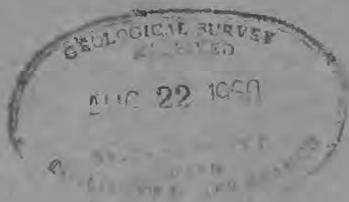


Comprehensive Survey of Sedimentation in Lake Mead, 1948-49

GEOLOGICAL SURVEY PROFESSIONAL PAPER 295

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Q. TURBIDITY CURRENTS

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A turbidity current can be simply defined as a current that carries fine-grained sediment in suspension. Johnson (1939) first introduced the name as a synonym for density current (Daly, 1936) and suspension current (Stetson and Smith, 1938). Water charged with fine suspended particles is denser than clear water of the same temperature and salinity, and, because of its greater density, the water that carries suspended sediment can flow beneath less dense clear water. If, for example, a river carrying an appreciable amount of suspended sediment enters a quiet body of clear water of the same temperature and salinity, the turbid water will plunge beneath the mass of clear water and travel by gravity along the floor of the standing body of water. Bell (1942a) has referred to this type of turbidity current as an underflow.

In nature, however, the temperature and salinity of a standing body of water are seldom the same from top to bottom. The oceans as well as most lakes have a distinct stratification in both temperature and salinity, the lower layers commonly being colder and more saline than the upper layers. Since water increases in density with decrease in temperature (to 39°F) and increase in salinity, the lower strata are denser than the upper strata. In some cases the density of turbid river water entering a lake is greater than the density of the upper lake layers but not as great as the density of the lower strata. Under these conditions the turbid river water sinks beneath the lake surface and flows on one of the lower water layers of higher density. This type of turbidity current has been termed an interflow by Bell (1942a).

Still another type of turbidity current, recognized by Bell but not included in the definitions of other investigators, is called an overflow. Overflows occur when the muddy river water is less dense than the water at the surface of the lake, and, as the name implies, the muddy river water flows over the lake surface. In order for this type of flow to take place, the sediment-laden river water must be warmer or less saline, or both, than the underlying lake water.

Most definitions of density currents (Daly, 1936; Stetson and Smith, 1938; Johnson, 1939; Kuenen and

Migliorini, 1950) require that they have a higher density than the water at the surface of the lake, and consequently do not include the type of current referred to as an overflow. Bell (1942b), however, broadly defines a density current as a gravity flow of liquid or gas through, under, or over a fluid of approximately equal density. He uses the phrase, "of approximately equal density," to exclude specific types of gravity flows that are not truly density currents. A river flowing beneath air has been cited by Bell as an example of a gravity flow that does not meet the requirements of a density current because of the very great difference between the density of water and air. When referring solely to movement of water masses in relation to each other, however, there is no need for including Bell's concept "of approximately equal density."

Bell's definition of a density current, when applied to water masses, includes all currents that are produced by differences in density. Some of them are produced solely by differences in temperature or salinity, whereas others may originate, at least in part, from differences in the amount of suspended sediment. The type of density current in which suspended sediment accounts for part of the difference in density is referred to in this paper as a turbidity current. Thus, a turbidity current can be defined as a gravity flow of turbid water through, under, or over water of different density. Part of the difference in density is produced by the suspended sediment, but suspended sediment is not always the dominant factor. In the overflow type of turbidity current, the lower density is due to higher temperature or lower salinity or both. Similarly, in the interflow or underflow type of current, suspended sediment may not account in some cases for as great a part of the higher density as does lower temperature or higher salinity.

Our knowledge of density currents in general, and of turbidity currents in particular, is still fragmentary, and there are many unsolved problems. Some of these unanswered questions occur even in the matter of definition. The reader may well ask how a density current is to be distinguished from other movements of water that result from differences in density, from the circula-

tion patterns described by Anderson and Pritchard (p. 139) for instance, or even from the seasonal turnover of lake water in temperate regions. The answer may be in the mixing of waters: a density current moves through still water with very little mixing, (p. 109) and remains identifiable because of the lack of mixing. Density currents degenerate by mixing with the surrounding water and pass into anonymity.

