Comprehensive Survey of Sedimentation in Lake Mead, 1948-49

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N. CHARACTER OF THE ACCUMULATED SEDIMENT


METHODS OF INVESTIGATION

The field investigation of the accumulated sediment in Lake Mead was made between December 1947 and April 1949, using modern oceanographic equipment and techniques. A plane-personnel boat, furnished by the Navy and equipped for light hydrographic work, was used extensively in the collection of samples from the upper layers of the deposited sediment and of the suspended sediment in the overlying water. Profiles obtained by echo sounding (chap. G), supplemented by many line soundings and bottom samples, constitute the basic data used in determining the areal distribution and surface features of the accumulated sediment. The pontoon barge, equipped with powerful winches and a boom capable of handling heavy coring devices, was used in obtaining cores from the accumulated sediment.

Samples and soundings of the bottom in the shallow water of Lower Granite Gorge were obtained from a sea sled or air boat, a fast, shallow-draft vessel powered by an airplane engine and propeller mounted at the stern of the boat. The sea sled proved highly successful in traversing the shallow river bars and fast water in Lower Granite Gorge, where boats of more conventional design could not be operated.

Preliminary soundings and samples from the bottom of Lake Mead, together with data collected during density-current studies prior to 1947 (National Research Council, 1949), showed that most of the sediment in the lake had accumulated in the area of the submerged Colorado River channel and in the northern part of the inundated Virgin River valley (Overton Arm).

In order to obtain a representative picture of the accumulated sediment, 46 cores and more than 300 samples were collected. The cores were cut into segments 6 to 12 inches long and stored in airtight containers. Counting these core segments, more than 1,800 samples were studied. The number of cores and samples of various types and their distribution throughout the lake are summarized in table 18, and the location of all coring and sampling positions are shown in plate 19. Characteristics of the samples and associated hydrographic data are summarized in a supplemental report (U.S. Geol. Survey, 1954).

Of the 46 cores, 43 were collected in the vicinity of the inundated Colorado River channel between the mouth of Lower Granite Gorge and Hoover Dam, and 3 were obtained near the mouth of the Virgin River in the northern part of Overton Arm. No cores were collected from the sediment deposits in Lower Granite Gorge, because that part of the deposit consists chiefly of compact sand that could not be sampled at depth by conventional coring methods.

The sediment deposit between Pierce Basin and Hoover Dam is chiefly soft mud, which could readily be sampled at depth. At most stations in Boulder Basin and Virgin Basin, cores were collected from the total thickness of the accumulated sediment, but the lower part of the deposit was penetrated in only a few places farther east. Compact layers of silt and sand,

<table>
<thead>
<tr>
<th>Coring or sampling instrument</th>
<th>Black Canyon</th>
<th>Boulder Canyon</th>
<th>Boulder Canyon</th>
<th>Virgin Basin</th>
<th>Temple Bar area</th>
<th>Virgin Canyon</th>
<th>Gregg Basin</th>
<th>Iceberg Canyon and Pierce Basin</th>
<th>Lower Granite Gorge</th>
<th>Overton Arm</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gravity corer</td>
<td>15(1)</td>
<td>148(5)</td>
<td>59(2)</td>
<td>184(10)</td>
<td>68(3)</td>
<td>66(2)</td>
<td>114(5)</td>
<td>213(7)</td>
<td>0</td>
<td>12(3)</td>
<td>881(38)</td>
</tr>
<tr>
<td>Piston corer</td>
<td>0</td>
<td>130(2)</td>
<td>78(1)</td>
<td>68(1)</td>
<td>17(1)</td>
<td>0</td>
<td>0</td>
<td>249(5)</td>
<td>0</td>
<td>0</td>
<td>673(25)</td>
</tr>
<tr>
<td>Snapper sampler</td>
<td>44</td>
<td>41</td>
<td>36</td>
<td>41</td>
<td>16</td>
<td>22</td>
<td>31</td>
<td>48</td>
<td>0</td>
<td>0</td>
<td>270</td>
</tr>
<tr>
<td>Digger</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>9</td>
<td>0</td>
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<td>Pick</td>
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<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>4</td>
<td>0</td>
<td>4</td>
</tr>
<tr>
<td>Total</td>
<td>60(1)</td>
<td>342(7)</td>
<td>164(3)</td>
<td>295(11)</td>
<td>159(4)</td>
<td>91(2)</td>
<td>145(5)</td>
<td>507(10)</td>
<td>15</td>
<td>30(3)</td>
<td>1,806(46)</td>
</tr>
</tbody>
</table>

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which had been contributed by slumping of the reservoir walls or deposited by the Colorado River during the initial filling of the reservoir, limited the depth of penetration in some areas; but in others, notably between Iceberg Canyon and Pierce Basin, the length of the core tube was the limiting factor. A maximum depth penetration of 95.5 feet (core 63) was reached by the coring equipment at mile 283.64,\textsuperscript{14} in the lower part of Pierce Basin.

Most of the cores were obtained with a gravity corer, similar in design to the coring instrument described by Emery and Dietz (1941) but modified to accommodate the great thickness of the sediment accumulated in Lake Mead. The purpose of this device is to obtain a continuous core of the strata penetrated. As the name implies, the gravity corer is forced into the bottom by the gravitational pull exerted on the tube and the attached weights. Altogether, 38 gravity cores were obtained. Penetration depths ranged from 2.0 to 95.5 feet, and the cores ranged in length from 1.0 to 31.0 feet. The recovery ratios ranged from 24.6 to 57.7 percent and averaged 35.5 percent, as shown in table 19.

The gravity corer commonly yields a shortened or compressed core because of sidewall friction and resistance of the material to penetration. Emery and Dietz have demonstrated that, in a deposit whose density increases with depth, the sidewall friction and resistance to penetration balance each other in such a way that equal increments of each layer are obtained. These observations are substantiated in the most part by cores taken from the sediment accumulated in Lake Mead. Laminae ranging in thickness from a fraction of an inch to several feet are preserved in the cores with little deformation. The ratios of core length to penetration depth are plotted in figure 44. A best-fit visual line drawn through these points shows that the relation between core length and penetration depth is approximately linear. This relation has been used in adjusting the positions of samples from the cores to their estimated depths in the place of occurrence.

Toward the end of the field period, a new type of coring device was constructed by the Geological Survey and used at Lake Mead. This instrument, known as a piston corer, was adapted by W. O. Smith from the device designed by Kullenberg (1947). The piston corer is essentially a gravity corer that utilizes the hydrostatic pressure at the bottom to force the sediment into the tube. The same drawbacks that were discussed in connection with the gravity corer—namely, the internal sidewall friction and the resistance of the \footnote{Distances are measured downstream from the Geological Survey marker opposite the mouth of the Paria River, along the pre-Lake Mead channel of the Colorado River.}

sediment against being pushed aside or downwarped at the bottom of the tube—apply also to the piston corer, but to a lesser degree. The piston corer, by utilization of hydrostatic pressure, effectively increases the resistance of the sediment against being pushed aside or downwarped. As a result, the cores are considerably longer than those taken by the gravity de-
The hydrostatic pressure is great enough, cores equal in length to the depth of penetration can be obtained. The eight cores obtained with this instrument were extremely useful in evaluating the accuracy of depth corrections applied to gravity core samples, and in providing relatively undisturbed samples for laboratory analyses.

As shown in table 20, the piston cores ranged in length from 36.5 to 75.0 feet and the depths of penetration ranged from 25.5 to 79.0 feet, thus representing a range in recovery ratios of 70.2 to 143 percent. The low recovery ratios of cores K1 and K2 were caused by loss of sediment from the bottom of the tube and by operational errors, resulting in the failure of the tube to sample the upper few feet of sediment. Core shortening also occurred in shallow-water areas where hydrostatic pressure was probably insufficient to overcome the internal sidewall friction between the sediment and the coring tube, as for example, cores K5 and K6. The high recovery ratios of cores K1c and K7 resulted from failure of the tube to penetrate the sediment deposit to its full length. Under such conditions, withdrawal of the instrument created an initial upward movement of the piston while the tube was still stationary, creating a vacuum in the tube and thus inward movement of extra sediment under hydrostatic pressure.

Except for cores K5 and K6, only minor adjustments in the positions of the samples in the core tube were required to obtain their approximate depths in place. Physical properties of gravity core samples, corrected for depth in place, correlate closely with the physical properties of the piston core samples taken at the same locations.

Samples of sediment in suspension and in the soft upper layers of the accumulated material west of mile 279.3 were obtained with a Foerst sampling bottle, modified for sampling of the soft mud in Lake Mead. The modified Foerst sampler is essentially an open lucite cylinder with rubber stoppers mounted at both ends, with a heavy brass weight, attached to the top stopper and suspended below the cylinder, to pull the instrument through mud and to insure positive closing action at depth. The device is lowered to the selected sampling depth in an open position, which allows a free flow of material through it. When the sampling depth is reached, a messenger is sent down the cable to trip the stopper release mechanism and hold the sample within the cylinder. Samples taken with the Foerst bottle measure about 18 inches in length, of which the lowest part appears to consist of material that entered the tube from the depth of maximum penetration and is probably uncontaminated by sediment from higher levels. Only the bottom 4 inches of each sample was saved for laboratory analysis.

Foerst samples were collected at 35 stations, 32 of which have the same field locations as the gravity cores (pl. 19). Because depths of the Foerst samples could be measured accurately, they were extremely useful in checking the corrected depths of gravity core samples obtained at identical positions. Throughout their range of overlap there was good correspondence between the physical properties of Foerst samples and gravity core samples.
In the area immediately above Hoover Dam and below the location of the cofferdam (p. 113), the accumulated material was too fluid to be retained by either the gravity corer or the piston corer. No difficulty was encountered, however, in sampling this part of the deposit to a maximum depth of 99 feet with the weighted Foerst sampling bottle. Descriptions of the Foerst samples are given in a supplemental report (U.S. Geol. Survey, 1954).

The Foerst sampler was also used extensively for measuring the depth to the interface between the lake water and the accumulated sediment, and for providing information on the nature of that interface. Measurements to the level of the surface of the deposit by this method were accurate to within a few tenths of a foot, whereas the limit of accuracy of echo-sounding measurements in most areas was from 1 to 3 feet. Except for a few periods when the bottom of the eastern part of the lake was masked by turbidity currents (p. 165), the interface between the water and the accumulated sediment was sharp and distinct.

Samples from the surface of the sediment deposit in Overton Arm and a few samples of the original lake bottom in areas of nondeposition were obtained with a snapper-type bottom sampler designed by LaFond and Dietz (1948). In Lower Granite Gorge samples from the subaqueous part of the deposit were collected with a dipper, and the subaerial part of the deposit was channel-sampled with a geologist's pick. The various types of surface samples are listed separately in table 15, but all are grouped as “grab samples” in plate 19 (in pocket).

**MISCELLANEOUS OBSERVATIONS**

Although the collection of cores and samples from the accumulated sediment received the greatest emphasis, a number of other studies were undertaken. These studies included the measurement of vertical temperature gradients in the sediment deposits and photography of the lake bottom in a few areas of critical interest. In areas where there was only a thin layer of sediment, penetration measurements were made to determine its thickness. A large number of water samples collected in conjunction with studies of the water of the lake (chaps. K–M) were analyzed for their suspended sediment. The measurements, together with the results of the circulation studies, provided considerable information on the effectiveness of turbidity currents as agents of sediment transportation.

**LABORATORY STUDIES**

Laboratory studies of samples and cores began in the spring of 1948, in space provided by the Bureau of Reclamation in the Hoover Dam powerhouse, and continued concurrently with the field work until April 1949. Routine analyses of all cores and samples included more than 1,400 water-content measurements, about 300 particle-size analyses, 117 specific-gravity determinations, and a comparison of the color of all cores and samples with the standard Munsell soil-color chart. In addition, the specific weights (p. 153) of 74 piston-core samples were determined directly in the field, primarily to check the accuracy of computed specific-weight values obtained from water-content and specific-gravity measurements, and also to measure directly the volume of gas (mostly methane) in the cores.

Since April 1949 several other types of analyses requiring specialized equipment and techniques have been made. Among these are the determinations by the writer of the organic content and calcium carbonate content of several selected samples, the bacteriological and biochemical studies by F. D. Sisler (p. 187-193), and analyses by the U.S. Bureau of Mines of the gas occurring in the deposits. The Bureau of Mines also investigated the sediment for its ceramic qualities and other commercial uses; the geochemical laboratories of the Geological Survey at Washington, D.C., made chemical, X-ray, and spectrographic analyses of a number of samples; and George Tchillingarian of the University of Southern California investigated the suitability of the sediment for use in a drilling fluid. The results of these various special analyses are presented in the discussion of the characteristics of the accumulated sediment.

Most of the laboratory methods used in measuring the physical properties of the Lake Mead sediments do not differ markedly from standard procedures outlined in most textbooks on sedimentary petrology and soil mechanics. However, because of their critical bearing on the results of the sedimentation studies as a whole, a brief discussion of them is given here.

**WATER CONTENT AND AIR-DRY MOISTURE CONTENT**

The method of measuring the water content and air-dry moisture content consists of weighing out about 25 grams of the wet sample, exposing it to the air for several days until dry, and weighing again (Sherman, 1951). The sample is then allowed to dry in an oven at a temperature of 105°C for 24 hours, after which it is weighed a third time. The difference between the wet weight and the oven-dry weight is a measure of the water content and may be computed from the formula:

\[
W, C. = 100 \frac{W_w - W_d}{W_w}
\]
where $W_c$ is the water content in percent, $W_w$ is the weight of the wet sample in grams, and $W_d$ is the weight of the oven-dry sediment in grams.

The air-dry moisture content is obtained from a similar formula:

$$M.C. = 100 \frac{W_d - W_a}{W_a},$$

where $M.C.$ is the air-dry moisture content in percent, $W_a$ is the weight of the air-dry sample in grams, and $W_d$ is the weight of the oven-dry sediment in grams. Variations in the air-dry moisture content have proved useful in the selection of samples with significant differences in texture for particle-size analyses (Sherman, 1951). Terzaghi and Peck (1948) have shown that the air-dry moisture content is inversely related to the average particle size, ranging from a fraction of 1 percent for sand to 6 or 7 percent for clay. These observations were verified by the Lake Mead measurements where the air-dry moisture content ranges from 0.1 percent for medium sand to about 6 percent for clay having a median particle diameter less than 1 micron.

**SPECIFIC GRAVITY OF SEDIMENT PARTICLES**

The specific gravity of the sediment particles was determined by the conventional pycnometer method described by Krumein and Pettijohn (1938). Relatively large samples weighing 5 to 6 grams, were used in order to avoid errors introduced by working with small differences in weights. Care was taken to remove all air bubbles from the pycnometers by applying suction to them for about 12 hours before the final weighings were made. On 72 samples, selected from widely separated positions, 117 specific-gravity measurements were made. Duplicate analyses of 45 of the samples show that the variation of measurement by this method is not greater than 0.5 percent.

The specific gravities of silt and clay samples range from 2.640 to 2.760, and of sand samples from 2.630 to 2.660. The mean specific gravity of silt and clay samples is 2.705 and of sand samples is 2.645. These mean values have been used in the indirect determination of certain other physical properties of the sediment deposits, which are described in the following pages.

**DENSITY, POROSITY, AND SPECIFIC WEIGHT**

The density of a sediment deposit is the ratio of the weight of the sediment plus its included water (or, in the more fluid samples, of the water and its included sediment) to the weight of an equivalent volume of water alone. It is recognized that the density of water changes with temperature, and these changes are significant factors—for instance, in the development of turbidity currents (chap. Q). However, these are small in comparison with the changes that result when appreciable quantities of mineral particles are added to the water. In the determinations of density of sediment deposits, therefore, it is assumed that the weight-volume ratio of water remains constant.

