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MUDFLOW OF 1941 AT WRIGHTWOOD, SOUTHERN CALIFORNIA

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ABSTRACT

During early May of 1941 the southern California mountain resort of Wrightwood was partly inundated by surging flows of muddy debris which occurred daily for more than a week. The immediate cause of flowage was rapid melting of deep winter snow. Intense shattering and rapid weathering of the bedrock (Pelona schist) within the San Andreas rift zone at this location contributed materially to preparing debris for flowage.

Field studies, eyewitness accounts, and movie films provide the following information. Debris was transported 15 miles by the mudflow, and on a gradient as low as 75 feet per mile at the outer extremity. The flow advanced in successive waves or surges of "slimy gray cement-like" mud containing abundant stones. Velocities of the surge fronts ranged from a few to nearly 15 feet per second and averaged close to 10 feet per second during the more fluid phases. The fronts of the more fluid surges slithered and splashed along about like a rapidly advancing tongue of water. No breaker-like motion was evident, although the top of the front tended to shoot ahead of the base. In more viscous surges a bouldery embankment developed at the front and was shoved along by the material following behind.

One sample of the fluid debris had a density of 2.4, indicating a water content of 25–30 per cent by weight. Calculated viscosities range from 2×10^3 to 6×10^3 poises. An average sorting coefficient of 3.94 indicates poor sorting, although somewhat better than in many glacial tills which the flow deposits strongly resemble. Earlier mudflows have occurred here, and others will undoubtedly take place in the future.

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Introductory Statement

On May 7, 1941, the resort community of Wrightwood was startled by surging flows of muddy debris which swept down Heath Canyon on the north flank of the San Gabriel Mountains and inundated the outskirts of the village. During the height of activity at midday these waves or surges occurred in rapid succession and consisted of "highly fluid slimy cement-like" mud containing abundant stones.

Courtesy WrightwoodCalif.com

Some damage resulted, but no persons were injured. The surges occurred daily for more than a week, but the activity ceased at night. The water was supplied through rapid melting of deep snow at the head of Heath Canyon by unseasonably warm weather.

Unfortunately, neither of us was in southern California at the time, but valuable observations and motion pictures were made by engineers and geologists attached to various government agencies dealing with flood-control problems, as well as by local residents and other eyewitnesses who came from considerable distances to look upon this spectacle. Additional information has been obtained from study of the source area, the flow path, and the flow deposits at intervals from 1948 to 1952. An increasing interest in mudflows, their products and geological significance, motivates preparation of this report.

Appreciation is expressed for eyewitness accounts furnished by V. S. Aronovici, Emil Blum, E. L. Hamilton, D. V. Harris, George Richardson, the E. L. Schuylers, M. B. Scott, H. C. Troxell, A. W. Walker, and Royal Ward. Troxell, Aronovici, and Hamilton kindly made available their motion pictures. C. H. Gleason and R. E. Amidon (1941) generously permitted quotation and digest of material in their unpublished report on the Wrightwood flow. Hugo Benioff and H. C. Stetson assisted on special points, and J. P. Buwalda and R. H. Jahns aided with constructive suggestions. All these services are gratefully acknowledged.

Location and Physical Setting

Wrightwood lies 42 airline miles northeast of Los Angeles near the southern edge of Mojave Desert (Fig. 1) in San Bernardino County, California (34° 21.5′ N., 117° 37.5′ W.). The area of the 1941 mudflow is covered by the San Antonio and Shadow Mountains quadrangles. Vertical air photographs taken before and after the flow show part of its path.

In this area the rugged north face of San Gabriel Mountains rises abruptly 4000 to 5000 feet above the gently sloping desert floor. Wrightwood lies within the mountains, south of the northernmost mountain ridge, and near the outlet of Swarthout Valley, an anomalous

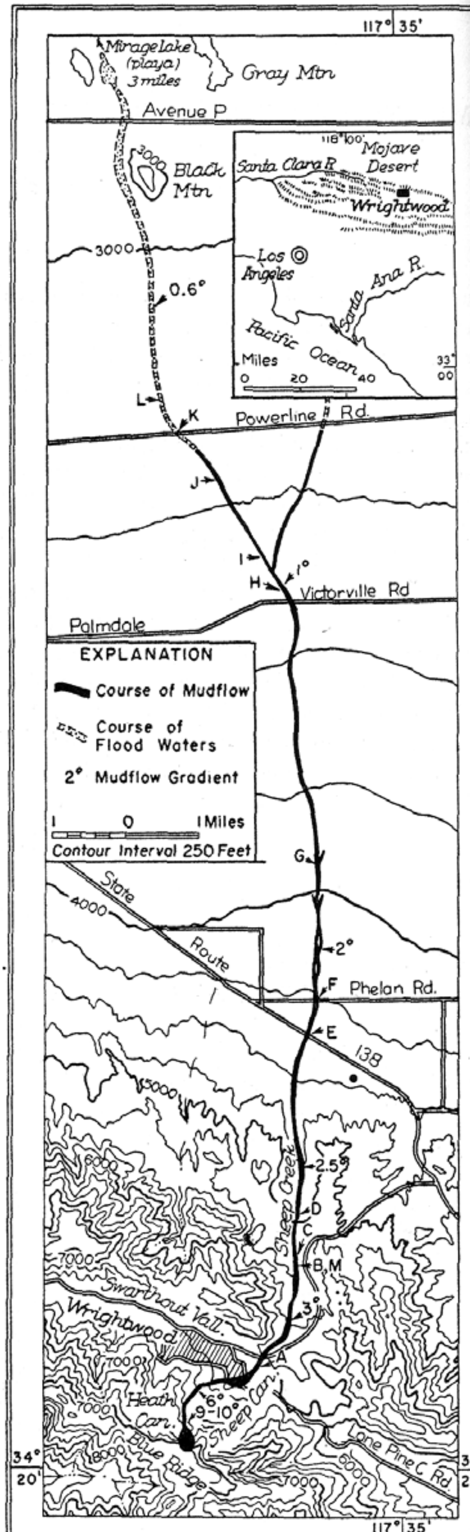

FIGURE 1.—MAP OF WRIGHTWOOD MUDFLOW AND ENVIRONS

Courtesy WrightwoodCalif.com

longitudinal valley along the San Andreas rift (Noble, 1927; 1932). The eastward continuation of this great fault is marked by the course of Lone Pine Canyon (Fig. 1), and the north face of the mountains is here determined by displacements along subsidiary faults roughly parallel to the San Andreas on the north.

The Wrightwood flow originated in a raw scar at the head of Heath Canyon near the southern edge of the San Andreas rift zone. It followed the course of Heath Canyon and subsequently the channel of Sheep Creek. The debris originated at altitudes between 7250 and 8250 feet and descended nearly 5000 feet in reaching its outermost point, 15 miles to the north.

Bedrock in the source area is the Pelona schist (Noble, 1927, p. 28–29) which here consists largely of well-foliated rocks of a variety of textures and compositions. The most abundant rock is a nodular muscovite quartz albite schist. More limited are amphibolite schist, slightly calcareous schist, and a few layers of quartzitic material. Foliation dips consistently into slopes (Fig. 2) from which the debris was derived, but the rock is so badly fractured and sheared, presumably because of proximity to the San Andreas fault, that attitude of the foliation is not particularly significant. Local rumor to the effect that the mudflow was related to an earthquake is not confirmed by records at the Caltech Seismological Laboratory in Pasadena, but comminution of the rock by earlier fault movements is a significant contributing factor.

