ART. XXIII.—*The Old River-beds of California*; by JOSEPH LECONTE.

[Read before the National Academy of Sciences, Oct. 29, 1879.]

OLD river-beds are found in nearly all countries which have been affected by drift-agencies. In nearly all such countries, too, these old beds are filled to great depths with river deposit. But the old river-beds of California are in several respects entirely unique. In most other countries, as for example, in Europe and Eastern United States, the new or present river-beds occupy the same position as the old; while in middle California the rivers have been *displaced*, by lava flows, from their former position and compelled to cut entirely new channels. Again: in certain portions of Europe and in Eastern United States, the old river-beds are broad, deep troughs, filled sometimes several hundred feet deep with detritus, into the upper parts of which the present much shrunken streams are cutting their narrower channels on a *higher* level; while in California the displaced rivers have cut their new channels 2000 to 3000 feet deep in solid slate, leaving the old detritus-filled channels far up on the dividing ridges. In northeastern United States the drainage system has remained substantially unchanged since early Tertiary, or even still earlier times; while in middle California the Tertiary drainage system seems to have been obliterated and the streams have been compelled to carve out to a much deeper level an entirely new and independent drainage system, having the same general direction but often cutting across the former. In the one case the old beds *underlie* the new, while in the other they *overlook* them from the tops of the neighboring ridges. Furthermore, in California the detritus which fills the old river-beds is nearly always capped with lava or other volcanic material, clearly indicating the cause of the displacement. If to all these peculiarities we add the usually extreme coarseness of the detritus which fills the river-beds of California, consisting as it does largely of pebbles and bowlders, compared with the fine silts which fill the old river channels of the Eastern coast, and we will see how marked is the contrast in many respects.

For all that is known concerning the old river-beds of California, we are up to the present time almost wholly indebted to Professor Whitney. His valuable investigations on this subject were published in the first volume of the Geological Survey of California in 1865. He has also recently published a fuller description and a complete map of them. His views have therefore been before the scientific public for many years, and are so well known that a bare enumeration of their main features is all that is required here. Whitney shows: 1. that there is in California an old river-system entirely different from the present river-system; 2. that the old channels were filled by detritus, and the detritus covered by lava-streams; 3. that the lava flows, completing the filling of the channels, diverted the streams and forced them to cut for themselves new channels; 4. that the displaced streams cut their new channels to a much lower level than the old, so that these latter are now found on the present divides. My own observations entirely confirm these results, and they form therefore my starting point. Whitney also regards the old detritus as the representative of at least the whole Pliocene and the Lava flow as its closing event. In what respects my own views are an extension of Whitney's, and in what respects they differ from them, will be sufficiently indicated in what follows.

The general relation of the old and the new beds is well shown in the following figures taken from Geological Survey of California. In figure 1 the old and new beds are parallel, and the section is across both; while in figure 2 the new beds have cut across the old, and the section is along the old and across the new.

This peculiar relation of the old to the new river-beds does not characterize the whole Pacific slope, but only the auriferous slate belt of middle California. It is not found in the Coast Range, nor in the region of the granite axis of the

1.

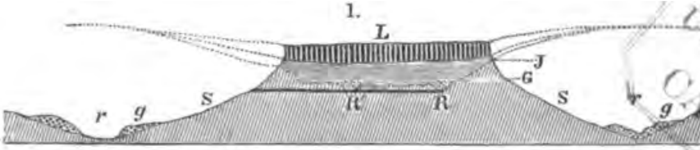

FIG. 1.—Section across Table mountain: *L*, lava; *SS*, sandstone;* *G*, old gravel; river-bed; *S*, slate bed rock; *r*, present river; *g*, present gravel.

2.

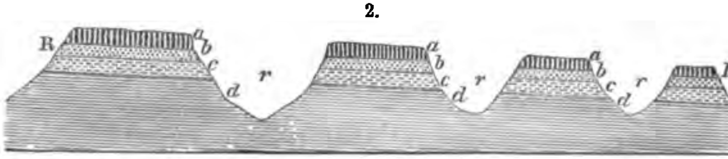

FIG. 2.—Lava stream cut through by modern rivers: *aa*, basalt; *bb*, volcanic ashes; *cc*, Tertiary; *dd*, Cretaceous; *RR*, direction of old river-bed; *rr*, of new river-bed.