In 74 piston-core samples the density was determined as the weight of the water-saturated sample divided by its volume, both expressed in metric units. The densities of these samples ranged from 1.275 to 1.971. In other samples the original volume could not be determined, because of changes occurring during collection. For these samples the density was determined indirectly by the formula

$$D = \frac{W_w}{V_{wa} + \frac{W_d}{8g}},$$

in which $W_w$ is the weight of the water-saturated sample; $V_{wa}$ the volume of interstitial water; $W_d$ the weight of the oven-dried sample; and $8g$ is the specific gravity of grains (as mentioned above).

Porosity, the ratio of the volume occupied by water to the total sample volume, is expressed as a percentage. In the 74 piston-core samples the volume of water was determined by weighing the sample before and after ovendrying at 105°C, assuming a constant weight-volume ratio for the water. In the other samples the porosity was computed from the formula

$$P = \frac{100V_{wa}}{V_{wa} + \frac{W_d}{8g}},$$

where $V_{wa}$ is the volume of interstitial water as determined by oven-drying, $W_d$ is the weight of the dried sample, and $8g$ is the specific gravity of the mineral grains.

Specific weight, the ratio of the weight of the solid mineral particles to the volume of the sample, is expressed in pounds per cubic foot. In the 74 piston-core samples the specific weight was determined directly as the weight of the oven-dried sample divided by the original volume of the sample and multiplied by 62.43. For other samples the specific weight was computed by the formula

$$S_w = \frac{62.43W_d}{V_{wa} + \frac{W_d}{8g}},$$

where $S_w$ is the specific weight in pounds per cubic foot and other factors have been identified above. No corrections have been made for the volume of gas in place, but the maximum error in these indirect determinations is estimated at less than 1 percent, based on measurements of the quantity of gas in 74 samples from widely separated positions.
Because of its limited application in most geological studies, specific weight is commonly not included among the physical properties of sediments. However, it finds wide application in reservoir engineering practice. In the Lake Mead investigations the specific weight is particularly useful because it provides a relatively simple method of obtaining the total weight of the solid mineral particles deposited in the reservoir.

**GAS VOLUME IN PLACE**

The direct method of analysis of the piston-core samples measures the volume of gas as well as the volume of the solid mineral particles and interstitial water, but the gas in the sample occupies a much larger volume at the surface than at its true depth in place. When samples from the accumulated sediment are raised to the surface, they experience a pressure change that is equal to the difference between the pressure in place and atmospheric pressure at the surface. If no gas is present in the sediment, the sample is unaffected by this pressure change, but if gas is present, it expands to several times its volume in place. The volume of gas in samples at the surface reached a maximum of about 12 percent, but when corrected for changes in hydrostatic pressure, the maximum volume of gas in place was about 2 percent. Because of this gas expansion, direct measurements of specific weight, density, and porosity have maximum errors of approximately 5, 9, and 10 percent, respectively.

The percentage volume of gas contained in the sediment in place is obtained by the following formula:

\[
G = \frac{V_w - (V_{ws} + V_d)}{V_w} \times 100 \times \frac{P_a}{P_o}
\]

where \( G \) is the percent gas volume in place, \( V_w \) is the volume of the sample in cubic centimeters at atmospheric pressure, \( V_{ws} \) is the volume of interstitial water in cubic centimeters, \( V_d \) is the volume of the solid mineral grains (equivalent to the weight of the dry sediment in grams divided by the specific gravity of the grains), and \( P_a \) is the ratio between the pressure at the depth from which the sample was obtained and atmospheric pressure. The effect of temperature changes on the relative gas volumes is considered negligible and has been omitted from the formula.

**PARTICLE SIZE**

Determinations of particle size were made of 300 samples of fine-grained sediments, selected from widely distributed positions, both geographically and in depth, and considered, therefore, to be representative of the accumulated sediment as a whole. Sand and gravel samples from the sediment accumulated in the Lower Granite Gorge were analyzed by sieving, whereas the samples containing silt and clay were analyzed by a combination of sieving and pipetting. The methods of size analysis follow closely the general procedures outlined by Krumbein and Pettijohn (1938). However, the pretreatment of silt and clay samples differs in some significant details from most standard procedures. Since the pretreatment has a particularly critical bearing on the results of the analyses, a fairly complete description of the method used in determining the particle-size distribution of silt and clay samples is given here.

The method consisted of weighing a sufficient amount of the sample to provide about 10 grams of solid mineral particles for pipette analysis. The exact weight of the solid mineral particles was then computed from previous determinations of the water content. This procedure was followed in order to avoid drying the sample, and especially to avoid the arduous task of disaggregating the sample mechanically after it had been dried. All organic matter in the material was then removed by treating the sample with 100 cc of a 6-percent solution of hydrogen peroxide, and placing it in a boiling water bath for about 14 hours. The dissolved solids were then removed from the material by five complete washings and filtrations with a porcelain filter, after which the sample was transferred to a soil dispersion cup. A dispersing agent consisting of 75 cc of 0.1-normal sodium hexametaphosphate \((\text{NaPO}_4)_6\) buffered to a pH of 9 as suggested by Tyner (1939) and diluted with 200 cc of distilled water, was added to the sample, which was allowed to soak overnight. The material was then mixed in the dispersion cup for 10 minutes, washed through a 62-micron sieve into a 1-liter graduate cylinder, and brought up to a volume of 1,000 cc by the addition of distilled water.

If the material retained on the 62-micron sieve amounted to more than 2 percent of the total weight of the sample, it was dry-sieved through a nest of Tyler standard screen sieves, the nominal openings of which increase uniformly from 62 microns to 4,000 microns according to the Udden (1914) and Wentworth (1922) scales, combined as shown in table 21. The individual fractions of each grade scale were weighed and recorded. This part of the procedure was omitted for samples containing less than 2 percent of sand, and the material retained on the 62-micron mesh was recorded as the weight of the particles with diameters greater than 62 microns.

The dispersed sediment in the liter graduate was agitated for 1 minute, after which the suspended particles were allowed to settle. According to Stokes' law, a small spherical particle in liquid settles at a constant velocity that is a function of the size, shape, and density.
of the particle and of the density and absolute viscosity of the settling medium. From this relation the depths to which limiting particle sizes will travel during a given time may be computed. Samples of the suspended sediment, 25 cc in size, were withdrawn from these selected depths at measured time intervals. The limiting diameters chosen for the analyses of the Lake Mead samples correspond to the diameters smaller than 62 microns shown in table 21. Withdrawals at the limiting diameter of 0.5 micron were made, however, only for samples having an exceptionally large proportion of fine-grained material.

After the sample fractions had been dried, the residues were weighed with an accuracy of 1 mg, corrected for the weight of the dispersing agent, and converted into terms of the original weight of the total amount of suspended material. The differences between the converted weights of successive sample fractions represent the amount of material contained in the individual size grades. For example, the difference between the converted weights of the first and second fractions represent the amount of sediments contained in the coarse silt grade, 62-31 microns.

Table 21.—Combined Udden and Wentworth size classification

<table>
<thead>
<tr>
<th>Grade-size limits, diameters in microns</th>
<th>Name</th>
<th>Grouping used in this report</th>
</tr>
</thead>
<tbody>
<tr>
<td>Larger than 256,000...</td>
<td>Boulder</td>
<td>Gravel.</td>
</tr>
<tr>
<td>256,000 to 64,000...</td>
<td>Cobble</td>
<td>Very coarse sand and granules.</td>
</tr>
<tr>
<td>64,000 to 2,000...</td>
<td>Pebble</td>
<td>Medium and coarse sand.</td>
</tr>
<tr>
<td>4,000 to 2,000...</td>
<td>Granite</td>
<td>Fine and very fine silt.</td>
</tr>
<tr>
<td>2,000 to 1,000...</td>
<td>Very coarse sand</td>
<td>Medium silt.</td>
</tr>
<tr>
<td>1,000 to 500...</td>
<td>Course sand</td>
<td>Silt.</td>
</tr>
<tr>
<td>500 to 250...</td>
<td>Y medium sand</td>
<td>Fine clay.</td>
</tr>
<tr>
<td>250 to 125...</td>
<td>Fine sand</td>
<td>Medium and coarse clay.</td>
</tr>
<tr>
<td>125 to 62...</td>
<td>Very fine sand</td>
<td>Fine clay.</td>
</tr>
<tr>
<td>62 to 31...</td>
<td>Coarse silt</td>
<td></td>
</tr>
<tr>
<td>31 to 16...</td>
<td>Medium silt</td>
<td></td>
</tr>
<tr>
<td>16 to 8...</td>
<td>Fine silt</td>
<td></td>
</tr>
<tr>
<td>8 to 4...</td>
<td>Very fine silt</td>
<td></td>
</tr>
<tr>
<td>4 to 2...</td>
<td>Course clay</td>
<td></td>
</tr>
<tr>
<td>2 to 1...</td>
<td>Y medium clay</td>
<td></td>
</tr>
<tr>
<td>1 to .5...</td>
<td>Fine clay</td>
<td></td>
</tr>
</tbody>
</table>

The true limiting diameters differ slightly from those shown in table 21 because of small variations in the densities and shapes of particles and because of slight variations in the density and viscosity of the settling medium. The density and viscosity of the settling medium are mainly functions of its temperature, and therefore can be evaluated readily from temperature measurements. In the final computations these limiting diameters have been corrected both for temperature of the settling medium and for density of the particles, but no correction has been applied for the variation of particle shape from that of a true sphere.

The use of a dispersing agent in the laboratory analysis of the fine-grained materials poses a dilemma: On the one hand, the individual particles of deposited silt and clay, particularly if the sediment is dried or compacted, require a dispersing agent for their separation; on the other hand, such a dispersing procedure probably has no natural counterpart in Lake Mead. In order to assess the discrepancy that might accrue from the dispersing technique, duplicate analyses were made of fine silt and clay samples, showing a considerable range in texture, using untreated lake water. The results of these analyses are compared in table 22 with those obtained by dispersing the sediment. It is evident from these analyses that the silt and clay particles have settled to the bottom as flocculated masses, not as discrete units; and as would be expected, the finest material exhibits the greatest degree of flocculation. Similar studies of suspended sediment from Lake Mead turbidity currents (Sherman, 1953) and investigations of the suspended sediment in the Colorado River (Grover and Howard, 1938) show that the smaller particles also travel in a flocculated state. Sherman points out that floccule structure is at least partly a function of salinity; however, particles larger than approximately 24 microns in diameter do not enter into floccule formation, regardless of salinity, but act independently in suspension.

Table 22.—Median particle diameters of samples from bottom-set beds of the Colorado delta, as determined by analyses in a dispersed medium and in untreated lake water

<table>
<thead>
<tr>
<th>Sample</th>
<th>Position, as miles</th>
<th>Sediment depth, in feet</th>
<th>Dispersed medium</th>
<th>Untreated lake water</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>Median diameter, in microns</td>
<td>Effective median diameter, in microns</td>
</tr>
<tr>
<td>14</td>
<td>262.3</td>
<td>0</td>
<td>5.0</td>
<td>13.0</td>
</tr>
<tr>
<td>15</td>
<td>287.5</td>
<td>0</td>
<td>7.0</td>
<td>11.5</td>
</tr>
<tr>
<td>67</td>
<td>300.1</td>
<td>71.6</td>
<td>.5</td>
<td>10.0</td>
</tr>
<tr>
<td>19</td>
<td>335.5</td>
<td>0</td>
<td>.9</td>
<td>11.0</td>
</tr>
</tbody>
</table>

1 Sediment dispersed with 0.896 gram of sodium hexametaphosphate (NaPO₄)₆, per liter of suspension.
2 Salinity of untreated lake water is approximately 700 ppm.

The data obtained from the sieve and pipette analyses were plotted as cumulative curves, an example of which is shown in figure 45. Attempts were made to measure the diameters of particles as fine as 0.25 micron, but the results were erratic and undependable. It was concluded that the dimensions of clay particles less than about 0.4 micron in diameter (corrected for particle density and temperature of the settling medium) could not be measured accurately by the pipette method. Krumbein and Pettijohn (1938) and others have also concluded that particles finer than approximately 0.5 micron in diameter do not obey Stokes' law, but behave rather as a colloidal suspension. This explanation accounts for the incompleteness of the curve...
shown in figure 45, which is typical of most of the cumulative curves for silt and clay samples from Lake Mead. From these curves, interpolated percentages of the amount of sediment in the various size grades were computed. Because of the extremely fine texture of most samples, it has been desirable in the presentation of results to group together some of the Udden-Wentworth grade scales (table 21).

Values of the statistical constants employed by Trask (1932)—namely, the median diameter and the coefficients of skewness and sorting—have also been determined and tabulated. The median diameter indicates the midpoint by weight of the size distribution, as determined from the cumulative curve. The coefficient of sorting is a statistical measure of the uniformity in size of the sediment particles, and is defined as

$$S_s = \sqrt{\frac{Q_3}{Q_1}},$$

where $S_s$ is the coefficient of sorting, $Q_1$ is the lower quartile and $Q_3$ is the upper quartile when the frequency of sizes is cumulated in order of increasing size. For spheres of uniform size the coefficient of sorting would be 1.0; increase in this coefficient indicates a poorer degree of sorting. Trask has called samples well sorted if they have a coefficient of sorting less than 2.5, and poorly sorted if their coefficient of sorting is greater than 4.5.

The asymmetry of the size-distribution curve, as shown by the position of the mode or peak of the distribution and its distance from the median, is measured by the coefficient of skewness, $S_k$, and may be computed from the formula,

$$S_k = \frac{Q_3 - Q_1}{3M^2},$$

where $Q_1$ and $Q_3$ are the same quartile diameters used in the equation for the coefficient of sorting, and $M$ is the median diameter. If the modal diameter is smaller than the median diameter, $S_k$ is greater than 1; but if it is greater, $S_k$ is less than 1.

The median diameter, coefficient of sorting, and coefficient of skewness for gravity-core sample 266 (fig. 45) are fairly characteristic of other silt and clay samples from Lake Mead. However, many of the samples are finer grained; so fine, in fact, that as much as 50 percent of the sample consists of particles smaller than 0.5 micron. The quartiles making up less than 25 percent of these samples could not be obtained from the cumulative curves, and it is impossible to determine sorting and skewness coefficients.

**DISTRIBUTION OF SEDIMENT**

The sediment that has accumulated in Lake Mead has formed two deltas, one of which extends from Bridge Canyon to Hoover Dam along the submerged channel, or thalweg, of the Colorado River, and another of much smaller size along the inundated Virgin River channel. They are referred to in this report as the Colorado delta and the Virgin delta respectively. Plate 20 shows the areal distribution of the deltas and their relations to the submerged river channels, and also shows the vertical distribution and surface features at 18 sections across the deltas and at selected positions throughout the reservoir.

**COLORADO DELTA**

Most of the sediment brought into Lake Mead is supplied by the Colorado River; it accumulates in the Colorado delta. The coarser particles are dropped at or near the entrance of the river into the quiet lake water, whereas the finer particles are transported into the deeper parts of the reservoir. Turbidity currents, developed at the mouth of the Colorado River (chap. Q), have been active in delta development since the inception of Lake Mead. During most seasons of the year these currents travel along the submerged channel of the Colorado River and deposit sediment continuously along its course. Several turbidity currents have traversed the entire length of the reservoir (p. 203), but others have probably traveled only short distances into the lake. These currents and the through-going inundated Colorado River channel along which they travel account for the exceptional length and extreme narrowness of the Colorado delta. As shown in plate 20, the Colorado delta is confined almost entirely to the area of the submerged Colorado River channel extending from Bridge Canyon to Hoover Dam, a distance...
of about 120 miles as measured along the course of the old channel.

