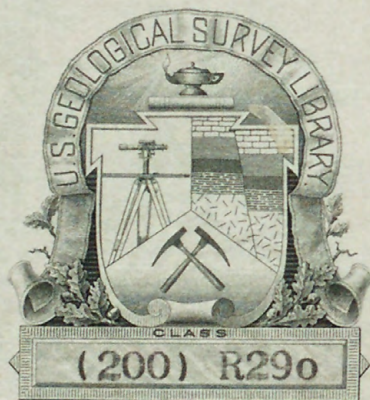






159769



no. 236, 1954



(200)

R290

No. 236

1954

✓  
U. S. Geological Survey  
Reports open file.



JAN 1957



(200)  
R 290  
no. 236

U. S. Geological Survey  
[ Reports - open file series ]  
**LAKE MEAD SEDIMENTATION**

by

Howard Ross Gould



(Released Feb. 15, 1954)

U. S. Geological Survey

**OPEN FILE REPORT**

This report is preliminary and has not been edited or reviewed for conformity with Geological Survey standards or nomenclature.



# TABLE OF CONTENTS

|                                                | PAGE |
|------------------------------------------------|------|
| INTRODUCTION . . . . .                         | 1    |
| Scope of the investigation . . . . .           | 3    |
| Previous work . . . . .                        | 7    |
| Acknowledgments . . . . .                      | 14   |
| THE LAKE . . . . .                             | 16   |
| Dimensions . . . . .                           | 16   |
| Bottom topography and lithology . . . . .      | 20   |
| METHODS OF INVESTIGATION . . . . .             | 31   |
| Field work . . . . .                           | 31   |
| Collection of cores and samples . . . . .      | 33   |
| Gravity cores . . . . .                        | 37   |
| Piston cores . . . . .                         | 39   |
| Peerst samples . . . . .                       | 44   |
| Grab samples . . . . .                         | 46   |
| Miscellaneous observations . . . . .           | 48   |
| Laboratory studies . . . . .                   | 50   |
| water content and air-dry moisture content . . | 51   |
| Specific gravity of sediment particles . . . . | 53   |
| Density, porosity, and specific weight . . . . | 54   |
| Correction for gas in samples . . . . .        | 56   |
| Gas volume in situ . . . . .                   | 57   |



## PAGE

|                                                         |     |
|---------------------------------------------------------|-----|
| Grain size distribution . . . . .                       | 58  |
| Methods . . . . .                                       | 58  |
| Presentation of data . . . . .                          | 63  |
| CHARACTERISTICS OF THE ACCUMULATED SEDIMENT . . . . .   | 69  |
| Distribution . . . . .                                  | 69  |
| Colorado delta . . . . .                                | 69  |
| Virgin delta . . . . .                                  | 75  |
| Deposits at the mouths of minor tributaries . . . . .   | 77  |
| Physiography of the deltas . . . . .                    | 79  |
| Colorado delta . . . . .                                | 79  |
| Topset beds . . . . .                                   | 79  |
| Channel characteristics . . . . .                       | 80  |
| Terraces, levees, and marginal<br>depressions . . . . . | 83  |
| Foreset beds . . . . .                                  | 94  |
| Bottomset beds . . . . .                                | 96  |
| Virgin delta . . . . .                                  | 100 |
| Growth and structure of the Lake Mead deltas . . . . .  | 103 |
| Colorado delta . . . . .                                | 105 |
| Growth in February and March 1935 . . . . .             | 106 |
| Growth from April 1935 to March 1936 . . . . .          | 110 |
| Growth from April 1936 to July 1937 . . . . .           | 113 |
| Growth from July 1937 to December 1948 . . . . .        | 114 |



|                                      | PAGE |
|--------------------------------------|------|
| Structure in 1948 . . . . .          | 118  |
| Virgin delta . . . . .               | 125  |
| Physical properties . . . . .        | 129  |
| Texture and stratification . . . . . | 130  |
| Topset and foreset beds . . . . .    | 130  |
| Bottomset beds . . . . .             | 136  |
| Water content and porosity . . . . . | 144  |
| Specific weight . . . . .            | 149  |
| Gas content . . . . .                | 156  |
| Sediment temperature . . . . .       | 161  |
| Chemical properties . . . . .        | 167  |
| Chemical analyses . . . . .          | 167  |
| Spectrographic analyses . . . . .    | 170  |
| Clay minerals . . . . .              | 172  |
| Calcium carbonate . . . . .          | 172  |
| Organic content . . . . .            | 177  |
| Biochemical properties . . . . .     | 179  |
| Amount of sediment . . . . .         | 182  |
| Volume . . . . .                     | 182  |
| Weight . . . . .                     | 186  |
| Total weight . . . . .               | 186  |
| Mean specific weight . . . . .       | 188  |
| Median particle size . . . . .       | 188  |

|                                                      | PAGE |
|------------------------------------------------------|------|
| Average chemical composition . . . . .               | 193  |
| Potential economic use . . . . .                     | 195  |
| TRANSPORTATION OF SEDIMENT BY TURBIDITY CURRENTS . . | 199  |
| Definition . . . . .                                 | 199  |
| Relation to river discharge and lake                 |      |
| stratification . . . . .                             | 202  |
| Overflows . . . . .                                  | 203  |
| Interflows . . . . .                                 | 206  |
| Underflows . . . . .                                 | 207  |
| Velocity, density, and thickness . . . . .           | 214  |
| Amount of sediment and distance of travel . . . .    | 215  |
| Change in slope and width of the channel . . . .     | 219  |
| Size of suspended particles . . . . .                | 220  |
| Virgin River turbidity currents . . . . .            | 221  |
| EROSION IN THE RESERVOIR . . . . .                   | 225  |
| Landslides . . . . .                                 | 226  |
| Wave-cut terraces . . . . .                          | 233  |
| Solution . . . . .                                   | 236  |
| Erosion of the delta surface . . . . .               | 242  |
| RATE OF SEDIMENTATION . . . . .                      | 244  |
| Estimate based on total weight of sediment           |      |
| accumulated in Lake Mead . . . . .                   | 244  |



|                                                      |     |
|------------------------------------------------------|-----|
| Comparison with estimate based on stream             |     |
| gaging measurements . . . . .                        | 244 |
| SEDIMENTATION IN RELATION TO RESERVOIR UTILIZATION . | 248 |
| Sediment-storage capacity above the permanent        |     |
| spillway level . . . . .                             | 249 |
| Sediment compaction . . . . .                        | 255 |
| Pattern of sedimentation in the future . . . . .     | 262 |
| Complete filling . . . . .                           | 263 |
| Half-way point in reservoir filling . . . . .        | 271 |
| Filling to the sill of the lower gates at            |     |
| the intake towers . . . . .                          | 282 |
| Terminal slope and residual storage . . . . .        | 285 |
| Life of the reservoir . . . . .                      | 297 |
| Rate of sedimentation, 1935-48 . . . . .             | 297 |
| Rate of sedimentation, 1926-48, based on             |     |
| suspended sediment records at the Grand              |     |
| Canyon station . . . . .                             | 298 |
| Rate of sedimentation, 1911-48, based on             |     |
| suspended sediment records at Yuma,                  |     |
| Arizona . . . . .                                    | 299 |
| Rate of sedimentation, 1897-1948, based on           |     |
| water and sediment records at the Grand              |     |
| Canyon station . . . . .                             | 300 |

|                                                                                                              |     |
|--------------------------------------------------------------------------------------------------------------|-----|
| Rate of sedimentation, 1240-1245, based<br>on tree-ring studies in the tributary<br>drainage basin . . . . . | 301 |
| Estimates of life expectancy based on<br>sedimentation rates . . . . .                                       | 304 |
| Modification by future natural and<br>developmental factors . . . . .                                        | 307 |
| RATE OF EROSION FROM THE TRIBUTARY DRAINAGE BASIN . .                                                        | 309 |
| RELATION TO STREAM PROCESSES IN THE LOWER COLORADO<br>RIVER . . . . .                                        | 313 |
| SUMMARY AND CONCLUSIONS . . . . .                                                                            | 316 |
| REFERENCES . . . . .                                                                                         | 327 |



