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# MUDFLOW AS A GEOLOGIC AGENT IN SEMIARID MOUNTAINS

BY

ELIOT BLACKWELDER

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# MUDFLOW AS A GEOLOGIC AGENT IN SEMIARID MOUNTAINS[1]

BY ELIOT BLACKWELDER

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## INTRODUCTION

In Utah, Nevada, and other more or less arid parts of the western United States the steeper slopes of most of the mountains are fringed with alluvial deposits, which form bajadas, or alluvial slopes. The unit of a series of such deposits is the alluvial fan, the apex of which is in the mouth of a mountain canyon.

The surfaces and the eroded sections of these fans show two features by which they can be distinguished from the alluvial deposits of moister regions: many of the fans are strewn with large, isolated boulders, and the deposit as a whole consists of beds of unassorted and unstratified earthy material, a heterogeneous mixture of particles of all sizes, which in that respect resembles glacial till and some volcanic agglomerates. Lawson[2] has given it the convenient name "fanglomerate."

These deposits have generally been supposed to be formed by floods, although floods normally assort their loads to some degree and leave their deposits perceptibly stratified. The products of stream action are

[1] Manuscript received by the Secretary, December 8, 1927.

[2] A. C. Lawson: The petrographic designation of alluvial fan formations. Univ. of California Publications, Dep. G, vol. 7, 1913, pp. 325-334.

gravel, sand, or silt, not a bouldery earth or clay. Although short, swift floods may carry boulders and may deposit a poorly classified mixture of particles, their product is not devoid of bedding. Furthermore, it is difficult to understand how a thin flood, that is not confined in a definite channel, can sweep boulders weighing hundreds of tons several miles out on a plain with a gradient of only 4 to 6 degrees. It is now known that these unstratified deposits are the products, not of ordinary water floods, but of mudflows.

The mudflow has long been known to physiographers as a variety of landslide intermediate between a typical landslide and a water flood. Such flows have been reported from many parts of the world, where earthy material on steep slopes becomes soaked with rain or snow water. Sir Martin Conway[3] found them in parts of the Himalayas in India. They are found also in the Alps and in the Rocky Mountains of the United States, as described by Howe[4] and others. Rickmers,[5] who observed them in the mountains of Turkestan, describes them under the name "mudspates" and gives excellent views of them. Mudflows accompany many explosive volcanic eruptions, because large quantities of volcanic dust are mixed with the water of copious thunderstorms. Herculaneum was buried by such a mudflow from Mount Vesuvius in the great eruption in 79 A. D.

Nevertheless the geologic importance of mudflows has been but little appreciated by most geologists and physiographers. They are not given much space in most textbooks of geology. The writer found mudflows mentioned in only six representative modern textbooks and manuals, and only two gave to them as much as a paragraph. Even in those two books they appeared to be regarded as unusual phenomena, confined chiefly to such mountains as the Alps and the Himalayas and to volcanic eruptions. It is safe to assume that students in university courses in geology learn very little about mudflows, and hence most geologists have but little initial acquaintance with this important element in land erosion. Yet in our semiarid and even our arid regions they are not rare and peculiar phenomena, but normal agencies of gradation, which aid greatly in forming the débris fans that border many high mountain ranges.

[3] Martin Conway: Informal remarks given in The Geographical Journal, vol. 30, 1907, p. 501.

[4] Ernest Howe: Landslides on the San Juan Mountains, Colorado. U. S. Geol. Survey, Prof. Paper 67, 1909.

[5] W. R. Rickmers: The Duab of Turkestan. Cambridge, 1913.

## Descriptions of Individual Flows

The earliest description of mudflows that I have seen is that given by McGee[6] in an article on sheetfloods in northern Sonora and southwestern Arizona. He described one such flow as "a thick film of muddy slime viscously rolling over a gently sloping plain" (page 100). Again, he refers to the sheetflood as "a sort of mudflow" (page 108). Walther[7] mentions a similar type of flood, that he likens to a "sand porridge" ("Sandbrei"), spreading over the plains in deserts.