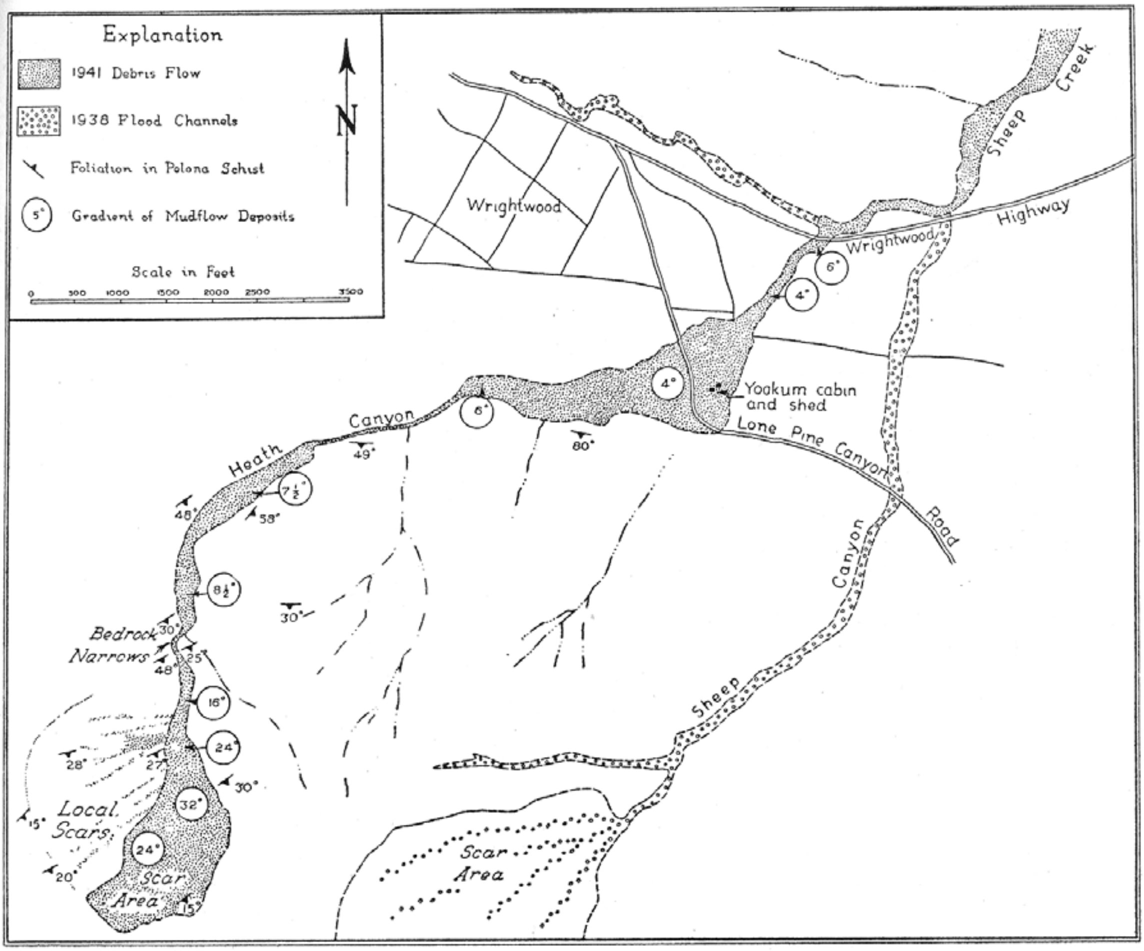

FIGURE 2.—MAP OF SOURCE AREA AND UPPER PART OF WRIGHTWOOD MUDFLOW

North of the San Andreas rift are slightly gneissic Mesozoic granitic rocks with inclusions of schist and Paleozoic marble (Noble, 1927, p. 30). Beds of Quaternary fanglomerate lie in fault contact with the older rocks at the edge of the desert, and the desert itself is mantled with younger alluvium swept down from the

Courtesy WrightwoodCalif.com

mountains. The area north of the rift contributed little debris to the 1941 flow.

The climate of this region is semiarid. Annual precipitation on the mountains just south of Wrightwood is approximately 26 inches (Storey, 1948, Fig. 4), and Big Pines Recreation Area, 4 miles west and 800 feet higher than Wrightwood, records 25 inches with extremes of 15 and 48 inches annually and a monthly maximum of 18.4 inches.[1] Precipitation decreases rapidly northward onto the desert with 8 inches annually only 10 miles north of Wrightwood. Winter snow may linger into early summer in protected high spots on the north side of the mountains, and occasionally it remains in the basin at the head of Heath Creek until mid-July.

The area around Wrightwood supports a coniferous forest, chiefly ponderosa pine at 5700 to 6800 feet and mixed ponderosa pine and fir to higher elevations. Interspersed is some scrub oak, and from 5700 to 4750 feet oak, piñon, and Joshua trees predominate with considerable brush including manzanita.

Terminology

The Wrightwood phenomenon has all the characteristics of a mudflow (Blackwelder, 1928, p. 466), in part of the alpine type (Sharpe, 1938, p. 59). A variety of names has been applied to flows of mud (Sharpe, 1938, p. 57), and the fact that they are not composed solely or even predominantly of mud has given rise to such terms as mud-rock flow (Bailey, Forsling, and Becraft, 1934, p. 1; Marsell, 1949, p. 114–115), mud-rock flood (Croft and Marston, 1950, p. 92), and debris flow (Jahns, 1949, p. 12). Debris flow has also been applied (Gilluly, Waters, and Woodford, 1951, p. 228) to a feature earlier identified as an earth-flow (Blackwelder, 1912, p. 487) and certainly not qualifying as a mudflow.

Debris flow should be used as a general designation for all types of rapid flowage (Sharpe, 1938, p. 49) involving debris of various kinds and conditions. Mudflow is simply a variety of debris flow in which the mud, although not necessarily quantitatively predominant, endows the mass with specific properties and modes of behavior which distinguish it from flows of debris devoid of mud. Thus, the Wrightwood phenomenon is a debris flow of the variety mudflow.

Description of the Flow

Dimensional Relations

The mudflow of 1941 carried approximately 15 miles northward from its source, making a maximum descent of 5000 feet (Fig. 1). Water runoff continued 9 miles farther, reaching Mirage Lake, a desert playa. In spite of this considerable length and a volume possibly as great as 1,200,000 cubic yards (Gleason and Amidon, 1941), this flow does not compare in size with great volcanic lahars (Scrivenor, 1929, p. 434). The gradient along its course decreases from roughly 9° in upper Heath Canyon, below the bedrock narrows, to somewhat less than 1° (75 feet per mile) at the outermost point (Figs. 1, 2).