## LIST OF TABLES

| TABLE                                                                                                                                                                                                     | PAGE |
|-----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|------|
| 1. Distribution of Cores and Samples from the<br>Sediment Accumulated in Lake Mead . . . . .                                                                                                              | 35   |
| 2. Penetration Depths and Core Lengths<br>Obtained by Gravity Core Sampler . . . . .                                                                                                                      | 41   |
| 3. Penetration Depths and Core Lengths<br>Obtained by Piston Core Sampler . . . . .                                                                                                                       | 43   |
| 4. Combined Udden-Wentworth Size Classification .                                                                                                                                                         | 61   |
| 5. Size Classification as used in this Report . .                                                                                                                                                         | 66   |
| 6. Comparison of the Median Particle Diameters<br>of Samples from the Bottomset Beds of<br>the Colorado Delta as Determined by<br>Analyses in a Dispersed Medium and in<br>Untreated Lake Water . . . . . | 142  |
| 7. Analysis of Gas from the Colorado Delta . . .                                                                                                                                                          | 157  |
| 8. Chemical Analyses of Samples from the<br>Sediment Accumulated in Lake Mead . . . . .                                                                                                                   | 168  |
| 9. Spectrographic Analysis of Samples from<br>the Bottomset Beds of the Colorado<br>Delta . . . . .                                                                                                       | 171  |

## TABLE

## PAGE

|     |                                                                                                                   |     |
|-----|-------------------------------------------------------------------------------------------------------------------|-----|
| 10. | Calcium Carbonate and Organic Matter in<br>Selected Samples from the Colorado<br>Delta . . . . .                  | 173 |
| 11. | Sediment in Individual Areas . . . . .                                                                            | 185 |
| 12. | Estimated Average Chemical Composition of<br>the Sediment Accumulated in the Colorado<br>Delta . . . . .          | 196 |
| 13. | Estimated Weight, Volume, and Specific<br>Weight of the Sediment in Lake Mead<br>when it Becomes Filled . . . . . | 268 |

## LIST OF FIGURES

| FIGURE                                                                                                                                                     | PAGE |
|------------------------------------------------------------------------------------------------------------------------------------------------------------|------|
| 1. Location Map Showing the Relation of Lake<br>Mead to the Colorado River Basin . . . . .                                                                 | 2    |
| 2. Lake Stage Hydrograph . . . . .                                                                                                                         | 17   |
| 3. Index Map Showing the Various Basins and<br>Canyons of Lake Mead and Their Relation<br>to the Inundated Colorado and Virgin<br>River Channels . . . . . | 19   |
| 4. The Grand Wash Cliffs Viewed from Pierce Basin .                                                                                                        | 21   |
| 5. Aerial View of Boulder Canyon and Virgin Basin .                                                                                                        | 24   |
| 6. Steeply Dipping Pennsylvanian and<br>Mississippian Strata near the Head of<br>Iceberg Canyon (Colorado River-mile 287) . . .                            | 27   |
| 7. Black Canyon and Boulder Basin Viewed from<br>the Air . . . . .                                                                                         | 28   |
| 8. U. S. Navy Plane Personnel Boat Rigged for<br>Light Hydrographic Work . . . . .                                                                         | 32   |
| 9. Map Showing the Location of Cores and Samples<br>from the Sediment Accumulated in Lake Mead . .                                                         | 36   |
| 10. Gravity Corer Being Assembled for its Trip into<br>the Accumulated Sediment . . . . .                                                                  | 38   |



## FIGURE

## PAGE

|                                                 |    |
|-------------------------------------------------|----|
| 11. Relation of Core Length to Penetration      |    |
| Depth for Gravity Core Sampler . . . . .        | 40 |
| 12. Modified Peerst Sampler Containing Sample   |    |
| From the Sediment Surface, Showing the          |    |
| Sharpness of the Water-Sediment Inter-          |    |
| face at the Bottom of the Lake . . . . .        | 47 |
| 13. Snapper Type Bottom Sampler . . . . .       | 49 |
| 14. Typical Cumulative Size-Frequency Curve for |    |
| Silt and Clay Samples from the Sediment         |    |
| Accumulated in Lake Mead . . . . .              | 64 |
| 15. Map and Cross-Sections Showing the          |    |
| Distribution of Sediment Accumulated            |    |
| in Lake Mead . . . . .                          | 70 |
| 16. Entrance of the Colorado River into         |    |
| Pierce Basin in November 1948 . . . . .         | 73 |
| 17. Underwater Photograph of the Bottom of      |    |
| Lake Mead Beyond the Margin of the Colo-        |    |
| rado Delta North of River-Mile 341 . . . . .    | 78 |
| 18. Annual Profiles of the Colorado Delta Along |    |
| the Thalweg of the Colorado River . . . . .     | 81 |
| 19. Marginal Lake Resulting from Daming of      |    |
| Tributary by Natural Levees in the Sub-         |    |
| aerial Part of the Colorado Delta . . . . .     | 85 |

| FIGURE                                                                                                                                                           | PAGE |
|------------------------------------------------------------------------------------------------------------------------------------------------------------------|------|
| 20. Close-Up View of the 1948 Terrace Being Cut<br>Back by the Colorado River in Pierce Basin . .                                                                | 87   |
| 21. Gas Pits in the 1948 Terrace near the<br>Colorado Delta Front . . . . .                                                                                      | 88   |
| 22. Close-Up View of One of the Large Gas Pits<br>Showing the Circular Orifice at the<br>Bottom of the Pit through which Gas<br>Escapes to the Surface . . . . . | 89   |
| 23. Upstream View of the 1948 Terrace in which<br>the Colorado River has Entrenched Itself . . .                                                                 | 91   |
| 24. Topographic Map of Pierce Basin . . . . .                                                                                                                    | 95   |
| 25. Structural Section of the Colorado Delta<br>Showing Relation of Bottomset Beds to<br>Topset and Foreset Beds . . . . .                                       | 116  |
| 26. The Temple in 1934 and 1948 . . . . .                                                                                                                        | 123  |
| 27. Textural Characteristics of the Surficial<br>Deposits of the Colorado Delta Along the<br>Thalweg . . . . .                                                   | 133  |
| 28. Typical Vertical Sections of the Bottomset<br>Beds of the Colorado Delta Showing the<br>Variations in Water Content and Median<br>Particle Size . . . . .    | 138  |

| FIGURE                                                                                                                                                            | PAGE |
|-------------------------------------------------------------------------------------------------------------------------------------------------------------------|------|
| 29. Section of Core from the Bottomset Beds<br>of the Colorado Delta, Showing Thin<br>Black Organic Layers and Jelly-Like<br>Character of the Material . . . . .  | 140  |
| 30. Core Section Immediately above that<br>Shown in Figure 29 . . . . .                                                                                           | 140  |
| 31. Pathograms across the Bottomset Beds of the<br>Colorado Delta Showing Their Increase in<br>Consolidation Upstream from Hoover Dam . . .                       | 147  |
| 32. Specific Weight of the Sediment Accumulated<br>in the Colorado Delta along the Thalweg . . .                                                                  | 152  |
| 33. Relation of Gas Content, Organic Content,<br>and Temperature Gradient in Longitudinal<br>Section through the Colorado Delta . . . . .                         | 160  |
| 34. Vertical Distribution of Temperature in the<br>Bottomset Beds of the Colorado Delta . . . . .                                                                 | 163  |
| 35. Lake Head Outline Map Showing the Location<br>of the Eight Areas for which Separate<br>Sediment Volume Computations have been made .                          | 184  |
| 36. Cumulative Curves Showing the Estimated<br>Average Size Distribution of the Accumu-<br>lated Sediment in Each of the Eight Se-<br>lected Lake Areas . . . . . | 190  |