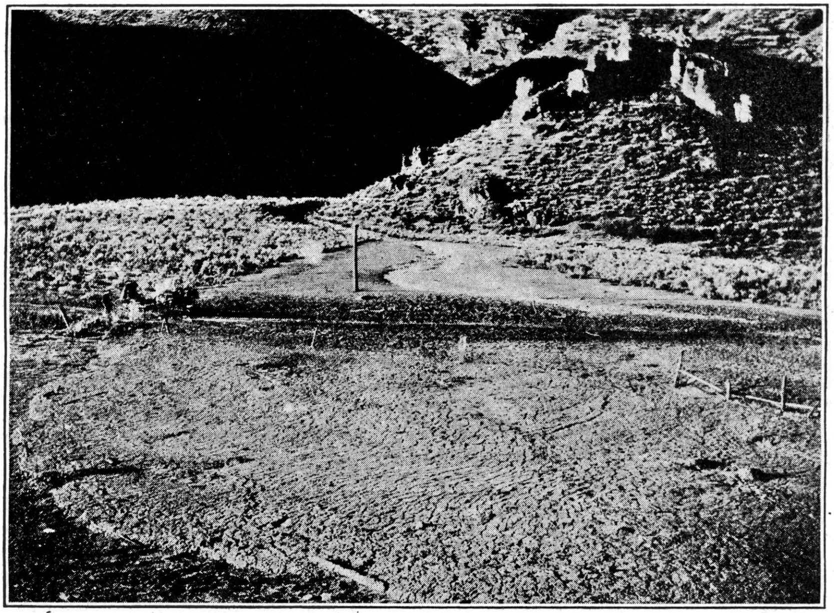

**Figure 1.—*Small Mudflow near Morgan, Utah***
**Shows the expanded end and the abrupt margin.**

In the summer of 1909 there was a short but heavy rainstorm in the Bear River Range, near Morgan, Utah. Figure 1, reproduced from a photograph taken by the writer a few days after the storm, shows that a lobate layer of mud, less than a foot thick, was added to the surface of the alluvial fan, although it covered less than a quarter of its area. This mud behaved in most respects like a viscous fluid, such as honey or hot tar. The margin of the flow, although only 8 inches high, is steep. The fence post, just inside the margin, was carried from the edge of the

[6] W J McGee: Sheetflood erosion. Bull. Geol. Soc. Am., vol. 8, 1897, pp. 87-112.
[7] Johannes Walther: Das Gesetz der Wüstenbildung, 2d Ed., 1924, p. 191.

road but was not buried. The flowage within the mass created low, concentric wrinkles, which may be seen in some parts of the figure. This was a small but typical mudflow. The opportunity to photograph such a feature in its entirety is probably rare.

Two much larger mudflows, which occurred on the west side of the Wasatch Range, at Willard and at Farmington, in Utah, in August, 1923, have been described by Pack.[8] I examined the flow at Willard, and that at Farmington was observed in passing. The known facts about the storm and the effects it produced are given in Pack's interesting account.

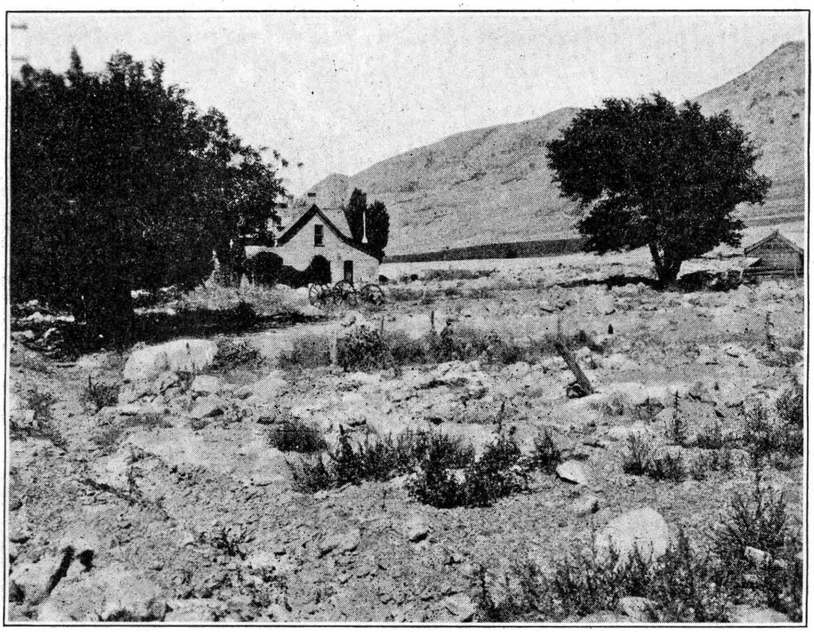

FIGURE 2.—*A Detail of the Willard Mudflow*

A well-kept garden transformed over night into a waste of mud and boulders.

At the time of my first visit to the canyon, in 1909, it was an ordinary, V-shaped mountain canyon, whose sides were graded at angles of from 30 to 35 degrees and were covered with soil or rock waste, which was slowly creeping down the slope. This material was more or less securely held in place by a mass of grass, herbage, and shrubbery, and by scattered groves of trees. In the bottom of the canyon was a small brook and a steep but passable wagon road. At the time of the storm the rain was

[8] F. J. Pack: The torrential potential of desert waters [Utah]. Pan-American Geol., vol. 4 (40), 1923, pp. 349-356.

probably concentrated in the more spacious upper part of the valley. The storm not only washed large quantities of soil down the slopes into the main channel but caused many landslides, which partly choked the bottom of the canyon with slippery, water-soaked masses of soil, reinforced with twigs and branches of trees. The lower part of the canyon, which is confined between precipitous walls of Cambrian quartzite, is narrower and has a considerably steeper descent. The churned-up mass of slimy earth, trees, and boulders gathered momentum as it descended this gorge and burst forth upon the plain at the village of Willard with sufficient impetus to carry it halfway down the slope of the fan. It covered the former surface with a layer of bouldery mud 3 to 4 feet deep. The flow deployed rapidly through the village, surrounded houses, carried off small outbuildings bodily or crushed them like eggshells, and overspread the concrete highway for hundreds of feet. The road surface was not injured by the mudflow and has since been cleared off. The front of the flow was about 3 feet high and almost as steep as the edge of a lava coulée. The most striking characteristic of the flow is the abundance of boulders, which range in longest diameter from 1 to 15 feet. Subsequent excavations made along the highway showed that many of these boulders do not rest on the ground beneath the flow, but lie on the flow itself. The whole mass is as unstratified as glacial till.