This factor of mixing may account for the very small number of density currents that have been identified in the density-current investigations beginning in 1937, chiefly in Boulder Basin. The inflowing river water is always somewhat turbid, and is commonly different from the lake water also in temperature and salinity. Thus, at the entrance of the river into the lake, conditions should generally be favorable for density currents, and particularly for turbidity currents. But, as pointed out by Anderson and Pritchard (1951, p. 53)—

Virgin Basin acts as a large "mixing bowl" in which the large seasonal variations in salinity of the inflowing Colorado River waters are smoothed to nearly their mean value. Below Virgin Basin the water is nearly uniform with respect to salinity.

Mixing in Virgin Basin may also account for the general clarity and fairly uniform temperature of the water downlake in Boulder Basin. However, the earliest observed turbidity currents passed through Boulder Basin and Hoover Dam with suspended load and dissolved solids correlative with those measured at Grand Canyon (p. 109).

RELATION TO RIVER DISCHARGE AND LAKE STRATIFICATION

Turbidity currents are developed at the mouths of both the Colorado and Virgin Rivers, and they have transported a tremendous quantity of silt and clay to the deeper parts of the lake. The Virgin River turbidity currents are of relatively minor significance and they have not been studied intensively. Turbidity currents are always present near the mouth of the Colorado River, but only rarely do they flow the entire length of the lake. The three types of currents designated above as overflow, interflow, and underflow all occur in Lake Mead, but underflow is by far the dominant and most important type.

OVERFLOWS

Overflows occur only during the late spring and early summer (usually from late April to early July) when the incoming river water is less dense than the water at the surface of the lake. The inflow during this period is derived principally from the rapid melting of snow in the Upper Colorado River basin and represents the maximum inflow for the year. The temperatures of the river water and the lake surface water are ap-

proximately the same, but the salinity of the inflowing water is much lower than that of the lake water (p. 108). The river in this period commonly carries a higher proportion of sand grains than in other seasons (p. 106), and these coarse particles are deposited in the topset and foreset beds of the Colorado delta. Thereafter the inflowing water, even with the finer sediment remaining in suspension, may have a density lower than that of the lake. Under these conditions the turbid river water spreads out over the lake surface, rapidly at first and then progressively more slowly as the overflow continues downlake.

Owing to the decreasing velocities and to the mixing of the overflow with the denser lake water, a large part of the sediment is dropped from suspension during the first few miles of travel. The rapid settling of the suspended sediment and the mixing of the overflow with the underlying lake water is well illustrated by a series of observations made in May 1948 at mile 287.5, about 10 miles downlake from the entrance of the Colorado River into Lake Mead at that time. The proportion of sediment by weight increased progressively from 0.013 percent at the surface to 0.110 percent near the bottom of the lake.

Although a considerable amount of suspended sediment settles out of the overflows in the eastern part of the reservoir, enough may remain in suspension to give the lake surface a perceptibly turbid appearance far from the river entrance. However, the turbid overflows seldom extend west of Virgin Basin and they apparently never reach the dam (National Research Council, 1949). This conclusion is supported by the distribution of logs and other debris along the lake shore. During most seasons, logs carried into the lake by the Colorado River remain stationary near the river mouth, but during periods of overflow (late April to early July) they are carried downlake and eventually become stranded along the shoreline. East of Virgin Basin the coves and gently sloping beaches are littered with logs, but to the west there are no such accumulations. The westernmost boundary of the overflow in May 1948 was detected in the center of Virgin Basin. The suspended sediment in this region ranged from 0.007 percent at the lake surface to 0.008 percent at the bottom.

Bell (1942b, p. 30) has illustrated by laboratory experiment that particles, dropped from an overflow, upon approaching the bottom may continue to travel downstream as an underflow. Because of the difficulty in distinguishing movement of a thin layer of very fluid sediment over the bottom of a lake, there is no direct evidence that this type of flow occurs in Lake Mead. However, it is evident from the distribution of the ac-

cumulated sediment (pl. 20) that small underflows must take place along the steep slopes normal to the submerged channel of the Colorado River. If minor underflows of this type were not active in Lake Mead, the sediment that is dropped from overflows would be expected to accumulate over a great part of the lake bottom. Investigations of the accumulated sediment show that essentially all the sediment brought into the lake by the Colorado River turbidity currents has accumulated in the region of the submerged Colorado River channel, and that no appreciable amount of sediment from this source has accumulated in other areas of the lake bottom. It seems probable, therefore, that the sediment dropped from the overflows in the shallow lake areas travels along the bottom until it comes to rest in the deep submerged channel of the Colorado River. There is no evidence that the material, upon reaching the submerged channel, continues to move as an underflow in a downlake direction.