Sierra Range. Neither is it found, at least in any marked degree, in extreme northern California nor in Oregon, nor yet in southern California. It seems to be confined mainly to the slate belt of the western slope of the Sierra from Plumas

* The material here called sandstone is a cemented river sand. It is usually covered with tufa or tufaceous conglomerate and this latter with lava.

county on the north to Tuolumne county on the south inclusive, a distance of about 250 miles, and from the San Joaquin and Sacramento plains on the west to about 4000 feet elevation on the Sierra slope on the east, a breadth of about 35 miles.

There is no problem in California geology more important, and yet none more difficult—none more enticing and yet none more baffling—than the mode of filling of the old river-beds and the cause of the displacement of the streams. The opportunities of study are abundant, for in many places the old beds have been bared, and complete sections of their fillings made by the operations of hydraulic mining; but the phenomena are so extremely complex and difficult of interpretation that we are not yet prepared for a final theory. I have on several occasions utilized my vacations by the study of these old channels and their fillings. In 1877 I examined those about Forest Hill; in 1878 those in Tuolumne county. Very recently under the intelligent guidance and kind assistance of Mr. Hughes, the superintendent of the Blue Tent mines, I have made a more extended and thorough examination than ever before. Extensive gravel deposits exist on both sides of the South Yuba River for many miles. This is in fact the finest mining region in the State. I went up one side and down the other and examined these in succession. I wish now to very briefly present the conclusions to which I have provisionally come by much reflection on the observations made on this and on previous occasions. I present them with some misgivings, well knowing that much more complete and detailed observations are necessary before an entirely satisfactory theory can be reached.

General Description.

It is well known that in hydraulic mining the whole thickness of the old river-channel-fillings is worked down and carried away by the prodigious force of the hydraulic jets. In such a mine, therefore, we always have the old bed bared over the whole area cleared, and the fillings exposed from bottom to top, on the face of an ever-receding vertical cliff 200 to 400 feet high.

The Bed.—The old stream-bed thus exposed has a shallow, trough-like form, i. e. is lowest in the middle and rises gently on both sides. These higher sides of the trough are called the "*rims.*" The *bed-rock*, which is usually slate with nearly vertical cleavage, retains usually its original soundness and hardness, but in some places is more or less decomposed, and sometimes, while retaining its form, is completely changed into plastic clay. In all cases it is worn into irregular and fantastic hollows and channels, and often into deep pot-holes. As there is no apparent relation between the hardness or softness of the bed-rock and the amount of wear, it is certain that the softening has taken place since the filling. The surface-forms of the bed-rock are precisely such as are always produced by swift currents carrying coarse materials—precisely such as are *now* produced in the artificial channels through the rim-rock by the rushing torrents loaded with pebbles and gravel, resulting from the incessant play of the hydraulic jets against the cliff.* There can be no reasonable doubt, therefore, that these trough-like depressions are really the old channels of rushing torrents loaded with eroding materials.

The general form of the wide, shallow, trough-shaped channels of the old rivers is in marked contrast with the deep, sharply V-shaped cañons which characterize the present rivers in the same region.

The filling.—The cliff exposed by hydraulic mining, consists usually from bottom to near the top, of distinctly but irregularly stratified material. The lowest portion next the bed-rock, sometimes a few feet, sometimes many feet in thickness, is a conglomerate of pebbles and bowlders often of large size, with a paste of sand and plastic clay usually of a slate-blue color. This is the "*Blue gravel*" of the miners. The pebbles and bowlders are usually well rounded ("wash gravel"), but in a few channels I have found them sub-angular, like those of *till.* Above the Blue gravel, the whole way up to near the top, the material consists of alternate layers of pebbles, gravel, sand and clay, usually of a yellowish or reddish color. The pebble layers occur in lenticular masses, and the sands and clays are often cross-laminated. In many cases the whole material is more or less firmly cemented by lime carbonate or by silica, so that the cliff must be loosened by blasting before it can be washed down by the hydraulic jets. Irregularly distributed throughout the whole mass are found fragments or sometimes large trunks of drift timber, oak, maple and conifers, in a lignitized or else in a slicified condition. In some cases the lignitizing change has progressed but a little way. I found at Sailor's flat, beneath the volcanic cap, to be presently described, logs of Redwood (Sequoia) or of cedar (*Libocedrus*) probably the latter, in which the bark was still tough and fibrous although the wood was soft and could be cut like cheese. In the finely stratified sands and clays are found beautiful impressions of leaves of many kinds. According to Lesquereux these leaves indicate a Pliocene age for the deposits. More rarely mammalian bones have been found. Among these are allies of the rhinoceros, hippopotamus and camel, indicating, like the leaves a Pliocene age, but also in many undoubted cases the mam-