The mudflow at Willard was immediately followed by a typical water flood, which lasted with diminishing power for several hours. This flood cut a steep-sided trench, 15 to 25 feet deep and 30 to 60 feet wide, through the mudflow and down into the older layers of the fan. It tore a gap in the concrete highway and spread a rudely assorted layer of coarse gravel and small boulders far out beyond the end of the mudflow, but it did not remove the concrete slabs from the site of the breach.

It seems that the Willard mudflow was a normal but rare occurrence. The conditions observed in the canyons suggest that at any one locality two such events may be separated by centuries of time, during which the soil covering, talus slopes, and vegetation are regenerated. Similar mudflow deposits may be recognized on the alluvial fans of the Wasatch and many of the other higher and steeper mountain ranges of the Great Basin. They are especially prominent on the east flank of the Ruby Mountains of Nevada, the Steen Mountains of southern Oregon, the east base of the Walker Range, Nevada, and the White Mountains and the Sierra Nevada in California.

As a mudflow is a comparatively rare event and in any one mountain canyon occupies only a fraction of an hour, few people have had the opportunity of observing one in action. To Mr. Harry R. Johnson, of

Los Angeles, California, the writer is indebted for the following account of a mudflow seen by Mr. J. S. Douglas, superintendent of the San Emigdio Rancho, about 1905, at the southern end of the San Joaquin Valley, in California.

"Some time before the mudflow made its appearance its dull, heavy roar could be heard from up the canyon, quite distinct from and rising above all the other noises of the storm, reminding one of the breakers against a rocky shore. As it issued from the narrow mouth of the side canyon it was accompanied by a cloud of dust, occasioned by the breaking up of huge masses of dry soil from projecting points in its rush down the canyon. Through the dust glimpses could be had of great piles of drift, with an occasional tree turning end over end. After descending about one-half mile from the mouth of the smaller canyon, this wave came to a full stop, only to be succeeded in a few minutes by another wave, larger and swifter than the first. There was no dust with this or any of the succeeding waves, but immense masses of rock, many of which must have weighed several tons, were dancing along on the surface, apparently as light as corks, supported by the earthy mass beneath. This wave extended about half a mile further down the canyon than the first, when it also came to a stop, having spread to the full width of the main canyon, which is here about a quarter of a mile. In a few minutes another wave of mud swept by, followed by others at intervals of a few minutes, each succeeding wave getting thinner and traveling with greater velocity than the preceding one, until finally, in about half an hour, the mass was no longer mud, but a steady rush of yellow, foaming water, at first probably a hundred yards wide in the main canyon, but gradually reducing in width and increasing in depth and swiftness as it washed out a channel in the soft mud. As to the distance of the action of this flow and the size of the rocks moved by it, a sandstone boulder carried down by it from a point seven miles up the canyon has a height of 8 feet, a length of 16 feet, and a width of 12 feet. On the plains about 5 miles east of the mouth of the canyon several masses much larger than this one can be seen. These also were brought down a canyon by cloudbursts."

Mr. Johnson also relates his own observations of a mudflow that was much smaller and thinner, but perhaps of a more common kind:

"The flow originated in a cloudburst on the northwest slope of Midway Peak and extended along the larger tributary canyons in a northeast direction for about 4 miles. Where this main canyon opens out into the lower marginal hills of the Great Valley, the front of the mudflow appeared to be a more or less dry mass of brush and rubble, but behind this mass the material grew increasingly more liquid. At the edge of the flatter valley area the mudflow began to spread out fanwise, and after gradually freeing itself of the heavier material continued to flow out as a slurry, which spread itself more or less in the form of mud distributaries. The edge of such a flow is very sharp where its encroaching slightly cracked surface apparently rolled over the loose gravel of the older surface and solidified in such a way as to form a clearly defined rounded margin directly upon dry, undisturbed pebbles." (See figure 5.)

On the west slope of Owens Valley, between Lone Pine and Independence, the base of the Sierra Nevada is bordered by an inclined plain, 6 to 8 miles wide, which has an average slope of about 6 degrees. This plain has generally been interpreted as a series of confluent alluvial fans. Many observers have noticed with surprise the abundance of huge granite boulders on its surface. Blocks 10 to 20 feet in diameter are common and several between 40 and 50 feet long have been noted. These are not talus blocks that have rolled down from the imposing scarp to the west, for many of them stand 4 to 6 miles out from the mountain base. When the inclined plain is closely examined it is found to be far from smooth in detail, for it includes curved bouldery terraces having fronts 1 to 4 feet high. The material in the terraces is almost wholly unstratified and unsorted.

These deposits had generally been considered alluvial fan gravel laid down by water floods. To the writer, who examined the district in the spring of 1925, they seemed much like the mudflows of the Wasatch Range, and the whole plain appeared to be a series of overlapping tongue-shaped layers produced not by normal water floods, but by mudflows. This view was confirmed by Tolman, who in the summer of 1925 was in Owens Valley when several new mudflows were formed, and who saw their effects within a few hours after the storms that produced them. He presented his observations and conclusions in a paper read before the Le Conte Geological Club at Stanford University, California, in 1926, but this paper has not yet been published.