Although the overflow type of turbidity current predominates in late spring and early summer, interflows and underflows may occur for short periods when the density of the inflow is sufficient to cause the river water to plunge beneath the lake surface.

INTERFLOWS

Interflows are apparently of minor significance compared to overflows and underflows. Anderson and Pritchard (p. 132, 134) indicate that interflows during 1948 were most prominent in August and September, but conditions continued favorable throughout the autumn. During the summer the temperatures of the river and the lake surface water were about the same, but the salinity of the incoming water was considerably greater than the salinity of the lake surface layer. However, the density of the river water, even with its dissolved and suspended load, was not as great as that of the colder water at the bottom of the lake. Under these conditions the turbid river water sinks through the light surface layer and spreads out at intermediate depth over denser water, thus conforming to the definition of an interflow. The suspended sediment readily settles to the bottom within a few miles of the river entrance, but the high salinity of such interflows can be identified for a considerable distance downstream and thus distinguishes the interflow from the lake water above and below it.

UNDERFLOWS

Underflows are the dominant and most important currents transporting sediment within Lake Mead. Whenever the density of the inflow is greater than the density of the lower lake layers, the turbid water plunges beneath the lake surface and travels downlake

along the submerged channel of the Colorado River. In late spring and summer, overflows and interflows are periodically replaced by underflows, and during fall and winter there is a continuous movement of turbid water along the lake bottom. Water discharged by the Colorado River from October to April is colder and more saline than the deep water in the eastern part of the lake. Owing to these factors and to its suspended sediment, the muddy river water sinks rapidly beneath the clear lake water and travels along the submerged Colorado River channel. During this period the division between the turbid river water and the clear lake surface is sharp and distinct as shown in plate 17 and is commonly marked by a collection of logs. This line of demarkation, known as a convergence (p. 135), denotes a downlake movement of water at the bottom and an uplake movement at the surface. The debris collects at the line where the opposing surface currents meet.

Most underflows do not reach the western part of the lake, but at least 12 conspicuous underflows have traveled along the old Colorado River channel from the river mouth to Hoover Dam. Most of these occurred during the first 7 years of reservoir operation (1935-1941), when the lake was 70 to 120 miles long (fig. 24). The only major flow of turbid water to reach the dam since 1941 arrived in the fall of 1947, when the distance between the river mouth and the dam was about 78 miles. Although these extensive currents are comparatively rare, they have transported a tremendous quantity of sediment great distances from the head of the lake.

The first three major underflows arrived at Hoover Dam during 1935, when the lake was 70 to 90 miles long. As pointed out by Howard (p. 109), these underflows were related to large increases in the quantity of suspended sediment carried by the Colorado River past the Grand Canyon gaging station. There is no record of underflows reaching the dam during the latter part of 1936 and the early part of 1937, but the density-current records of the Bureau of Reclamation (National Research Council, 1949, p. 20) indicate that by June 1937 the diversion tunnel, through which water had previously been discharged, was covered by about 10 feet of sediment. Thus it appears that the flow of turbid water through the lake was as prominent in 1936 and 1937 as in 1935.

Since June 1937, monthly measurements of the sediment level at the intake towers (National Research Council, 1949, and Bur. Reclamation, 1949 and 1953) reveal the periods during which conspicuous flows of turbid water have reached Hoover Dam. The periods of underflow are marked by a rapid rise in the top

of the sediment accumulation behind the dam, whereas the intervals between periods of underflow are marked by a gradual but progressive lowering of the sediment surface due to compaction.

The fluctuations in sediment level at the dam are shown in the graphs of plate 26, which also show the approximate daily densities of the incoming river water during the 14-year period from 1935 to 1948. These densities were computed from measurements of temperature, salinity, and suspended sediment of the Colorado River as recorded at the Grand Canyon gaging station (p. 103), using the method outlined by Rubey (1938), who states that densities computed by his method probably have an average error of about 0.0003 gram per cubic centimeter. In the computations, the density of the suspended solids was taken as 2.67, as determined by direct measurement, rather than the assumed value of 2.60 used by Rubey. In the absence of temperature data for the period February 1, 1935, to September 30, 1936, it is assumed that the temperature in that period varied in about the same manner as in 1939.