The flow was largely confined by pre-existing channels to a path 20–150 feet wide, and this helped to extend the distance covered, an influence noted by Buwalda (1951). The maximum width mantled by flow deposits, about 1000 feet, is on the debris cone at Wrightwood where the surges debouched from the narrow channel of upper Heath Canyon (Fig. 2). Detritus would have been spread even more widely here except for a flood-control channel and confining embankments constructed after floods of March, 1938. Other embankments hastily thrown up by bulldozers while the 1941 flow was in progress confined it further. Material that crossed the Wrightwood cone was reconcentrated into the narrow channel of Sheep Creek, but it spread out again upon emerging onto the bajada north of the San Gabriel Mountains. Several short lateral lobes and a crude anastomosing pattern were formed below Highway 138, and a width of nearly 300 feet was attained at Phelan road. Farther out on the desert the flow path was narrower, not exceeding 50–150 feet in most places, and with a braided pattern where a single confining channel was lacking. About 0.5 mile below the Palmdale-Victorville road the flow bifurcated,

[1] Precipitation records at Big Pines kindly furnished by the Los Angeles County Flood Control District.

Courtesy WrightwoodCalif.com

the main path continuing north-northwest toward Mirage Lake and the side branch extending north-northeast to the vicinity of the Powerline road (Fig. 1).

Data from Eyewitness Accounts and Motion Pictures

Cause and duration.—Actual observation of the flow was limited to the area around Wrightwood and to the channel of Heath Creek up to the source. It is clear from reports of local residents that rapid melting of heavy winter snow during a week of exceptionally warm weather in early May was the immediate cause of flowage. No rain fell just before or during the event. In this respect, the Wrightwood situation resembles that of lofty desert ranges in Asia where numerous mudflows are produced by melting of snow at high altitude (Conway, 1893, p. 292). The flow of Mt. Bandai, Japan, in 1938 was of similar origin (Iida, 1938, p. 681). Lack of flowage during the night at Wrightwood was probably due to reduced nocturnal melting. Surges of muddy debris occurred daily for a week to 10 days from May 7, 1941, and occasional flows may have continued for 2 or 3 weeks. The peak of activity was attained on May 11 and 12.

Nature of flowage.—The debris came down the channel above Wrightwood in a succession of waves or, more appropriately, surges which usually started about 9:00 or 9:30 in the morning, reached a peak of frequency in the early afternoon, and tapered off to an end by late afternoon. Fluidity was greatest at midday when the surges succeeded each other at intervals of a few seconds to tens of minutes. At other times, particularly in late phases of the activity, hours intervened between surges. Gleason and Amidon (1941, p. 3) attribute the surges at Wrightwood to (1) periodic sloughing of debris in the source area, (2) temporary choking of the channel, (3) caving of undercut banks, and (4) friction between the moving debris and the channel. Factors 1 and 2 are considered the most significant.

Successive waves or pulsations are characteristic of mudflows (Blackwelder, 1928, p. 470; Singewald, 1928, p. 482; Jahns, 1949, p. 11–13) and of some water floods (Hovey, 1909b, p. 421). Waves are commonly caused by local choking of the channel with coarse debris and subsequent collapse of the dams as fluid material collects behind them (Conway, 1907, p. 502; Rickmers, 1913, p. 195; Pack, 1923, p. 352; Taylor, 1934, p. 439; Woolley, 1946, p. 80).

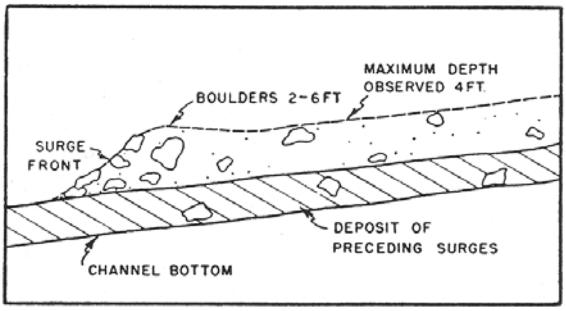

FIGURE 3.—SKETCH OF LONGITUDINAL SECTION THROUGH ADVANCING MUD SURGE
(After Gleason and Amidon, 1941)

E. L. Hamilton's motion pictures clearly illustrate this behavior in the Wrightwood flow and also show that material left in the channel by an earlier surge can be set in motion again. The coming of a new surge was sometimes heralded by the roar of sliding in the source area, and the surge itself made a noise like that of concrete in a mixer. Bumping boulders shook the ground, and the splashing of fluid mud was audible. The bedrock narrows at the foot of the source area was frequently choked by coarse detritus, so that the flowing debris piled up to a thickness of 20–30 feet and spilled over the downstream end of the narrows in a massive cascade, shown in V. S. Aronovici's movie.

In the narrow, confined channel above Wrightwood, the front of an advancing fluid surge at the height of activity slithered and slopped along much like the front of a rapidly flowing tongue of water or the swash from breakers on a beach. There was little evidence of breaker-like rolling under, although the top part tended to override and shoot ahead of the base. The lack of more conspicuous rolling under may have been due in part to "greasing" of the channel by preceding flows. A bouldery embankment formed at the front of more viscous surges (Fig. 3), and the boulders therein rolled, twisted, and shifted about but for the most part did not appear to be rolled under. Instead, they were pushed along by the finer

Courtesy WrightwoodCalif.com

more fluid debris impounded behind the bouldery dam and swept along by the mud leaking through it. The fronts of fluid surges ranged from a few inches to about 4.5 feet high. The maximum depth measured in the following body of a surge was 4 feet (Gleason and Amidon, 1941, p. 5). As the material became more viscous, particularly in late phases of the activity, velocities decreased, and the bouldery fronts became more massive, steeper, and higher. One such front photographed in motion down a confined channel by H. C. Troxell was between 10 and 15 feet high and consisted largely of boulders 2–3 feet in diameter.

Flow debris accumulated to a maximum thickness of 6 feet over a wide area on the Wrightwood cone near Lone Pine Canyon road, and some surges set up translatory waves less than a foot high which traveled through at least the surficial part of this accumulation. Such waves were observed by D. V. Harris and photographed by V. S. Aronovici.

Velocity of flow.—Surge front velocities measured by competent engineers range from 1 to 2 feet per second to a maximum of 14.5 feet per second. The average of 11 measurements by Gleason and Amidon (1941, p. 4) is 9.4 feet per second, and D. V. Harris (personal communication) reports velocities of 8–11 feet per second. A figure of 9–10 feet per second for the larger surges during the height of activity appears representative. Conway (1893, p. 291) reports speeds of 5 miles per hour (7.4 feet per second) in Himalayan flows.

Properties of the flow debris.—The flowing material was light gray and of mushy to soupy consistency "just like freshly mixed concrete". Much of it consisted of silt, sand, and pebbles less than 1 inch in diameter. The largest boulders were about 6 feet in diameter, and 2- to 3-foot boulders were common near Wrightwood. They were transported in the body of the surges as well as in the snout and clearly did not move in suspension, as sometimes reported "Boulders" bobbing about in the flow proved to be chunks of compact, mud-covered snow from the source area (D. V. Harris and E. L. Hamilton, personal communications).