## General Characteristics

The best description of desert mudflows that has come to the writer's attention is given by Rickmers.[9] Under the coined term "mudspate," he describes them in part as follows:

"The typical mudspate consists of mire charged with a great number of rock-splinters and blocks, but sometimes it may be composed almost entirely of clean stones ranging in size from a peppercorn to large boulders. . . . As to the limits of definition, they can not, of course, be drawn with mathematical precision, being comprised within a wet landslip and a flooded torrent overcharged with rubble.

"When a gentle slope of grit and shingle has been soaked like a sponge by rain or melting snows, there may come a time when it bulges out and slides off in the manner of a bogburst on Irish moors. Slipping into chan-

[9] Idem, pp. 193-197.

nels and gullies, this mass is mixed with more water, attains a higher speed, and carries away soft material as well as rocks which it finds on its way. It is during this descent that the mudspate generally acquires its characteristic composition, for only by movement can an even mixture of liquid and solids be maintained. It is neither dry nor is there much free water, but the whole mass appears like a rapid flush of mud, although frequently the rock waste is so rough as not to suggest what is popularly called mud. Enormous boulders will float in this thick porridge like cork on water or iron on quicksilver . . .

"The typical mudspate track does not, however, readily associate itself with the ravine of a permanent or powerful mountain stream, for the simple reason that the catchment area and bed of a torrent that works throughout the year are already deprived of the bulk of easily shifted material. Operating with a minimum of water, the mudspate liquefies itself automatically when, during its descent, it has become too thick. Stopping for a while, it dams up the water runlet in the gully and then proceeds again, repeating, if needs be, the process several times.

"Intermittent water supply owing to a dry climate, absence of a strong vegetation, and barren mountain flanks reaching up to the snowline are the conditions which favor the mudspate as a habitual and periodical phenomenon.

"When not too liquid, the discharge forms a snout or tongue . . . This is the lobate shape assumed by all viscous matter, such as snow avalanches, glaciers, lava, honey, peat-bogs, and the like. But this happens only when the mixture is fairly thick and is allowed to rest on gentle inclines. The other extreme is represented by narrow gorges ending in a river which prevents accumulation. Usually the mudspates build up an irregular cone or delta furrowed by one or more characteristic gullies. These are deep and narrow trenches with very steep and smooth sides. The sudden gushes loaded with angular fragments act like a rapid liquid file, which rakes and rasps the channel, at the same time plastering it with mud pressed against the wall. Most of the smaller dejections regularly use this gully, which also serves as bed to an insignificant or intermittent stream. But many downpours miss this chute and large ones overflow it, so that in this way a talus is raised. . . .

"When left to itself on an even slope, the middle of the mud runs faster, because there is less friction, while at the sides, retarded by friction, deposition takes place, giving rise to an embankment, so that the crawling Leviathan builds its own track. It consists of a shallow rill with a welt on either side."

The descriptions given above indicate that the mudflow of the semiarid mountain canyon is intermediate between the better known landslide and the ordinary stream-flood. There are, in fact, all gradations between them; but the mudflow is more closely akin to the landslide than to the stream-flood. The mudflow contains just enough water to swell the clay colloids, reduce internal cohesion, and make the mass slippery. Pack[9] cites proof that there was not enough water in the Farmington mudflow itself to cause even a trickle of water away from the margin. In most respects the mass behaves much like a lava flow. In its ability to carry large boulders on its surface it bears some resemblance to the still more slowly moving glacier. Observers are not wholly agreed as to how the mass moves, but the various phenomena indicate that it slides or glides over the surface without that internal churning that characterizes a rapid stream of water. Irregularities in the base

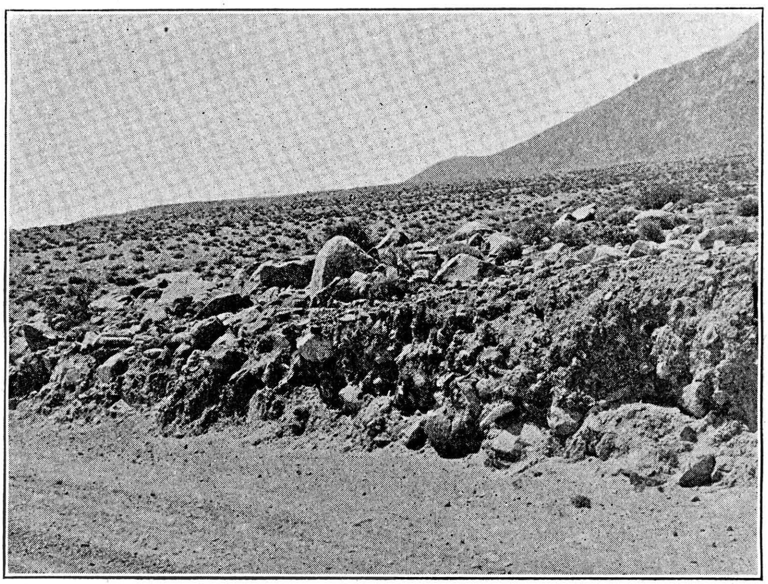

FIGURE 3.—*Road-cut in a Mudflow near Walker Lake, Nevada*

Shows the bouldery surface and the lack of stratification. The largest boulder is about 6 feet long.

doubtless cause some commotion, but many of them, such as trees, are sheared off and carried forward.

