

ART. IV.—*On the Extinct Volcanoes about Lake Mono, and their relation to the Glacial Drift*; by JOSEPH LECONTE.

[Read before the National Academy of Sciences, April 16, 1879.]

IN 1870, and again in 1872, in company with a party of students and graduates of the University of California, I visited the Mono region. But on both occasions my attention being specially directed to the study of the ancient glaciers, I examined the volcanoes only somewhat cursorily. In 1875 with a similar party I again visited the same region, and this time remained longer and examined more carefully, though on account of an unfortunate accident, not so long or so carefully as I desired. I have put off from year to year the publication of the results of my observations in the hope of again visiting the region and settling some doubtful points which still remained. There seems now, however, little likelihood that I shall ever be able to carry out my intention, for other questions of still greater interest have in the meantime engaged my attention. I will therefore no longer withhold my imperfect observations, hoping that they will be corrected and extended by others.

General description of the region.—*Eastern slope of the Sierra.*—As already explained in previous papers,* the general form of the Sierra is that of a great wave ready to break on its eastern side. It rises from the San Joaquin plains by a gentle slope which extends 50 to 60 miles, reaches a crest 13,000 feet high, then plunges downward by a slope so steep that it reaches the plains of Mono 6000 ft. above sea level, in five or six miles. In glacial times, long, complicated glaciers with many tributaries occupied the western slope, while on the east, comparatively short simple glaciers came down in parallel streams and ran far out on the level plain and into the swollen waters of Lake Mono, which, then nearly 700 feet above its present level and far beyond its present limits, washed against the base of the Sierra itself. There can be no doubt that these glaciers formed icebergs which floated on the surface of the great inland sea and dropped débris over its bottom.

The Plains.—Surrounding Lake Mono and sloping imperceptibly to its surface, is a nearly level desert plain, covered with volcanic sand interspersed with fragments of pumice and obsidian, and overgrown with sage-brush (*Artemisia tridentata*). It is undoubtedly an old lake bottom, subsequently covered with volcanic ashes. The dreary prospect of this desert is relieved by the magnificent irregular Sierra wall trenched with deep cañons; by long parallel moraine ridges stretching like arms from the mouth of each cañon, five or six miles out on

* This Journal, III, v, 325, 1873; x, 126, 1875; xvi, 95, 1878.

the level plain, and bounding the pathways of ancient glaciers; by a fine cluster of recently extinct volcanic cones fifteen to twenty in number and very perfect in shape, and finally by the bright waves of the lake studded with picturesque islands.

Moraines.—Some of the parallel moraines which form so conspicuous a feature of the scene, especially those of Bloody cañon, I have already described.* From the top of any of the higher volcanic cones, many others may be seen stretching out upon the plain. These moraine ridges average 300 to 400 feet in height and five to six miles in length, but some of them, especially those at the head of Rush Creek, are much higher. The view of glacial moraines here presented is incomparably the finest I have ever seen.

Lake.—Lake Mono is a fine sheet 14 by 10 miles in extent. There being no outlet the waters are of course saline. It is essentially a strong solution of sodium carbonate, with smaller proportions of lime carbonate, common salt and borax. To the taste it is simply a concentrated solution of carbonate of soda. While camping on its margin we found its powerful detergent property very useful in clothes-washing. The mineral contents are probably partly the concentrated leachings from the volcanic rocks which cover the whole plains—the alkaline silicates of these rocks being changed into alkaline carbonates by carbonic acid of the air—and partly contributed by springs which issue in many places from the bottom and around the margins of the Lake, and were probably more numerous and active in former times. In any case, the lake waters are now but the concentrated residues of a much larger body of water, as plainly shown by the terraces to be presently described. During the process of concentration the less soluble lime carbonate has been deposited in strange irregular masses of calcareous tufa. These curious fungoid and coralloid masses, some of them six to ten feet in height, stand up thickly on the level shores and in the shallow marginal waters of the lake. At a distance they look like the half-submerged stumps of a forest of gigantic trees. This carbonate of lime deposit is evidently identical with the thinolite deposit described by King† as occurring in such immense quantities about the residual lakes of the Nevada basin farther north, and which as he shows is a pseudomorph of carbonate of lime after Gay-Lussite. The conditions under which the deposit took place about Mono are probably, however, slightly different from those in Nevada, and I believe throw much light on the general question of thinolite deposits. It deserves careful study and I hope to take it up in a subsequent paper. Farther east, near Columbus, Nevada, in the region of the dried-up lakes left at the extreme southern exten-

* This Journal, III, v, 325. † Geol. Exploration 40th Parallel, i, 508, and seq.

sion of King's ancient lake *Lahontan*, occur remarkable deposits of ulexite (soda-lime borate) which also deserve separate study.