The eastern 43 miles of the lake, occupying the narrow Lower Granite Gorge of the Grand Canyon and the eastern part of Pierce Basin, have been filled with sediment to a level higher than the average lake level (about 1,170 feet altitude). As shown by sections $A-A'$ to $E-E''$ (pl. 20), the Colorado delta progressively increases in thickness from Bridge Canyon to mile 277.8, where it attains a maximum thickness of 270 feet. Topset beds make up the surface of this part of the delta, and the Colorado River now flows over them to its position of discharge in Pierce Basin (fig. 16). This part of the lake has reverted to fluvial conditions except at high reservoir levels, when the lake extends into Lower Granite Gorge. Although some of the topset beds in the Lower Granite Gorge are above the average operating level of the reservoir (about 1,170 feet altitude), and in some places above the level of the permanent spillway crest (1,205.4 feet elevation), the delta in its present stage of development does not extend upstream from the original eastern end of the reservoir at mile 235.

West of mile 277.8, the delta lies entirely beneath the average lake surface (about 1,170 feet elevation) and is confined to the region of the submerged Colorado River channel. Foreset beds make up the surface of the delta east of mile 279.3; but from that point to Hoover Dam, a distance of about 75 miles, the delta is composed of bottomset beds.

In Iceberg, Virgin, Boulder, and Black Canyons steep walls bound the sediment on both sides, but in the intervening basins the delta spreads out over the terraces that flanked the inundated Colorado River channel. It is still confined, however, to the general area of the thalweg.

The valleys of tributaries to the Colorado River west of Iceberg Canyon are filled to the level of the sediment in the thalweg, but east of that canyon the sediment from the Colorado River has accumulated in the tributary valleys to somewhat higher levels. The most striking example of tributary filling occurs in Virgin Basin, where the bottomset beds of the Colorado delta fill the lower 2½ miles of the inundated Virgin River valley to the same level as the sediment in the central part of the Virgin Basin (pl. 20). The best examples of tributary filling east of Iceberg Canyon are afforded by Grapevine Bay and Grand Bay. The sediment in Grapevine Bay, about a mile south of the Colorado River channel at mile 279.3, is as much as 25 feet above the level of the sediment in the channel. Similarly, some of the sediment accumulated in Grand Bay, about 1½ miles north of the thalweg at mile 284.6, is almost 50 feet above the level of the sediment in the thalweg.

Sections $F-F''$ to $N-N'$ (pl. 20) show the range in sediment thickness from the foot of the delta front to Hoover Dam. The sediment accumulated in this region has a minimum thickness of 45 feet at mile 314.1 (section $J-J'$), midway between the mouth of Virgin Canyon and Virgin Basin. From this position the delta thickens in both directions along the length of the submerged Colorado River channel. At the foot of the delta front (section $F-F''$) this part of the deposit attains a maximum thickness of 155 feet. Immediately behind Hoover Dam at section $N-N'$ the accumulated sediment is 106 feet thick.

### VIRGIN DELTA

The Virgin River has supplied only about 2.4 percent of the total volume of sediment accumulated in Lake Mead; the Virgin delta is, of course, very much smaller than the Colorado delta. As shown in plate 20, the Virgin delta occupies only the upper 14 miles of Overton Arm, and there it is restricted chiefly to the inundated channel and flood plain of the Virgin River.

Although the structure of the Virgin delta is not as clearly defined as the structure of the Colorado delta, it also probably consists of topset, foreset, and bottomset beds. At its northern end at mile 35.8,\(^{16}\) the delta has a thickness of less than 1 foot; the thickness increases to a maximum of 22 feet at mile 27.4 (section $Q-Q'$, pl. 20), and then decreases in thickness to less than 1 foot at its lower end at mile 21.4.

Between the toe of the Virgin delta and Lower Narrows of Overton Arm (mile 9.3), a very thin layer of sediment has accumulated in the bottom of the former Virgin River channel. This layer is so thin that it could not be detected by echo sounding, but penetration measurements and bottom samples show that a layer of silt and clay with a maximum thickness of about 2 feet overlies the original sandy bottom of the Virgin River channel in this area. Because of the sparseness of observations, it is not known whether this layer is continuous or present only in isolated patches. Apparently, most of this material has been supplied by turbidity currents that were developed by the Virgin River.

### DEPOSITS FROM SMALL TRIBUTARIES

Muddy Creek and other small tributaries to Lake Mead have undoubtedly supplied some sediment, but

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\(^{16}\) Distances on the Virgin River are measured along the pre-Lake Mead channel, upstream from its junction with the Colorado River.
the total quantity has been too small to be detected on the lake bottom. Numerous soundings at the mouths of Muddy Creek, Las Vegas Wash, and Hualapai Wash show no evidence of sediment accumulation in these areas. Samples from the inundated Muddy Creek channel (G528-G530, pl. 19) and penetration measurements at these sampling locations likewise suggest that no sediment has accumulated at the mouth of Muddy Creek.

Some of the cores obtained from the lake bottom contain material that was probably brought in by minor tributaries, or by slumping directly into the lake. Examples are described of sediment that is probably of local origin near Detrital Wash (p. 171) and The Temple (p. 171). The total quantity of these contributions to the delta is negligible in comparison with the amount that has come from the Colorado and Virgin Rivers.

The accumulation of sediment along the thalwegs of the Colorado and Virgin Rivers and its absence in other parts of the lake are indicated by many lines of evidence. Both the acoustical sounding records (fig. 46) and numerous line soundings in all parts of the lake outside the thalweg areas agree with the topography of the original lake bottom, except in a few areas affected by landslides and wave action (p. 209, 212). Soundings weights and various oceanographic instruments that were lowered to the bottom encountered no sediment beyond the limits of the channels and their associated flood plains and terraces, although in the thalweg areas these instruments were generally covered with a thick coating of mud. Furthermore, underwater photographs of the bottom outside of the channel areas show that the vegetation growing on the reservoir floor prior to inundation has not been covered by sediment. Temperature measurements obtained by bathythermograph also denote the areal distribution of the accumulated sediment along the thalweg of the Colorado River. The temperature of the bottom in areas of sediment accumulation is higher than the temperature of the bottom in areas of nondeposition (p. 181).

**PHYSIOGRAPHY OF THE DELTAS**

**COLORADO DELTA**

**TOPSET BEDS**

The topset beds that make up the surface of the Colorado delta in Lower Granite Gorge have an average slope of 1.2 to 1.3 feet per mile, over which the Colorado River flows to its position of discharge in Pierce Basin (fig. 16). Because of extreme fluctuations in river discharge and changes in lake level, the topset beds are reworked extensively. During late spring and summer, when the lake is at its highest stage, a considerable thickness of sediment is added to the topset beds in the region covered by backwater. In fall and winter, however, the lake level declines, the river cuts a channel into the deposit as it flows toward the receding lake, and the topset beds become deeply dissected. Although the actual level of the topset beds varies considerably as a function of lake stage and river discharge, observations taken by the Lower Granite Gorge field party from the fall of 1948 to the spring of 1949 show that the average gradient of 1.25 feet per mile is virtually unchanged throughout the year.

As shown by annual profiles of the Colorado delta surface (pl. 13), the average gradient of the Colorado River channel in Lower Granite Gorge has decreased from 7 feet per mile before the inception of Lake Mead to 1.25 feet per mile in 1948. Profiles from 1937 to 1947 are based on data collected during density-current investigations (National Research Council, 1949, and U.S. Bur. Reclamation, 1949), whereas the 1948 profile, which shows considerable detail, is based on soundings during the 1948-49 survey.

The profiles represent the approximate position of the delta surface at the end of each calendar year. In constructing them, an attempt was made to distinguish between sediment that had been deposited and that which was still in suspension above the delta surface. As a result the profiles in plate 13 differ slightly in some places from the altitudes of the water-sediment interface as initially recorded. Because of inadequate data, the profiles in Lower Granite Gorge required considerable extrapolation for years prior to 1948, but they are sufficiently accurate to show that the declivity of the topset beds during this period has been markedly less than the slope of the buried Colorado River channel.

The filling of the narrow V-shaped bottom of Lower Granite Gorge has produced other notable changes in the characteristics of the Colorado River. Prior to the flooding of the reservoir, the Colorado River in this region was confined to a narrow, sinuous canyon, ranging in width from less than 100 feet near Bridge Canyon (section A—A', pl. 20) to about 250 feet near the Grand Wash Cliffs (section E—E'). By 1948, however, the Colorado River had been elevated to a considerably wider part of the canyon. The width of Lower Granite Gorge at the surface of the topset beds then ranged from 200 feet at Bridge Canyon to 2,000 feet near the Grand Wash Cliffs. Although the Colorado River channel in 1948 did not occupy the full width of the gorge, except during extreme floods and at high lake stages, it was a great deal wider than the former channel at the bottom of the canyon. As shown by sections
A–A’ to E–E’, the width of the 1948 channel ranged from 200 to 600 feet, two to three times as wide as the former channel in the bottom of the canyon.

With its lesser slope and greater width, the Colorado River in Lower Granite Gorge had assumed by 1948 the characteristics of a mature stream, in contrast to the vigorous young stream that formerly flowed in the narrow V-shaped notch at the bottom of the gorge.

In 1948 the Colorado River channel throughout most of its length followed a meandering course, which conformed in general to the winding plan of Lower Granite Gorge. The convex sides of its meanders extended several feet above the water surface, whereas the concave sides stood at considerably lower levels and in some places were cut back to the bare rock walls of Lower Granite Gorge. Large eddies formed where the river changed its course abruptly and cut deep holes in the channel. As shown in plate 13, the 1948 channel was characterized by numerous bars and holes, similar to those recorded in the buried Colorado River channel (U.S. Soil Conservation Service, 1935). In Lower Granite Gorge the Colorado River, like other meander-
A. View of one of the many tributaries sealed off by a natural levee, behind which a narrow lake has formed.

Higher terrace and natural levee covered by vegetation were probably formed during 1941. The 1948 terrace appears in foreground.

B. Upstream view of the 1948 terrace, in which the Colorado River has entrenched itself.

The higher, vegetation-covered terrace in background was probably formed in 1941.
CLOSEUP VIEW OF THE 1948 TERRACE BEING CUT BACK BY THE COLORADO RIVER IN PIERCE BASIN

Columns of cross-bedded sand capped by mud-cracked layer of clayey silt are plunging into the turbulent river below.
A. GENERAL VIEW

Large pit in foreground is about 7 feet in diameter.

B. CLOSEUP VIEW OF ONE OF THE LARGE GAS PITS

Note circular orifice at the bottom of the pit, through which gas escapes to the surface.

GAS PITS IN THE 1948 TERRACE NEAR THE DELTA FRONT
ing streams, is continuously changing its course in response to variations in river current, sediment load, and water discharge.

In the latter part of 1948 the river channel was flanked along most of its length by river terraces and natural levees. In the western part of the gorge the terraces commonly occupied half of the canyon width, but in the narrow eastern section they had been removed by undercutting or reduced to thin remnants against the canyon walls. Tributary canyons of Lower Granite Gorge were dammed by these natural sediment barriers, behind which shallow depressions have formed at the margins of the delta surface. Water discharged by several of the tributaries was captured in the depressions, thus forming lakes or ponds of clear water effectively isolated from the turbid water of the Colorado River (pl. 214).

The sediment embankments across the mouths of some of the larger side canyons had been subsequently breached by water discharged from their tributaries, probably during flash floods. Most prominent among these were Spencer Canyon, Surprise Canyon, and Reference Point Canyon. However, the embankments were still intact across the mouths of other large tributary canyons, notably Separation Canyon, Helldiver Canyon, and Salt Creek Canyon.

At the time of the 1948–49 survey the terrace that was most extensive, most nearly continuous, and most prominent as seen from the river was the delta surface that had been developed at the time of high lake stage in the summer of 1948. The river entrenched its channel into this surface as the lake level receded from 1,193 feet in July to 1,165 feet in December and 1,150 feet in March 1949. The resulting terrace was continuous from Bridge Canyon to the mouth of the Colorado River in Pierce Basin. As shown in plate 20, the 1948 terrace ranged in altitude from 1,213 feet at mile 239.5 (section B–B') to 1,170 feet in Pierce Basin (section F–F').

Along most of its length the 1948 terrace had extremely little relief (pl. 21B). Natural levees generally rose less than 2 feet above the terrace level, although locally they were 4–5 feet high. In the narrow eastern end of Lower Granite Gorge the levees commonly abutted abruptly against the canyon walls, but in the western part of the gorge and in the eastern end of Pierce Basin the levees were parallel to the channel and as much as 200 feet from the canyon walls.

Between the levees and the canyon walls numerous small depressions ranged in depth from a few inches to about 7 feet. As the lake receded these depressions became isolated ponds, several of which were subsequently drained as the Colorado River cut into the 1948 terrace en route to the lake. This drainage resulted in the cutting of deep, narrow clefts tributary to the incised channel of the Colorado River. These were particularly prominent in the eastern part of Pierce Basin near the delta front, where they provided excellent exposures of the crossbedded structure of the topset beds.

In the eastern part of Lower Granite Gorge the 1948 terrace deposit was composed almost entirely of crossbedded sand. However, in the wider western part of the gorge and in the eastern end of Pierce Basin, a layer of clayey silt about 1.5 feet thick covered the crossbedded sand of the 1948 terrace deposit. This material was deposited in the slack lake water that flooded the western part of the gorge in the summer of 1948. During a short period of observation in March 1949, the 1948 terrace was about 20 feet above river level and was being cut back at a rate of 5 to 10 feet per hour in the vicinity of the delta front (pl. 22).

Well-developed mud cracks and gas pits characterized the surface of the 1948 terrace near the delta front. The gas pits, first described by Maxon (1940), were conical in shape, with openings at the bottom through which gas escaped to the surface (pl. 23). The pits were 2 to 10 feet in diameter at the surface and 1 to 4 feet deep. The diameter of the gas vent at the bottom of each pit ranged from 1/2 to about 2 inches.

The occurrence of gas pits on the exposed terrace near the delta front and the emanation of gas from the submerged deposit in Pierce Basin clearly indicate that gas is being squeezed out of the bottomset beds by the tremendous weight of the rapidly advancing forest and topset members. The gas is principally methane resulting from the decay of organic matter in the bottomset beds (see analysis, table 23).

In Lower Granite Gorge east of mile 267.5, a terrace about 25 feet above the 1948 terrace could be clearly identified. This higher terrace was discontinuous and ranged in altitude from 1,226 feet at mile 242 to 1,196 feet at mile 267.5 (fig. 16). It was probably formed during the summer of 1941 when the lake surface reached an altitude of 1,220.4 feet, the highest water level in the reservoir's history. A small remnant of this higher terrace may be seen at the right of section D–D' (pl. 20). Upstream from mile 242, the higher terrace has been removed in most places during subsequent periods of flood.

Well-developed natural levees rise 2 to 10 feet above the higher terrace along its outer margins. These are best preserved where they cross the mouths of tributary canyons, as shown in sections B–B' and D–D' (pl. 20). Like the terrace upon which they rest, the levees were probably formed during the high lake stage of 1941.
This dating is supported by the annual profiles of the delta surface. As shown in plate 13, the topset beds in 1941 extended only as far west as mile 266, which corresponds closely with the western terminus of the higher terrace and its superimposed levees. The higher terrace and levees are absent farther west because the topset beds in the western part of Lower Granite Gorge were not formed until after 1941.