## FIGURES

## PAGE

|     |                                                                                                                                                                                                            |     |
|-----|------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|-----|
| 37. | Cumulative Curves Showing the Estimated<br>Average Size Distribution of the<br>Sediment Accumulated in Several of<br>the Lake Areas Combined . . . . .                                                     | 192 |
| 38. | Relation between Computed Density of<br>the Colorado River Water at the<br>Grand Canyon Gaging Station and<br>the Arrival of Turbid Underflows at<br>the Dam . . . . .                                     | 210 |
| 39. | Distribution of Density in Vertical<br>Section of the November 1948 Underflow . . . .                                                                                                                      | 216 |
| 40. | Percentage Distribution of Sediment<br>Transported by Turbidity Currents in<br>Relation to Distance from the Eastern<br>End of the Reservoir Measured along<br>the Buried Colorado River Channel . . . . . | 218 |
| 41. | Landslide on the North Wall of Virgin<br>Canyon near its Mouth . . . . .                                                                                                                                   | 227 |
| 42. | View of a Prominent Landslide on the East<br>Side of Gregg Basin near the Mouth of<br>Hualpai Wash . . . . .                                                                                               | 229 |
| 43. | Northward View near the Apex of the Same<br>Landslide Shown in Figure 42 . . . . .                                                                                                                         | 230 |

| FIGURE                                                                                                                                                                    | PAGE |
|---------------------------------------------------------------------------------------------------------------------------------------------------------------------------|------|
| 44. Southward View of the Landslide Shown<br>in Figure 42 . . . . .                                                                                                       | 231  |
| 45. Shoreline Changes on the North Side of<br>Las Vegas Bay Resulting from Under-<br>cutting and Caving of Weakly Cemented<br>Clastics of the Muddy Creek Formation . . . | 234  |
| 46. Truncation of Steep-Sided Headlands of the<br>Muddy Creek Formation along the Shore<br>of Lake Mead Southwest of Colorado<br>River-Mile 315 . . . . .                 | 235  |
| 47. Solution and Terracing of Gypsum Reefs<br>and Low-Lying Islands on the South<br>Side of the Virgin Basin near the<br>Mouth of Detrital Wash . . . . .                 | 238  |
| 48. Solution Cavities in Interstratified<br>Siltstone and Gypsum Beds of the Muddy<br>Creek Formation in Las Vegas Bay . . . . .                                          | 239  |
| 49. Diagrammatic Representation of the Surface<br>of the Sediment Accumulated in Lake<br>Mead when Filled to the Permanent Spill-<br>way Crest at Hoover Dam . . . . .    | 253  |

| FIGURE                                                                                                                                                                                                                                                                              | PAGE |
|-------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|------|
| 50. Water Content and Specific Weight of Silt<br>and Clay, Plotted as a Function of Depth . .                                                                                                                                                                                       | 257  |
| 51. Curve Showing the Estimated Sediment Storage<br>Capacity of Lake Mead when the Accumu-<br>lated Sediment reaches the Altitude of<br>the Permanent Spillway at Hoover Dam . . . .                                                                                                | 267  |
| 52. Cumulative Curve Showing the Estimated<br>Weight of Sediment and of Coarse and<br>Fine Components when the Reservoir is<br>Filled with Sediment . . . . .                                                                                                                       | 270  |
| 53. Diagrammatic Map Showing the Bottom Topo-<br>graphy of Lake Mead at its Terminal Stage .                                                                                                                                                                                        | 295  |
| 54. Relation between Annual Runoff and Suspended<br>Sediment at the Grand Canyon Gaging<br>Station from 1926 to 1947 . . . . .                                                                                                                                                      | 302  |
| 55. Graph Summarizing the Several Estimates<br>of Time when the Sediment Surface at<br>Hoover Dam will reach the Lower Intake<br>Gates (895 Feet Altitude), the Upper<br>Intake Gates (1,045 Feet Altitude), and<br>the Permanent Spillway Crest (1,205 Feet<br>Altitude) . . . . . | 306  |



Lake Mead, created in 1935 by the construction of Hoover Dam on the Colorado River, is the site of deposition of most of the sediment that formerly accumulated in the Colorado delta at the head of the Gulf of California. In 1948, an intensive investigation of the lake and its accumulated sediment was undertaken by the U. S. Geological Survey in cooperation with the U. S. Bureau of Reclamation, the U. S. Navy Department, the U. S. Coast and Geodetic Survey, and the Scripps Institution of Oceanography.

The primary purpose of this investigation was to determine the amount and rate of sediment accumulation in the lake during the first 14 years (1935-1948) of its existence and to evaluate insofar as possible the effect of sedimentation (both present and future) on the normal functions of Lake Mead and Hoover Dam: that is, of controlling floods, supplying water, and producing electrical energy. A further objective was to obtain fundamental data on the physical, chemical, and biochemical properties of the sediment and on the processes of sedimentation so that the results could be applied to other lakes and reservoirs and to a variety of geologic problems of broad scope.

To determine the distribution and volume of the accumulated sediment, the lake bottom was surveyed with recording echo-sounding equipment. The resulting topographic

map was then compared with the pre-Lake Mead map, and the volume of accumulated sediment was computed.

In order to obtain a representative picture of the sediment accumulation, it was systematically cored and sampled. Altogether 46 cores and more than 300 samples were collected. Counting the cores, which were cut into small segments, a total of 1806 samples were studied in the laboratory. Routine analyses of water content, specific weight and color were made of all samples. Other analyses, including mechanical composition, grain specific gravity, gas content and composition, chemical composition, clay mineral composition, and spectrographic and x-ray analyses were made of fewer samples, carefully selected, however, in order to provide representative material from the sediment accumulation as a whole.

The major results and conclusions of this study are as follows:

1. During the 14-year period, 1933-47, approximately 1,426,000 acre-feet, or almost one-half cubic mile of sediment has accumulated in Lake Mead. This has reduced the total water-storage capacity below the altitude of the permanent spillway crest by about 5 percent.

2. The total weight of the sediment accumulation is estimated at 2.014 billion tons, representing an average

annual rate of sedimentation of 144 million tons.

3. This material forms two deltas, one built by the Colorado River, and the other, much smaller, built by the Virgin River. The Colorado delta extends the entire length of the lake, a distance of 120 miles measured along the submerged course of the Colorado River, whereas the Virgin delta is restricted chiefly to the upper 14 miles of the inundated Virgin River valley.

4. Of the total volume of sediment, more than 97 percent is in the Colorado delta, and less than 3 percent is in the Virgin delta.

5. In structure the Lake Mead deltas are similar to those formed in other lakes, being composed of topset, foreset, and bottomset beds and of particles which grade from coarse to fine with increasing distance from the river mouths.

6. The topset and foreset members are composed chiefly of sand which is deposited directly by the river. In contrast, the bottomset beds are composed of silt and clay carried into the lake by turbidity currents. Approximately 30 percent of the entire accumulation has been transported and deposited by turbidity currents.