Terraces.—I have already mentioned the terraces about Lake Mono. Several of these are very distinct and traceable all around the lake. But they are seen in greatest number and most distinctly on the west side, where the lake approaches the Sierra and the hills rise abruptly from the lake-level. Five or six may here be counted, rising one above the other like level benches, the highest being, according to Whitney, 680 ft. high. These terraces are undoubtedly the marks of old lake levels, and show not only a former greater depth but also a much greater extent of the lake waters. The highest level traced about the lake would reach the moraines at the foot of the Sierra, extend beyond the plains on every side, and enclose an area many times greater than the present lake-area. There can be no doubt therefore that the great glaciers of that time ran into the lake and formed icebergs.

Islands.—Near the center of the lake there is a group of volcanic islands in direct line with the groups of volcanic cones on the plains to the south and doubtless a continuation of the same line of volcanic activity. The largest of these islands is about $2\frac{1}{2}$ miles long, a mile wide and about 300 feet high. It is composed mainly of extremely fine, whitish material, beautifully and very finely laminated, the differently colored laminæ being very distinct and scarcely thicker than cardboard. This material is spoken of by Whitney* as volcanic ashes. Under the microscope it proves to be composed wholly of *diatom shells* with only an occasional grain of sharp sand. There is no doubt therefore that it was deposited very slowly in calm waters, in the middle of the lake and beyond the reach of detritus. The stratification is mostly horizontal; only in two or three places where the deeper strata are exposed on the cliffs by the action of waves, I observed a slight dip, and in one place a gentle but distinct *anticline*, showing a quiet upheaval of the whole mass, as I think, by volcanic forces. In the highest parts of the island, the soft, horizontally-laminated earth is sculptured by erosion into sharp pinnacles and turrets like bad-land structure on a small scale. On the eastern portion of the island a considerable area of black basaltic rock is exposed, but this is no where more than 50 feet high. Where the diatomaceous earth comes in contact with the basalt, the former always overlies the latter in undisturbed horizontal layers. I conclude therefore that the basalt preceded the formation of the diatomaceous mud, was once entirely covered by the latter, and was subsequently exposed by erosion.

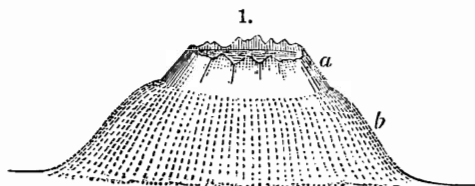
* Geol. Survey of California, i, 453.

Steam and boiling water issue in many places in this rocky portion of the island and in the shallow water in the vicinity. I observed also in the earthy portion crater-like depressions, containing a little saline water, which were probably produced by similar fumarole action now extinct. According to Whitney (p. 453) two distinct true craters occur in the basalt on the northeast portion of the island; but these I did not see.

The other and much smaller islands I did not have time to visit, but according to Whitney, they are wholly basaltic, and the largest of them is 300 feet high, and is a well-defined volcanic cone.

The general conclusion, at which I arrived from my examination of the largest island, was that the basaltic portion was first formed at the bottom of the lake, or else subsequently submerged; then the diatomaceous mud was deposited, covering it up completely; then the fine mud-bottom was raised into an anticline and exposed as an island by the fall of the lake level, and finally erosion sculptured the whole, and in part exposed the underlying basalt.

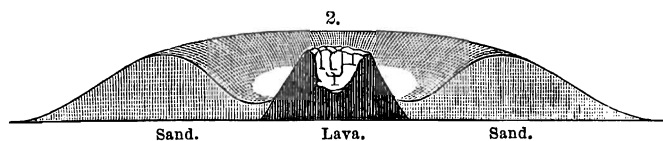
Volcanoes on the Plains.—We have already alluded to a conspicuous group of volcanic cones situated on the level plain south of the lake. These are twenty or thirty in number, extending in a line from near the margin of the lake to a distance of ten to fifteen miles, and vary in height from 200 to 2,700 feet above the plain. Partly from the recency of their



extinction, and partly from the small rainfall of the region, they are, some of them, as perfect in form as if they were still in action. A good general view of these is given by Whitney in his account of this region. The typical form of the more perfect is shown in fig. 1, which, though intended only as a diagram, is yet a tolerably correct outline of the highest and most perfect. The upper part *a* is a light-colored pumiceous lava, and the lower part *b* is covered with sand of the same.