* It is well to note here the prodigious rapidity of this erosion. In the North Bloomfield mine, the pebble-loaded torrent, working eight months per year, has cut in four years a channel three feet wide and fifty feet deep in solid slate.

moth, the great mastodon and a tapir, undistinguishable from the living species, indicating a Quaternary rather than a Pliocene age. These Quaternary remains have been in several instances found under the volcanic caps in the lowest blue-gravel, next to the bed-rock. Several examples of this kind are now in the museum of the University. Some human remains and implements are also supposed to have been found in this detritus, but the authenticity of these is disputed by many.

In several cases I observed in the vertical cliff of detritus distinct curved lines of discontinuity, concave upward, indicating sub-channels cut in the main mass of detritus. Undoubtedly the main channel had been first filled, then partly swept out by erosion, and then re-filled. This observation is important, as it seems demonstrative of a true river agency.

The lower portion of the detritus, the so-called blue gravel, differs from the upper portion partly in structure, but chiefly in color. In structure it is almost if not quite devoid of lamination; and when the rock fragments are sub-angular it is almost undistinguishable from true *till* or ground-moraine. In most cases, however, its pebbles and bowlders are perfectly rounded. Its blue color is undoubtedly due to the fact that its iron is in the form of ferrous instead of ferric oxide. There is no such line of demarkation between the blue and the red gravel as would indicate a different origin. On the contrary the irregularity of the plane of contact and the shading of the color shows a downward progressive oxidation of iron, greater in some places than in others.

The capping.—Above the detritus which constitutes the main portion of the filling of most of the old river-beds, we nearly always find a capping of volcanic matter 50 to 150 feet thick. This is sometimes hard basalt underlaid by tufaceous conglomerate, but more usually tufaceous conglomerate only.

3.

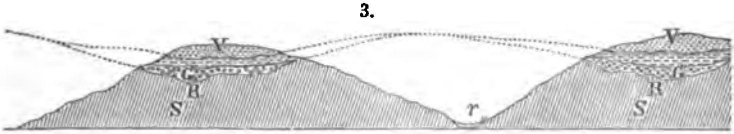

FIG. 3.—*SS*, slate bed rock; *RR*, old river bed; *r*, present river bed; *GG*, old river gravel; *VV*, volcanic conglomerate.

In this latter case, however, the presence of scattered blocks of basalt on the surface often indicates the *former* existence of a thin basaltic cap which has been removed by erosion. When a basaltic cap remains it gives rise to flat table-topped ridges as in figures 1 and 2. Otherwise the ridges become rounded by erosion. Figure 3 is an ideal section showing the more usual form. When the cap consists of tufaceous conglomerate above, the whole thickness of the filling, including the volcanic cap, may be washed down together by hydraulic process, although the latter is of course barren matter; but when the cap is basaltic the auriferous gravel can only be worked by the slower process of drifting. In this case only the lower portion is extracted. In all cases the volcanic cap, especially the tufa, has furnished down-percolating, alkaline waters holding silica in solution. The condition of greater or less saturation (with perhaps other conditions)* seems to have determined whether this solution deposits or takes up silica. When it deposits, the gravel is cemented and the drift-wood is petrified; when it takes up silica the volcanic and slate pebbles are rotted down to "*putty stones*" and the bed rock is softened to a greater or less depth.†

The tufaceous conglomerate which is so constant an attendant of the old river gravels consists of a soft, earthy, reddish tufa, enclosing rounded pebbles of all kinds, volcanic, slate and quartz and of all sizes, distributed more or less abundantly but irregularly through its mass. It is probably volcanic ashes washed down from the higher Sierra slope by rain and melting snow. But the absolute absence of the least trace of stratification (which I sought for in vain) seems to show that the quantity of ash in proportion to water was so great that it was literally a mud-flow gathering pebbles in its course. In some cases, however, are found alternate layers of gravel and tufa. Where the basaltic lava occurs it always nearly overlies the tufa.