7. Approximately 10 percent of the total weight of the accumulated sediment consists of calcium carbonate. Of

the total amount of calcium carbonate, 5 percent has been precipitated from the lake water and 95 percent has been carried into the lake in the detrital load of the Colorado River.

8. The content of organic material in the bottomset beds of the Colorado delta averages 0.93 percent, whereas that of the topset and foreset beds averages 0.14 percent. The considerable amount of organic material in the bottomset beds has given rise to a large bacteria population which approximates that found in raw sewage. As a result of bacterial activity, an appreciable amount of gas (chiefly methane) is being produced from the decomposition of organic matter. Bacterial activity also appears to be chiefly responsible for heating of the bottomset beds.

9. Studies of the mass chemical properties of the Colorado delta show that the bottomset beds are made up chiefly of hydrous aluminum silicates and hydroxides of iron and aluminum, whereas the topset beds consist predominantly of detrital fragments of quartz. Likewise, the foreset beds are made up chiefly of quartz, but they are slightly higher in hydrous silicates and hydroxides than the topset beds. The composition of the topset beds is similar to the average composition of river sands,



and the composition of the bottomset beds corresponds closely with the average composition of shales. The estimated average composition of all the sediment in the Colorado delta corresponds closely with the average composition of samples from the Mississippi delta.

10. The life expectancy of Lake Mead, based on considerations of future sediment compaction, sediment-storage capacity of the reservoir, and various rates of sedimentation, is estimated at 325 to 520 years. These estimates are based on the assumption that no sediment will be passed through the dam and that no additional regulatory storage will be in effect upstream. However, if sediment is regularly and intentionally passed through the dam and if upstream reservoirs are constructed, the "life" of Lake Mead will be increased many centuries.

11. The total weight of mineral particles deposited in Lake Mead from 1935 to 1948, together with the total weight of dissolved solids transported into the lake during this interval is estimated at 2.16 billion tons. This value provides a rather accurate estimate of the average rate of erosion from the drainage basin tributary to Lake Mead. According to this estimate, a layer of soil with an assumed porosity of 50 percent and an average thickness of 0.113 inch has been removed from the basin from 1935 to 1948. If

this rate were to continue in the future, a layer of soil with an average thickness of 1 foot would be removed every 1,260 years. Expressed in terms of unweathered rock with an assumed porosity of 15 percent, the entire area (168,000 square miles) of the tributary basin would be lowered by erosion 1 foot every 2,150 years.

# INTRODUCTION

Lake Mead, created by the construction of Hoover Dam, is located on the Colorado River approximately 430 miles above its mouth on the Gulf of California and about 960 miles below its headwaters in north-central Colorado (Fig. 1). It receives the total discharge of water and sediment from 69 percent of the Colorado River drainage basin, comprising 168,000 square miles or about 5 percent of the continental area of the United States.

This area includes portions of five of the physiographic provinces outlined by Kenneman (1935, pl. 1): (1) the Middle Rocky Mountain Province, (2) the Wyoming Basin, (3) the Southern Rocky Mountain Province, (4) the Colorado Plateau Province, and (5) the Basin and Range Province.

Probably no region of comparable size in the United States exhibits greater relief or more diverse lithology. It has an average altitude of more than 7,000 feet and consists of igneous, metamorphic, and sedimentary rocks which range in age from pre-Cambrian to Recent.

Owing chiefly to the higher relief and greater rainfall, the area above Hoover Dam furnishes somewhat more than 69 percent of the water and sediment supplied by the Colorado River drainage basin as a whole. The water



FIGURE 1

LOCATION MAP SHOWING THE RELATION OF LAKE MEAD  
TO THE COLORADO RIVER BASIN

Dotted line denotes the southern boundary of that portion of the basin which is tributary to Lake Mead. Map taken in part from U. S. Bureau of Reclamation, The Colorado River, p. 62, 1946.



delivered to the lake is stored only temporarily, but the sediment is permanently deposited. Thus, a very large proportion of the detritus that was formerly deposited in the Colorado delta at the head of the Gulf of California is now accumulating in Lake Mead.

Most of the water and sediment is furnished by the Colorado River, but minor amounts are also supplied by the Virgin and Muddy Rivers. All other valleys tributary to Lake Mead are normally dry and furnish runoff only during exceptional floods.

#### Scope of the Investigation

Since the beginning of water storage behind Hoover Dam on February 1, 1935, engineers and geologists alike have been interested in the rate of sediment accumulation in the lake and the processes by which the sediment is transported, deposited, and compacted. Engineers are interested in the sedimentary processes primarily as they are related to reservoir utilization and to the planning of future reservoirs, whereas geologists are most concerned with understanding these processes in order to interpret their action on similar sediments in the past and to provide a basis for predicting their action in the future.

Moreover, the sediments accumulated in Lake Mead give the geologist an unusual opportunity to determine with

considerable precision the rate of erosion from a significant portion of the United States, an area which for the most part is still in its youthful stage of dissection. Of still further interest are the mass physical and chemical properties of the accumulated sediment because they furnish valuable quantitative information on the changes that accompany large scale transformation of lithified strata into fine sedimentary debris.

The soil conservationist is interested in these same properties, but from quite a different point of view. He is more directly concerned with the destruction of fertile soils by erosive processes and the effects of this destruction on the economic and cultural development of the Colorado River drainage basin.

Finally, there has been a great deal of interest concerning the effect of Hoover Dam and Lake Mead on the sedimentary processes in downstream areas of the Colorado River, particularly in the Colorado delta at the head of the Gulf of California. For many thousands of years prior to the construction of Hoover Dam, the products of erosion derived from the Colorado River drainage basin had accumulated in this delta. With the closure of the diversion tunnels around Hoover Dam in 1935, Sykes (1937, p. 174) and others predicted that the Colorado River channel downstream

from Lake Mead would undergo considerable adjustment and that the growth of the Colorado delta as a major phenomenon would rapidly come to an end.

By the fall of 1947, almost 13 years after the inception of Lake Mead, a considerable quantity of sediment had accumulated in the reservoir resulting in an appreciable reduction in its water storage capacity. However, neither the quantity of sediment nor the amount of water storage reduction were known with sufficient accuracy to permit the most efficient and economical operation of the reservoir. Area-capacity curves<sup>1</sup> based on the original dimensions of the reservoir were far outdated, and new, accurate data were badly needed. In order to obtain this information and also to determine the relationship of sedimentation in Lake Mead to the broader problems outlined above, the U. S. Bureau of Reclamation requested the U. S. Geological Survey to undertake an intensive investigation of the lake sediments and the processes affecting their deposition and compaction.

Because of its great diversification, this investi-

---

<sup>1</sup>Area-capacity curves are graphic plots of reservoir level versus water surface area and water storage capacity. By use of these graphs, the area of the water surface and the reservoir storage capacity may be readily determined for any particular water level.

gation required the services of the Water Resources, Topographic, and Geologic Divisions of the Survey and the active assistance and cooperation of the U. S. Navy and the Scripps Institution of Oceanography. The Topographic Division assumed the responsibility of establishing a horizontal control network for use in locating field positions. Mapping of the lake bottom was undertaken jointly by the Water Resources Division of the Survey and the U. S. Navy. The Water Resources Division also assumed the task of preparing new area-capacity curves for the reservoir. A study of the physical and chemical properties of the lake water was undertaken jointly by the U. S. Navy Electronics Laboratory and the U. S. Geological Survey. Investigation of the characteristics of the accumulated sediment and the processes of sedimentation in Lake Mead was carried out by the Geologic Division of the Survey with the assistance of the Water Resources Division and the U. S. Navy. As a part of these studies, the Microbiology Division of the Scripps Institution of Oceanography investigated the bacteria in the bottom sediments. This report describes the work of the Geologic Division which was undertaken by the writer under the general supervision of Charles B. Hunt and Roger B. Morrison.