In many cases I observed a very perfect cone-and-rampart structure, such as is known to be produced by great eruptions, followed by smaller ones; or perhaps in some cases by an engulfment of the crater into the base of the cone. The most perfect example of this kind is found in a small and easily accessible cone, not far from the lake. Fig. 2 is an ideal

section and half perspective view of this cone. It consists of a low sand cone about 200 feet high, with a perfect circular crater one and a half to two miles in circumference, from the center of which rises a trachytic cone and crater of much smaller dimensions, to about the same height. From the



shattered condition of the inner cone, Mr. Muir suggested to me the possibility of the engulfment of the upper rocky portion into the lower sandy portion of a once much higher cone. But, in many other cases observed, this explanation is evidently untenable; for in some cases we found several small cones surrounded by one rampart. Such could only be formed by successive eruptions.

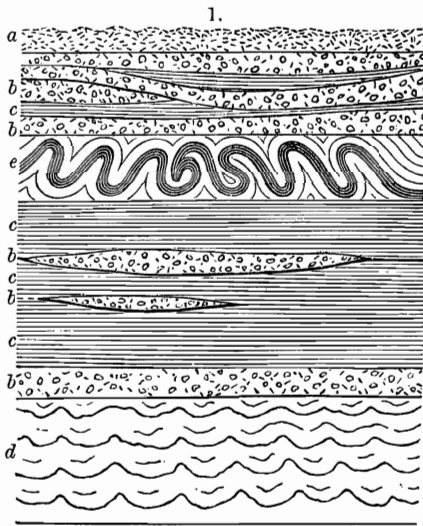
The material erupted by these volcanoes is in some cases basalt, but by far the largest amount consists of feldspathic slags, pumice and pumiceous sands and ashes. The whole plains of Mono are covered to a depth of many feet with a nearly white volcanic sand, mingled with fragments of pumice and obsidian.

Age of the Mono Volcanoes.—There is abundant evidence that these volcanoes have been active, and therefore that they assumed their present forms since the epoch of great separate glaciers in this region (Champlain). Whether they also existed and erupted previously is perhaps doubtful though probable. The evidences of the extreme recency of the eruptions, which determined their present forms, are as follows:

1. We have already shown the splendid scale on which glaciers were once developed in this region. We have already given reasons for thinking that they ran down the Sierra, out on the plains and into the lake, and produced icebergs there. It is impossible that the volcanic cones, if they then existed, could have escaped the powerful action of ice, and the equally powerful action of other meteoric agencies, so characteristic of that epoch, which must have entirely destroyed their form. The remarkable perfection of their conical forms and of their craters is therefore strongly presumptive if not demonstrative, of the fact of their eruption since the disappearance of the glaciers.

2. All the streams, which run from the Sierra into Lake Mono, cut into the level plains 100 to 150 feet deep. Fine sections of the materials of the plains are thus exposed. Fig. 3 is the upper portion of such a section about eighty feet perpen-

dicular. The lower portion of the cliff, being covered up by talus, is not represented. It is seen that nearly the whole is an ordinary modified drift, composed of irregularly stratified sands and clays, *cc*, intermingled with layers of pebbles and gravel, *bb*. But there are other parts that deserve more special notice. The stratum *e* is a fine light-colored clay, through which runs



- a* = unstratified volcanic sand.
bb = pebble and gravel.
cc = fine sand and clay stratified.
d = strata crumpled by moving strata.
e = strata scrolled by same agency.

a deep chocolate-brown lamina scrolled in the most complex and beautiful pattern; the stratum *d* is also strongly crumpled. This crumpling and scrolling of the strata could have been produced only by a glacier advancing on a bed of stratified clay, or else by the pushing of icebergs on a stratified lake bottom. I suppose the whole formation except *a* to have been produced by an alternately advancing and retreating glacier; now retreating and dropping material, to be carried and deposited by the river which flowed from its snout, now advancing and crumpling

the finer material of the lake bottom. It may be difficult to explain the details of the process, but I think it will not be doubted that the whole is a distinctly marked drift-deposit. Many other similar sections were observed; some of which were 150 feet thick.

Now covering everywhere this undoubted glacial material is found a layer of loose, unstratified volcanic sand and pumice, *a*, which has evidently never been touched by the action of water. It is a pure eolian drift. In the section it is about three feet thick, but it is really much thicker, as it thins off on the margin of the perpendicular cliff by falling, and thus contributes to the talus at its base. It is evident that the whole material of the section was deposited during glacial times, except *a*, which was drifted over the bared lake bottom since that time. But judging from the immense quantity of this loose material, covering as it does the whole plain many feet deep, it seems impossible that it is the mere result of disintegration of the vol-

canic cones in recent times. I suppose, therefore, that it is the result of sand and ash eruptions since the recession of the lake waters.