Bulk density of a sample of fluid debris, determined by San Bernardino County Flood Control engineers, was 2.4, indicating a water content of 25–30 per cent by weight. Maximum solid content of flow debris on the Wrightwood cone was calculated from other sample analyses at 79–85 per cent by weight, indicating a water content of roughly 15–20 per cent. Jahns (1949, p. 12) estimates that the solid material runs as high as 90 per cent in some debris flows. In the laboratory, a sample of the Wrightwood material flowed easily on a 7-degree slope when mixed with approximately 16 per cent water by weight. Density and water content are bound to vary widely, and densities around 2.0 (Woolley, 1946, p. 82) and water contents of 30–60 per cent (Rickmers, 1913, p. 194; Iida, 1938, p. 681) are reported in other flows. Motion pictures of Wrightwood surges at the peak of activity give an impression of high fluidity, even though water content may not have exceeded 30 per cent. Mud was occasionally splashed 20 feet into the air, and spectators on the banks were splattered. At other times the moving material was so viscous that stones thrown onto it caused no splash and sank slowly.

From these data on velocity and bulk density, plus information on thickness and ground slope obtained by field studies, it is possible to make a crude calculation of viscosity in the fluid material at Wrightwood where flowing without the restriction of a confining terminal embankment. The following formula was kindly derived by Dr. Hugo Benioff for this purpose: $n = \frac{\delta g \sin \theta Z_o^2}{2V_s}$ in which n = coefficient of viscosity, δ = density of the fluid debris, g = force of gravity, θ = angle of slope of the ground, Z_o = thickness of the flow, and V_s = velocity at the surface. Using a density of 2.4, a thickness of

PLATE 1.—SLUMP BLOCK AND BEDROCK NARROWS IN SOURCE AREA

FIGURE 1.—TILTED SLUMP BLOCK

Near top and close to east margin of source area at head of Heath Canyon. High-level alluvium exposed in background. Nov. 15, 1948.

FIGURE 2.—DOWNSTREAM END OF BEDROCK NARROWS AT FOOT OF SOURCE AREA

Looking upstream. Material for the mudflow was funneled through this gorge. Letters AA mark mouth of gorge.