The occurrence of enormous boulders several miles out from the mountain front may be explained as the result of single outbursts whereby the large blocks glide out on a thick layer of mud and come to rest as soon as the momentum of the flow is spent. Most of these boulders probably never move again, but lie there until decay reduces them to fine débris that is readily swept off by floods and winds.

In alluvial fans, mudflows and stream gravel deposits vary in proportions. Some fans may contain no mudflows. In most of the fans in

[9] Op. cit.

arid regions there is an interlamination of mudflows and washed gravel sheets comparable to the interbedding of lava flows and cinder beds in a composite volcanic cone. Many alluvial fans, especially those of steeper gradient, consist largely of mudflows, which overlap and bury here and there sinuous threads of stream gravel.

Desert mudflows range in thickness from an inch or two to several feet. According to my observations, most of them are 6 to 20 inches thick. The thinner mudflows are fluid and move somewhat rapidly. They carry small stones but not large boulders. The thicker mudflows, many of

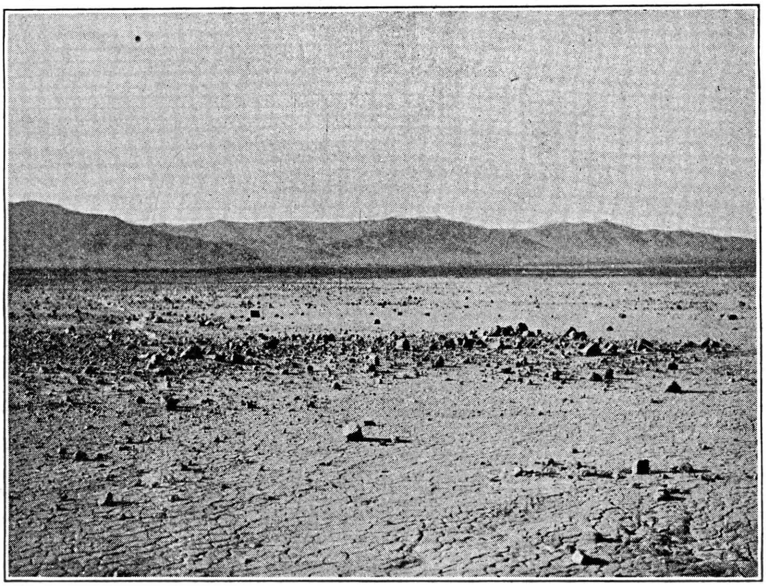

FIGURE 4.—*Deflated Mudflow on the Edge of a Playa*

The larger stones and the lobate form of the mudflow still remain, but the fine material has been swept off by the wind and rain. Coyote Playa, near Barstow, California.

which are 3 to 6 feet high at their edges, are characteristic of the steeper fans at the bases of the highest and most precipitous mountains, such as the White Mountains and the Sierra Nevada in California. It is only these thick flows that carry the huge boulders. Between the thickest and the thinnest flows there are all gradations. The thick and very bouldery flows bring less fluid than the others, come to rest more quickly, and therefore build the upper part of the fan. The thin and more fluid mudflows go much farther out and form distributaries, and many of them reach the margin of the playa. Most desert playas are more or less completely margined by overlapping mudflows—a fact that has not been generally known until recent detailed studies were made by Ekblaw,[10] because they were usually so greatly deflated as to be hard to recognize.

In detail there is much variety among mudflows. The thinner flows, which consist chiefly of fluid mud, generally follow the shallow, water-worn channels that already traverse the fan. They spread beyond the channels in a series of lobes that suggest the pattern of certain oak leaves, the channel representing the midrib. The thin part outside the channel

FIGURE 5.—*Lobate Edge of a thin Mudflow*

A characteristic thin, fine-grained mudflow on the east side of the Stillwater Range, Nevada. The sharply delimited edge and broad expanse of cracked, sunbaked mud are characteristic.

congeals first and dries, forming the usual polygonal cracks, but the mud in the channel continues to move somewhat longer and shrinks considerably, although likewise forming a superficial crust of dry cracked mud. As the more liquid lower part moves on down the channel, the surface subsides and longitudinal cracks are formed. In some respects the behavior of such a mudflow resembles that of certain lava flows.

Examination of the site of the Willard mudflow showed that its power in the mountain canyon was very great, for the sides of the canyon are torn and scarred; but after it issued from the canyon and spread out

[10] G. E. Ekblaw: Clastic deposits in playas. Unpublished thesis for Ph. D., Stanford University, 1927.

upon the plain, its energy must have been quickly dissipated, for it was not sufficient to carry the flow to the lower edge of the gravel fan. This is typical of most of the mudflows observed by the writer in the arid West.

Where the mud is more viscous and sticky, the sides of the main channel are ripped up into a kind of levee, which may be caused by the adhesion of part of the mud to the banks of its channel. As only the