The density of the water entering the main body of Lake Mead, after the coarser sediment particles have been deposited in the Lower Granite Gorge and Pierce Basin, is undoubtedly somewhat lower than the density of the water passing the Grand Canyon gaging station. However, it seems a fair assumption that the daily variations in the amount of sediment still in suspension when the turbid river water enters the lake are roughly in the same proportion as the variations in the suspended sediment content of the Colorado River at the Grand Canyon gaging station. Of course, these variations are not synchronous, owing to the time required for water to flow from the Grand Canyon station to the head of Lake Mead. Computations by Rubey (1938) indicate that the time required for water to travel from the Grand Canyon station to the eastern end of the lake ranges from 1 to 4½ days, the shorter travel times occurring during periods of floods. Howard notes (p. 103) that the turbid flows of 1935 passed through Hoover Dam about 8 days after they were observed at Grand Canyon.

The data presented in figure 26 show clearly that the rises in the sediment level behind Hoover Dam follow the peak water densities of the Colorado River at the Grand Canyon station. Some lag may be expected between the appearance of high-density water at the Grand Canyon station and the rise in the sediment level behind the dam, because of the time required for the high-density water to travel from the Grand Canyon station to Hoover Dam. This travel time does not account, however, for the total time separation of the curves in figure 26. Observations of the sediment level

behind the dam are made only once each month; it is therefore possible that the time of arrival of turbid underflows at the dam may be missed by as much as 30 days.

Even though the times of arrival of underflows at Hoover Dam since June 1937 are known less accurately than those in 1935, many of the rises in sediment level behind the dam are clearly related to peak water densities at the Grand Canyon station. Most of these periods of underflow have been associated with peak river-water densities of 1.02 or greater, although two of the underflows are associated with relatively low densities of river water. In March 1935 the maximum density of the river water prior to the arrival of the first major underflow at the dam was only 1.012, and in May 1939 a conspicuous underflow was associated with peak densities of only 1.006. On the basis of these observations alone, it is evident that other factors in addition to density determine the distance that underflows move along the bottom of Lake Mead. Variations in the size of the suspended particles, their degree of flocculation, the duration and volume of high density inflows, mixing of the inflow with the lake water, and changes in the slope and width of the channel over which underflows move may influence the distance of travel of underflows in the lake. From the records of density currents to date, however, density appears to be a dominant factor.

VELOCITY, DENSITY, AND THICKNESS

One of the most striking features of the underflows is their extremely low velocity. Bell (1942a, p. 522) estimated that the average velocity of one of the underflows reaching the dam in 1935 was approximately 0.83 foot per second. Records since 1937 (National Research Council, 1949, and U.S. Bur. Reclamation, 1949) show that the average velocities of the later currents were generally about 0.5 foot per second and might be as low as 0.3 foot per second. These records also indicate that the underflows travel much more rapidly over the steeper, upper parts of the delta than over the lower parts. Mean velocities of 1.0 foot per second are common near the river mouth where the turbid water plunges down the face of the delta front, but by the time these currents reach the flat floor of the Boulder Basin, their velocities are less than 0.25 foot per second and are commonly too low for measurement.

In most of Lake Mead, underflows are confined to the submerged channel of the Colorado River and are generally only a few feet thick. Between the entrance of the river in 1948 and the mouth of Iceberg Canyon (a distance of about 14 miles), abundant mixing of the muddy inflow and the lake water occurred several

tens of feet above the reservoir bottom, but west of Iceberg Canyon the underflow of turbid water was confined to the very deepest part of the reservoir.

In late November 1948, an underflow of muddy water extended into the eastern part of Virgin Basin. Observations of this current showed a very sharp interface between the muddy flow at the bottom of the lake and the clear water above. The average thickness of the underflow west of Iceberg Canyon was about 3 feet and its density ranged from approximately 1.001 at the top to about 1.20 at the bottom. In figure 55 the typical vertical distribution of density of the November 1948 underflow is shown in a section taken at the mouth of Virgin Canyon. The marked increase in density near the bottom of the underflow probably represents a division between material that is still in motion and that which was recently deposited, but as this contact is somewhat transitional, it is shown in figure 55 as a gradational zone.