Courtesy WrightwoodCalif.com

FIGURE 1

FIGURE 2

SLUMP BLOCK AND BEDROCK NARROWS IN SOURCE AREA

Courtesy WrightwoodCalif.com

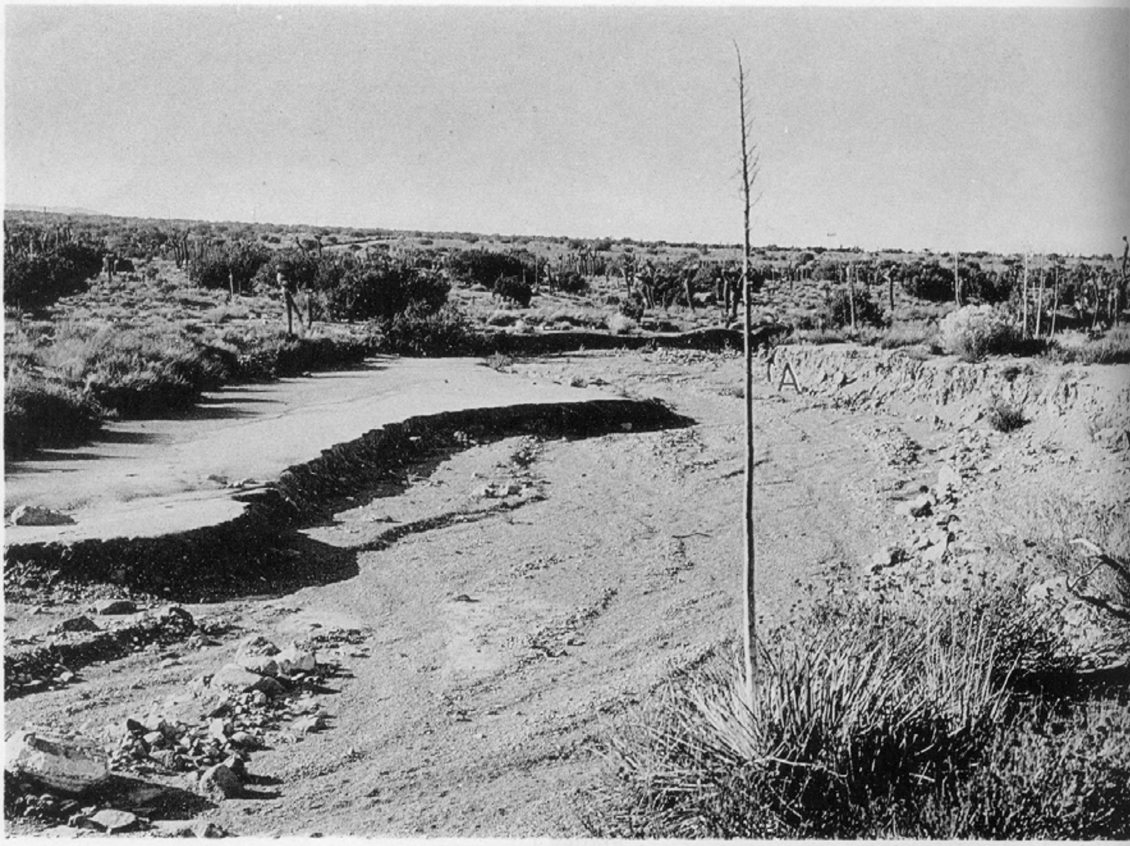

FIGURE 1

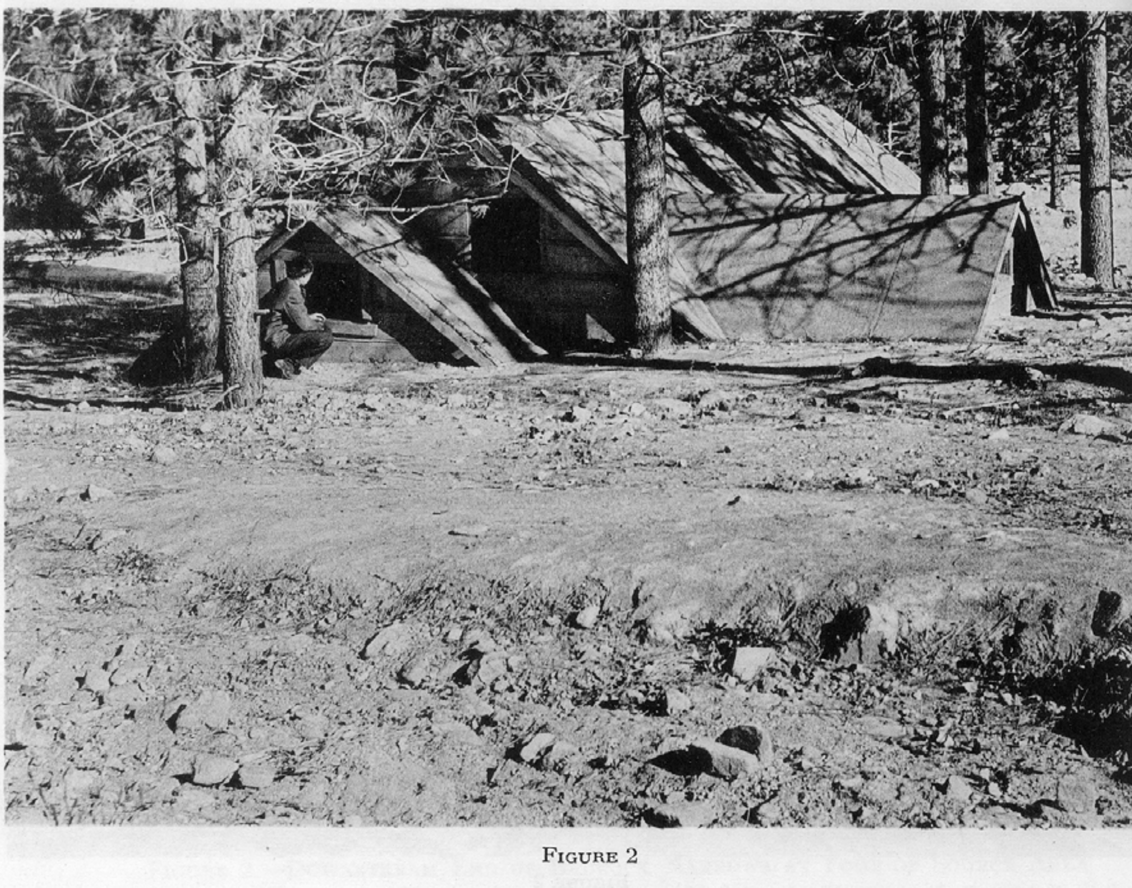

FIGURE 2

MUDFLOW TERRACE AND BURIED CABIN

Courtesy WrightwoodCalif.com

76.2 cm, a slope angle of 6°, and surface velocities from 300 to 120 cm per second, the coefficient of viscosity ranges from 2.1×10^3 to 6×10^3 poises. This, of course, is a rough figure as the basic data are crude, and the formula used involves simplifying assumptions among which are Newtonian viscosity, no marginal or terminal influences, no slip on the base and no shear stress on the upper surface, and laminar flow parallel to the base. None of these assumptions need be completely valid, but they are not unreasonable for purposes of approximation, and it is worth nothing that Iida (1938, p. 681) experimentally determined a viscosity of 10^3 poises for flow debris containing 23 per cent water.

Channel modification.—The observations of Gleason and Amidon (1941, p. 6) suggest considerable deepening and some widening of the channel above Wrightwood during the flow, and headward migration of a prominent knickpoint was observed. This erosion must have occurred during the most fluid phases of the activity. Stiff viscous flows occasionally filled the channel to such a degree that overflowage occurred.

Debris flows are often followed and partly dissected by flood water (Conway, 1893, p. 291; Blackwelder, 1928, p. 469–470; Taylor, 1934, p. 440; Troxell and Peterson, 1937, p. 87), but this is not universal (Jahns, 1949, p. 13). No flood waters succeeded the Wrightwood flow, although a modest stream of water ran in the channel for several days after the flow.

Mudflow of 1943.—Moving pictures of debris surges in upper Heath Canyon made almost exactly 2 years later, May 10, 1943, by H. C. Troxell provide further data on flow mechanism and behavior. These surges did not get below the bend of Heath Canyon and were not widely known or observed. They occurred late in the afternoon and came at intervals of about half an hour, each wave being preceded by the noise of sliding in the scar area at the head of Heath Canyon. The surges moved at a speed of several feet a second (2–3 miles per hour), and the channel was flushed out by more fluid material following the stiff viscid snout of each surge. The water, as in 1941, was supplied through melting of heavy winter snow by a spell of warm weather.

Source Area

According to local residents, the great raw scar at the head of Heath Canyon, clearly the source of the 1941 mudflow, was in existence long prior to that event. The geological section shows that it has produced similar flows in times past and will undoubtedly give rise to others in the future. The face of the scar rises 1000 feet at a steep angle, and at its top is a nearly vertical arcuate scarp, 100–150 feet high. Much of the scar is mantled with tough coherent debris, rich in fines, which becomes mobile whenever sufficiently moistened, as shown by small tongues of debris extending across snow banks on the scar area in May, 1949. Shearing and fracturing of the Pelona schist bedrock followed by weathering have produced copious amounts of fine micaceous debris particularly suited for flowage. The scar faces north, and the water supplied by melting snow is supplemented by seeps, emerging from the rock. The abundant moisture facilitates weathering by chemical alteration, and mechanical disintegration is probably promoted by numerous fluctuations across the freezing point.

Small slump blocks, bearing large coniferous trees, dot the scar area, particularly the eastern part. Backward rotation of the blocks is recorded by tilting of the trees at angles up to 28° (Pl. 1, fig. 1). A few trees are tilted forward, presumably because their roots have been loosened so they naturally lean downhill.

Cores were taken from tilted trees on several blocks with the hope that changes in growth related to slumping and tilting would be reflected in the rings, thus dating the movement. This technique has been successfully used on the Gros Ventre slide in Wyoming by Lawrence (1950, p. 246; personal communication). Variations in ring widths recorded at

Plate 2.—MUDFLOW TERRACE AND BURIED CABIN

Figure 1.—Mudflow Terrace Along Left Bank of Sheep Creek

Just north of Highway 138. Note thin layer of flow debris overlapping right bank at A.

Figure 2.—Cabin of Sidney Yoakum at Wrightwood

Filled and buried to the eaves by 1941 mudflow.

Courtesy WrightwoodCalif.com

Wrightwood are irregular and erratic, giving no consistent picture even for trees on the same block. Probably slumping has reoccurred several different times, and each block may be made up of units which have behaved differently. Possible climatic changes affecting tree growth are a further complication.

At the lower end of the scar is a bedrock narrows 200–300 feet long, 15–20 feet wide at the bottom, and 75 feet deep with extremely steep walls (Pl. 1, fig. 2). All debris from the scar passes through this gorge which functions as a bottleneck. Remnants of debris fills, up to 75 feet thick, upstream from the narrows suggest that material gradually accumulates behind the bottleneck until an exceptional supply of water makes the detritus mobile. V. S. Aronovici's films and observations show that the narrows were periodically choked with coarse detritus during the 1941 flow and that subsequent collapse of the jam under increasing pressure of material accumulating upstream gave rise to a surge of debris travelling rapidly downstream.

Sheep Canyon, east of Heath Canyon (Fig. 2), has a similar headwater scar but without a gorge at its foot. No mudflow came out of upper Sheep Canyon in 1941, probably because sufficient material had not accumulated to generate a flow. The debris appears to be carried away periodically by water floods like that of March, 1938.

Nature of Mudflow Deposits

Constitution and Characteristics

Fines are abundant in the flow deposits, and the numerous large rock fragments are predominantly angular or subangular. Sorting is poor and bedding is nil, except far out on the desert where some crude layering is visible. This structure probably represents a successive superimposition of thin flow units. At Wrightwood, as in other areas, the material looks exactly like some glacial tills (Blackwelder, 1928, p. 465, 469; Bonney, 1902, p. 8). The flow detritus was derived almost wholly from the Pelona schist. Little material was picked up from rocks north of the San Andreas fault, as only occasional fragments of granitic gneiss and marble are seen. Local chunks of oxidized sand and gravel were derived from near-by channel banks through undercutting and caving. Toward its head the flow contains many tree trunks, and elsewhere tin cans and a highway "Danger" sign were incorporated in the deposit.