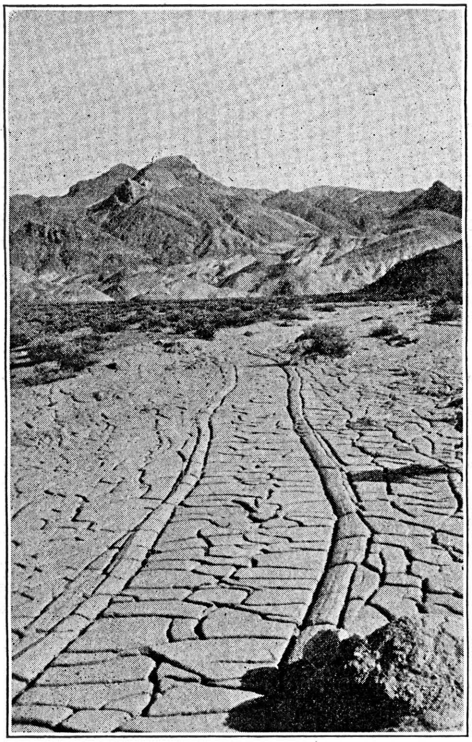

FIGURE 6.—*Axial Channel of a thin Mudflow*

This rather fluid mudflow, on the east side of the Stillwater Range, was partly directed by a shallow stream-cut trench. The mud seems to have continued moving in the trench after it had congealed on both sides. (Photograph by Siemon Muller.)

stiffer mud behaves thus, such levees are confined to steep fans or to talus cones. Flows of this kind have been well pictured by Rickmers in his description of the mountains of Turkestan, but they may be seen also in Nevada and other arid regions.

Doubtless there are other variations, due not only to differences in the character of the mud and in the amount of water but to the steepness of the slope and the quantity of material and probably to other causes.

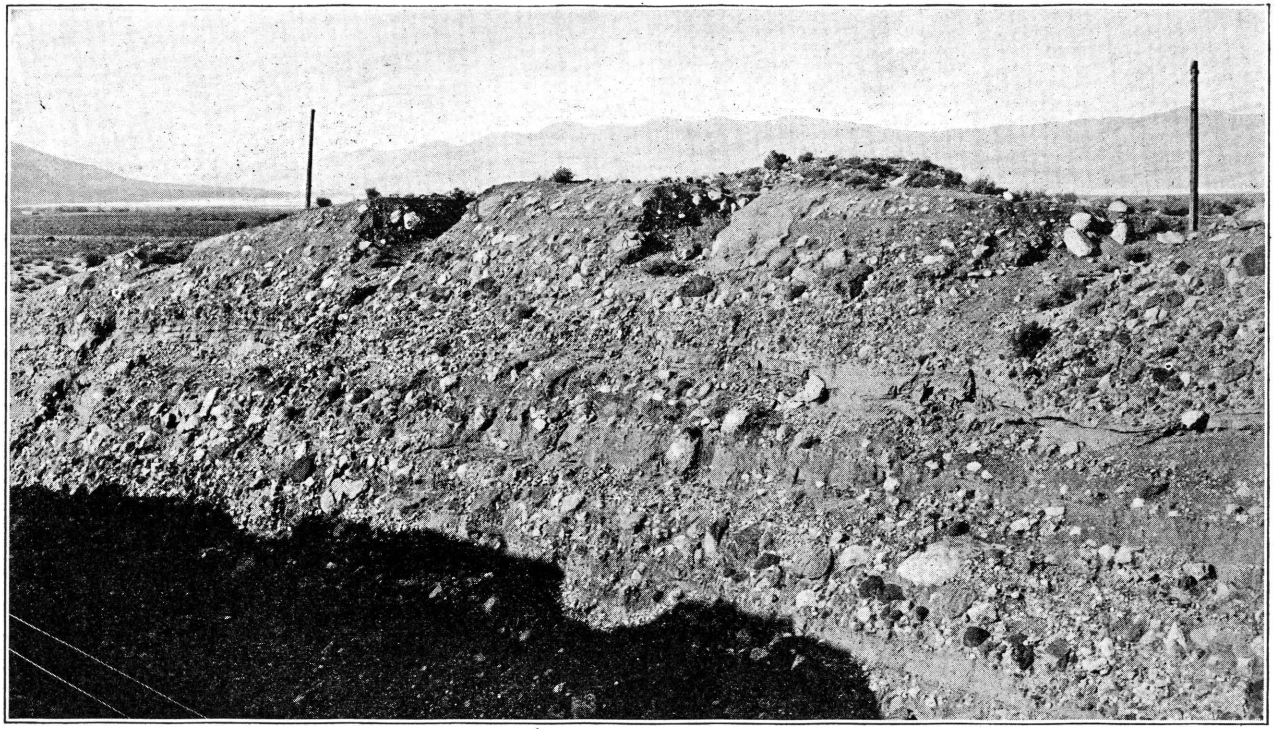

FIGURE 7.—*Cross-section of successive Mudflows*

The bouldery mudflow layers in this alluvial fan alternate with thin beds of water-deposited gravel and sand. A railroad cut south of Owens Lake, California. The largest boulder is 8 feet in diameter.

The compound structure of alluvial fans has an important effect on the underground water supply in its neighborhood. In fans that consist largely of mudflows these form impervious layers, which restrain the migration of underground water. The only aquifers in such fans are the stream-channel deposits of gravel, and as these are narrow and irregularly distributed wells not far apart may differ notably from each other in the quantity of water they furnish and in the depth at which water is reached. The imbricated structure of the fan also causes local artesian flows.

## Conditions Favoring Mudflows

The conditions that favor the development of mudflows appear to be the following: (1) unconsolidated material that becomes slippery when wet; (2) slopes steep enough to induce flowage in such viscous material; (3) abundant water; (4) insufficient protection of the ground by forest. All these conditions need not be present in equally high degree. A relatively small quantity of slippery material well distributed through a body of cracked but otherwise hard rock may lubricate the entire mass and permit flowage. The slope need not be very steep if the material and the water supply are unusually favorable. Mudflows may occur even in a dry region at times of exceptional rainfall or when snow is melting. Thus the excessive potency of one factor may counterbalance the relative deficiency of another.