AMOUNT OF SEDIMENT AND DISTANCE OF TRAVEL

It was estimated (p. 195) that about 50 percent of the total weight of sediment accumulated in the Colorado delta is contained in the fine-grained bottomset beds. Practically all of this material was transported by turbidity currents developed at the mouth of the Colorado River. Cores from the bottomset beds provide no information as to the relative quantities of material that were transported into the lake by the three types of turbidity currents: overflows, interflows, and underflows. It is clear, however, that most of the sediment

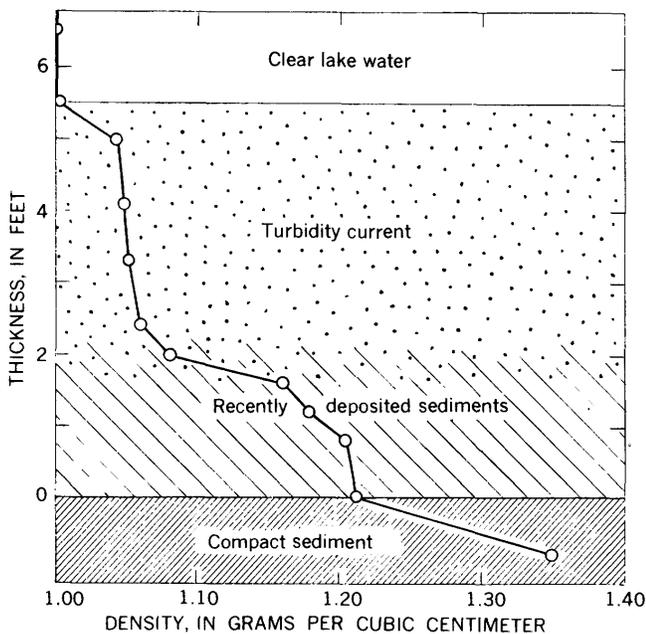


FIGURE 55.—Distribution of density during underflow of November 1948 in vertical section at mile 301.9, in Virgin Canyon.

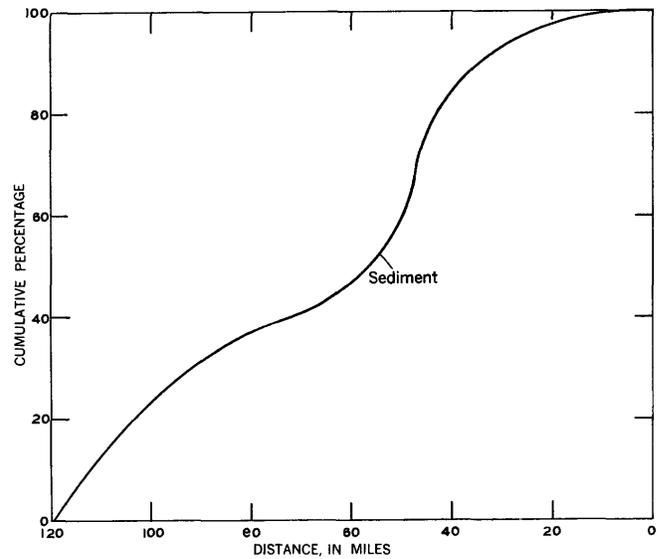


FIGURE 56.—Percentage distribution of sediment transported by turbidity currents in relation to distance from the east end of the lake, measured along the buried Colorado River channel. Curve shows only the percentage distribution of sediment transported by turbidity currents, not the ratio of such sediment to total sediment.

in Boulder Basin was transported by underflows, because interflows have never been identified in that basin and overflows rarely extend west of Virgin Basin.

In figure 56 the percentage distribution of sediment transported by the Colorado River turbidity currents is plotted against the distance from the eastern end of the reservoir at Bridge Canyon, measured along the buried Colorado River channel. This figure shows that about 80 percent of the sediment carried by turbidity currents accumulated on the reservoir floor at a distance of more than 43 miles from the head of the reservoir, and that 23 percent accumulated at a distance of more than 100 miles. Owing to the advance of the delta front into the lake, it is not known precisely how far this material was transported. It is known, however, that most of the sediment in Boulder Basin was transported at least 70 miles before finally coming to rest. These long-ranging flows of turbid water could, in all probability, have continued for many more tens of miles, if Lake Mead had been large enough.