The Wrightwood mudflow debris can usually be identified by the above characteristics plus a fresh gray color, by topographic forms such as lobate tongues and marginal terraces (Pl. 2, fig. 1), and by abundant bubble holes in the matrix. Bubble holes are not an absolute criterion, for water-laid material may contain bubbles particularly if laid down over dry ground. Nonetheless, at Wrightwood bubbles are more abundant and more uniformly distributed through the fine matrix of the flow deposits than in any of the associated water-laid materials. Abundant inclusions of wood and bark fragments, chips from pine cones, and rabbit droppings also suggest mass flowage, for most of this light material should have been floated away if water were the transporting medium. Rickmers (1913, p. 195) notes that wood fragments, relatively rare in alluvial deposits, are common in the mudflows of Turkestan. Cumulative curves based on mechanical analyses also help distinguish mudflow from water-laid deposits, as shown by comparison of samples K to M with samples A to J (Fig. 5). In some cut banks a distinct unconformity can be seen between the flow debris and underlying alluvium.

Size Relations of Constituents

Larger fragments in the flow debris decrease progressively in size outward from the source, but this is not true of the finer constituents. The largest boulders, 4–6 feet in diameter, are above Wrightwood. At Lone Pine Canyon road the largest stones are 2–3 feet in diameter, and 6–12 inches is the predominant size. At the 5150 contour on Sheep Creek, a lobate debris tongue contains many 12- to 18-inch boulders, and at the Palmdale-Victorville road a similar tongue includes 6- to 12-inch stones. Occasional boulders up to 2 feet in diameter are seen as far out as Phelan road and up to 18 inches at the Palmdale-Victorville road. The 1941

Courtesy WrightwoodCalif.com

deposit in the main path near the Powerline road is devoid of stones, but concentrations of boulders 4–12 inches in diameter, and occasionally larger to 2 feet, are seen along the north-northeast branch of the flow between the Palmdale-Victorville and Powerline roads. At least some of this coarse material is in an older debris flow, and the stones in the 1941 debris may have been picked up from this earlier deposit. A decrease in both size and amount of coarse debris outward from the source is further demonstrated by convergence of the median grain size values for complete samples and for material of less than 4.76 mm diameter in each sample (Fig. 4).

The plot of median grain size (Fig. 4) for materials of less than 4.76 mm diameter is noteworthy for its erratic fluctuations and the lack of a consistent decrease outward from the source, at least until the outer limit of mud flowage is passed. This is logical, for a flow has no obvious means of sorting its fine constituents, only the larger stones are gradually eliminated, giving a decrease in median size for the whole sample but not for the finer material. The erratic fluctuations in median grain size simply reflect the longitudinal inhomogeneity of the flow deposit, composed as it is of many individual debris tongues which differ from each other and which are not homogeneous within themselves.

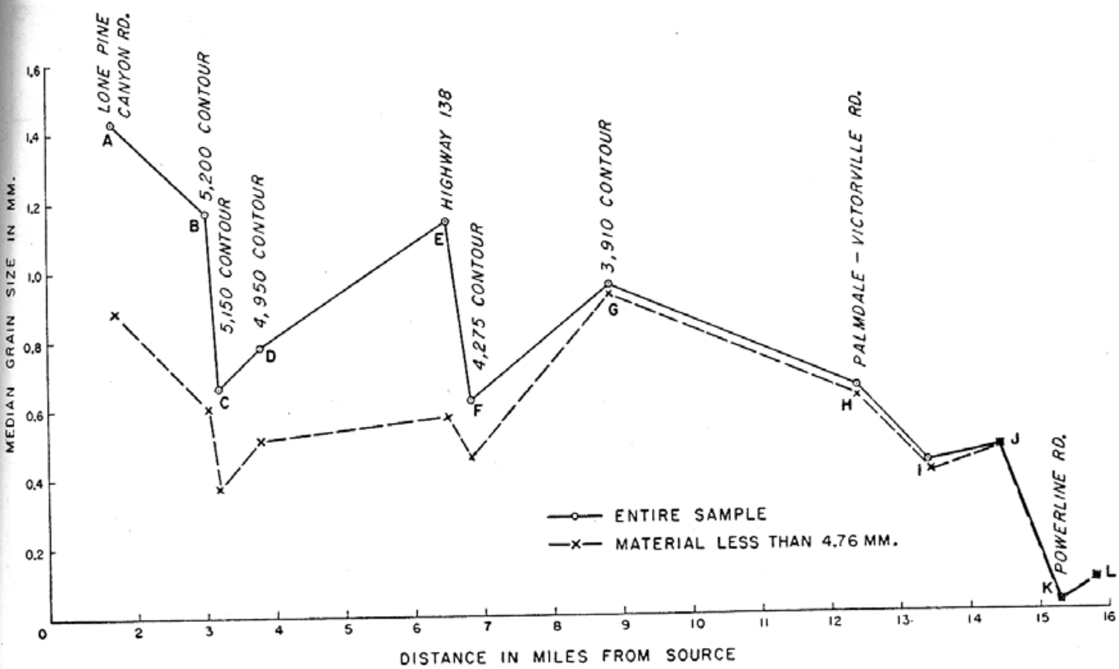

FIGURE 4.—PLOT OF MEDIAN GRAIN SIZE AGAINST DISTANCE FROM SOURCE FOR 1941 MUDFLOW DEPOSITS

Frequency curves for the 1941 mudflow debris are nearly all bimodal with the second and smaller maximum in the neighborhood of 0.025 mm. The frequency curve for a Utah flow (Crawford and Thackwell, 1931, p. 102–103) also displays a secondary maximum at about 0.037 mm, and Chawner (1935, p. 261) obtained a bimodal diagram from possible debris-flow deposits of the Montrose flood. Most bimodal curves are attributed to multiple sources of debris, and polymodal curves obtained in poorly sorted till presumably resulted from mixtures of debris from several places (Krumbein, 1933, p. 389–390; Deane, 1950, p. 24). At Wrightwood, multiple sources are not indicated by other relations, and the cause of the bimodal characteristic remains a mystery. It may be a function of grain-size distribution in the source rock or a product of peculiarities in disintegration of that rock. Actually the second maximum is so small that it would not attract attention were it less consistent.

Courtesy WrightwoodCalif.com

Mechanical analyses confirm other relations more or less evident from field study. The sorting ratio (S_o) is high, ranging from 2.67 to 5.03 with an average of 3.94. This is better than the sorting in some tills (Krumbein, 1933, p. 391; Krumbein and Pettijohn, 1938, p. 231–232; Deane, 1950, p. 16–17) with an average ratio of about 5. Considerable differences must be expected between and within various flow deposits, and an analysis of flow debris in Utah (Crawford and Thackwell, 1931, p. 102–103) yields a cumulative curve with a higher degree of sorting, therefore a lower sorting ratio ($S_o = 2.76$), than at Wrightwood. The source of the Utah debris, a sandy terrace of Lake Bonneville, is clearly a significant factor.