The ideal material for a mudflow is probably a gravelly or sandy mass containing enough silt, clay, or colloidal material to make it slippery when wet. If it contains a rather large amount of porous material, easily permeable by water, the entire mass will become saturated the more readily. In a deposit of coarse, angular talus, flowage is inhibited by the lack of lubricating material; but if the slope is steep and the quantity of water is sufficient, a flow may occur in sand that contains only a small proportion of clay or silt. Such flows have been observed on the sandy slopes of the hills between Indio and Garnet Stations, in the northern part of the Salton Desert of California. Mudflows occur where thick bodies of loose volcanic ash become mixed with plenty of water, although the material is generally much coarser than clay. Its high porosity probably favors flowage.

Oversteepened slopes, such as the undercut banks of streams and the walls of glacial cirques, are unstable, and, if their material is suitable, they are likely to regain a slope of equilibrium through mudflows. Illustrations of this fact are seen at many points along the new mountain highways of the Pacific coastal States, where deep excavations have left steep slopes in weak earthy material. In those States the expense of removing mudflow débris during every rainy season is large.

Abundant water is an obvious requirement, but some modifying factors must be considered. A region of frequent rains of moderate intensity is likely to be densely covered with forest, and the roots of the trees reinforce the soil and hold it in place. Again, very heavy rainstorms may wash away all the loose earth, so that no mudflows may be formed.

The most favorable combination of conditions for a mudflow, then, appears to be a mass of earthy material permeated with water somewhat rapidly but without much excess, situated on an oversteepened slope that is not well protected by forest cover.

## Mudflow Deposits in Ancient Formations

Lawson[11] has noted the apparent rarity of fanglomerates in described pre-Quaternary formations, but suspects that some have been overlooked. He cites the Gila conglomerate (Pliocene?) of southern Arizona and the basal part of the Newark (Upper Triassic) in New Jersey and New England. Both of these formations have peculiarities that strongly suggest the presence of mudflows. Formations in which mudflows predominate are widely distributed in the Mojave Desert and in other parts of southeastern California. These have been best described by Vaughan.[12] Part of the basal beds of the Wasatch conglomerate (Lower Eocene) in western Utah may be of this character, and mudflow beds are probably common among the Tertiary formations of Asia and other continents. Woodford[13] has described a boulder fanglomerate of Miocene age on the California coast between Los Angeles and San Diego. After a careful analysis of the whole problem, he concludes that the formation consists largely of mudflows and probably originated under conditions more or less like those now existing along the western slope of the Wasatch Range of Utah.

Although mudflows are by no means rare in moist regions, their deposits are likely to be removed by rivers and thus redistributed. It is therefore believed that they form extensive and thick accumulations only in dry regions. If this belief is well grounded, the presence of mudflow fanglomerates in ancient formations may be regarded as evidence that the climatic and topographic conditions of that time and place resembled those of the Great Basin region of today.

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[11] A. C. Lawson: Op. cit.

[12] F. E. Vaughan: Geology of San Bernardino Mountains north of San Gorgonio Pass. Univ. Calif. Pub., Dep. G, vol. 13, 1922, pp. 319-411.

[13] A. O. Woodford: The San Onofre brecai—its nature and origin. Univ. Calif. Pub., Dep. G, vol. 15, 1925, pp. 159-280.

## Summary

In the mountains of semiarid regions there are occasional heavy rainstorms, called cloudbursts, which cause either floods or mudflows. The flood sweeps large quantities of washed gravel, sand, and clay, and even small boulders, down to the alluvial fan and spreads them out in radial channels. The mudflow acts like a lava stream and forms a solid plate, covering part of the fan. The material of the flow is till-like in its lack of stratification and sizing. Boulders weighing hundreds of tons may be carried on its surface miles away from the mountain front. They are not rolled. Mudflows are dominant components of the steepest fans of semiarid mountain ranges. Dense forests or extreme aridity are unfavorable conditions. On the low mountains, in the driest parts of the country, such as western Arizona, there is too little vegetation to permit the accumulation of much soil, and the prevalent bare rock and angular rubble or coarse sand afford unsuitable material for the formation of mudflows.

## Discussion

Joseph T. Singewald, Jr.: Much of my geologic work has been done in mountainous regions that have a semiarid climate, and I have often seen the results of mudflows. The description of them by Dr. Blackwelder and his analysis of the conditions that give rise to them are of special interest to me because, as he points out, his paper discusses a geologic agent that has received very little attention in geologic literature and the significance of which has been inadequately recognized.