The Colorado delta deposits along the thalweg of the river have a minimum thickness of 45 feet at mile 314.1 in the Temple Bar area, about 40 miles above Hoover Dam. The progressively increasing thickness east of this point is normal for a sediment-laden stream entering quiet water. The increasing thickness to the west may be attributed to Hoover Dam, which arrested the infrequent but farthest-traveling turbidity currents and caused deposition of their suspended loads. In

open water, some of these currents might have continued for tens or even hundreds of miles, and the total thickness of deposition would generally decrease progressively from the point of entrance of the inflowing water, doubtless with modifications resulting from configuration of the bottom.

CHANGE IN SLOPE AND WIDTH OF THE CHANNEL

The sediment that has accumulated in the Colorado delta has reduced the average slope of the former Colorado River channel from 5 feet per mile to about 3 feet per mile. The greatest reduction in slope occurs in Boulder Basin, where the declivity of the sediment surface is less than 1 foot per mile. As shown in plate 13, this reduction in slope occurred prior to 1942, when Boulder Basin received most of its sediment. Because of the rapid rate of sedimentation in the first 7 years of reservoir operation, the width of the channel was also greatly increased. As the continued underflow of turbid water is controlled in part by the slope and cross-sectional area of the channel, it is possible that this early reduction in slope and the increased width of the channel may be partly responsible for the decreased flow of turbid water into the western part of the lake since 1942 (pl. 26). However, periods of high-density inflow have occurred only rarely in recent years, and they may be the chief reason for the dearth of major underflows since 1942.

SIZE OF SUSPENDED PARTICLES

Assuming that the deeply buried bottomset beds in Lower Granite Gorge are similar in texture to the bottomset beds west of the Colorado delta front, we can obtain a fair estimate of the average size distribution of the particles transported by the Colorado River turbidity currents. According to this estimate (areas 1-5, fig. 54) the suspended particles have an average median diameter of 1.65 microns (in dispersed state) and consist of 67 percent clay (smaller than 4 microns), 32 percent silt (4-62 microns) and less than 1 percent sand (larger than 62 microns).

Even though the range in size of the sediment particles is small, the bottomset beds are horizontally graded, the coarsest particles being deposited near the river mouth and the finest at the greatest distance from the source. This relation is illustrated in figure 53, where the size characteristics of samples from each of the seven subdivisions of the Colorado delta are combined and averaged so as to give a composite size distribution curve for each of the divisions. Curves for areas 1 through 5 show the gradation in particle size of material transported by turbidity currents,

whereas the curves for areas 6 and 7 include sand and coarse silt that has not been transported by turbidity currents.

As mentioned previously (p. 155) the sediment in the bottomset beds of the Colorado delta in its natural condition does not settle out as discrete particles, but as flocculated masses that are 2 to 20 times larger than the individual grains (table 22). Similar studies of suspended sediment in the Lake Mead underflows (Sherman, 1953) and in the Colorado River (Grover and Howard, 1938, p. 728-729) show that the material also travels in a flocculated state.