In this study 46 cores and more than 300 samples of



the lake sediments were obtained and their physical and chemical properties measured. Observations were made of the alteration of the reservoir boundary by chemical solution and precipitation, wave erosion, sliding, and slumping. Turbidity currents, which have been active agents of sediment transportation in Lake Mead since its inception, were also studied throughout the field period.

#### Previous Work

The history of geologic investigations in the Lake Mead area began with the exploration of the lower Colorado River by Ives (1861) almost a century ago. Starting from the head of the Gulf of California in December 1857, he and his party navigated the Colorado River to the mouth of Las Vegas Wash about 6 miles north of the site of Hoover Dam. In his account of this part of the Lake Mead area, Ives was particularly impressed with the narrowness of Black Canyon, its numerous rapids, swift water and sheer walls, and with the vivid colors of the volcanic rocks in the southeastern part of the Boulder Basin.

In 1869, Powell (1875) and his party on their famous expedition through the Grand Canyon reached the Lake Mead area. Powell includes a general description of the physiographic features of the area adjacent to the Colorado River between Bridge Canyon and the mouth of the Virgin River

where he left the expedition. In 1871 a party from the Wheeler (1889, pp. 152-171) expedition ascended the Colorado River from Fort Mojave to Diamond Creek, 52 miles above the mouth of the Grand Canyon. G. K. Gilbert, who was a member of this party, described the rocks in Black, Boulder and Virgin Canyons and included a stratigraphic section of the rocks exposed near the mouth of the Grand Canyon (Wheeler, 1875).

A few years later Eutton (1882, pp. 10-11) presented a brief account of the physiographic features and a description of the rocks of the Grand Wash Cliffs that mark the western boundary of the Colorado Plateau Province in the Lake Mead area. Shortly after the turn of the century, Spurr (1903, pp. 131-139) made a reconnaissance of the geology of the Virgin and Muddy Mountains in the vicinity of Lake Mead.

Beginning with the studies of Lee (1908) the geological investigations in the Lake Mead area have been pursued in considerably greater detail, and most of them have been directly or indirectly related to the U. S. Bureau of Reclamation's program of controlling and utilizing the water of the Colorado River. Although Lee's studies were of a preliminary nature, designed in part to investigate various reservoir sites, his work represents the first

serious attempt to untangle the complex geologic history of the area along the Colorado River between the Grand Wash Cliffs and Hoover Dam.

Following the work of Lee, the U. S. Bureau of Reclamation in cooperation with the U. S. Geological Survey undertook an intensive investigation of the region bordering the Colorado River for the purpose of locating and evaluating dam sites. The results of some of these studies have been reported by LaRue (1925), and an excellent description of the rocks of the inner gorge of the Grand Canyon between Bridge Canyon and Pierce Basin is presented by H. C. Moore in an appendix to LaRue's report. As a part of these studies, Hanson (1923, 1930) mapped in detail the rocks exposed in Boulder and Black Canyons and carried out an investigation of the salt deposits in the Overton Arm and Virgin Basin of Lake Mead.

C. P. Berkey and W. J. Mead, as members of the Colorado River Board, collaborated in these studies which led to the selection of the Black Canyon dam site, and Berkey was retained as a consultant by the U. S. Bureau of Reclamation during the construction of Hoover Dam. A thorough account of the geologic investigations prior to the selection of the dam site and during the construction

period is contained in the final reports of the Boulder Canyon Project (U. S. Bureau of Reclamation, 1950).

Closely allied to these investigations are the detailed geologic studies of the Muddy Mountains and surrounding areas in the Lake Mead region undertaken by Longwell (1928) in 1919. During the winter and spring of 1934 he (Longwell, 1936) carried out a careful systematic study of the geology of the reservoir floor between Hoover Dam and the Grand Wash Cliffs which in less than a year was to be covered by Lake Mead. His detailed maps and informative account of the geologic features of the original reservoir floor have been of considerable aid to the writer in interpreting subsequent changes in the bottom of Lake Mead.

Prior to 1935, the most accurate topographic maps available were those prepared by the U. S. Bureau of Reclamation and the U. S. Geological Survey in 1922 and 1923 as part of a series entitled "Plan and Profile of the Colorado River from Lee's Ferry, Arizona, to Black Canyon, Arizona-Nevada, and Virgin River, Nevada". These maps have a contour interval of 50 feet on a scale of 2 inches to the mile, and in the Lake Mead region cover all of the area below an altitude of 1250 feet. In addition, a topographic map covering about 15 square miles around Hoover Dam on a



scale of 1 inch to 400 feet and a contour interval of 5 feet was prepared by Brock and Weymouth in 1930.

The original capacity of the reservoir had been computed from measured areas on the "Plan and Profile Topographic sheets", but because of their wide contour interval and small scale, the accuracy of the computed capacity was in question. To insure the most efficient operation of the reservoir and to provide an adequate basis for future measurements of storage loss resulting from sediment accumulation, a more precise estimate of the original reservoir capacity was needed. This required remapping of the reservoir bottom and construction of more accurate topographic sheets. An interesting account of these investigations, undertaken jointly by Fairchild Aerial Surveys, the U. S. Soil Conservation Service, and the U. S. Bureau of Reclamation in 1935, has been presented by Brown (1941). With the exception of a small region in the southwestern part of Boulder Basin the new set of topographic maps based on this survey covers all the area below an altitude of 1,400 feet between Hoover Dam and Colorado River-mile 222, 13 miles upstream from the eastern end of Lake Mead. Altogether, there are 47 5-minute quadrangle sheets with a contour interval of 10 feet on a scale of 1 : 12,000. These maps were used extensively in the 1943 survey both as an

aid to navigation and as a basis for computing the volume of the sediment accumulated in Lake Mead.

Investigations since the flooding of the reservoir have been concerned mainly with the transportation and accumulation of sediment in the lake and with the circulation and chemical properties of the lake water. In 1936 the U. S. Bureau of Reclamation began an investigation of the water characteristics and the surficial sediment layer at a station immediately upstream from Hoover Dam, and in 1937 this program was expanded to include similar observations at five stations along the length of the reservoir. Data collected at these stations between the summer of 1937 and the fall of 1946 appear in three volumes recently published by the U. S. Bureau of Reclamation (1941, 1947), and the records of subsequent years are available in unpublished reports of the U. S. Bureau of Reclamation. These reports contain a wealth of data on turbidity currents in Lake Mead, a part of which have been analyzed by Bell (1942 a and b).

Closely allied to these investigations are the observations made by the U. S. Geological Survey of the water discharge and suspended sediment carried by the Colorado River past the Grand Canyon gaging station (Howard, 1947), about 265 miles above Hoover Dam, and the Willow Beach gaging station, 10 miles below the dam. It was on the

basis of records from these stations that Grever and Howard (1938) first detected turbidity currents in Lake Mead.

From 1935 to 1948, the U. S. Coast and Geodetic Survey in cooperation with the U. S. Bureau of Reclamation has carried out an investigation of local seismic activity and subsidence in the Lake Mead area. The results of various parts of this study have been described in the final reports of the Boulder Canyon Project (U. S. Bureau of Reclamation, 1939) and in subsequent papers by Mead and Carder (1941), Jones (1942), Carder (1945), and Carder and Small (1948).