A mudflow that deploys from a side valley or ravine over a broad main valley, or over a plain in the form of an alluvial fan, or that becomes a part of a fan which is being built up both by mudflows and by torrential dumpings, soon loses its diagnostic surface features, so that its real character becomes obscured. Because geologists have regarded mudflows as an exceptional geologic agent, they have not been on the lookout for them, and in places where the evidence has been obliterated or obscured their existence has been overlooked. In other places the flow took place under such conditions that the origin of the stream of débris is suggested immediately to the most casual observer. The Slumgullion mudflow near Lake City, Colorado, is an outstanding example because of its magnitude and its unmistakable character. An excellent description of this flow is given by Ernest Howe.[14] It flowed about 5 miles westward down Slumgullion Gulch to Lake Fork and about three-fourths of a mile north-

[14] Ernest Howe: Landslides of the San Juan Mountains, Colorado. U. S. Geological Survey, Prof. Paper 67, 1909, pp. 40-41.

ward down Lake Fork, a descent of 2,600 feet. It dammed the valley of Lake Fork sufficiently to form Lake San Cristobal, which has a length of 2 miles. A magnificent panorama of the flow is obtained from the mountain on the west side of Lake Fork above the old Golden Fleece Mine.[15]

The greatest mass of mudflow débris that I have seen I had the opportunity of viewing only from a train window. In northwestern Argentina, on the railroad from Jujuy to La Quiaca, near the station of Volcan, the broad valley of the Rio Grande is filled to great depth with detrital material, including boulders and rock masses of all sizes, which has flowed out of a side valley that joins that of the Rio Grande on the west. Unfortunately, the day was rather cloudy and clouds were hanging low on the mountains, so that, though I could see some miles up the tributary valley over the top of the rock stream, the view to its source was obscured. The deposit was obviously not a sheet-flow; it was a stream of unknown length, but a number of miles of it were visible, so that it did not represent an alluvial fan or cone; and it was quite distinct from a landslide or a rock slide. The stream is so large that it must represent the piling up of recurrent flows during a long period. The physiographic and geologic conditions near the head of the valley must be unusually favorable for the formation of mudflows. I quote from my notebook a description of the lower end of the stream in the Rio Grande Valley:

> "As it flowed out of a side valley [I use the word 'flow' because its shape exactly resembled that of a flowing glacier], there was a little back flow up the main valley, but the principal movement was down the Rio Grande. The upper surface of the mass was convex and sloped down more steeply at the end, producing a configuration like that of the end of a glacier."

I saw a flow of mud of smaller magnitude, but highly impressive, near Sihuas, in the Andes of central Peru, in the spring of 1924. Late one afternoon, as we were nearing the town of Sihuas, in the valley of the Rupac River, we found the trail blocked by a mudflow that was coming out of a small side valley and continuing its course down the Rupac Valley. It extended across the river bed to the stream, which it forced against the opposite bank. It was too late in the day to attempt to take our pack train down the river below the end of the flow and try to work our way up along the other side of the valley, so we were forced to make our camp there and wait until morning to get across. The Rupac Valley is a characteristic valley of a semiarid mountainous region. At this point its elevation is about 9,000 feet, and the mountains on either side

[15] Idem, Pl. XX, B.

rise rather steeply 3,000 to 5,000 feet. The river has a wide, flat bed, which is filled only at times of flood, and ordinarily, as on this day, the river is only a narrow stream. The slopes of the valley show the physiographic features that are characteristic of the Peruvian Andes. The upper slopes present a mature topography and the lower slopes are the steep sides of a recently entrenched river valley. The rocks in the vicinity consist of a series of dark shales and slaty shales, into which are intercalated some beds of hard limestone and more beds of quartzite, some of which are rather thick. Very little rain falls in the bottom of the valley and on the lower slopes of the mountain sides, but local heavy afternoon thundershowers are frequent around the summits of the mountains and on the upper slopes. Such thunderstorms had raged that afternoon in the higher altitudes, but no rain had fallen in the valley. The rain had saturated the soil and disintegrated black shale on a steep bench high up on the mountain until it became soft and plastic enough to flow down into the narrower and steeper ravine, which led into the Rupac River. The increasing declivity of the lower slope accelerated its movement, so that it flowed out into the main valley with force enough to spread some distance downstream along the gentle grade. The flowing material consisted of a black, pasty mud, which carried within it blocks and pieces of sandstone that it had engulfed along its course. Its flow was not continuous, but came in intermittent waves. The approach of a new wave was heralded by the rumbling of the blocks of sandstone that were being carried along. As the wave passed the observer the thick, viscous mud emitted a crackling sound. The mode of motion of the wave suggested the accumulation of the material at some higher point until the resistance of the viscous material in front was overcome. In this way the resisting material was both overflowed and pushed ahead by the advancing wave. The next morning the movement had ceased, and there appeared before us a bed of soft, black mud out of which projected countless blocks of sandstone. Over the mud trickled small rivulets of water, which seemed to result from the thickening and dewatering of the mud, though they may have represented the normal drainage of the ravine. Our mules were forced across the mudflow without cargoes, and we and our equipment were carried across on the backs of our Indians, who carefully made their way by treading the projecting blocks of sandstone. Later, when we again traversed this trail, the mud had hardened and the small stream had cut a new channel in it to its confluence with the Rupac River.

The three localities that I have described present the combination of conditions which Dr. Blackwelder has set forth as those favorable to the occurrence of mudflows. The Rupac River flow, which I saw in motion, consisted of well lubricated earthy material (disintegrated black shale) which had suddenly been thoroughly saturated with water. Its movement started on an oversteepened mountain slope, which was without the protection of forest covering, and it flowed down like thick tar, with sufficient momentum to carry it well down the valley floor. Dr. Blackwelder has done good service by calling the attention of geologists to this phenomenon and by giving so clear an account of its nature and its causes.