Nearly all the higher parts of the country are covered both with the gravel and with the tufa. The lava is also very widely spread. The indications are that these materials formed at one time an almost universal covering, but subsequent erosion has left them in ridges and patches.

Explanation of the phenomena above described.

There are many difficult and important questions suggested by the phenomena above described which press upon us for solution. "How were the old river beds filled with detritus?" "How were the streams displaced from their old beds?" "Why have the new channels been cut so much deeper than the old?" "When did these events occur?" I shall take these four points in the order mentioned.

1. *The mode of filling of the old river-beds.*—There are three possible modes in which we may conceive these beds to have

* In silicification of wood there is little doubt that the percolating alkaline waters charged with silica are neutralized by the acids of organic decomposition, and the silica thus rendered insoluble is deposited then and there (see author's Elements of Geology, p. 193.)

† In many of the hydraulic mines, especially in the Dardanelle mines near Forest Hill, I found in certain parts all the slate and volcanic pebbles while still retaining their form perfectly, reduced to a soft soapy bluish clay. These are called putty stones. It is evident their silica has been extracted by alkaline waters.

been filled with detritus. 1st. They may have been filled by glaciers slowly and steadily retreating up the valleys, dropping their debris on their way, the debris perhaps afterwards modified by currents from the melting glacier. 2d. They may have been filled successively from mountain foot toward mountain crest with detritus brought down by the rivers into a bay or fiord which steadily moved up the valley by subsidence of the land until the sea stood 4,000 feet above its present level. Or 3d, they may have been filled in all parts nearly simultaneously by true river action in the same way as river-channels elsewhere have been or under certain conditions are now filled.

I shall not discuss the first and second. I mention them because each, but especially the second, has been held by some persons. I have kept them constantly in mind during all my observations but have been compelled to abandon them as untenable. I am quite sure that no one can examine these deposits carefully without being convinced that they are true river deposits, though formed, certainly, under very exceptional conditions. It is these conditions which I now wish if possible to realize in imagination.

That the conditions were really exceptional is very evident on a little reflection. The present rivers in all this region run with high velocity, have cut very deep channels and are still cutting: why then should the former rivers in the same region have *filled* up instead of cutting their channels? The difficulty is not removed by supposing a lower velocity; for the character of the deposits, especially the great bowlders, often many tons weight, show a much higher velocity than now exists. With such rushing torrents why did the beds fill up instead of cutting deeper? To this I answer: any current, however swift, will deposit if *only its load be sufficient.* Every current has a certain amount of energy, and can therefore do a certain amount of work, increasing of course with the velocity.* This energy is usually divided between the work of transportation and the work of erosion. If the load of transported matter be moderate, a large amount of energy is left over for erosion; but if the load of transported matter be very great, the whole energy may be expended in transportation and none is left for erosion—the limit is reached at which erosion ceases and deposit commences. Now, since transported detritus is the main erosive agent, it follows that in every stream there is a certain amount of detritus which produces the maximum erosion. Pure water has little effect for want of erosive agent; too much material also produces little effect, because too much energy is consumed in carrying.

It is evident therefore that all that is necessary to cause any stream to deposit is to increase its load beyond the

* Gilbert, this Journ., vol. xii, pp. 16 and 85, 1876.