3. We have already described the material of the largest island as being composed wholly, except a portion of the eastern part, of a fine infusorial earth, horizontally stratified with laminæ of slightly different colors, so thin as to give specimens an almost agate-like beauty. This material was evidently deposited in the middle and deepest part of the lake, beyond the reach of coarser sediments, at a time when the place of the island was still a lake bottom. Now, that this occurred during or after the epoch of great glaciers, is demonstrated by the fact that scattered sparsely through this fine laminated material, and lying on its surface, having been washed out by erosion, I found many boulders, both worn and angular, of Sierra granite and slate, and also of obsidian. These could have been brought there only by the agency of floating ice, either as icebergs or as shore ice. If by icebergs, of course during the epoch of great glaciers; if by shore ice, either during that time or still later, for manifestly the boulders were brought down to the shore from the Sierra during that time. It is evident, therefore, that the stratified mud was formed and the boulders were dropped during the period of great glaciers or later. But still later the island itself was upheaved by volcanic action, as shown by the anticlinal position of the strata at the base, and by the solfataric action still going on. The formation of this island I suppose to have been coincident with the last eruptions of the volcanoes on the plains.

4. Within the craters of several of the volcanic cones on the plains, I found pebbles and angular fragments of granite of a peculiar reddish color from the presence of a rose-colored feldspar. Whitney observed the same, and accounts for them in the following manner: They could not, he thinks, have been brought by glaciers or by water, for this is inconsistent with the perfect shape of the cones. He rightly concludes therefore that *they must have been ejected from the volcanoes*. But if so, he says, "*they must have been torn off from the underlying granite, through which the eruptive matter has forced its way, as is seen everywhere in the Sierra.*"* On the contrary, I account for them in a wholly different way. The fragments which I saw were some of them angular—true; but *most of them were well-worn pebbles*. There is not the slightest doubt that *these were pebbles of the drift-layer which everywhere underlies the loose sand of the plains*. The eruptive forces broke through this drift-layer, and the ejected pebbles fell back into the crater. They demonstrate that the cones and craters, where they are found, not only

* Geol. Survey of Cal. vol. i, p. 455.

erupted, but *were wholly formed*, after the epoch of the pebble drift.

I think, therefore, there can be no doubt that all of these volcanoes erupted, and many of them were wholly formed after the epoch of great glaciers (Champlain). Whether any of them preceded that epoch is doubtful. I have never seen any undoubted evidence that they did. If the bowlders found on the island were carried there by icebergs, then volcanic action preceded the epoch of icebergs, for many of the fragments are volcanic; but they may have been carried by shore ice at a later time. Again, I believe the rocky part of the island is older than the sedimentary part, for the latter seems to have been deposited on the former. If the sedimentation was Champlain, then the rocky part was probably pre-glacial; but the sedimentation may have been later.

Sequence of Events.—Assuming that the island strata belong to the epoch of great glaciers, then the order of events was something like this:

1. Volcanic eruptions on the plains producing obsidian, fragments of which were afterwards carried by ice and dropped in mid-lake. At the same time also, the basaltic part of the islands was formed.

2. Then followed the period of great glaciers and flooded lakes, or Champlain epoch. The lake was nearly 700 feet higher than now. Its waters covered the whole plains and washed against the Sierra; and glaciers from this range ran far into the lake and formed icebergs, which floated over its surface and dropped rock-fragments over its fine mud bottom.

3. Volcanic forces, acting quietly like the solfataras and fumaroles still existing, heaved up the stratified mud-bottom of the mid-lake into a gentle mound with quaquaversal dip of the strata, but not rising to the surface. Coincident with this were the eruptions of the plains volcanoes.

4. The lake then dried away gradually to its present level, leaving the terraces as its old flood-marks, and exposing the rounded mud-island; and erosive agents then sculptured this into its present turreted form and cut away its margin to its present limits, and exposed the mud-covered older basaltic part.