The latest accounts (Carder, 1945; Carder and Small, 1948) show a concentration of epicenters of several hundred local earthquakes in the Boulder Basin and a less prominent concentration in the Gregg Basin of Lake Mead. It was concluded from these studies that the local earthquakes in the Boulder Basin were caused by downfaulting of an underlying crustal block along previously established fault planes which were probably active in pre-Pleistocene time. The renewed activity has been ascribed to the sudden loading of about 12 billion tons of water on the floor of the Boulder Basin. Likewise, the earthquakes in the Gregg Basin are caused apparently by local subsidence, but the relation between settling and reservoir loading is not so

clearly defined as in the Boulder Basin.

A net of first-order levels established by the U. S. Coast and Geodetic Survey in 1935 was rerun in 1941 when the lake was filled to near capacity. The results of this study show a general subsidence of the reservoir floor which reached a maximum of 12 centimeters in the northwestern part of the Virgin Basin. Carder (1945) suggests that this subsidence resulted from the weight of the overlying water, which has been estimated at 41.5 billion tons (U. S. Bureau of Reclamation, 1939) when the reservoir is filled to capacity. This level net was rerun again in 1949, but no published account of the results is yet available.

#### Acknowledgments

The writer wishes to express his appreciation to F. C. Ames, F. W. Kennon, and G. O. Crouch, Tennessee Valley Authority employee on loan to the Water Resources Division of the U. S. Geological Survey for their helpful assistance throughout the field period and for providing information on the storage capacity of various selected areas in Lake Mead. He is particularly indebted to Irving Sherman of the Water Resources Division and to Forrest Hoover of the U. S. Bureau of Reclamation for their valuable help in the laboratory and in the field. A. D. Gilger and W. B. Norwood also gave important assistance in the field study. Acknowledgment is due the personnel of



the U. S. Navy under the command of Lieutenant G. C. McCall for their cooperation and assistance in obtaining cores from the sediment accumulated in Lake Mead. The cooperative interest of C. P. Vetter, J. W. Stanley, C. C. Heddens, and many other members of the U. S. Bureau of Reclamation greatly expedited field work. Grateful appreciation is extended to the Allan Hancock Foundation and the Department of Geology of the University of Southern California for providing laboratory facilities and office space following the completion of field work. Most of the drawings for the report were prepared by K. H. Koford. Finally, I wish especially to express my indebtedness to K. C. Emery, H. E. Morrison, and C. B. Hunt for their many valuable suggestions throughout the course of the study and for their critical reading of this report. Particular gratitude is due, also, to Thomas Clements, W. B. Easton, H. H. Merriam, G. L. Sandy, D. A. McNaughton, and J. W. Reith who read and criticized the report.

## THE LAKE

### Dimensions

In discussing the original dimensions and configuration of Lake Mead, it is convenient to assume that the filling of the reservoir was rapid and that the accumulation of sediment during this period did not reduce its dimensions appreciably. As shown in figure 2, however, the reservoir was not completely filled until the summer of 1941, 6½ years after water was initially impounded behind Hoover Dam. During this period a considerable quantity of sediment accumulated in the reservoir, resulting in a reduction of its dimensions. Nevertheless, the above assumption seems necessary to avoid making a complicated distinction between the initial dimensions of the reservoir (before filling) and the initial dimensions of Lake Mead (after filling).

The top of Hoover Dam, located about 600 feet above the stream bed in Black Canyon, is at an altitude of 1,232 feet. The water in the reservoir can approach this height, but it does not generally exceed the altitude of the permanent spillway crest (1,205.4 feet). At this stage, the lake initially inundated an area of 142,500 acres (232.0 square miles) and had a capacity of 28,7¼,000 acre-feet

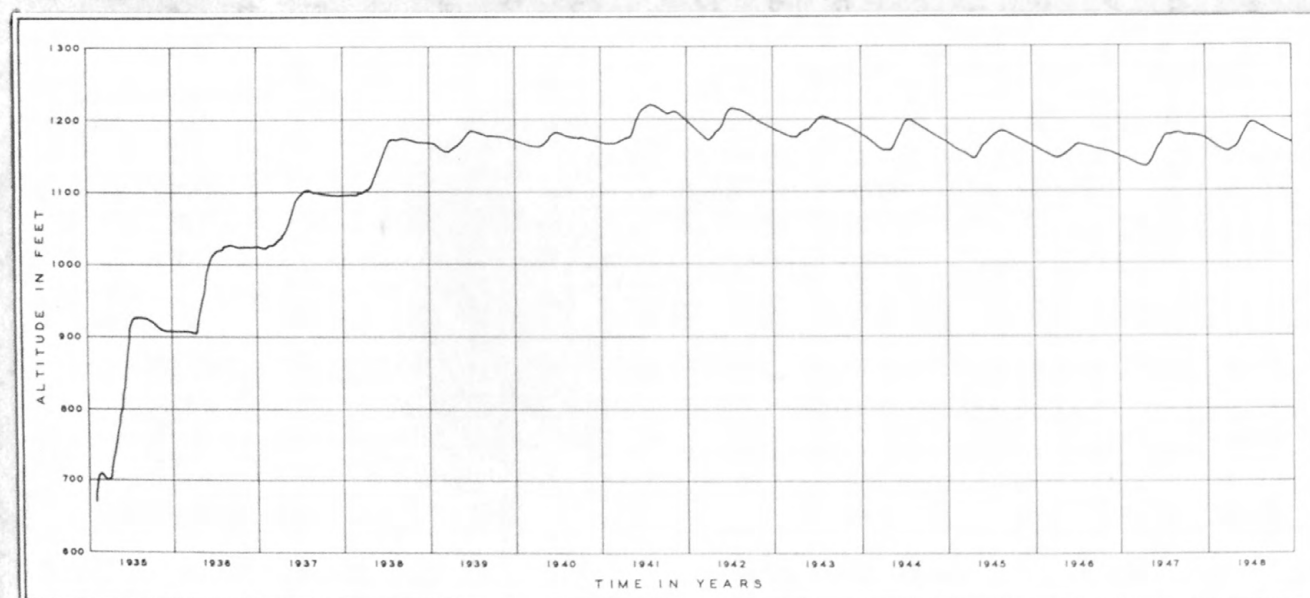


FIGURE 2

LAKE STAGE HYDROGRAPH, 1935-1948  
Data plotted from U. S. Bureau of Reclamation records.

(8.5 cubic miles).

In outline, the lake has roughly the shape of an inverted "T", the inundated area along the Colorado River corresponding to the cross of the "T" and the submerged Virgin River valley forming its stem (fig. 3). Initially, the lake covered approximately 120 miles of the Colorado River channel and the lower 35 miles of the Virgin River channel.

Because of the rapid rate of sediment accumulation, the initial dimensions of Lake Mead have been somewhat reduced. By December 1948, the eastern 43 miles of the lake, occupying the narrow Lower Granite Gorge of the Grand Canyon, had been filled with sediment to a slightly higher altitude than the mean operating level of the reservoir (approximately 1,170 feet). Consequently, this part of the lake has reverted to fluvial conditions, and the Colorado River in 1948 entered the lake in Pierce Basin, 43 miles west of its former entrance at Bridge Canyon. Similarly, the northward extension of the lake has been shortened about 5 miles by the accumulation of sediment at the mouth of the Virgin River.