limits of its energy. This principle is well understood by hydraulic miners. The amount of water gathered in the sluices from the hydraulic jets must be duly related to the amount of earth removed. If the water is in excess, the precious water is wasted and the erosion of the sluices is very great; if the earth is in excess the sluice is choked, even though the velocity under proper conditions is sufficient to carry bowlders of several cubic feet. The water must be *well-loaded* but not *over-loaded.* The same important principle is well illustrated by the phenomena of the floods of the tributaries of the Sacramento River. As I learn from my nephew, Julian LeConte, who has been engaged in the hydrographical survey of this river, at the time of flood, the rushing waters first come down Feather River bringing only fine silt and clay; the water rises and increases proportionally in depth. Next comes the great mass of coarse sediment, sand, gravel and pebbles creeping slowly along the bottom and filling up the bed twenty feet deep; the water though in full flood is but little deeper (though much wider) than before the flood.* Lastly, as the water falls and has less sediment to carry, it again takes up the sediment previously deposited and scours out the channel even though its general velocity is now far less than when the same was deposited. In this case the filling is not permanent; but cases are not wanting of steady building up by rivers of very high velocity. According to the authority already mentioned the Yuba River at Marysville has permanently filled up its beds 30 feet deep, and 15 miles above Marysville 115 feet deep, in the last 30 years. This is wholly due to the large increase of transported matter produced by the operations of hydraulic mining. Again, according to Captain Dutton,† the Colorado River through its cañon and the Platte River over the plains have about the same slope, viz: eight feet per mile; but while the Colorado has cut its wonderful cañon and is still cutting, the Platte has filled up its channel and is still filling. The sole difference is the amount of load carried; the Colorado is *under*loaded, the Platte *over*loaded.

It is evident therefore that river deposits cannot, like ocean and lake deposits, be taken as a measure of time. Rivers either erode or build up by deposit. If they build, they almost always build very rapidly; for the carrying power of running water varies at so high a rate that a very slight change in conditions affects enormously the amount of deposit. While they build, therefore, they build rapidly but are liable under even very slight change of velocity or amount of sediment to scour out again. For example, Feather River fills up 20 feet in a single flood and scours out again when the flood subsides.

* The rise of the surface is about 23 feet; the filling of the bed 20 feet.
† Nature, vol. xix, p. 274, 1879.

But if the overloaded condition be permanent or habitual, then the building is permanent as well as rapid. For example, the Yuba River above Marysville has built up 115 feet in 30 years. I believe that most thick river deposits, whether of the present or of previous epochs, have been made in comparatively short space of time.

Now the phenomena of the old river-gravels, as I have described them, are precisely those of deposits made by the turbulent action of very swift, shifting, overloaded currents; only in this case the currents must have been far swifter and more heavily loaded than any existing currents. The detritus of the old river beds is usually exceptionally coarse; therefore the rivers at the time of deposit must have been exceptionally rapid; and therefore also the quantity of material necessary to overload them must have been exceptionally great; and therefore finally the process of filling was probably exceptionally rapid. It might have occupied years, or even centuries, but was geologically a very rapid process. Now I cannot conceive how all these conditions could have been fulfilled, except by the rapid melting of extensive fields of ice or snow. But why —it will be asked—was the detritus not carried away again? I answer: Because immediately after the filling was completed the detritus was protected and the rivers displaced by the lava-flood. This brings me to the next question, viz:

2. *The cause of the displacement of the rivers.*—As already shown, the mere filling up of the river channels with detritus alone would never have displaced the streams. On the contrary, as soon as the conditions determining the filling were changed, the rivers would immediately have commenced cutting into the detritus as they have done on the Eastern coast; and, on account of the high slope of their channels, would ere this have completely swept it all out, as they have done in Southern California. The protection of the detritus and the displacement of the streams is due wholly to the lava flood.

Middle California lies on the southern skirt of the great lava-flood of the Northwest.* The center of the great outflow was the Cascade and Blue Mountains. In Oregon the lava is 3,000 feet thick and therefore completely conceals the previous surface configuration of the country. In extreme northern California it is still a universal mantle several hundred feet thick, and therefore the old river beds with few exceptions are hopelessly concealed. In Middle California we find it reduced to ridges and patches by erosion, but originally it probably was even here a nearly universal mantle, covering the whole surface, except some highest points, and substantially obliterating the drainage system. But yet this lava mantle was not so

* See article by the writer on this subject in this Journal, vol. vii, p. 167, and p. 279, 1874.

thick but that subsequent erosion has cut through the *thinner* parts, i. e., on the previous higher ground. Immediately after the obliteration of the previous drainage system, the rivers, of course, commenced cutting a new system, having the same general trend (for this is determined by the general mountain slope), but wholly independent of, and therefore often cutting across, the older system. Furthermore the streams in forming their new beds seem to avoid the places of the old beds, for there the lava would be thickest, and cut their channels on the old divides for there the lava was thinnest and therefore soonest removed by general erosion, or perhaps was absent altogether.