Extending downstream from the western terminus of the 1941 terrace (mile 267.5) to mile 270.5 are isolated remnants of another terrace that is about 10 feet above the 1948 terrace. Spotty remnants of this and possibly other terraces are also visible upstream from mile 267.5, but they are not continuous enough to allow definite correlation with lake stage. It seems probable, however, that they are remnants of formerly continuous terraces developed during 1942 when the lake level rose to 1,213 feet, and perhaps during the somewhat lower stages in 1943 and 1944. The absence of terraces corresponding to the high lake stages of other years is readily explained by the fluctuations in lake stage (fig. 18). All terraces developed prior to 1941 have evidently been buried by the 1941 terrace deposit. Similarly, the terraces developed during 1945, 1946 and 1947 have been buried by the 1948 terrace deposit.

The progressive upbuilding of the delta in the eastern part of Lake Mead insures that terraces will continue to be only temporary features of the physiography. Generally the only prominent terrace will be formed by the delta surface that developed at the time of the high lake stage each year, and was subsequently entrenched. The delta deposits during years of exceptionally high lake stage, such as 1941 or 1942, may persist as terraces for several years; but they too will eventually be buried.

**FORESET BEDS**

The foreset beds that made up the delta front in Pierce Basin in 1948 dipped sharply beneath the lake surface for a distance of about 1 1/2 miles (miles 277.8 to 279.3) measured along the course of the submerged Colorado River channel (pl. 24). Near its southern margin the delta front ranged in slope from about 300 feet per mile near the top to less than 25 feet per mile near the foot, and averaged about 100 feet per mile.

In contrast, the surface slope of the delta front in its central and northern portions had been greatly modified by turbidity currents flowing over its surface. As shown in plate 24, this part of the delta front was traversed by a narrow valley, the axis of which extended into the mouth of the Colorado River. At the foot of the delta front the valley broadened out onto the gently sloping surface of the bottomset beds. The average surface slope of the delta front measured along the valley axis was about 55 feet per mile. It is not known whether this valley represented active erosion by turbidity currents or merely a lower rate of deposition along the axis of the currents where velocities are higher (p. 213). However, in either case it is only a temporary feature, for the chief sedimentary process is deposition, as shown by the 43-mile advance of the delta front from 1935 to 1948.

**BOTTOMSET BEDS**

From the foot of the delta front to Hoover Dam, the average declivity of the bottomset beds in 1948 was about 4 feet per mile, ranging from an average of 9 feet per mile between the delta front and the mouth of Iceberg Canyon to less than 1 foot per mile in the southern part of Boulder Basin. As shown in plate 13, there was a marked reduction in slope of the bottomset beds beginning in the vicinity of Virgin Canyon and extending westward to the dam. This reduced slope is adjusted in part to the size of the sediment particles, the velocities of turbidity currents carrying these particles, and in part to compaction, but the chief controlling factor appears to be the basining effect of Hoover Dam. As noted on page 157, the bottomset beds in 1948 had a minimum thickness of 45 feet at mile 314 and increased to 106 feet at the dam. If Hoover Dam had been constructed several hundred miles downstream, the thickness of the bottomset beds west of mile 314 should have continued to decrease, which would have resulted in a somewhat greater slope of these beds. Above mile 314, it may be postulated that the declivity is approximately equivalent to that of a delta built into a lake of "infinite extent". Below this point, the increased thickness and reduced slope are a resultant of two factors: (1) The progressively declining thickness of the delta if the dam were not there and (2) the accumulation of sediment trapped by the dam. The most notable example of basining effect is, of course, in Boulder Basin, where the slope of the bottomset beds averaged only 1.2 feet per mile in 1948.

Plate 13 also shows that the position of minimum sediment thickness, which denotes the eastern limit of basining effect, has migrated progressively farther upstream. In 1937 the position of minimum thickness was at mile 334 near the head of Boulder Canyon, and in 1938 it regressed to mile 308 near the mouth of Virgin Canyon. Since 1938 the position of minimum thickness has remained essentially stationary in the eastern part of the Temple Bar area and the western part of Virgin Canyon (miles 306 to 314).

In transverse section the surface of the sediment deposit was essentially level along most of its length, the deposit at the sides extending only a few feet above
character of the accumulated sediment

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the center elevation (pl. 20). However, within 5 miles of the delta front the margins of the sediment were as much as 25 feet above the sediment surface along the thalweg, as illustrated in section F–F', plate 20.

One of the most striking features in the northern part of Pierce Basin was the continuation of the channel that traversed the delta front (pl. 24). The channel was bordered on both sides by underwater ridges which in section F–F' (pl. 20) rise about 5 feet above the center of the channel. The ridges were, in turn, bordered by slight depressions in the sediment surface. These features have a marked resemblance to the natural levees and delta-flank depressions in Lower Granite Gorge.

West of mile 283 the difference between side and center elevations was generally less than 2 feet, but even in this region marginal ridges could be identified across the mouths of some of the larger tributaries entering the submerged Colorado River channel. A ridge rising about 2 feet above the average sediment level had formed across the mouth of Grand Bay at its intersection with the submerged Colorado River channel. Although field evidence was inconclusive, there was a suggestion of a similar bar across the mouth of the Overton Arm near the former junction of the Virgin and Colorado Rivers.

At the great bend of the inundated Colorado River channel, where it turns abruptly south from a general west-trending course, the accumulated sediment on the inside of the curve (mile 345 to 347) stood in 1948 about 5 feet higher than the general sediment level at the outside of the curve. This feature bears a marked resemblance to the sediment accumulations on the convex sides of meanders of the Colorado River as it flows across the subaerial part of the delta in Lower Granite Gorge. Like the underwater "levees" and marginal depressions bordering them, the building-up of sediment on the convex side of the great bend of the inundated Colorado River channel suggests that turbidity currents flowing along the lake bottom conform to the same mechanical principles as streamflow, an observation that has been reached independently by Menard and Ludwick (1951).

Except in the vicinity of the delta front, the interface between the surface of the bottomset beds and the overlying lake water was very clearly defined during most of the observation period; there was no mixing of the soft accumulated sediment with the lake water. For a short period in April 1948, however, and for a slightly longer period in November and December 1948, the water-sediment interface in the eastern part of the lake was obscured by turbidity currents that flowed in a thin layer along the lake bottom. In April the flow of turbid water extended only to the western end of Iceberg Canyon, but in November and December suspended sediment was encountered immediately over the bottom as far west as mile 318, or nearly to the eastern end of Virgin Basin.

virgin delta

Except for their subdued relief, the surface features of the Virgin delta in 1948 were generally similar to those of the Colorado delta. The topset beds made up the surface of the upper 8 miles (Virgin River, mile 35.8 to mile 27.4) of the Virgin delta. They had an average surface slope of 10.7 feet per mile, which is a reduction of 2.6 feet per mile from the average gradient of the Virgin River channel (13.3 feet per mile) in this region before the inception of Lake Mead. North of mile 30.2 the surface of the topset beds was above the mean lake level of approximately 1,170 feet, but between miles 30.2 and 27.4 the topset beds were exposed only at low lake stages. A break in slope at altitude 1,140 feet marked the delta front, where the topset beds grade into the foreset beds.

In contrast to the buried Virgin River channel, which has an average width of about 800 feet, the channel traversing the topset beds in 1948 averaged only about 350 feet in width. The topset beds of the Virgin delta, like those of the Colorado delta, are being reworked continuously in response to changes in lake stage and river discharge. In 1948 the Virgin River channel was flanked along most of its length by a well-defined terrace, which was 3 to 7 feet above the river channel (sections O–O' and P–P', pl. 20). Bordering the channel and superimposed on the terrace were broad natural levees that stood only 1 to 2 feet above the terrace level. The levees, in turn, were flanked by slight depressions in the delta surface which generally were less than 5 feet deep.

At the surface, this part of the Virgin delta was composed chiefly of cross-bedded sand, but between mile 30.2 and the delta front at mile 27.4 the sand was overlain by a layer of soft clayey silt that was only a few inches thick. This material was probably deposited in the slack water that flooded the lower part of the topset beds during the highest lake stages of 1948.

Foreset beds formed the delta surface between miles 27.4 and 26.7. These had an average downstream slope of 29 feet per mile. South of mile 26.7 the surface was composed of bottomset beds with an average declivity of 14 feet per mile. At the toe of the delta (mile 21.4) the bottomset beds graded into the profile of the former Virgin River channel. As noted previously, however, a layer of silt and clay ranging from
a few tenths of a foot to about 2 feet in thickness had accumulated, at least in isolated patches, between the toe of the Virgin delta and Lower Narrows (mile 9.3) of Overton Arm. This layer, like the bottomset beds of the Colorado delta, was undoubtedly deposited by turbidity currents and is regarded, therefore, as an incipient extension of the bottomset beds of the Virgin delta into the deeper parts of Overton Arm.

As shown by sections Q–Q' and R–R' (pl. 20), the bottomset beds were essentially level in cross section, the sediment at the sides rising only a few feet above the center elevations. Submerged tributaries to the inundated Virgin River channel had been filled to the level of the sediment in the channel. The most prominent example of tributary filling was at mile 25.0, where the bottomset beds of the Virgin delta extended almost one-half mile into the lower part of the Muddy Creek valley (pl. 20). Submerged ridges, such as those observed at the margins of the bottomset beds of the Colorado delta, are not present or are too inconspicuous to be detected by underwater soundings.

**GROWTH AND STRUCTURE OF THE DELTAS**

Deltas are characteristically formed by sediment-laden streams where they enter the ocean or other bodies of still water. The growth of the delta may be analyzed conveniently with reference to the point at which the flowing water meets the still water: Sediment is dropped in the river bed as water velocities are reduced; additional sediment is carried to the edge of this graded slope and dropped into the deeper still-water body to form foreset beds; finer material is carried farther out into the stillwater body and there forms the bottomset beds. As deposition continues the foreset beds are built out progressively farther over the bottomset beds, and in turn are covered by topset beds; also the gradient of the stream is modified and sediment is deposited upstream from the original mouth. Thus the delta grows outward in the still-water body by deposition of foreset and bottomset beds, and by its deposition of topset beds it grows upward. It also projects backward into the original channel of the stream that provides the source material.

The growth of deltas in Lake Mead is necessarily more complex than in streams debouching into an ocean or into a lake that has a relatively constant level. During the first 6½ years of the lake history, the point at which the river entered still water migrated from Boulder Basin to Bridge Canyon in Lower Granite Gorge (a distance of more than a hundred river-miles), with variations each year corresponding to the fluctuations in lake stage. In July 1941 the lake reached a maximum level of 1,220 feet, and since then it has generally been at altitudes ranging from 1,150 to 1,200 feet, reaching a minimum level of 1,134 feet in April 1947. Since 1941 the river has entered the lake either in Pierce Basin or in the western part of Lower Granite Gorge.

A general idea of the growth of the Colorado delta from 1937 to 1948 may be obtained from the profiles of plate 13, but there is no similar information concerning the development of the Colorado delta during its earlier stages. Prior to the 1948–49 survey there had been no investigation of the Virgin delta, and so we have little knowledge of its growth. The numerous samples and cores collected during the 1948–49 survey do not furnish much additional information on the growth of the deltas, but they do provide a fairly complete picture of the structure of the Colorado delta and a more general picture of the structure of the Virgin delta.

**COLORADO DELTA**

The initial stages of development of the Colorado delta must be described largely on the basis of indirect evidence obtained by analysis of records of lake level, and of the sediment suspended in the river water as it passed the Grand Canyon gage station (p. 103). Some of the cores obtained during the 1948–49 survey have included the entire thickness of the delta material, and these indicate the characteristics of the earliest deposits; however, the earliest delta sediments may be indistinguishable from river sediments deposited prior to 1935.

In many places, the age of sediments in the bottoms of these cores may be determined by reference to elevations shown on the 1935 topographic maps (U.S. Soil Conservation Service, 1935), because these maps generally depict the reservoir floor prior to sedimentation. The topography of Black Canyon and Boulder Basin, as portrayed by the maps of 1935, was taken from the Brock and Weymouth survey of 1930 (Brown, 1941), and except for possible changes in the topography of the Colorado River channel between 1930 and 1935, the maps give an accurate representation of the pre-Lake Mead topography in this area. Upstream from Boulder Basin the 1935 maps were constructed from aerial photographs, supplemented with planetable data in the Virgin River valley and with cross sections across the Colorado River channel. The photographs, planetable survey of the Virgin River valley, and Colorado River cross sections upstream from Pierce Basin were all obtained prior to inundation.

However, flooding and delta deposition began in some areas prior to the surveys for these maps. Sections across the Colorado River channel between Boulder Basin and Pierce Basin were not obtained until it had
been covered by the rising lake water; but they were made within a period of a few days to 3 weeks after inundation. Accumulation of sediment between the time of inundation and the time of survey was enough in some areas to cause appreciable discrepancies between the aerial photographs and the cross-section data, and in the compilation of the 1935 topographic maps, corrections were applied so as to reproduce the approximate topography of the area prior to inundation (Brown, 1941). In other areas the sediment that accumulated in the channel along much of its length was evidently too thin to be detected by this means, and it has probably been included as part of the pre-Lake Mead topography.

GROWTH IN FEBRUARY AND MARCH 1935

In the first 2 weeks after Hoover Dam was closed on February 1, 1935, the impounded water rose to an altitude of 700 feet. This water carried about 1 million tons of suspended sediment as it passed through Grand Canyon. It seems likely that sand was deposited at the mouth of the Colorado River as it migrated upstream with the rising lake level, and this resulted undoubtedly in the accumulation of a thin deposit of sand along the bottom of the channel between Hoover Dam and the western end of Boulder Canyon. Owing to the rapid flooding of this area, the sand layer is probably not more than a few inches thick.

The lake level remained at about 700 feet altitude from February 15 to April 1. At that time the mouth of the Colorado River was located near the head of Boulder Canyon (mile 334), about 20 miles upstream from Hoover Dam. A considerable thickness of sand must have accumulated in the bottom of the channel near the head of Boulder Canyon, for the river carried more than 4 million tons of sediment at Grand Canyon during this interval. These deposits of sand, in the form of incipiently developed topset and foreset beds, would constitute the initial development of the Colorado delta.

Even at this early stage, the role of turbidity currents in transporting silt and clay particles into the deeper parts of the lake had become firmly established (p. 109). Apparently sediment was transported from the mouth of the Colorado River along the lake bottom and through Hoover Dam. Other material was undoubtedly deposited as bottomset beds between the head of Boulder Canyon and the dam, but in cores from the accumulated sediment these cannot be distinguished from the overlying bottomset beds deposited in later years.

Of the 10 cores obtained from the channel area between Hoover Dam and the head of Boulder Canyon, only 3 (cores 7, 17, and K2, pl. 19) extended through the thick accumulation of fine-grained bottomset beds into an underlying layer of sand. Since the coring devices cannot penetrate sand to any great depth, only the upper part of the sand layer was sampled. Very likely the sand at the bottom of the cores was obtained from a thin layer laid down during the early stage of reservoir filling, but we cannot be certain of this because of its probable similarity to the sand of the Colorado River channel prior to inundation. In core 7, taken near the head of Black Canyon, sand was encountered at a depth of 88 feet underlying the fine-grained bottomset beds; this corresponds closely with the thickness of accumulated sediment as computed by difference between the 1948 topography and the pre-Lake Mead topography. Assuming that there was no change in channel topography between 1930 and 1935, the sand may be interpreted as coming from the pre-Lake Mead channel or from a very thin sand layer deposited in the channel during its flooding in February 1935.

