 12 minutes, and their amplitude from 3.7 to 12 inches. These may have been true Seiches, but their characteristic rhythmical features have not been detected.

From the soundings executed by me along the greatest axis of this lake, (nearly north and south) the mean depth of water along this dimension cannot be much less than 400 meters: this would make the time of one complete longitudinal Seiche about 18 or 19 minutes. The mean depth along the transverse dimension is, probably, considerably smaller; perhaps, about 250 meters: this would make the time of one complete transverse Seiche about 13 minutes. As soon as the duration of these rhythmical oscillations has been accurately determined by observation, the problem may be reversed: for, the time being known, the same formula may be used for finding the mean depth of the lake along its two principal diameters.

Origin of Lake Tahoe. — In discussing the "Origin of Lakes," we have indicated the reasons why it is highly improbable that the basin of Lake Tahoe was scooped out by glacial agencies.[1] It is almost certain, however, that this lake was once wholly occupied by ice. In other words, in the fullness of glacial times, this vast lake-basin constituted a huge *Mer de Glace*, receiving tributaries from all directions except the north. As the Glacial Epoch waned—as the great *Mer de Glace* melted away, and the lake-basin became occupied by water—the tributaries still remained as separate glaciers flowing into Lake Tahoe. The investigations of my brother, Professor Joseph Le Conte, have shown (*Am. Journ. Sci.*, 3rd Series, Vol. 10, p. 126.—1875), that three of

[1] *Vide* "*Science Record*," Vol. 2, No. 3, pp. 17, 18. San Francisco, March, 1880.

these tributaries have left their traces near the southern and southwestern shores of this lake. (1st). The "Fallen-Leaf Lake" glacier once came down the cañon at its upper end, and filling it 300 meters or more deep, scooped out the charming "Fallen-Leaf Lake," just where it struck the plain and changed its angle of slope. (2d.) A similar glacier, in its descent to Lake Tahoe, scooped out the basin containing the beautiful "Cascade Lake." (3d.) And lastly, "Emerald Bay"—which is almost a lake, being nearly separated from Lake Tahoe by a shallow bar—was doubtless scooped out by a descending glacier.

Somewhat later in geological times, Lake Tahoe was, as it is now, filled with water; while glaciers from the surrounding amphitheater of mountain peaks debouched into its waters, and formed icebergs which floated on its surface. Thus, while it is in the highest degree probable that the small lakes near the southern and southwestern margin of Lake Tahoe are really glacier-scooped rock basins, yet the position of the principal lake, countersunk between two ridges of the Sierra Nevada, seems to render it probable that its basin may, in reality, be a "Plication-hollow," or a trough produced by the formation of two parallel mountain ridges, and afterwards modified by glacial agency; that it is, in fact, a feature of mountain formation and not of glacial sculpture.

Fauna of Lake Tahoe.—So little is known of the fauna of this lake, that this notice is introduced principally for the purpose of directing the attention of the naturalists of our country to this rich domain for observation and discovery. There can be no question but that careful investigations would here be rewarded by results as interesting and important as those obtained by the researches of the Swiss naturalists in relation to the fauna of the lakes of that country.

During the soundings made by me in Lake Tahoe, specimens of mud were obtained from its bottom at various depths and positions. Microscopic examinations of these, very kindly executed by Mr. H. C. Hyde, formerly President of the "San Francisco Microscopic Society," show that they were rich in beautiful and novel forms of Diatomaceæ. Numerous species of the lower orders of animals are, doubtless, domiciled more than four hundred metres below the surface of this lake, amidst the reign of perpetual darkness. This is, assuredly, a most inviting field of research and discovery for the rising generation of American naturalists.

Conclusion.—The shores of Lake Tahoe afford the most beautiful sites for summer residences. When the State of California becomes more populous, the delicious summer climate of this elevated region, the exquisite beauty of the surrounding scenery, and the admirable facilities afforded for fishing and other aquatic sports, will dot the shores of this mountain lake with the cottages of those who are able to combine health with pleasure. But it must be remembered that the prolonged severity of the winter climate, and especially the great depth of snowfall, render these elevated situations unfit for permanent residences. According to the observations of Dr. G. M. Bourne, during the winter of 1873–74, the aggregate snowfall near the shores of this lake amounted to more than thirty-four feet. In fact, frequently there are not more than four months in the year in which the ground on the margins of this lake is entirely free from snow, and the vast gorges which furrow the sides of the surrounding amphitheater of lofty mountain peaks are perpetually snow-clad. Hence, it is unreasonable to assume that many persons besides the wealthy will be able to enjoy the luxury of private residences here, which can be occupied only during the warm months of the year. Nevertheless, when the refinement and taste incident to the development of an older civilization shall have permeated the minds of the wealthier classes of citizens, this charming lake region will not only continue to be the favorite resort of tourists and artists, but will become, during the summer season, the abode of families whose abundant means enable them to enjoy the healthful climate, the gorgeous scenery, and the invigorating sports which lend an inexpressible charm to a sojourn on its shores.

Amidst the magnificent nature that surrounds this region, there should be an inspiration corresponding more or less with the grandeur of the aspect of the material world. The modifications impressed upon the moral and intellectual character of man by the physical aspects of nature, is a theme more properly belonging to those who have cultivated the æsthetic side of humanity. The poet and the painter can alone appreciate, in the fullness of their humanizing influence, the potent effects of these æsthetic inspirations. The lake districts in all Alpine countries seem to impress peculiar characteristics upon their inhabitants.

When quietly floating on the placid surface of Lake Tahoe, the largest of the "Gems of the Sierra"—nestled, as it is, amidst the huge amphitheatre of mountain peaks—it is difficult to say whether we are more powerfully impressed with the genuine childlike awe and wonder inspired by the contemplation of the noble grandeur of nature, or with the calmer and more gentle sense of the beautiful produced by the less imposing aspects of the surrounding scenery. On the one hand, crag and beetling cliff sweeping in rugged and colossal massiveness above dark waves of pine and fir, far into the keen and clear blue air; the huge mantle of snow, so cumulus-like in its brightness, thrown in many a solid fold over ice-sculptured crest and shoulder; the dark cathedral-like spires and splintered pinnacles, half snow, half stone, rising into the sky like the very pillars of heaven. On the other hand, the waving verdure of the valleys below, the dash of waterfalls, the plenteous gush of springs, the laugh and dance of brook and rivulet as they hurry down the plains. Add to this picture the deep repose of the azure water, in which are mirrored snow-clad peaks as well as marginal fringes of waving forests and green meadows, and it is difficult to decide whether the sense of grandeur or of beauty has obtained the mastery of the soul.

John LeConte.