Again: we have already seen that the rush of overloaded waters which filled the old river-beds with detritus, could have been produced only by rapid melting of snow and ice. We have seen also that the process of filling must have been comparatively rapid. Still further we have seen that the detritus must have been quickly protected and the streams diverted by the lava-flow. Bearing these things in mind we are naturally led, nay we are almost driven, to the conclusion that the approach of the subterranean heat of the impending lava-flow was the cause of the rapid melting of the snow and the consequent rush of the overloaded waters which filled the channels with detritus. Before the melting was completed the ash-eruptions had already commenced, and mud-streams, followed by lava-streams, completed the work of obliteration. We see precisely the same phenomena on a *small scale*, in the destructive floods and mud-streams which precede and accompany the eruptions of volcanos like Cotopaxi, whose summits are capped with perpetual snow. In the case we are discussing, however, instead of a volcanic peak, a great mountain range covered with snow, erupted.

Some geologists of the Uniformitarian school, may object to the foregoing views, as savoring too much of Catastrophism. In answer I would remark that it is simply impossible to account for wholesale obliteration of a river system except by something like a catastrophe. Powell and Dutton* have shown that of all geographical features, river courses in elevated regions are the most permanent. In early Tertiary times the Green River was winding its devious course southward when the Uinta Mountains commenced to rise directly athwart its pathway; but the river maintained its level and its course by cutting downward in proportion as the mountain rose upward. Farther south the Colorado plateau commenced to rise; but the river still maintained its level and its course by cutting downward in the same proportion. When once a river, as it were, bites in and gets a grip upon the rocky bones of the

* Powell, Exploration of Colorado river, p. 152; Dutton, Nature, vol. xix, p. 247 and 272, 1879.

country it does not easily loose its hold. Rivers with deep channels like those of California will not change. Their channels must be obliterated, and then they make new channels. Such obliteration can only take place by submergence and prolonged sedimentation or else by a lava-flood.

We have seen that tufaceous conglomerate usually underlies the basaltic lava and covers the detritus even where the lava is wanting. It is evident therefore ash eruptions preceded the basaltic flow. The washing down of these ashes as mud streams completed the filling and then the lava flood covering all prevented the re-cutting of the channels in the same places. Furthermore, if we imagine the ash flood as even more general than the lava flood, it is easy to see how the new channels would commence between the lava streams, i. e., between the old stream beds, and once commenced would continue to cut in these places.

King* has drawn attention to the fact that in the same locality and therefore presumably from the same subterranean igneous reservoir *acid* eruptions immediately precede *basic* eruptions. He accounts for this order by supposing a gradual separation, by gravity from the same fused magma, of a lighter, acid, less fusible portion as a sort of scum on the surface of a denser, basic, more fusible portion. Eruption would of course commence with the ejection of the upper, acid, and finish with the lower, basic, portion. The eruptions of which we have been speaking seem to confirm this idea. The imperfectly fused, or aqueo-igneously fused, upper and more acid portions were ejected first as *ashes* and only later the igneously fused, basic, bottom portions were ejected as basaltic flows.

The conditions necessary to produce the double system of river-channels are peculiar and found only in the Sierra range of Middle and Northern California. In extreme Northern California and especially in Oregon the lava flood is so thick that the buried old river system is not revealed by erosion—the present rivers are running far above the old rivers. In Southern California on the contrary the rivers have never been displaced by lava, for the lava flood did not reach so far. If these channels were ever filled with detritus, this has not only been swept out again, but the rivers have continued to deepen their channels even to the present time. The double river system of Middle California is the result of the fact that this part lay in the extreme skirts of the great lava flood. In British Columbia beyond the limits of the lava flood, the relation of the new to the old river beds, as I learn from Mr. Amos Bowman, is again like those of the Eastern States. The rivers are now cutting into the detritus which fills the broader and deeper channels of the old rivers.

* Exploration of 40th Parallel, vol. i, Systematic Geology, p. 715.

3. *Why the modern rivers have cut to a lower level.*—I have already in a previous article* given reason to believe that the great lava flood of the Northwest came not from craters but from great fissures, and that the force of eruption was not the pressure of elastic gases merely, but also the lateral squeezing by which mountain ranges are elevated. It is almost certain, then, that coincident with the outflow of lava in California there was an increase in the elevation of the Sierra range. The inevitable effect of this would be the cutting of the new channels below the level of the old, and thus finally the singular relation between the old and the new channels which now exists.