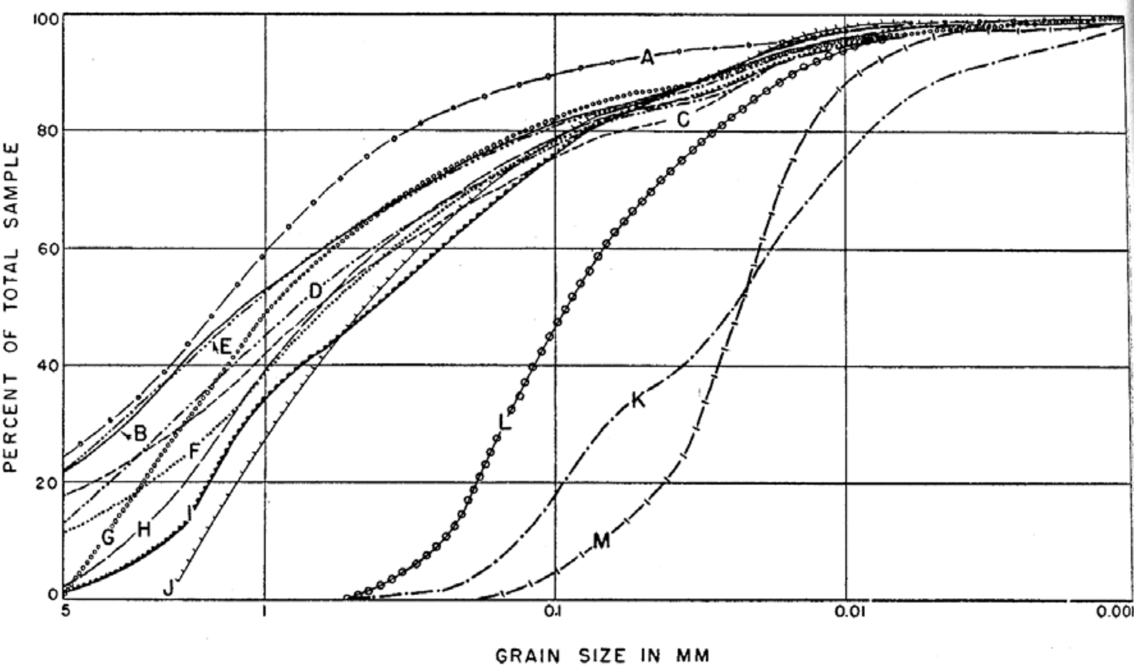

FIGURE 5.—CUMULATIVE CURVES FOR SAMPLES OF 1941 MUDFLOW
For locations of samples see Figure 1. Samples A to J are mudflow materials, and samples K to M are waterlaid detritus.

Thickness

The thickness of flow deposits decreases outward from the source but with great variation owing to accumulation in irregularities of the ground or behind obstructions. In the source area, above the bedrock narrows, remnants of debris fills indicate a thickness of 50–75 feet, and chunks of flow debris cling to the walls of the narrows 15–20 feet above its floor. Downstream the thickness decreases rapidly, attaining a maximum of 6 feet in the vicinity of Wrightwood and not more than 2–4 feet along the course of Sheep Creek. The maximum thickness at Phelan road is about 4 feet, at the Palmdale-Victorville road it is 20 inches and somewhat less at the Powerline road. Older debris-flow deposits are exposed in places beneath the 1941 debris (Fig. 6, II) and give an erroneous impression of thickness unless properly identified. This proved especially troublesome at the Palmdale-Victorville road where the 1941 debris was first thought to be 3 feet thick. Subsequent discovery of an intercalated layer of oxidized wind-blown silty sand showed that this thickness included both the 1941 and older flow deposits. Other exposures of the older flow debris were subsequently found between the Palmdale-Victorville and Powerline roads.

Outer Limit of Mudflow

Determination of the outermost limit of mud flowage, the point at which mass movement gave way to water transport, is difficult, but the cumulative curves from mechanical analyses give considerable aid and confirm conclusions based on field observations. Along the main path, the change occurred about 0.5 mile above

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(south of) the Powerline road. The cumulative curves (Fig. 5) for samples H, I, and J between the Palmdale-Victorville and Powerline roads strongly resemble those of unquestionable flow repair. A cabin and shed, owned by Sidney Yoakum, about 50 yards below the Lone Pine Canyon road were buried to the eaves by debris (Pl. 2, fig. 2). Curiously, neither building

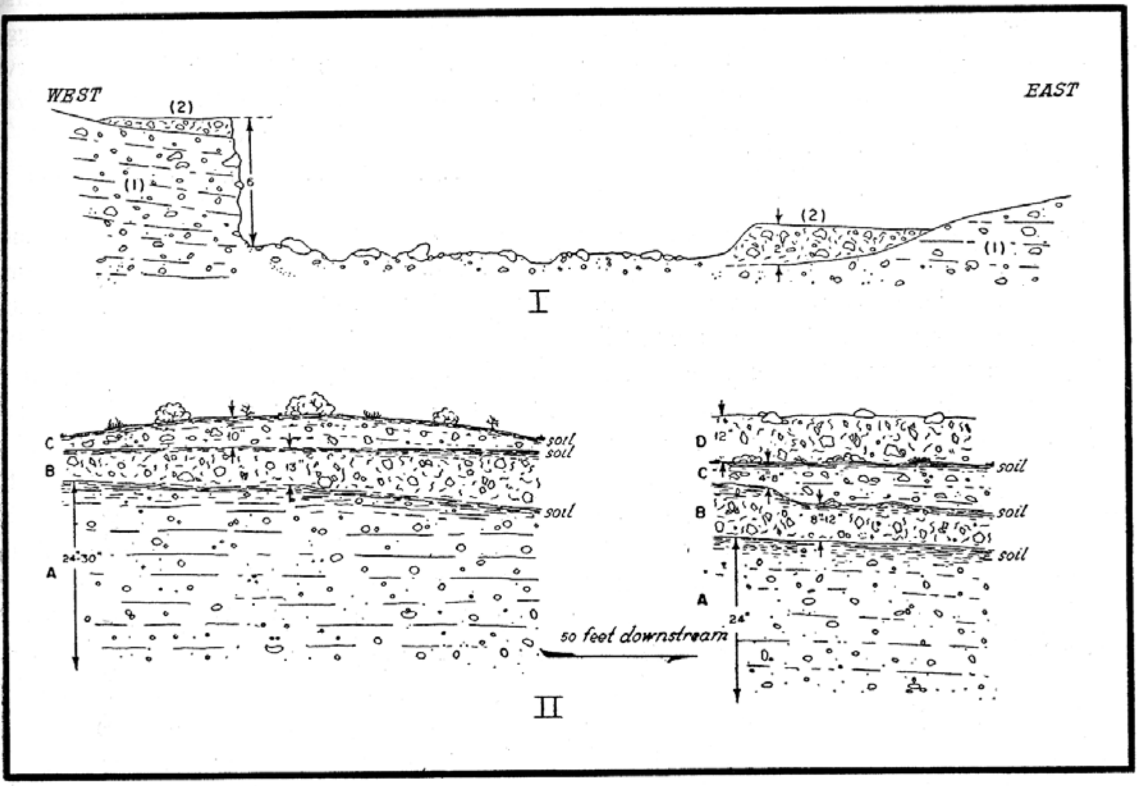

FIGURE 6.—DETAILS OF MUDFLOW RELATIONS

I. Overtopping of high bank on outside of curve
(1)-Alluvial gravel
(2)-1941 mudflow deposits

II. Relation with alluvial gravels and older mudflow deposits
A—Oxidized alluvial gravel with prominent soil layer at top
B—Pre-1941 mudflow deposit with dark soil layer at top
C—Local alluvial deposits derived from nearby slopes with weak soil layer and brush at top
D—1941 mudflow deposits, fresh, gray, no soil and burying brush on top of alluvial material (C)

debris. By comparison, the curves for samples K and L near the Powerline road are strikingly similar to that of a water-laid silt (sample M, Fig. 5). Cumulative curves for samples collected along the north-northeast branch indicate mass movement almost to the Powerline road. Thus, flowage occurred along both the main path and the north-northeast branch for approximately 15 miles from the source at the head of Heath Canyon.