At the head of Boulder Canyon (cores 17 and K2), sand was encountered at depths of 55 to 60 feet below the 1948 sediment surface, and 5 to 10 feet above the buried Colorado River channel as portrayed by the 1935 topographic maps. Although the pre-Lake Mead channel topography in this area was not mapped until after its inundation, the aerial photographs may well have indicated the approximate topography of the channel before flooding. If this supposition is correct, the 5 to 10 feet of sand in the bottom of the channel probably is made up of topset and foreset beds deposited during the interval from February 15 to April 1, 1935, when the mouth of the Colorado River remained stationary near the head of Boulder Canyon.

Although only fragmentary data are available from this earliest stage of reservoir filling, it seems reasonable to conclude from the analysis above that a layer of sand, ranging from only a few inches in thickness in Black Canyon to 5 or 10 feet at the head of Boulder Canyon, accumulated in the bottom of the Colorado River channel during February and March 1935. This layer probably consists of incipiently developed topset and foreset beds deposited at the mouth of the Colorado River as it receded upstream with the rise in lake level. The silt and clay particles supplied by the Colorado River during this period were transported into the deeper parts of the lake and laid down on top of these topset and foreset beds, or carried through the tunnels at Hoover Dam (p. 109). As the lake continued to rise and after it reached a fairly stable level, silt and clay were added to the earlier bottomset beds. Slumping of adjacent canyon walls may account for
some of the thin layers of sand (p. 171) interstratified locally with the silt and clay of the bottomset beds.

**GROWTH FROM APRIL 1935 TO MARCH 1936**

As a result of the spring floods in 1935 the lake surface rose rapidly from its altitude of 700 feet on April 1 to 293 feet in July, and then remained relatively constant until April 1936. Between July 1933 and April 1936 the Colorado River entered the lake in Pierce Basin near mile 276, about 80 miles upstream from Hoover Dam. The river mouth at that time was about 2 miles east of the river entrance in 1948, but the channel was more than 200 feet below the 1948 channel. A considerable thickness of sand must have been deposited as topset and foreset beds near the mouth of the Colorado River during the 9-month interval from July 1935 to April 1936, but they are now deeply buried and we have no record of them.

Also, a layer of sand probably overlies the buried Colorado River channel between the head of Boulder Canyon and Pierce Basin, deposited at the mouth of the Colorado River as it receded upstream between April and July 1935. However, the channel in this area was not mapped until after its inundation, and therefore subsequent to the accumulation of sand at the mouth of the Colorado River as it receded upstream. Except in areas of exceptionally thick deposits where corrections have been applied (Brown, 1941, p. 492), this sand layer has evidently been mapped by the Soil Conservation Service as part of the pre-Lake Mead topography. Consequently, its thickness cannot be obtained by measuring the difference between the depth at which sand was encountered and the thickness of the accumulated sediment as determined by topographic changes from 1935 to 1948.

Brown estimates that the accumulation of sediment in the channel during the 1935 survey has resulted in a probable volumetric error in reservoir capacity of only about 1 percent of 1 year’s sediment accumulation, or about 1,000 acre-feet. If this material were distributed evenly over the channel bottom between the head of Boulder Canyon and Pierce Basin, it would form a layer about 3 inches thick.

In view of the considerable quantity of sediment carried into the reservoir by the Colorado River during the flooding of the channel between the head of Boulder Canyon and Pierce Basin (April–June 1935) this estimate seems somewhat low. According to Howard (1947), a total of 873.2 million tons of sediment was carried in suspension by the Colorado River past the Grand Canyon gaging station during this period, of which about 1.9 million tons was carried on through the reservoir and dam by turbidity currents (Grover and Howard, 1938). From studies of the texture and specific weight of the accumulated sediment (p. 195) it seems reasonable to assume that at least 50 percent (43 million tons) of the load is made up of sand, which, when accumulated in the reservoir, has an average specific weight of about 93.8 pounds per cubic foot. In confirmation, mechanical analyses of the suspended sediment at Grand Canyon in April to June 1935 (Howard, 1947) show that sand-size particles exceeded 50 percent of the total on most days, particularly on the days when the river was carrying the greatest sediment load.

Computations based on these values suggest that a total volume of 20,000 acre-feet of sand accumulated in the reservoir during this interval. Supposedly, this material was dropped near the river mouth as it receded upstream from the head of Boulder Canyon to Pierce Basin prior to the 1935 channel survey. If this material were evenly distributed over the bottom of the Colorado River channel between the head of Boulder Canyon and Pierce Basin, it would form a layer about 5 feet thick. Like the sand underlying the bottomset beds in the western part of the lake, this deposit is interpreted as topset and foreset beds laid down during the early stage of delta development. Cores from the sediment accumulated between the head of Boulder Canyon and Pierce Basin provide little information on the characteristics of the sand accumulated at the bottom of the buried Colorado River channel.

**GROWTH FROM APRIL 1936 TO JULY 1937**

During this period the lake rose in two stages from altitude 910 feet to 1,100 feet. During the period April to July 1936 the water surface rose to 1,020 feet, where it remained essentially stationary until March 1937. With the second rise (March–July 1937) the water surface attained an altitude of 1,100 feet. In response to these changes the mouth of the Colorado River receded eastward from Pierce Basin about 34 miles into the Lower Granite Gorge. From July 1936 to March 1937 the mouth of the Colorado River was in the vicinity of mile 255, and in July 1937 the river entered the lake near mile 244, about 110 miles upstream from Hoover Dam.

There is no record of sedimentation in the reservoir from April 1936 to July 1937, but it is assumed that the previously established pattern continued essentially unchanged. Sand, dropped near the river mouth as it receded upstream, probably accumulated in topset and foreset beds along the bottom of the channel in the western part of the Lower Granite Gorge. The thickness of these beds is unknown, but presumably they are thickest in the vicinity of mile 255, where the
mouth of the river remained essentially stationary from July 1936 to March 1937. During this period the finer particles—silt and clay—were carried into the deeper parts of the lake and deposited in the bottomset beds.

**GROWTH FROM JULY 1937 TO DECEMBER 1948**

The surfaces of the topset beds in Lower Granite Gorge and of the foreset beds in Pierce Basin are made up principally of hard, compact sand. In contrast, the surface of the bottomset beds to the west consists of extremely soft mud, the solid particles of which are composed of silt and clay. This marked change in sediment texture and consistency occurs at the foot of the delta front (mile 279.3) where the slope decreases abruptly from about 55 feet per mile to 15 feet per mile. The break in slope between the foreset beds and the bottomset beds is thus related to the change in texture, the coarser sediment making up the steeper slope. By extending this relation to the successive advances of the delta front (pl. 13), the contact between the bottomset beds and the overlying foreset and topset beds that accumulated in the eastern part of the lake from 1937 to 1948 may be projected as illustrated in figure 47. The lower topset and foreset beds shown in this diagram accumulated during the filling of the reservoir, whereas the upper topset and foreset beds were deposited after the lake reached a relatively stable stage. The bottomset beds were deposited both during the filling of the reservoir and during the period of stable lake level.

No cores were obtained during the 1948 survey from the sediment accumulated in Lower Granite Gorge, and it is impossible to verify the accuracy of this division. However, a number of drill cores, extending to maximum sediment depths of 75 feet, were taken in the eastern part of Lower Granite Gorge (mile 236.3 to mile 240.1) by the Bureau of Reclamation in 1941 and 1942. Logs of these cores, as recorded by Murdock (1942), show that the sediment in this region consists of sand and silt, with a small amount of gravel near the bottom of the buried Colorado River channel. This suggests that the delta in the eastern part of Lower Granite Gorge is composed wholly of topset and foreset beds, confirming the interpretation shown in figure 47.

The Lower Granite Gorge part of the Colorado delta did not begin its development until the water level of the reservoir reached an altitude of about 1,100 feet in July 1937. Following that date the lake surface remained fairly stable, oscillating between a minimum altitude of 1,095 feet in February 1938 and a maximum of 1,220 feet in July 1941. By 1948 this part of the delta occupied the entire Lower Granite Gorge from Bridge Canyon to the delta front in Pierce Basin. In the same period many tens of feet of silt and clay accumulated in the bottomset beds that extend to Hoover Dam. These beds in the western part of the lake provide a thick cover over the part of the Colorado delta that was formed during the early stages of reservoir filling from February 1935 to July 1937.

**STRUCTURE IN 1948**

The structure of the Colorado delta along the thalweg in 1948 is indicated by figure 47. Because of inadequate data it is impossible to make an accurate di-

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16 Murdock, J. N., 1942, Unpublished reports in the files of the U.S. Bureau of Reclamation, Salt Lake City, Utah.
A. VIEW OF THE TEMPLE, ARIZ., IN 1934

The talus cone and underlying cliff were subsequently covered by Lake Mead. Photograph by C. R. Longwell.

B. VIEW IN 1948, SHOWING FRESH LANDSLIDE SCARS ON THE FACE OF THE TEMPLE

Photograph by Bureau of Reclamation.
vision between the topset and foreset beds at the bottom of the channel and the overlying bottomset beds, and the contact shown in figure 47 is therefore diagrammatic. In the eastern part of Lower Granite Gorge, the delta is made up entirely of topset and foreset beds that accumulated after the lake reached a relatively stable stage in July 1937. In the western part of the gorge and the eastern part of Pierce Basin, bottomset beds are shown as sandwiched between the older topset and foreset beds at the bottom of the channel and the younger topset and foreset beds exposed at the delta surface. The older topset and foreset beds accumulated during the filling of the reservoir, whereas the overlying topset and foreset beds were deposited after the water level reached a relatively stable stage. West of the delta front a thick section of bottomset beds overlies a thin section of topset and foreset beds; the bottomset beds there have been accumulating continuously since the area was first inundated by the lake in July 1935. In contrast, the topset and foreset beds were deposited during the first 5 months (February–June 1935) of reservoir filling.

The bottomset beds in Boulder Basin and Boulder Canyon range in thickness from 60 to 106 feet, and are generally thickest near the dam. Of the five deep cores from the thalweg area, three (cores 3, 16, and 76, pl. 19) terminated in compact silt and clay at points 3 to 10 feet above the buried Colorado River channel, but cores 73 and 74 bottomed in layers of silt and clay interbedded with thin laminae of sand. In core 73 the sand laminae are prominent throughout the lower 25 feet of the section, but in core 74 they are present only in the lower 5 feet. These cores are located along the margin of a prominent underwater landslide (p. 209) and it is likely that the sand was contributed by this source. The presence of sand also accounts for the limited penetration by coring devices in this area. However, sediment from local sources constitutes a negligible proportion of the total deposit in Boulder Basin.

In Virgin Basin, 10 cores (15, 18–23, 25–26, and K3, pl. 19) extended to within 5 feet of the pre-Lake Mead bottom as portrayed by the 1935 topographic maps. Core 24 falls about 18 feet short of the bottom owing to the slumping of sand and coarse silt from adjacent reservoir walls into the buried Colorado River channel. Cores 20, 21, 25, and 26 (at the margin of the delta near the former junction of the Colorado and Virgin Rivers) extended through the total thickness of accumulated sediment. Sand from the bottoms of cores 20, 25, and 26, and small twigs and humus layers from the bottom of core 21 were probably obtained from the surface of the original reservoir floor.

Of the seven cores from the thalweg area, core 18 is the only one that terminated in sand at the bottom of the channel. All other cores bottomed in compact layers of silt and clay a few feet above the buried channel.

Locally the bottomset beds in the Virgin Basin are interstratified with thin layers of sand, most of which were probably contributed by slumping of adjacent reservoir walls. However, near the intersection of Detrital Wash and the Colorado River channel there are two layers of gypsiferous sand interbedded with the silt and clay of the bottomset beds that cannot be easily attributed to slumping. These layers are 10 to 20 feet above the channel bottom and average about 1 to 2 inches in thickness. The upper layer is at an altitude of about 763 feet, corresponding to the 1939 sediment level near the intersection of Detrital Wash with the Colorado River channel (miles 323 to 325, pl. 13), and may have been derived from the scour of Detrital Wash near its entrance into Lake Mead, probably during the exceptional floods of 1939 (Gatewood, 1945). The lower gypsiferous layer is at altitude 755 feet and may have been deposited in 1938; like the upper layer, it was probably derived from the scour of Detrital Wash, in which there are outcrops of gypsum. As in Boulder Basin, the sediment in the Virgin Basin that has been derived from local sources is negligible in quantity. Practically all the accumulated sediment has come from the Colorado River and has been deposited in bottomset beds of the Colorado delta.

Between the eastern end of Virgin Basin (mile 320) and the foot of the delta front in Pierce Basin (mile 279.3) only a few cores were obtained from the deepest layers of the accumulated sediment. Along the thalweg between the mouth of Virgin Canyon and the east side of Virgin Basin, only one of five cores extended through the full thickness of sediment; this core (K4) was made up entirely of silt and clay from the bottomset beds. The other four cores (38 to 41) fell short of the original lake bottom by distances ranging from 5 to 18 feet. The deeper layers could not be penetrated, probably because of the presence of sand and coarse silt that had slumped from adjacent reservoir walls into the bottom of the channel.

Core 40, with its several thin layers of sand and coarse silt interbedded with fine silt and clay of the bottomset beds, is an excellent example of the sort of stratification that results from periodic slumping of adjacent canyon walls. In this area the layers of coarser material were probably derived from The Temple, a limestone-capped butte that rises vertically almost 500 feet above the lake surface (pl. 25A, B).
In Virgin Canyon and Gregg Basin, only two of eight cores (cores 45 and 46) penetrated the entire accumulation of bottomset beds, and these were from the margins of the delta where the sediment is less than 30 feet thick. The other cores (42, 43, 44, 47, 59, and K5) fell short of the original lake bottom by distances ranging from 7 to 26 feet. Since none of these cores bottomed in sand, it is apparent that the limited penetration resulted from the greater consolidation of the deeper layers of the bottomset beds.

Between the mouth of Iceberg Canyon and the foot of the delta front, complete sections of the accumulated sediment were obtained only along its thin margins in Grapevine Bay and Grand Bay. As shown by cores 69 and 71 the delta in these areas is about 70 feet thick and is made up entirely of layers of silt and clay. Along the thalweg, the delta ranged in thickness from about 100 to 150 feet and the depth of penetration was limited by the lengths of the core tubes and not by compact sand or consolidated layers of silt and clay in the lower part of the channel. The maximum sampled depth, core 63, was 95 feet. The cores in the thalweg area, like those from the delta margins, are made up wholly of bottomset beds.

At the foot of the delta front the soft mud of the gently inclined bottomset beds grades abruptly into the hard compact sand of the foreset beds that make up the delta face in the central part of Pierce Basin. Owing to the compactness of the foreset beds, cores of the delta in Pierce Basin were limited to very shallow depths: Core 68, taken near the head of the delta front, extended only 2.0 feet into the hard sand of the foreset beds. Core 65 and core K7, taken near the foot of the delta front, reached depths of about 26 feet and penetrated 21 feet of poorly consolidated silt and clay underlain by about 2 feet of compact sand and silt. Since the sand and silt could not be penetrated farther, its thickness is not known, but it suggests an interfingering of the foreset beds with bottomset beds near their contact at the foot of the delta front.