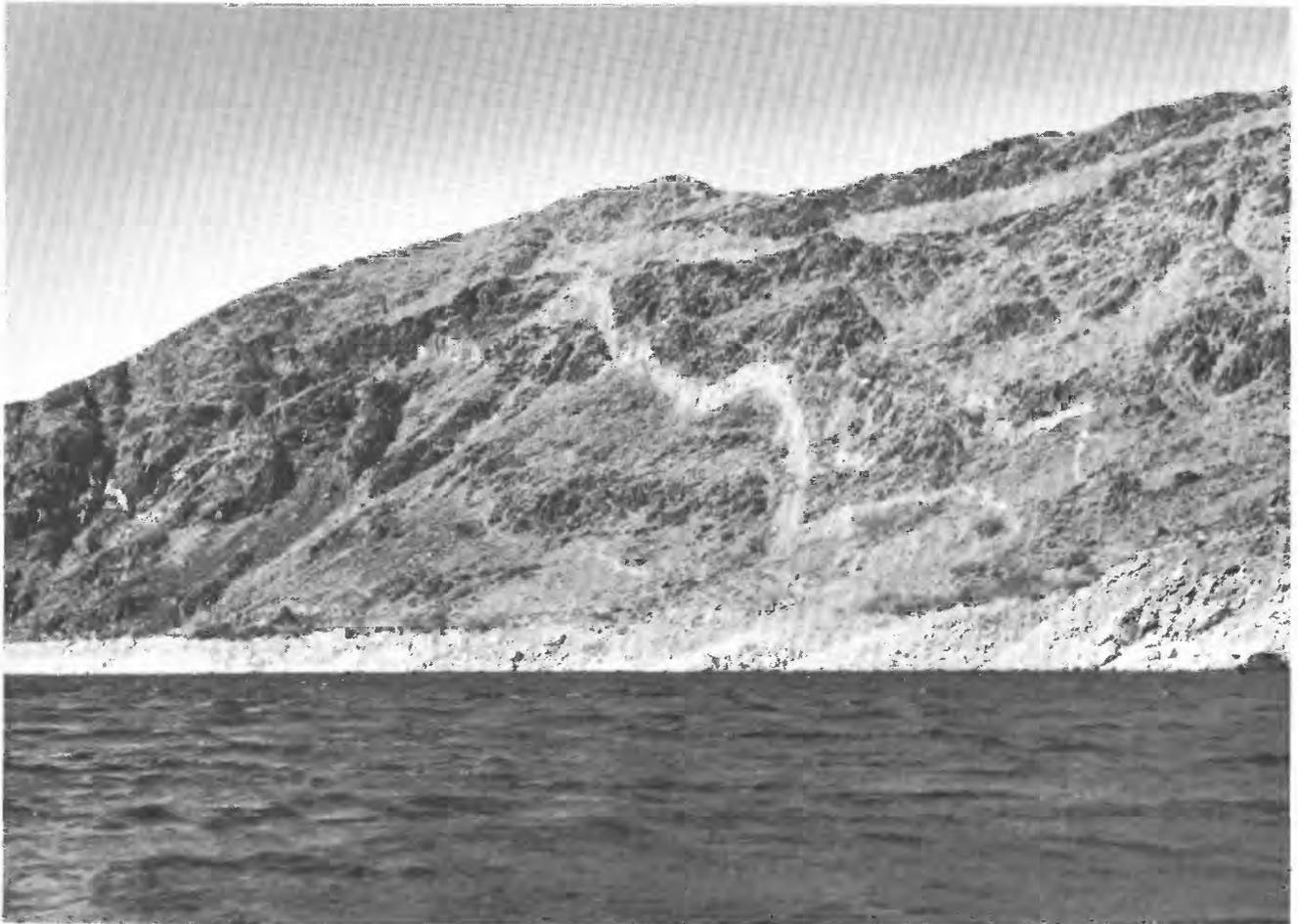
Flocculation of fine sediment has been cited by Johnson (1939) and others as a condition which probably prevents the formation of extensive turbidity currents, but the validity of this assertion is open to question. As pointed out by Bell (1942a, p. 541), flocculation causes rapid settling, but floccules, because of their large volume of entrapped water, may behave as a fluid that will flow on much gentler slopes than unflocculated material. Hence it appears that flocculation may actually assist in producing and maintaining turbid underflows.

VIRGIN RIVER TURBIDITY CURRENTS

The Virgin River turbidity currents, although of little quantitative significance, are worthy of brief mention. Essentially all of the sediment carried into the lake by the Virgin River has accumulated in the upper 14 miles of Overton Arm, and it is apparent that most of the Virgin River turbidity currents have extended only a short distance into Lake Mead. However, there is evidence that some underflows of turbid water have traveled through most, if not all, of the inundated Virgin River channel.

Our knowledge of these extensive currents is based entirely on data obtained at the Lower Narrows, 9.3 miles upstream from the former junction of the Virgin River and the Colorado River. Records obtained by the Bureau of Reclamation at this station show that suspended silt and clay particles were present in the former Virgin River channel from January to March 1938 and again from June to September 1938. From January 1939 to February 1940, the suspended sediment disappeared completely as shown by the presence of clear water in contact with the sandy bottom of the channel. It appears that essentially no sediment was permanently deposited from these early underflows as they moved through Lower Narrows.