Lake rising again.—The existence of salt and alkaline lakes shows an extreme dryness of climate. But the climate of the desert region has not always been dry. During the Champlain epoch the interior plains were covered with immense sheets of water, of which the present saline lakes are the isolated residues. Gilbert has shown that at that time Great Salt Lake contained 400 times as much water as now, and that it drained northward through the Snake and Columbia Rivers into the

Pacific ocean. King has shown that the Nevada basin was at the same time occupied by a vast irregular sheet of nearly equal extent, stretching southward as far as Columbus, Nevada. Pyramid, Winnemucca, Carson, Humboldt, and Walker Lakes, are the concentrated residues of this great lake. Lake Mono also, we have seen, at the same time, was a great sheet of water, whether connected with the other or not is not known. There has been therefore an increasing dryness of climate in that region since the Champlain. Is it still progressing, or has it reached its maximum? This is an important question for the Pacific States.

From my observations on Lake Mono, I have no doubt that its level, at the time of my visit, was rising and had been rising for ten or fifteen years. The evidence is as follows: Around the margin of the lake I found everywhere old fences of sheep *corrals* and old trails submerged many feet deep. While visiting the island I found the vegetation of the island, sage brush (*Artemisia tridentata*), and grease wood (*Sarcobatus vermiculatus*), submerged in five feet of water, and of course killed. Residents about the lake state that the waters have risen ten to twelve feet in ten or fifteen years. I might be disposed to doubt these observations if the same phenomena had not been observed in other lakes in the same dry region. Salt Lake is known to have risen ten to fourteen feet in twenty five years and submerged large tracts on its flat margins, and the water by analysis is far less salt than formerly. Pyramid Lake, according to King, has risen nine feet, and Winnemucca Lake twenty-two feet in only four years—1867–1871. The same is said to be true of Walker Lake and of Owen Lake.

The cause of this is evidently increase of rain-fall and snow-fall, chiefly the latter. In this connection it may be well to mention an additional evidence of increasing snow-fall in the Sierra. I have in a previous paper† drawn attention to a moving snow-field, or rather an imperfect *glacier*, occupying the great cirque at the top of Mount Lyell, the feeble remnant of the great Tuolumne glacier of glacial times. At the foot of this *glacieret* there is as perfect a terminal moraine as ever was seen. It is a crescentic pile of rock fragments twenty feet high, fifty feet wide at base, and about a mile long. The fragments were brought down by the moving ice from the vertical cliffs of the cirque. Many similar fragments are seen lying on the glacier on their way to the moraine, and in various stages of advance. Now not only does this moraine show no signs of being left by a *retreating* glacier, but on the contrary I think it shows signs that the ice is *advancing*. For the snout of the *glacieret* is not only pressed hard against the moraine but the

* This Journal, III, v, 325.

outer slope of the moraine, when I saw it, in 1872, was just at the *limit of stability*—the least disturbance caused the fragments to roll down. It would seem therefore that the moraine is being pushed slowly forward. Whether the same is true still I know not.*

King, in his recent volume on Systematic Geology, already referred to, has drawn attention to still other evidence of snow advance in the high Sierra. According to him, above the timber belt, there is a comparatively bare region of one thousand feet vertical, on which for ages there has been too much winter snow to allow the growth of timber. In the timber region bordering the bare region there are many trees which have two hundred and fifty annual rings. These trees have therefore been growing securely for two hundred and fifty years. But since 1860 the snow has so advanced upon the timber region that these great trees are being destroyed by avalanches. It would seem therefore that not only has there been recent advance, but that it is the first advance for two hundred and fifty years.

The rise of the lakes in the desert region is therefore undoubtedly the result of a climatic cycle. But whether the cycle be a long or a short one; whether it be a geological cycle of increasing snow-fall—a turn of the cycle of dryness which, commencing after the Champlain epoch, culminated in the present arid condition of the desert region—or whether it be only a climatic fluctuation of short duration, and of which therefore geology takes no account, such for instance as may be supposed to be connected with the sun-spot cycle, it is impossible with certainty to determine without observations extending through a much longer period of time. I have hitherto been disposed to think the latter more probable, but King's observations on destruction of trees by avalanches, would seem to point to the probability of a long cycle.

* King, in his recent volume on Systematic Geology of the 40th parallel, p. 477, says that all Mr. Muir's living glaciers of the Sierra are only moving snow-fields well known to the California surveyors. He then quotes Agassiz defining the distinction between such moving névés or snow-fields and true glaciers. This distinction according to Agassiz consists in the ability to bear rock fragments on its bosom and thus to form a moraine. Now, it is but justice to Mr. Muir to say that the ice in the Lyell-Cirque does bear large rock fragments on its surface and accumulates them at its lower limit as a perfect terminal moraine. Recognizing, however, the fact that this ice mass does not emerge from its native cirque, I have, in my paper on "Ancient Glaciers of the Sierra" (this Journal v, 325), called it a *Glacieret*.

Berkeley, California, March 1, 1879.