Measured from the altitude of the permanent spillway crest (1,205.4 feet), the maximum depth of the lake immediately upstream from Hoover Dam has been reduced from 575



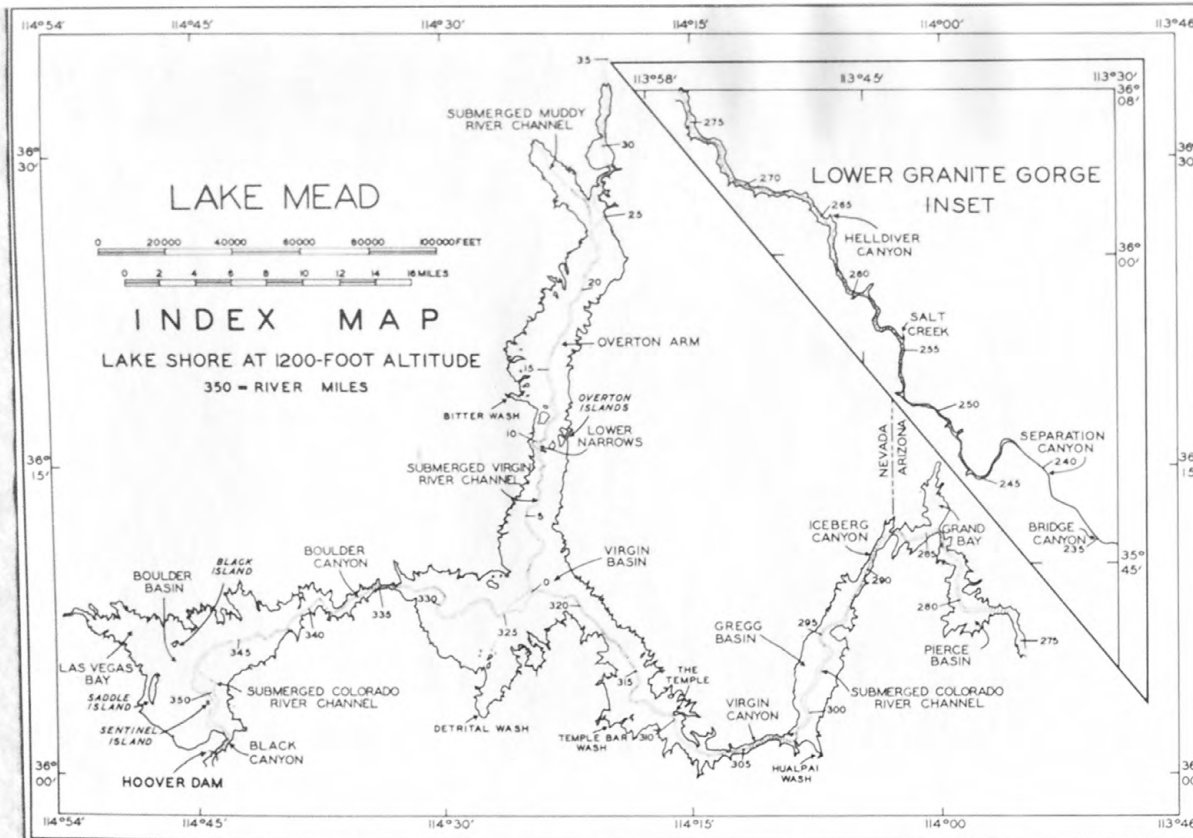


FIGURE 3

INDEX MAP SHOWING THE VARIOUS BASINS AND CANYONS OF LAKE MEAD  
AND THEIR RELATION TO THE INUNDATED COLORADO AND VIRGIN RIVER CHANNELS

River-miles along the Colorado River are measured downstream from the U. S. Geological Survey concrete gage well opposite the mouth of the Paria River, Arizona. River-miles along the Virgin River are measured upstream from its former junction with the Colorado River.

feet to 470 feet, and the original mean depth of the entire lake has decreased from 194 feet to 185 feet.

#### Bottom Topography and Lithology

The physiographic features and lithology of the original lake bottom have been thoroughly investigated and described by Longwell (1936), and it is largely from this source that the following summary is compiled.

The greater part of Lake Mead is located in the Basin and Range Province, but the eastern 43 mile section is situated in the western part of the Colorado Plateau Province. Marking the boundary between these major physiographic units are the Grand Wash Cliffs, an impressive escarpment which towers almost 4,000 feet above the lake surface (fig. 4). The face of the Grand Wash Cliffs is highly dissected by numerous small stream valleys, but the greatest chasm, the Lower Granite Gorge of the Grand Canyon, has been cut by the Colorado River. The easternmost 43 miles of the lake is contained in this gorge, the walls of which rise precipitously to an altitude of 5,000 feet or more. The rocks bounding the lake in this region consist of pre-Cambrian gneiss, schist, and coarse-grained igneous rocks, overlain by a thick section of Paleozoic formations. Above the bedrock in the bottom of the canyon is an unconsolidated Recent fill of silt, sand, and gravel that was



FIGURE 4

THE GRAND WASH CLIFFS VIEWED FROM PIERCE BASIN

deposited in the Colorado River channel before the inception of Lake Mead. In the eastern part of the gorge between Bridge Canyon and Separation Canyon this deposit ranges in thickness from 8 feet to 17 feet (Murdoch, 1942). The occurrence of unconsolidated materials in a river of such size and gradient (approximately 7 feet per mile in the lower Granite Gorge) is truly remarkable. However, this occurrence corresponds to similar conditions at numerous other points along the Colorado River which indicates that the river throughout most of its course does not flow on bedrock. Originally the width of this part of the lake ranged from approximately 200 feet near Bridge Canyon to more than 2,000 feet at the Grand Wash Cliffs, and its depth ranged from 9 to 300 feet.

Directly west of the Grand Wash Cliffs and extending to Hoover Dam the lake lies entirely within the Basin and Range Province. The general north-south trend of the mountain ranges and the intervening basins is strikingly reflected in the irregular configuration of Lake Mead. In the mountainous regions the lake is restricted to narrow canyons excavated by the Colorado and Virgin Rivers, but in the intermontane basins the lake spreads out into a series of broad pools connected by the intervening canyons (fig. 3). The width of this part of Lake Mead ranges from less



than 700 feet near the head of Boulder Canyon to more than 3 miles in the Virgin Basin (fig. 5).

The rocks of the canyon areas are older and more resistant than those of the basin areas which consist chiefly of weak sedimentary beds derived in part from erosion of the adjacent mountains. In the canyon areas the lake is bounded by steep walls which rise in some places more than 1,500 feet above the water surface. In contrast, the topography in the basins consists chiefly of low hills, small sharply-incised valleys, and broad alluvial slopes of moderate gradient. Superimposed on these features are numerous remnants of stream terraces cut by the Colorado River as it lowered its bed from previously higher levels. Locally, differential erosion of more resistant strata in the basins has resulted in the formation of isolated relief features, some of which project above the lake surface as islands and others that remain as shallow reefs below the surface. Most prominent among the islands are Sentinel Island (formerly known as Fortification Rock), Saddle Island, and Black Island, in the Boulder Basin; the Overton Islands at the Lower Narrows of the Overton Arm; and the unnamed islands in the Virgin Basin a few miles west of the former junction of the Colorado and Virgin Rivers. The most extensive of the reefs consist of bedded gypsum



FIGURE 5

AERIAL VIEW OF BOULDER CANYON AND VIRGIN BASIN

The Virgin River valley is to the left in the background. At the top of the photograph are the Virgin Mountains and the Grand Wash Cliffs. U. S. Bureau of Reclamation photograph.

deposits in the southern part of the Virgin Basin and gypsum and conglomerate-capped banks in Las Vegas Bay.

Within the basins the Colorado and Virgin Rivers have entrenched themselves in inner valleys, falling by a series of terraces to flood plains paralleling their channels. To the sedimentologist these through-going channels and inner-valleys are the most significant topographic features of the reservoir floor, because they are the routes along which large quantities of fine sediment are transported to the deepest parts of the reservoir.