Again in March 1940 suspended sediment appeared in the bottom of the channel at Lower Narrows, but, in contrast to the earlier underflows, some of the sediment was deposited. Samples taken by the Bureau of Rec-



LANDSLIDE ON THE NORTH WALL OF VIRGIN CANYON, NEAR THE MOUTH

The 1941 high-water mark, which stands about 65 feet above the lake surface, has not been displaced. Photograph by Bureau of Reclamation, October 1953.

lamation in June 1940 showed that the bottom material was composed of sand, silt, and clay, and indicated that a very thin layer of silt and clay had been deposited on top of the sand in the inundated channel. Records obtained once or twice each year since June 1940 show that suspended sediment has appeared periodically in the submerged channel between 1942 and 1947. Suspended sediment was observed in the channel at Lower Narrows in April 1948, but by January 1949 it had disappeared. The suspended sediment at Lower Narrows commonly appears prior to the period of Colorado River overflows, and the Virgin River is evidently its source.

Part of the suspended sediment that moves along the former Virgin River channel has probably been derived from the Colorado River overflows. During the late spring and summer of 1948 the overflow of turbid water from the Colorado River extended northward from Virgin Basin into Overton Arm, indicating (p. 13) that at least part of the suspended sediment that was observed in the old Virgin River channel was dropped from the Colorado River overflows.

A layer of silt and clay ranging from a few tenths of a foot to about 2 feet in thickness has accumulated in the bottom of the inundated Virgin River channel between the toe of the Virgin delta and Lower Narrows (p. 172). This is regarded as an incipient extension of the bottomset beds of the Virgin delta into the deeper parts of Overton Arm. Whether or not this thin layer of accumulated sediment represents the total amount of material carried by the extensive Virgin River turbidity currents is not known. However, it is certainly possible that some of the sediment may have been carried along the entire length of the old Virgin River channel and deposited among the bottomset beds of the Col-

orado delta in the area of the former junction of the Colorado and Virgin Rivers.

REFERENCES CITED

- Anderson, E. R., and Pritchard, D. W., 1951, Physical limnology of Lake Mead: Navy Electronics Lab. Rept. 258, 152 p.
- Bell, H. S., 1942a, Density currents as agents for transporting sediment: *Jour. Geology*, v. 50, p. 512-547.
- 1942b, Stratified flow in reservoirs and its use in the prevention of silting: U.S. Dept. Agriculture Misc. Pub. 491, 46 p.
- Daly, R. A., 1936, Origin of submarine canyons: *Am. Jour. Sci.*, ser. 5, v. 31, p. 406-407.
- Grover, N. C., and Howard, C. S., 1938, The passage of turbid water through Lake Mead: *Am. Soc. Civil Engineers Trans.*, v. 103, p. 720-32.
- Johnson, D. W., 1939, The origin of submarine canyons: New York, Columbia University Press, p. 27, 52.
- Kuenen, P. H., and Migliorini, C. I., 1950, Turbidity currents as a cause of graded bedding: *Jour. Geology*, v. 58, p. 94-95.
- National Research Council, Interdivisional Committee on Density Currents, Subcommittee on Lake Mead, 1949, Lake Mead density current investigations 1937-40, v. 1, 2; 1940-46, v. 3; Washington, U.S. Bur. Reclamation, 3 v. 904 p.
- Rubey, W. W., 1938, Discussion of "The passage of turbid water through Lake Mead" by N. C. Grover, and C. S. Howard: *Am. Soc. Civil Engineers Trans.*, v. 103, p. 763-767.
- Sherman, Irving, 1953, Flocculent structure of sediment suspended in Lake Mead: *Am. Geophys. Union Trans.*, v. 34, p. 394-406.
- Stetson, H. C., and Smith, J. F., 1938, Behavior of suspension currents and mud slides in the continental slope: *Am. Jour. Sci.*, ser. 5, v. 35, p. 1-2.
- U.S. Bureau of Reclamation, 1949, Report of river control work and investigations in 1948 and 1949: Boulder City, Nev., Office of River Control, p. 43-124, figs. 44-46.
- 1953, Report of river control work and investigations in 1950 and 1951: Boulder City, Nev., Office of River Control, p. 55-94, figs. 45-47.