There is a certain definite relation between the slope and the amount of detritus which determines the depth of the cañons. If this relation be disturbed by increase of slope, the stream will strive to reëstablish it. All deep cañons have been cut in rising ground and for the purpose of reëstablishing this relation. Thus it has been with the great cañons of the plateau region; thus also with the cañons which trench the eastern slope of the Colorado Mountains; and thus it must have been with the cañons of the Sierra Nevada. Again there is a certain relation little understood, between rain-erosion and stream-erosion. In Tertiary times we may imagine the conditions were favorable for general rain-erosion and unfavorable for stream-erosion or cañon cutting; and the result was a system of broad, shallow, trough-shaped channels with low divides. Since glacial times, on the contrary, the conditions have been favorable here for cañon cutting. Among these conditions the slope is certainly most important. It is difficult to imagine that the Tertiary river channels should have remained so shallow after the erosion of the whole Cretaceous and Tertiary times, if the general Sierra slope were as high *then* as it is *now*, viz: 100 to 200 feet per mile. It is true that the great glaciers of glacial times have probably greatly assisted in cutting the present cañons; but this would only affect the amount of time required, not the final result; for if glaciers cut deeper than streams would have done, these streams would again fill up their channels until the proper relation was again established.

The elevation which I suppose took place in the Sierra range at the time of the lava flow, was evidently of a gentle kind, unaccompanied with crumplings and dislocations of the strata, and therefore undetectable except by the work of cañon-cutting. The axis of the Quaternary elevation on the eastern portion of the continent was probably along the valley of Mississippi River; the axis on this side was the crest of the Sierra, where it gave rise to fracture and outflow.

The places where the lava emerged have not been found with certainty. It was probably along or near the crest, where the

* This Journal, vol. vii, p. 177, 1874.

subsequent erosion has been so great that the evidences are mostly obliterated. In Alpine County, about Silver Mountain and about Markleeville, the Sierra crest is formed largely of volcanic rocks. From this region probably a large number of streams radiated. But over the larger portion of the high Sierra erosion has bitten so deep that the lava streams have been entirely removed. I have however observed many dioritic, doleritic and felsitic dikes in all the granite region above the lava flow. These I have thought are probably the exposed roots of the flow.

4. *The age of the old river gravels and of the lava flow.*—Whitney and Lesquereux, on the evidence of the organisms, especially the plants, refer the gravels to the Pliocene, and regard them as representing at least the whole of that epoch, and the lava flood as its closing event. My own conclusion differs a little from this. I have already shown that the accumulation of the gravels and their protection by the lava flow may be regarded as geologically almost simultaneous. I now add that these two events closed the Pliocene and inaugurated the Quaternary.

As already seen, the *mammalian* remains are a mixture of the characteristic Pliocene species still lingering and of characteristic Quaternary species just coming in. They undoubtedly therefore indicate a transition from Pliocene to Quaternary, and whether on these evidences we refer the gravels to late Pliocene or early Quaternary will depend upon whether we regard as the more important test of age, the extinction of old or the introduction of new species. The evidence from human remains and implements, if these be regarded as authentic, is certainly on the side of greater recency. The *Plants*, it may be admitted, are Pliocene. But plants are far less delicate tests of age than mammalian animals: for not only are they, by their lower organization, less sensitive to changes of the environment; but being incapable of voluntary migrations, they are often compelled to linger beyond the epoch to which they belong. It is natural to suppose, therefore, that the Pliocene flora would linger even into the Quaternary until destroyed by the extreme rigor of glacial climate, or else by some catastrophe like that of the lava flood.

Again: the general phenomena of the gravels and the manner of their accumulation, as I have explained them, are wholly those of the Quaternary period. They can hardly be explained except by the existence of glacial conditions. Also the gentle movement of elevation which we have supposed preceded and attended the lava flow is characteristic of the Quaternary everywhere. It is probable, therefore, that the gradual elevation and the attendant glacial conditions commenced and advanced until the former culminated in fracture and outflow of lava.