The foreset beds making up the delta front in Pierce Basin and the overlying topset beds to the east are not to be confused with the thin accumulation of topset and foreset beds deposited along the bottom of the Colorado River channel during the filling of the reservoir. The foreset and topset beds exposed in Pierce Basin and Lower Granite Gorge are building out over the thick accumulation of bottomset beds deposited in previous years. As the delta continues to grow, the bottomset beds in the western part of the lake will eventually be overridden also by the advancing foreset and topset beds.

**Virgin Delta**

The Virgin delta began its development in the early part of May 1935, when the rising water of Lake Mead reached the junction of the Virgin and Colorado Rivers. Before that time the Virgin River discharged its sediment into the Colorado River, which, in turn, carried the sediment downstream and deposited it in the embryonic Colorado delta that was forming in the western part of the lake.

From May to July 1935, the lake flooded the lower 12 miles of the Virgin River valley (Overton Arm), and the mouth of the Virgin River receded rapidly upstream to its intersection with Bitter Wash, about 3 miles north of Lower Narrows, where it remained essentially stationary until April 1936. With the second rise in lake stage (April–July 1936) the mouth of the Virgin River receded northward to mile 19.5, where it again became stationary until March 1937. After the third rise in level (March–July 1937) the Virgin River entered the lake near its intersection with Muddy Creek, 26 miles upstream from the former junction of the Virgin River with the Colorado River.

Sedimentation in the Virgin River channel during this early period of reservoir filling probably progressed in much the same fashion as in the Colorado River channel, the coarser particles dropping near the river mouth and the finer particles being carried into the deeper parts of the lake. However, the volume of sediment accumulated along the Virgin River channel evidently was very small. The 1948 topography of the lower 21 miles of the Virgin River valley showed no change from the pre-Lake Mead topography except near the former junction of the Virgin River with the Colorado River, where the bottomset beds of the Colorado delta transgressed the lower 21½ miles of the Virgin River valley. On the other hand, bottom samples G332, G333, G334, and G1250, and penetration measurements between miles 21.4 and 9.3 show that a thin layer of silt and clay overlies the sandy bottom of the Virgin River channel. Some of this material was evidently laid down during the flooding of Overton Arm (May 1935–July 1937), but, as previously noted, there is evidence that part of it was deposited from turbidity currents after the lake reached a relatively stable level in July 1937. Possibly the sand underlying the layer of silt and clay in the bottom of the Virgin River channel was deposited at the river mouth as it regressed upstream, but we cannot be certain of this because of its probable similarity to sand accumulated in the channel before the inception of Lake Mead.

Since there are no records of sedimentation in the upper part of Overton Arm prior to the 1948 survey, it
is impossible to trace the growth of the Virgin delta after the lake reached a relatively stable stage in July 1937. However, a very general idea of its structure may be obtained from samples and cores taken during the 1948 survey. Of three cores obtained between the toe of the Virgin delta (mile 21.4) and the foot of the delta front (mile 26.7), core 35 at mile 23.7 is the only one that penetrated the full thickness of the accumulated sediment, which included 3.5 feet of silt and clay overlying 1.5 feet of sand interbedded with thin layers of humus. Probably the sand and humus layers were obtained from the original prelake surface, although it is possible that some of the sand may have accumulated in the Virgin River channel during the filling of the reservoir.

At miles 24.5 and 26.1 the Virgin delta is about 10 feet thick, but only the upper few feet could be penetrated. Core 37 at mile 24.50 reached a depth of only 2.1 feet, and core 36 at mile 26.15 extended 5.7 feet into the delta. These cores show that the upper part of the delta was made up of layers of silt and clay; the lower part of the delta could not be penetrated, and its hard compact character suggests that it consisted chiefly of layers of sand. The sand layers are interpreted as topset and foreset beds that accumulated near the mouth of the Virgin River from July 1937 to April 1938, when it remained essentially stationary in the vicinity of mile 26.0. The overlying layers of silt and clay are interpreted as bottomset beds that were deposited in subsequent years when the Virgin River entered the lake several miles to the north.

Little is known about the structure of the Virgin delta north of the foot of the delta front at mile 26.7. The surface or near-surface layers of this part of the delta were made up chiefly of hard sand that could not be penetrated by the coring device. Between miles 26.7 and 30.2, samples G518 to G525, and penetration measurements show that the upper few inches of the delta was made up of soft clayey silt which, as previously noted, was probably deposited in slack water that flooded this part of the delta during the high lake stage of 1948. Immediately below the soft surface layer are layers of hard sand, which, as observed by F. C. Ames, were exposed at the delta surface north of mile 30.2. These sand layers are regarded as topset and foreset beds, the division being made at mile 27.4 where the delta profile steepens from 10.7 feet per mile to 29 feet per mile. Although no cores could be obtained from this part of the delta, it seems probable that the topset and foreset beds exposed at the delta surface are advancing over the bottomset beds that make up the delta surface south of mile 26.7.

**PHYSICAL PROPERTIES**

The Lake Mead deltas are made up almost entirely of particles of sand, silt, and clay. The sand was deposited at or near the mouths of the Colorado and Virgin Rivers and is confined, therefore, to the foreset and bottomset beds of the deltas. The silt and clay particles, on the other hand, have been carried into the deeper parts of the lake and deposited in the bottomset beds. As a result, the Lake Mead deltas are geographically graded, the coarsest particles accumulating at the heads of the deltas and the finest particles at the greatest distance from the source. This gradation in particle size has produced a gradational change in most other physical properties of the deltas. For example, the sand of the topset and foreset beds, because of its small volume of interstitial water, is hard and firmly packed. In contrast, the silt and clay of the bottomset beds have an extremely high water content, which has given them the consistency of a soft ooze.

Because the Virgin delta is of relatively minor significance, and because it has not been studied as intensively as the Colorado delta, the following discussion deals chiefly with the physical properties of the materials in the Colorado delta.

**TEXTURE AND STRATIFICATION**

Investigations of the topset beds of the Colorado delta were confined to the surficial material in the channel and to the exposed terraces, natural levees, and shallow depressions behind the levees. In the eastern part of Lower Granite Gorge the channel deposits are chiefly medium and coarse sand and small amounts of gravel, whereas the levees and terraces consist of crossbedded fine sand. Locally the upper layers of the terraces and levees have been reworked by the wind, which produced a veneer of well-rounded, frosted sand grains upon the river embankments in many places. Surface material in the depressions behind the natural levees consists of poorly sorted clay, silt, and fine sand that has been deposited beyond the reach of the main current in the channel.

The detrital particles in the western part of Lower Granite Gorge and in the eastern part of Pierce Basin are considerably finer than those in the eastern part of the gorge. As noted previously, the 1948 terrace in these areas is capped by a layer of poorly sorted silt and clay, which accumulated in the slack water that covered the area during the high lake stage of 1948. However, the sediment immediately beneath this layer, as well as the sediment in the channel, is chiefly fine sand. The detrital material in the delta depressions is clayey silt similar to that of the depressions upstream. In the central part of Pierce Basin the steep foreset...
beds exposed at the delta surface also consist of fine sand. The most striking feature of the topset beds is the virtual absence of coarse gravel, in both the active channel and the natural levees. Samples from the topset beds show that gravel is present only in the easternmost 2 miles of the reservoir (miles 235 to 237), and that it is confined to the center of the channel. No cores were obtained from this part of the delta during the 1948 survey, but cores taken in 1941 and 1942 indicated that sand and silt constituted practically the entire thickness of the delta east of mile 240 and that only small amounts of gravel were present near the bottom of the buried Colorado River channel. On the basis of these observations it appears that only a very small part of the detrital load carried into the lake by the Colorado River is gravel.

The horizontal grading of the delta materials is shown clearly in a longitudinal section (fig. 48). The sediment particles at the surface range in median diameter from 22.5 millimeters at mile 237.3 to less than 0.001 millimeter (1 micron) at mile 354.6. It is inter-
intersting to note also that the texture of the surficial sediment is intimately related to the slope of the delta profile. As shown by the cumulative percentage graph and the plot of median diameter, there is an abrupt decrease in grain size at the foot of the delta front. The material making up the steep foreset beds is chiefly fine and very fine sand, whereas the sediment at the surface of the gently sloping bottomset beds west of the delta front consists entirely of silt and clay. It is this relationship that has been used on page 169 to estimate the contact between the bottomset beds and the overlying topset and foreset beds in Lower Granite Gorge. The contact shown on figure 47 does not indicate subsequent compaction of the underlying bottomset beds caused by the weight of the foreset and topset members, but it does give some suggestion of the major textural changes in vertical section.

An interesting feature shown by figure 48 is the relation of the median particle diameter to the coefficients of sorting and skewness. The sorting of the sand of the topset and foreset beds is nearly perfect, and the size-frequency distribution is skewed only slightly toward the finer sizes as the median diameter decreases. In contrast, the silt and clay of the bottomset beds are poorly sorted, and the size-frequency distribution is skewed markedly toward the finer sizes. These relations suggest that the velocities of the Colorado River turbidity currents (p. 204) have been great enough to transport particles of all sizes in the silt and clay size range, but that the velocities have generally not been sufficient to transport sand. Values for sorting and skewness could not be computed for samples west of mile 302 (in Virgin Canyon) because of the large percentage of colloidal particles whose diameters could not be measured by conventional laboratory techniques.

Little is known about the texture of the incipiently developed topset and foreset beds that probably accumulated along the bottom of the Colorado River channel during the early stages of reservoir filling. Visual inspection of thin sand layers obtained locally near the bottom of the channel in the western part of the lake suggests, however, that they are similar in texture to the topset and foreset beds exposed at the surface in the eastern part of Pierce Basin and in the Lower Granite Gorge.

The topset and foreset beds of the Virgin delta have not been studied intensively, but from the limited data available they appear to be similar in texture to the topset and foreset beds of the Colorado delta. As previously mentioned, (p. 172), the topset and foreset beds south of mile 30.2 are covered by a thin layer of silt and clay, and samples from this part of the delta are confined largely to the upper silt and clay layer. The small quantity of sand in most of these samples was obtained from the surface of the underlying topset and foreset beds. A composite analysis of sample G520 shows that the sand component consists of 84 percent fine and very fine sand (62-250 microns) and 16 percent medium sand (250-500 microns); it has a median diameter of 100 microns and a sorting coefficient of 1.32. As determined by this analysis, the topset and foreset beds of the Virgin delta are markedly similar in texture to the topset and foreset beds of the Colorado delta. No samples were obtained from the topset beds exposed at the surface of the Virgin delta north of mile 30.2, but according to F. C. Ames, who investigated this part of the delta, they are made up predominantly of sand with a minor amount of silt.

The bottomset beds of the Colorado delta are composed of stratified silt and clay; because of their high water content they are exceedingly soft and jellylike. Only samples from the most deeply buried layers are sufficiently solid not to flow under their own weight. Probably the most striking characteristic of the bottomset beds is the presence of numerous gas cavities, which in some zones give the beds a spongelike appearance.

Textural variations in the bottomset beds are small in transverse section as compared to those in longitudinal and vertical sections, especially west of mile 285.0. Between miles 279.2 and 285.0 the sediment accumulated in the tributaries of the submerged Colorado River channel has a noticeably larger clay fraction than the sediment along the thalweg, doubtless because the finer sediment in the submerged tributaries—like that in the delta flank depressions of the topset beds—has been deposited beyond the reach of the currents in the main channel.

Variations in particle size in longitudinal section are well illustrated by figure 48. The median particle diameter grades from 6 microns at mile 279.3 to less than 1 micron at Hoover Dam. The relation between particle size and bottom slope is also clearly discernible in this diagram, the coarsest particles forming the steepest slope.

Vertical sections through the bottomset beds at any point show a considerable range in texture, as illustrated in figure 49. The comparatively large vertical variations in median diameter above Virgin Canyon (miles 301.9 to 279.3) suggest that the velocities and perhaps the courses of turbidity currents in this part of the reservoir have varied considerably. West of mile

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18 The method of analysis of these materials is such as to indicate the size distribution of individual particles, rather than the sizes of the floccules or aggregates that settled from the lake water (p. 154).
301.9 the size variations in vertical section become progressively smaller, except locally where sand and coarse silt from the reservoir walls have been added to the bottomset beds. However, the total volume of sediment deposited in this manner has evidently been quite small.

The bottomset beds have a distinct stratification, even where the textural variations are not large. Individual layers range in thickness from a fraction of an inch to several feet, and are thinner and more distinct above Virgin Canyon than they are in the western part of the lake. In a few places the separate layers are marked by abrupt changes in texture, but in most places they are differentiated only by slight variations in color, from grayish-brown to reddish-brown; by thin, black organic layers; or by an unusually high percentage of gas cavities. In a few places the strata between adjacent cores could be correlated on the basis of color, texture, thickness, or sequence of beds, but such correlations were not generally possible. The horizontal grading of the bottomset beds and the probable variations in the turbidity currents that have traveled through the lake (p. 202) may account for our inability to trace the individual layers of the bottomset beds for any great distance.

The bottomset beds of the Virgin delta, like those of the Colorado delta, are made up entirely of stratified silt and clay, the individual layers of which range in thickness from less than 1 inch to about 6 inches. In most places the layers are distinguished only by
changes in color, from reddish brown to gray, or by thin black layers of organic detritus. Porous gaseous layers are not prominent in the bottomset beds of the Virgin delta.

As shown by samples from cores and from the surface of the Virgin delta, the median particle diameter of the bottomset beds ranges from 8.2 microns, near the foot of the delta front (mile 26.7), to about 2.5 microns, near the southern end of the delta (mile 21.4). Farther south the median particle diameter of the thin layer of silt and clay in the bottom of the Virgin River channel decreases to about 1.6 microns at mile 15.1. The downlake decrease in median particle diameter of this thin layer suggests that it is an incipient extension of the bottomset beds of the Virgin delta into the deeper parts of Overton Arm.

Data on the textural variations in vertical section are available only in the vicinity of the delta front, where the bottomset beds range from 4 to 6 feet in thickness. To the north the bottomset beds are overlain by topset and foreset beds that could not be penetrated, and to the south they are in most places less than 2 feet thick. As shown by cores 35 and 36, the texture of the bottomset beds between miles 26.7 and 23.7 of the Virgin River ranges in vertical section from 3 to 30 microns. This corresponds closely to the vertical range in texture of the Colorado delta bottomset beds immediately west of the delta front at mile 279.3 of the Colorado River.

Taken as a whole, the bottomset beds of the Virgin delta are notably coarser than the bottomset beds of the Colorado delta. This may indicate that the sediment load of the Virgin River is lower in fine constituents than the sediment load of the Colorado River. On the other hand, the finer particles in the Virgin River may have been transported by turbidity currents down the relatively steep gradient of Overton Arm and deposited in the bottomset beds of the Colorado delta near the former junction of the Virgin River with the Colorado River.

**WATER CONTENT AND POROSITY**

The water content and porosity are of particular interest because they provide the best data as to the amount of compaction that has taken place in the accumulated sediment. When the silt and clay of the bottomset beds are deposited, the water content is commonly as much as 75 percent of the wet weight of the accumulated deposit, and the porosity is as much as 89 percent. As additional layers are deposited on top of those in place, the solid particles of the buried material are packed together more tightly and part of the interstitial water is driven out. The water content and porosity of the accumulated deposits are also related to the size, shape, and sorting of the constituent particles: Coarse, well-sorted, sandy materials have a lower water content than fine, poorly sorted silt and clay. This relation is illustrated abundantly in the Colorado delta where the water content ranges from 16 percent in the well sorted sand of the topset beds to 75 percent in the poorly sorted silt and clay of the bottomset beds, and the porosity ranges from 34 percent to 89 percent.