Attendant Features

Some damage resulted to highways, roads, buildings, and other works of man. At least 3 cabins and several garages or sheds at Wrightwood were damaged, two of the cabins beyond

appears to have been moved nor to have suffered damage other than burial and filling, probably because of low impact velocity and homogeneous flow. Similar occurrences elsewhere are reported (Troxell and Peterson, 1937, p. 87). The walls of other buildings at Wrightwood were said to be partly caved in. Warnings were ample so that no one was trapped, and most furniture was removed from the cabins. A small fruit orchard at Wrightwood was ruined by the flow, many trees being broken down or killed by partial burial. Roads were buried, but paving for the most part was not seriously damaged, a performance rather typical of mudflows (Blackwelder, 1928, p. 468).

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In upper Heath Canyon many large trees were uprooted, broken down, or so deeply buried at the base that they subsequently died. Many instances of severe battering of tree trunks can still be seen 2–3 feet above the level of the flow deposits. A 5-inch cobble was deeply embedded in the trunk of a pine 4 feet above the ground. Large stones were piled up around the bases of trees and bushes to form crude garlands, and below Wrightwood, brush was beaten down and buried.

Patches of splattered mud still adhere to trees and bushes several feet above the ground 10 years after the flow. Remnants of a thin plastering of gray mud, looking much like gunite, are also preserved on channel banks. The coherence and toughness of the fine flow debris when dry justifies to some degree the comparison with cement.

Boulder-rich, lobate debris tongues and levees, 1–1.5 feet high, are evident where Heath Canyon widens out below the bedrock narrows. Some of these may have formed in 1943. Small gullies tributary to Heath Canyon have been dammed by the lateral edges of such deposits. Higher levees were probably built along the main channel above Wrightwood, but these natural features are obscured by embankments built by bulldozers.

Striations and scratches on stones and bedrock produced by mud flowage were searched for assiduously but without much reward. Bedrock exposures in the narrows and a few boulders farther down the channel have some suggestive marking, but they are not diagnostic and do not compare with striations reported in other flow deposits (Hovey, 1909a, p. 413; Pack, 1923, p. 353; Scrivenor, 1929, p. 434; Blackwelder, 1930).

Small terraces have been formed by dissection of the flow deposits where the pre-existing channel was wide, flat-floored, and not filled to overflowing by debris (Pl. 2, fig. 1). The terrace surfaces are remarkably smooth, being broken only by minor surficial markings and the tops of partly buried boulders. The channel cut into the terraces is floored with gravel and boulders, the fines having been carried away by running water.

In going around a curve, the surges of debris piled up against the outside bank. In many places a bank 5–6 feet high was overtopped and a sheet of fine material 6–12 inches thick spread beyond, while the surface of the flow on the inside of the curve was at a much lower level (Fig. 6, I). Troxell and Peterson (1937, p. 85–86) report similar "toboggan sledding" on a larger scale, and it was observed in action along the channel above Wrightwood.

Other Mudflows at Wrightwood

The expectation that earlier mudflows must have come down Heath Canyon is confirmed by older materials in the Wrightwood debris cone closely resembling the deposits of 1941. In the bank of Sheep Creek at the 4950 contour, remnants of an older mudflow are preserved beneath a mantle of local alluvium which is buried by the 1941 flow debris (Fig. 6, II). Earlier mudflow deposits were also identified at several localities between the Palmdale-Victorville and Powerline roads.

On May 10, 1943, mudflows of small size and limited extent descended into the upper part of Heath Canyon. The climatological conditions giving rise to this occurrence were like those of 1941, and the event was successfully predicted by H. C. Troxell and M. B. Scott. This flow did not get below the bend of Heath Canyon above Wrightwood.

There is every reason to expect that subsequent mudflows will descend from the head of Heath Canyon whenever proper conditions arise, specifically: heavy winter snow and a generally cool spring followed by an exceptionally warm period of several days duration. These flows will probably not be as large as those of 1941 unless debris once again accumulates in large volume upstream from the bedrock narrows at the base of the scar area.

Summary

The significant points derived from study of the 1941 mudflow at Wrightwood are as follows:

1. Material was transported approximately 15 miles by mass flowage.

2. The gradient at the outer end of the flow is less than 1°, about 75 feet per mile, compared to slopes of 24°–32° in the source area and 9° in upper Heath Canyon.

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3. The mudflow deposits are an unbedded mixture of poorly sorted, fine to coarse debris incorporating battered fragments of wood, bark, pine cones, and other light materials which should have floated away in running water. The fine matrix contains many entrapped air bubbles giving a pseudo-vesicular structure.

4. Sizes of larger stones in the debris decrease irregularly outward from the source, but the median size of constituents less than 4.76 mm shows no regular decrease with distance. This is consistent with the mechanics of mass flow.

5. The average sorting coefficient (S_o) of 3.94 indicates a poor degree of sorting although somewhat better than in many glacial tills. Cumulative curves help to distinguish mudflow deposits from water-laid materials.

6. From eyewitness accounts, the flow advanced as a series of muddy debris waves or surges succeeding each other at intervals of a few seconds to several hours. Activity attained a peak in the early afternoon and appears to have ceased at night, probably because of decreased melting of snow.

7. At the height of activity, the larger more fluid surges traveled 9–10 feet per second, some attained 14.5 feet per second, but many were slower and velocities dropped to 1–3 feet per second as activity decreased.

8. The front of an advancing fluid surge was like the front of a rapidly flowing tongue of water, but, with increased viscosity, a terminal bouldery embankment developed and was shoved along by the more fluid material behind.

9. A sample of the fluid debris had a density of 2.4, indicating a water content of 25–30 per cent by weight.

10. Viscosity of the flow is calculated at roughly 2×10^3 to 6×10^3 poises.

11. A house and shed near the margin of the flow at Wrightwood were buried to the eaves and filled to approximately the same level inside without other apparent damage, and several other buildings were partly buried.

12. The various situations favorable to development of mudflows have been summarized by Rickmers (1913, p. 195), Blackwelder (1928, p. 478–479), and Sharpe (1938, p. 56). Here the essential conditions are: a raw slide area at the head of Heath Canyon, a badly sheared and shattered bedrock which yields much fine and poorly sorted micaceous debris upon weathering, a narrow rock gorge at the base of the source area behind which debris accumulates, and a north-facing slope upon which snow gathers deeply during winter and remains into late spring and early summer when it may, at times, be melted rapidly by an unseasonable warm spell.

13. Similar mudflows have occurred at this locality before and since 1941, and it can be predicted with confidence that others will come down from upper Heath Canyon in the future.

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