But on the other hand, it is certain that the Pliocene passed insensibly into the glacial epoch, and therefore that glacial conditions commenced in the Pliocene. Furthermore, it is certain that here in California glacial conditions continued and reached their acme *after the lava flow;* for glaciers occupied all the present cañons,* and *swept away all the lavas* from the granite axial region, exposing their roots, in the form of dikes.

In conclusion, therefore, it seems best to make both the accumulation of the gravels and the lava flow which protected them, the dividing line between the Pliocene and the Quaternary, although I believe that glacial conditions had already commenced when these events occurred.

In a previous article already referred to, I have shown that the great lava flood commenced in its central part in Oregon, about the beginning of the Pliocene epoch, and has continued there almost to the present time. But as in volcanos the eruptions commence and perhaps continue in a central crater, and as erupted matters accumulate, later eruptions occur also on the outer margins; so in this great area of fissure eruptions, the eruptive activity commenced first in the center, but as erupted matters accumulated, the eruptive activity spread centrifugally to more and more distant points until at the end of the Pliocene it had reached Middle California.

Thus it seems to me that the four questions suggested by the phenomena of the old river beds and their fillings, have been not only each answered, but they have been all connected together in a satisfactory manner.

Sequence of Events.

It may be well to briefly recapitulate the main points of my view, by narrating rapidly the events in the order of their sequence.

Immediately after the birth of the Sierra Nevada, at the beginning of the Cretaceous period, a drainage system commenced to be formed. This system we may be assured remained unchanged during the whole Cretaceous and Tertiary times, for, as already seen, river channels are remarkable for their permanency. The result of the river-work of all this time was a system of broad trough-shaped channels separated by low divides usually called the Tertiary or old river system. During all this time I suppose the amount of detritus was so related to velocity that there was neither much erosion on the one hand, nor deposit on the other—though on the whole erosion slowly progressed. Then commenced the glacial cold at the end of the Pliocene, a rising of the Sierra region, and the

* Some Ancient Glaciers of the Sierra. This Journal, vol. v, p. 325, 1873, and vol. x, p. 126, 1875.

high Sierra was mantled with snow and ice and glaciers probably occupied the higher portions of the river troughs, and thus large quantities of loose debris were prepared ready for transportation. Then the ground heat of the impending lava flow melted the ice mantle and caused the rushing overloaded torrents which filled up the river channels. This filling doubtless required many years, perhaps centuries, during which there were alternate partial scourings out and re-fillings, yet the whole was, geologically speaking, a rapid process. Then immediately thereafter occurred the fissuring of the high Sierra, and immense discharges of ashes which, washed down by the still melting snows, formed mud streams, which almost completely filled up the river channels, and often apparently overran the low divides. Immediately following the ash-eruptions, lava streams flooded the mountain-slope and completely obliterated the drainage system. Coincidently with the eruptions, and as their cause, there was a considerable elevation of the Sierra range, and increase of the mountain slope.

The previous drainage having been abolished, glaciers and rivers immediately commenced cutting a new system wholly independent of the previous one, though having the same general direction. In cutting these new channels the rivers seem to have shown a preference for the old divides, because there the lava was either wanting or thinner than elsewhere. As a result of the increased elevation of the Sierra, as well as an increase of the causes which produced the Glacial epoch, the reign of ice now reached its culmination. At this time not only was the high Sierra ice mantled and all its cañons filled with glaciers, but even the much lower Coast Range was snow-capped, and glaciers probably ran down its valleys nearly or quite into the Bay of San Francisco.* As another result of the increased elevation of the Sierra and the prodigious consequent erosion by ice and water of this time, and of water alone in subsequent times, the erupted lava was swept clean away from the greater portion of the high Sierra, leaving only the roots visible in the form of dikes, and the river channels lower down the slope were cut far below the detritus-filled and lava-capped old river channels, which are thus left high up on the present divides. Meanwhile meteoric waters percolating downward through the decomposing lava caps, and therefore charged with carbonates of soda and lime, and therefore also dissolving silica, cemented the gravels and petrified the drift wood, or else taking more silica, changed in places volcanic and slate pebbles and bed rock into clay.

Berkeley, Cal., Oct. 15, 1879.

* I have found what I regard as good evidence of glacial action about the site of the University, 300 feet above the Bay of San Francisco.