Because of insufficient data from the deeply buried sediment in the Lower Granite Gorge, the discussion of variations in water content must be confined to the bottomset beds west of the delta front, as represented by the typical sections of figure 49. The water content in all sections tends to decrease with increasing depth, but there are many inversions where the texture changes, as the water content is inversely related to the median diameter. The sections at miles 279.3, 283.6, 287.5, and 301.9 show many such inversions, owing to abundant textural changes in this portion of the delta. The correlation would doubtless be more evident if all samples had been analyzed for both particle size and water content; size analyses require so much time, however, that they were made only of samples showing the most significant textural changes. At miles 331.2 and 350.2, textural changes are fewer and smaller, and the water-content inversions are less pronounced. Immediately above Hoover Dam (mile 354.6) the texture of the material in vertical section is almost uniform and the decrease in water content with increasing depth is approximately linear. These diagrams also show that the lateral range in water content is closely related to textural variations in longitudinal section. At mile 279.3, where the average median diameter of the particles is about 10 microns, the water content ranges from 51 percent at the surface to about 30 percent at a depth of 21 feet. In contrast, the water content of sediment at the dam, where the average median diameter is less than 1 micron, ranges from 71 percent at the surface to 62 percent at a depth of 99 feet.

Probably a better picture of the lateral range in water content and consolidation of the bottomset beds of the Colorado delta can be obtained from the fathograms shown in figure 85. At mile 348.9 in Boulder Basin, where the bottomset beds have much interstitial water and are only slightly compacted, recorded sound reflected from both the surface of the bottomset beds and the underlying topography of the pre-Lake Mead bottom are clearly visible. The surface of the bottomset beds and the underlying topography at miles 324.3 in Virgin Basin and 295.5 in Gregg Basin can also be distinguished, but with greater difficulty. The dense-
ness of the record between the upper and lower traces at miles 324.3 and 295.5 results from the greater compaction and lower water content of the bottomset beds in these areas. Owing to the still greater compaction of the bottomset beds east of mile 295.5, the sound was completely absorbed before it reached the bottom of the buried Colorado River channel. Consequently, fathograms east of mile 295.5 show only the surface of the bottomset beds. A comparison of sediment compaction data with the fathograms suggests that the sediment becomes opaque to sound at 14.25 kilocycles when the water content reaches about 34 percent and when the specific weight approaches 70 pounds per cubic foot.

There are no data on the water content and porosity of the topset and foreset beds of the Virgin delta, but their general similarity in texture to the topset and foreset beds of the Colorado delta suggests that their water content and porosity are also similar. On the other hand, the bottomset beds of the Virgin delta at any given depth have a notably lower water content and porosity than the bottomset beds of the Colorado delta. For example, the water content of the surface layers of the Virgin delta bottomset beds ranges from 39 to 62 percent, and the porosity from 63 to 82 percent. In contrast, the water content of the surface layers of the Colorado delta bottomset beds ranges from 47 to 75 percent, and the porosity from 71 to 89 percent. The lower water content and porosity of the Virgin delta bottomset beds result apparently from their coarser texture.

In vertical section the water content and porosity of the Virgin delta bottomset beds decrease with increasing depth of burial. As shown by core 36 taken at mile 26.15, the water content ranges from 52.9 percent at the surface to 35.0 percent at a depth of 5 feet. The porosity in this same depth interval ranges from 75.3 to 59.3 percent.

**Specific Weight**

The specific weight of the sediment deposit is related to the same physical properties that were outlined in the discussion of water content and porosity; namely, the size and sorting of the constituent particles and the depth of sediment burial. Coarse sediments (sand and gravel) have a high specific weight when they are first deposited, because of the dense packing of the constituent particles. On the other hand, fine sediments (silt and clay) have a very low specific weight when they are initially laid down, because of the loose arrangement of the solid grains. This relation is well illustrated in the Colorado delta, where the specific weight ranges from 108 pounds per cubic foot for coarse sand to as little as 18 pounds per cubic foot for silt and clay.

If the accumulated material is very fine grained, the specific weight increases with the depth of sediment burial. The rate of increase in the specific weight of sand with depth of burial is small, owing to its initially dense packing. On the other hand, the loose arrangement of silt and clay particles is readily changed to a denser state as the depth of burial increases. This causes a marked increase in the compaction of silt and clay sediments, the deepest layers having the highest specific weight.

Both the horizontal and vertical variations in the specific weight of the Colorado delta are illustrated in figure 50. This diagram shows clearly that the specific weight of the topset and foreset beds exposed at the delta surface above mile 279.3 is greater than that of the most deeply buried bottomset beds west of the delta front, and that the specific weight of the bottomset beds increases with increasing depth. It is interesting to note, also, that the specific weight of the bottomset beds at any given depth decreases progressively from the foot of the delta front to Hoover Dam. This decrease is related primarily to the decrease in size of the constituent particles, as shown by comparison of the physical characteristics of two samples, one from a depth of 38.9 feet at mile 283.64 and the other from the same depth at mile 350.08. The sample at mile 283.64 had a median particle diameter of 22.0 microns and a specific weight of 62.1 pounds per cubic foot. In contrast, the sample at mile 350.08 had a median diameter of 0.73 micron and a specific weight of 32.5 pounds per cubic foot. In the deeper, unsampled layers of the bottomset beds, the specific weight has been obtained by linear extrapolation of specific weight data from higher levels. These extrapolations are denoted in figure 50 by dashed lines.

From the previous discussion of delta structure, it seems probable that a very thin layer of incipiently developed topset and foreset beds, formed during the early stages of reservoir filling, underlies the bottomset beds west of the delta front. Since there are no data on the specific weight of these beds, they have been included with the bottomset beds in this extrapolation. If the topset and foreset beds at the bottom of the channel are similar in specific weight to the topset and foreset beds exposed at the delta surface in Lower Granite Gorge, the extrapolated specific weight of the sediment along the bottom of the Colorado River channel west of the delta front is probably too low. The average specific weight of the topset and foreset beds in Lower Granite Gorge is estimated at 93.8 pounds per cubic foot, whereas the average extrapolated
Figure 50—Specific weight of the sediment deposit in the Colorado delta along the Thuleweg.

- Weight of dry sediment, in pounds per cubic foot of deposit.
- Mean lake level.
- Elevation in feet.
- Sediment surface.
- Colorado River profile in 1935.
- No data available.
specific weight of the sediment at the bottom of the channel west of the delta front is about 75 pounds per cubic foot. Since the volume of the layer of topset and foreset beds at the bottom of the channel is probably very small, it seems likely that use of the average extrapolated specific weight of 75 pounds per cubic foot has introduced no serious error in computations of the total weight of sediment accumulated in the Colorado delta.

No quantitative data are available on the vertical variations in specific weight of the sediment accumulated east of the Colorado delta front. Computations based on delta structure (fig. 47) and the volume of sediment suggest, however, that the sandy topset and foreset beds make up about 83 percent of the total volume of this part of the delta and that bottomset beds of silt and clay constitute only 17 percent.

According to laboratory experiments by Terzaghi (1925), the compaction and increase in specific weight of sand is insignificant when subjected to pressures less than about 100 pounds per square inch. Since the weight of the superposed load reaches this value only in the most deeply buried sand layers east of the delta front, the specific weight of the topset and foreset beds probably does not increase appreciably with increasing depth, and the specific weight of the surface material is presumed to be characteristic of all depths.

This conclusion is supported by specific-weight measurements of several sand samples from deep levels in the bottomset beds. This material, probably derived by slumping of the reservoir walls, has about the same specific weight at depths of 37 to 55 feet as the sand at the surface of the delta in Lower Granite Gorge. Consequently the specific weight of all the sand in the topset and foreset beds east of the delta front is estimated at 93.8 pounds per cubic foot, which is the average specific weight of 12 samples collected from the surface of the topset and foreset beds. Two other samples are not considered representative of the topset and foreset beds as a whole because of their coarseness and high specific weight; they have not been included in this average.

It has been assumed that the deeply buried bottomset beds east of the Colorado delta front are similar in texture to the bottomset beds immediately west of the delta front. Then the sediment in the two areas should have the same compaction properties, and the specific weight at any given level would be related to the depth of burial. The bottomset beds east of the delta front range in depth from 150 feet to about 250 feet. Data from the bottomset beds immediately west of the delta front are available, however, only to a sediment depth of 95 feet. By linear extrapolation of these data to greater depths, we obtain an estimated mean specific weight of 100 pounds per cubic foot for the deeply buried bottomset beds in the vicinity of the delta front.

No data are available on the specific weight of the Virgin delta topset and foreset beds. Their general textural correspondence to the topset and foreset beds of the Colorado delta suggests, however, that they are also similar in specific weight. It is assumed, therefore, that the Virgin delta topset and foreset beds have about the same average specific weight (93.8 pounds per cubic foot) as the topset and foreset beds of the Colorado delta.

Because of their coarser texture, the specific weight of the Virgin delta bottomset beds at any given depth is notably higher than the specific weight of the Colorado delta bottomset beds. The specific weight of the uppermost bottomset beds ranges from 62.0 pounds per cubic foot near the delta front to 30.6 pounds per cubic foot at the lower end of the delta. As shown by core 36, where the Virgin delta bottomset beds are thickest the specific weight ranges from 41.7 pounds per cubic foot at the surface to 68.7 pounds per cubic foot at a depth of about 5 feet.

**GAS CONTENT**

The occurrence of a considerable amount of gas in the sediments of the Colorado delta is indicated by abundant gas pits on the exposed terrace near the delta front and by a great number of unconnected gas cavities in the cores from the bottomset beds. Gas bubbles emanating from the subaqueous bottomset beds in Pierce Basin were sampled, and an analysis of the gas composition made by the U.S. Bureau of Mines Petroleum and Oil-Shale Experiment Station in Laramie, Wyo., showed the following constituents:

**Constituents of gas from the Colorado delta in Pierce Basin**

[Analysis by Petroleum and Oil-Shale Experiment Station, U.S. Bureau of Mines, Laramie, Wyo.]

<table>
<thead>
<tr>
<th>Gas</th>
<th>Percent</th>
</tr>
</thead>
<tbody>
<tr>
<td>Methane, CH₄</td>
<td>78.0</td>
</tr>
<tr>
<td>Nitrogen, N₂</td>
<td>16.3</td>
</tr>
<tr>
<td>Oxygen, O₂</td>
<td>4.8</td>
</tr>
<tr>
<td>Argon, Ar</td>
<td>0.4</td>
</tr>
<tr>
<td>Carbon dioxide, CO₂</td>
<td>0.5</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>100.0</strong></td>
</tr>
</tbody>
</table>

According to this analysis, the gas is composed principally of methane, some nitrogen and oxygen, and small amounts of argon and carbon dioxide. The nitrogen, oxygen, and argon are in roughly the same proportion as they are in air. The dissolved gases in the lake water overlying the bottomset beds are presumed to have been in equilibrium with the atmosphere, so that the proportions of nitrogen, oxygen,
and argon should be about the same in the water as in
the air. It seems a reasonable conclusion, therefore,
that most if not all of the nitrogen, oxygen, and argon
were introduced from the water into the gas bubbles
as they ascended from the bottomset beds to the lake
surface. The methane and carbon dioxide, on the other
hand, must have been produced by the biochemical
decomposition of organic matter in the bottomset beds.

Except for the small amount of argon, the gas con-
tained in the bottomset beds of the Colorado delta has
about the same composition as that reported by Shaw
(1913, 1914) of gas samples from the Mississippi delta.

Gas cavities occur at practically all depths in the
bottomset beds of the Colorado delta west of the delta
front; they are extremely numerous in some layers.
Deeper cavities are elongated in planes parallel to the
bedding, suggesting that the lateral expansion of the
gas has been greater than the vertical expansion as
the cores were brought to the surface.

When cores from the bottomset beds were raised to
the surface, it was found that the gas contained in them
expanded to several times its volume at depth, and
formed cavities ranging in diameter from less than 1
millimeter to about 15 millimeters at atmospheric pres-
sure. To obtain an estimate of the average gas con-
tent in place, 74 samples of measured volume were col-
lected from the bottomset beds of the Colorado delta.
These samples were obtained from localities widely
distributed, both laterally and vertically, and are con-
sidered, therefore, to be representative of the Colorado
delta bottomset beds as a whole. The volume of gas
in the sediment in place was calculated as outlined on
page 154.

At atmospheric pressure the gas volume may be as
much as 12 percent of the volume of the water-satu-
rated sediment, but the maximum gas content in place
is about 2 percent. In vertical section the gas content
does not vary systematically, but in longitudinal sec-
tion there is a general decrease in gas content downlake
from the delta front. The gas content, as determined
by averaging the individual measurements in each of
the six vertical sections of cores K1 to K6, ranges from
1.1 percent at mile 283.5 to 0.3 percent at mile 331.8
(fig. 51). The average of all determinations is 0.6
percent, which is probably representative of the average
gas content of the bottomset beds west of the Colorado
delta front.

The gas issuing from the pits in the surface of the
1948 terrace was doubtless being squeezed out of the
underlying bottomset beds by the weight of the topset
and foreset beds, and passed through those beds on
its way to the surface. No evidence was found of gas
originating in the topset or foreset beds.

\[ \text{Figure 51. Relations of gas content, organic content, and temperature}
\text{gradient in longitudinal section through the Colorado delta. Values}
\text{of organic content and gas content are averages of samples from}
\text{each of several vertical sections. Temperature gradient represents}
\text{temperature increase in the upper 40 feet of the accumulated}
\text{sediment.} \]

No measurements were made of the gas content of the
Virgin delta bottomset beds, but, from visual inspec-
tion of cores, gas cavities are not nearly so prominent
as they are in the bottomset beds of the Colorado delta
(see pl. 29).

\[ \text{SEDIMENT TEMPERATURE} \]

The temperature of the bottomset beds of the Colo-
rado delta is higher than that of the water in the reser-
voir immediately above them, and higher than would
be expected from the regional geothermal gradient.
Measurements since the summer of 1937 (National Re-
search Council, 1949) show that the surficial layers of
the bottomset beds everywhere are more than 5°F,
and in places as much as 9°F, warmer than the over-
lying lake water with which they are in contact.

In the cruises described by Anderson and Pritchard
(1951, p. 52) it was the practice to lower the bathy-
thermograph until it rested on the bottom at each sta-
tion. The weight of the bathythermograph commonly
caused the instrument to sink as much as 20 feet in the
soft mud before coming to rest. Temperature traces
generally showed a considerable increase in tempera-
ture just at the surface of the mud, but no increase in
the water immediately above the bottom.

In order to measure the temperatures of the deeper
sediments, a mud bathythermograph, especially de-
signed and constructed by the Navy Electronics
Laboratory, was lowered into the bottomset beds at
three localities between the foot of the delta front and
Hoover Dam. The mud bathythermograph is a modi-
fication of the conventional bathythermograph which
provides a continuous graphic record of the temperature as a function of depth. The chief modifications include the addition of a pointed nose, weighted so as to penetrate the sediment to considerable depth, and relocation of the temperature-measuring capillary tubing to reduce the hysteresis caused by mud clinging to the instrument. By lowering this instrument at a rate of less than 3 feet per minute, hysteresis was reduced enough that reasonably accurate records of temperature were obtained.

A record of temperature throughout the total thickness of bottomset beds was obtained immediately upstream from Hoover Dam. At localities in Boulder Canyon (mile 333.9) and Iceberg Canyon (mile 287.5) the bathythermograph was stopped by compact sediment at depths of 42 feet and 45 feet respectively. These measurements (fig. 52) show that the temperature of the bottomset beds increases with increasing depth and that the temperature gradient is much steeper near the foot of the delta front than it is near Hoover Dam.

The average temperature gradient ranges from 0.28°F per foot at mile 287.5 to 0.07°F per foot at mile 354.6. The traces at miles 287.5 and 354.6 show a distinct temperature stratification. The change in temperature at the water-sediment interface is abrupt in all records.

Several factors have contributed to the heating of the bottomset beds of the Colorado delta, but they have not been evaluated quantitatively. F. D. Sisler discusses several of the possible causes of this heating on pages 190–191, and concludes that biochemical processes probably account for most of the observed heating.

It is possible also that part of the heat may result from an initially higher temperature of the sediment when it was deposited in the bottomset beds. Density-current records prior to 1948 (U.S. Bur. Reclamation, 1941, 1947) show that the temperature of turbidity currents flowing along the bottom of the reservoir has generally been lower than the temperature of the overlying lake water. However, on March 28, 1939, a flow of
turbid water about 4° F warmer than the overlying water was detected at the bottom of the reservoir as far west as Boulder Canyon. The temperatures of some other flows may have been correspondingly high, but there are no records of them. A similar occurrence of warm turbidity currents flowing along the bottom of Elephant Butte Reservoir has been noted by Flick (1934).

The geothermal gradient near Hoover Dam has been estimated at about 0.013°F per foot (U.S. Bur. Reclamation, 1950, p. 177). If the vertical flow of heat through the bottomset beds were the same as that through the underlying and bordering rocks, heat of deep-seated origin would account for only a very small part of the heating observed in the sediments. The only hot springs known in the Lake Mead area are those discovered at the site of Hoover Dam during the construction period (U.S. Bur. Reclamation, 1950, p. 179). Possibly these springs have contributed a small amount of heat to the overlying bottomset beds in the vicinity of Hoover Dam, but they could not account for the general heating of the bottom sediments.

CHEMICAL PROPERTIES

Chemical, spectrographic, and clay-mineral analyses have been made of a relatively few samples, selected so as to provide a reasonably accurate picture of the general chemical composition of the accumulated sediment as a whole. Evidence of precipitation of calcium carbonate from the lake water led to a more intensive investigation of the content and distribution of calcium carbonate in the accumulated sediment. The organic matter in the sediment, because of its possible relation to the heating of the bottomset beds and to the evolution of methane, was investigated more thoroughly than most other constituents.

CHEMICAL ANALYSES

Eight samples from widely distributed localities were analyzed in the geochemical laboratories of the Geological Survey. Of these, seven samples from the Colorado delta include representative material from the topset, foreset, and bottomset beds; and one sample from the Virgin delta is representative of the bottomset beds.

The results of these analyses (table 23) show that the composition of the topset beds of the Colorado delta differs markedly from the composition of the bottomset beds. The bottomset beds of the Colorado and Virgin deltas are notably similar in composition. The topset beds of the Colorado delta are made up almost entirely of SiO₂, whereas the bottomset beds have an average SiO₂ content of only about 50 percent. Of the major constituents, Al₂O₃, Fe₂O₃, MgO, CaO, and K₂O are much more abundant in the bottomset beds. Likewise, the minor constituents Na₂O, TiO₂, P₂O₅, and MnO, are appreciably higher in the bottomset beds than in the topset beds. The foreset beds of the Colorado delta are intermediate in composition between that of the topset and bottomset beds, but more like the topset beds.

Judging from its high silica content, the sand of the topset beds is made up chiefly of detrital fragments of quartz. The silt and clay samples from the bottomset beds are made up chiefly of hydrous aluminum silicates and hydroxides of iron and aluminum, as shown by lower silica content, by appreciable quantities of Al₂O₃, Fe₂O₃, MgO, and K₂O, and by high ignition loss. The foreset beds, chiefly sand with small amounts of silt and clay, are made up of quartz fragments and a minor proportion of hydroxides and hydrous aluminum silicates.

TABLE 23.—Chemical analyses of samples from the sediment deposits in Lake Mead, in percent

<table>
<thead>
<tr>
<th>Location of sample, mile.</th>
<th>Colorado delta</th>
<th>Virgin delta</th>
</tr>
</thead>
<tbody>
<tr>
<td>Depth below sediment surface, feet</td>
<td>Topset beds</td>
<td>Foreset beds</td>
</tr>
<tr>
<td>SiO₂</td>
<td>255.5</td>
<td>277.9</td>
</tr>
<tr>
<td>Al₂O₃</td>
<td>46.7</td>
<td>46.4</td>
</tr>
<tr>
<td>Fe₂O₃</td>
<td>1.6</td>
<td>3.0</td>
</tr>
<tr>
<td>MgO</td>
<td>1.0</td>
<td>1.0</td>
</tr>
<tr>
<td>CaO</td>
<td>1.4</td>
<td>3.6</td>
</tr>
<tr>
<td>Na₂O</td>
<td>1.6</td>
<td>1.6</td>
</tr>
<tr>
<td>K₂O</td>
<td>0.6</td>
<td>0.6</td>
</tr>
<tr>
<td>TiO₂</td>
<td>0.2</td>
<td>0.2</td>
</tr>
<tr>
<td>P₂O₅</td>
<td>0.0</td>
<td>0.0</td>
</tr>
<tr>
<td>MnO</td>
<td>0.0</td>
<td>0.0</td>
</tr>
<tr>
<td>Ignition loss</td>
<td>1.1</td>
<td>1.1</td>
</tr>
</tbody>
</table>

| Total | 99.5 | 99.1 | 99.2 | 100.1 | 100.8 | 100.4 | 99.8 | 100.1 |

1 Total Fe expressed as Fe₂O₃.
2 Includes loss due to oxidation of FeO.
The composition of the sand in the topset beds of the Colorado delta is remarkably similar to the average composition of river sands listed by Clarke (1924, p. 507), except that it contains one-fourth the aluminum and about twice the calcium concentration shown in Clarke's average. Likewise, the composition of the bottomset beds of both the Colorado delta and Virgin delta corresponds very closely with the average composition of shales (Clarke, 1924, p. 30). The only notable differences are that the bottomset beds of the Lake Mead deltas contain about twice the calcium and only one-half the sodium concentration of the average shale.

**SPECTROGRAPHIC ANALYSES**

Six samples from the bottomset beds of the Colorado delta were analyzed spectrographically in the geochemical laboratories of the Geological Survey in Washington, D.C., using prepared soil samples and a sample of Mississippi River silt as comparison standards. Owing to their general similarity the analyses have been averaged for presentation. A. T. Myers, the analyst, states that the element composition of the silt and clay from the Colorado delta is of the same order as that of the Mississippi River silt, except that the Colorado delta samples contain only one-half the sodium and one-fourth the copper concentration found in the Mississippi River silt.

**Spectrographic analysis of samples from the bottomset beds of the Colorado delta**

<table>
<thead>
<tr>
<th>Constituent</th>
<th>Percent</th>
<th>Constituent</th>
<th>Percent</th>
</tr>
</thead>
<tbody>
<tr>
<td>SiO₂</td>
<td>0.0</td>
<td>ZrO₂</td>
<td>0.00X</td>
</tr>
<tr>
<td>Al₂O₃</td>
<td>X0.0</td>
<td>BaO</td>
<td>0.00X</td>
</tr>
<tr>
<td>Fe₂O₃</td>
<td>0X.0</td>
<td>NiO</td>
<td>0.00X</td>
</tr>
<tr>
<td>CaO</td>
<td>0X.0</td>
<td>CuO</td>
<td>00.00X</td>
</tr>
<tr>
<td>K₂O</td>
<td>0X.0</td>
<td>Cr₂O₃</td>
<td>00.00X</td>
</tr>
<tr>
<td>MgO</td>
<td>00.0X</td>
<td>V₂O₅</td>
<td>00.00X</td>
</tr>
<tr>
<td>Na₂O</td>
<td>00. X</td>
<td>Trace</td>
<td></td>
</tr>
<tr>
<td>TiO₂</td>
<td>00. X</td>
<td>Sr</td>
<td></td>
</tr>
<tr>
<td>P₂O₅</td>
<td>00. Y</td>
<td>Zn</td>
<td></td>
</tr>
<tr>
<td>MnO</td>
<td>00. 0X</td>
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</table>

1. Average for samples G15, G13, 27, 30, 42, and 62.

2. The first significant digit in the percentage composition is denoted by X. For example, the percentage of SiO₂ shown as X0.0 percent, indicates that the material contains between 10 and 90 percent SiO₂.

3. Additional elements, Ag, As, Au, Be, Bi, Cd, Co, Ge, In, La, Mo, and Zn were looked for but not found.

**CLAY MINERALS**

Clay-mineral analyses were made of four samples from the bottomset beds of the Colorado delta by George Tchillingarian of the University of Southern California. He reports that montmorillonite is slightly more abundant than illite and kaolinite, and that kaolinite is more prominent in the particles larger than 1 micron than in the smaller particles. This is in close accord with the earlier findings of Grim, Dietz, and Bradley (1949), which show approximately equal proportions of illite, montmorillonite, and kaolinite in the bottomset beds of the Colorado delta.

**CALCIUM CARBONATE**

To obtain an estimate of the quantity and distribution of calcium carbonate in the sediments of the Colorado delta, 34 samples from widely distributed positions were analyzed by the alkaliometer method outlined by Trask (1932, p. 97). These analyses (table 24) show that the sand of the topset and foreset beds contains much less calcium carbonate than do the silt and clay of the bottomset beds. The calcium carbonate content of the topset and foreset beds ranges from 2.3 to 6.4 percent and averages 4.6 percent. In contrast, the calcium carbonate content of the bottomset beds ranges from 10.2 to 19.7 percent and averages 16.1 percent. A marked increase in calcium carbonate is correlative with the abrupt decrease in grain size at the foot of the delta front at mile 279.3.

**Table 24.—Characteristics of calcium carbonate and organic matter in selected samples from the Colorado delta**

<table>
<thead>
<tr>
<th>Location, mile</th>
<th>Sample</th>
<th>Sediment depth, in feet</th>
<th>Median diameter, in microns</th>
<th>CaCO₃ in percent</th>
<th>Organic matter in percent</th>
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1. Organic carbon determined by chromic acid reduction, multiplied by 1.7.
Although the high calcium carbonate content of the bottomset beds is related to their fine texture, the percentage of calcium carbonate in individual samples does not vary systematically as a function of particle size. For example, sample SIO-1C, which has a median diameter of 0.8 micron, has about the same calcium carbonate content as sample 1029, which has a median diameter of 45 microns. Likewise there are no systematic lateral or vertical variations in the calcium carbonate content of the bottomset beds.

Similarly, the low calcium carbonate content of the topset and foreset beds is related to their coarse texture, but calcium carbonate determinations of individual samples do not vary systematically as a function of grain size.

No analyses have been made of calcium carbonate in samples from the Virgin delta. However, the calcium concentration in the Virgin delta bottomset beds (table 23) suggests that the calcium carbonate content of the Virgin delta is of the same order of magnitude as that of the Colorado delta.

The total weight of sediment in the topset and foreset beds of the Colorado delta is estimated (p. 195) to be approximately equal to that in the bottomset beds. From the average calcium carbonate content of the topset and foreset beds (4.7 percent) and of the bottomset beds (16.1 percent) it is estimated that the Colorado delta has an average calcium carbonate content of 10.3 percent. This estimate is considered to be applicable to all the sediment accumulated in Lake Mead because the contributions from the Virgin River and other sources are generally similar to those from the Colorado River and, in any event, constitute a very small proportion of the total.

Some calcium carbonate is precipitated from the lake water, as shown by thin calcareous incrustations on the reservoir walls and by deposits of calcium carbonate in the drainage tunnels of Hoover Dam. An analysis of the incrusting material by Wilson Orr of the University of Southern California shows that calcium carbonate constitutes approximately 90 percent of these precipitates. The remaining 10 percent consists of dead green algae which have been identified as the genus *Spyrogira* by E. Yale Dawson of the Allan Hancock Foundation at the University of Southern California.

The quantity of calcium carbonate in the accumulated sediment, however, is far greater than can be accounted for by precipitation from the lake. C. S. Howard states (p. 123) that about 9 million tons of calcium carbonate and 1 million tons of silica were precipitated from the lake water during the 14-year interval 1935–48. In terms of the 2,000 million tons (dry weight) of sediment that has accumulated in Lake Mead during the same period, the amount of precipitated calcium carbonate is 0.45 percent, and of silica, 0.05 percent.

From the great difference between the amount of calcium carbonate precipitated from the lake water (0.45 percent) and that contained in the accumulated sediment (10.3 percent), it is evident that large quantities of calcium carbonate are carried into the lake as part of the suspended load of the Colorado River. This conclusion is confirmed by analyses by Sykes (1937) of the suspended load of the Colorado River in the delta at the head of the Gulf of California. According to his average analysis, the suspended load has an average calcium carbonate content of 10 percent.

**ORGANIC CONTENT**

The organic matter in the accumulated sediment determines to a large extent the intensity of biochemical processes. Most of the organic matter is finely divided plant fragments, transported into the lake by the inflowing streams and deposited with the inorganic particles in the Lake Mead deltas. Some organic matter is also contributed to the sediment by fresh-water algae and subaerial vegetation growing in and about the lake. The luxuriant growth of green algae on the walls of the reservoir and the numerous salt cedar plants bordering the lake are destroyed periodically by rising water as the lake level fluctuates, thus providing an intermittent supply of organic detritus to the accumulated sediment. The thin organic layers distributed throughout most cores indicate periods of greater than normal contribution of organic detritus, either from lake sources or from the inflowing water.

To obtain an estimate of the quantity and distribution of organic matter, the organic carbon contents of 33 samples from the Colorado delta were measured by the chromic acid method (Allison, 1938). Organic matter is of course composed of oxygen, hydrogen, nitrogen, and other constituents in addition to carbon, but Trask (1932, p. 18) has found a fairly constant relation between organic carbon and total organic content. On the basis of this relation the organic content of the samples shown in table 24 was calculated by applying a factor of 1.7 to the organic carbon values, as recommended by Trask.

The silt and clay of the bottomset beds contain much more organic matter than does the sand of the topset and foreset beds. The average organic content of samples from the bottomset beds is 0.93 percent, and of samples from the topset and foreset beds, 0.14 percent. The concentration of organic particles in the bottomset beds is to be expected because they are low in density.
and would logically be deposited with finer inorganic particles. However, within the bottomset beds themselves there appears to be no clear relation between organic content and grain size, nor is there systematic variation in organic content in vertical section.

The organic content is notably higher near the foot of the delta front than in the western part of the lake. As determined by averaging the individual measurements in each of nine vertical sections, the organic content in longitudinal section shows a general but somewhat irregular decrease from 1.12 percent at mile 279.3 in Pierce Basin to 0.68 percent at Hoover Dam (fig. 51).

The gas content and temperature gradient of the bottomset beds have been plotted on the same graph as the organic content. The general similarity of the three curves suggests that the organic content, gas content, and temperature gradient are directly related. Where the organic content is high, the temperature gradient and gas content are also high; conversely, where the organic content is low, the temperature gradient and gas content are, in general, low.

Since organic material controls to a large extent the number of bacteria in sediments (ZoBell, 1939), we should expect the largest bacterial population to be concentrated where the organic material is most abundant. This relation of organic content, gas content, and temperature gradient is in accord with F. D. Sisler's findings (p. 190, 193) that bacteria and biochemical processes within the sediment are chiefly responsible for the production of gas and heating of the bottomset beds.

REFERENCES CITED

——— 1959, Boulder Canyon project final reports, Pt. III, Bull. 1.