In the deep narrow canyons of the lake the channels are, in places, less than 300 feet wide, and are bordered by almost vertical walls. In the broad basins, however, the river beds are many hundreds of feet wide, attaining a width of more than three-quarters of a mile in parts of the Virgin and Boulder Basins.

The rocks in the canyon areas are of all types, igneous, metamorphic, and sedimentary and range in age from pre-Cambrian to Recent. The steep walls bordering the lake in Virgin Canyon consist of pre-Cambrian schist, gneiss, and coarse-grained igneous rocks very similar to those underlying the lake near the mouth of the Lower Granite Gorge. The south wall of Boulder Canyon also consists of pre-Cambrian igneous and metamorphic rocks, whereas



the north wall is composed chiefly of highly altered Tertiary volcanic and sedimentary beds.

Iceberg Canyon, on the other hand, is aligned along a strike fault cutting across a thick section of steeply dipping pre-Cambrian schists and granites and sedimentary formations of Paleozoic age. The Paleozoic rocks consist chiefly of resistant limestone and lesser amounts of sandstone and shale. Pennsylvanian and Mississippian strata with an eastward dip of approximately 70 degrees form the west wall of the canyon (fig. 6). Differential erosion of these beds has given them an extremely ragged appearance, from which the name, Iceberg Canyon, has been derived.

In Black Canyon (fig. 7) the lake is bounded by steep walls of Tertiary andesitic lava flows and volcanic breccias locally interbedded with buffaceous sandstones and intruded by rocks of dioritic and basaltic composition.

Like the Lower Granite Gorge, all of these canyons are floored with unconsolidated Recent sediments which were deposited on the bedrock of the Colorado River channel prior to the formation of Lake Mead. In Boulder Canyon the unconsolidated fill has a maximum thickness of 151 feet, and in Black Canyon it is about 100 feet thick (U. S. Bureau of Reclamation, 1950). During the construction of Hoover Dam a sand timber was discovered about 50 feet above the





FIGURE 6

STEEPLY DIPPING PENNSYLVANIAN AND MISSISSIPPIAN STRATA  
NEAR THE HEAD OF ICEBERG CANYON (COLORADO RIVER-MILE 287)  
U. S. Bureau of Reclamation photograph

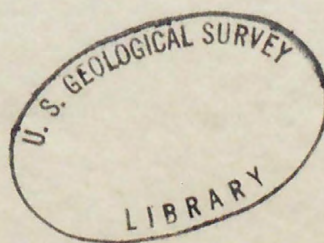






FIGURE 7

BLACK CANYON AND BOULDER BASIN VIEWED FROM THE AIR  
Sentinel Island appears at the left, and the mouth of  
Boulder Canyon may be seen in the distance. The tilted ba-  
salt capped block at the right is Fortification Hill. U. S.  
Bureau of Reclamation photograph.

bottom of the fill, thus indicating that at least the upper 50 feet of the unconsolidated debris had been reworked in recent times, probably during periods of great floods on the Colorado River.

In contrast to the older resistant rocks of the canyon areas, the rocks of the basin areas consist almost entirely of weak formations of Tertiary age overlain in many places by Quaternary river gravels and alluvium. The Tertiary formations are highly varied in lithology and thickness and exhibit marked changes in texture both vertically and laterally. They consist of clastics of all sorts; conglomerates, breccias, siltstones, and clays interbedded with great quantities of salt, gypsum, and fresh water limestone. Lava flows, volcanic breccias, and volcanic ash interbedded with the sediments are also widespread. According to Longwell (1936, p. 1413) these materials accumulated in interior basins bounded by steep mountain slopes, whereas the Quaternary terrace gravels and alluvium were deposited by a through-flowing stream.

From the point of view of the present studies the poorly consolidated Tertiary and Quaternary deposits are of the greatest interest because of their ease of erosion by shore action. Likewise, the extensive deposits of gypsum and the more limited outcrops of other salines are of



critical interest because of their susceptibility to solution by the water passing through Lake Mead. Gypsum deposits are widely distributed throughout the Virgin Basin, Overton Arm, Las Vegas Bay, and the northern part of the Boulder Basin. In the southern part of the Virgin Basin these beds have a total thickness of 400 to 500 feet, but in other areas they are rarely more than 25 feet thick. Outcrops of rock salt on the reservoir floor are much less extensive, being confined to several isolated areas in the Overton Arm and Virgin Basin north of the Colorado River channel.



## METHODS OF INVESTIGATION

### Field Work

The field work upon which this report is based began in December 1947 and was completed in April 1949. Unlike the conventional geological studies that utilize standard geologic methods, the Lake Mead investigations required the use of modern oceanographic equipment and techniques. Much of this equipment, including three plane-personnel boats, a picket boat, and a pontoon barge were furnished to the project by the U. S. Navy. Two of the plane-personnel boats were used principally for the transportation of field party members and for shore studies, whereas the third was equipped for light hydrographic work. This boat (fig. 6) 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. The picket boat, fitted with recording echo-sounding equipment, was engaged primarily in obtaining profiles of the lake bottom. It is on the basis of these profiles, supplemented with numerous line soundings and bottom samples, that the areal distribution and surface features of the accumulated sediment were determined. The pontoon barge, which was equipped with powerful winches and a boom capable of handling heavy



FIGURE 8

U. S. NAVY PLANE PERSONNEL BOAT RIGGED  
FOR LIGHT HYDROGRAPHIC WORK  
U. S. Bureau of Reclamation photograph



coring devices, was used in obtaining cores from the accumulated sediment.

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

#### Collection of Cores and Samples

Preliminary soundings and samples from the bottom of Lake Mead, together with data collected by the U. S. Bureau of Reclamation (1941, 1947) prior to 1947, showed that most of the sediment in the lake had accumulated in the region 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 as a whole, it was systematically cored and sampled. Altogether 46 cores and more than 300 samples were collected. For convenience in handling and to preserve the sediment in its natural state, the cores were cut into segments, ranging from 6 to 12 inches in length,

and stored in airtight containers. Counting the core segments, a total of 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 1, and the locations of all coring and sampling positions are shown in figure 9.

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

In contrast, the sediment between Pierce Basin and Hoover Dam is made up chiefly of soft mud which could be readily sampled at depth. At most stations in Boulder Basin and Virgin Basin, cores were obtained from the total thickness of the accumulated sediment, but cores from the lower part of the deposit were obtained only in a few places farther east. In some areas compact layers of silt and sand, contributed by slumping of the reservoir walls, or deposited by the Colorado River during the initial



TABLE 1  
Distribution of cores and samples from the  
sediment accumulated in Lake Mead

| Coring or<br>sampling<br>instrument | Sampling areas and number of cores and samples |               |                |              |                 |               |             |                                    |                     |             |              |
|-------------------------------------|------------------------------------------------|---------------|----------------|--------------|-----------------|---------------|-------------|------------------------------------|---------------------|-------------|--------------|
|                                     | Black Canyon                                   | Boulder Basin | Boulder Canyon | Virgin Basin | Temple Bar Area | Virgin Canyon | Gregg Basin | Iceberg Canyon<br>and Pierce Basin | Lower Granite Gorge | Overton Arm | Total        |
| Gravity<br>corer                    | 15<br>(1)                                      | 148<br>(5)    | 59<br>(2)      | 184<br>(10)  | 68<br>(3)       | 68<br>(2)     | 114<br>(5)  | 213<br>(7)                         | 0                   | 12<br>(3)   | 881<br>(38)  |
| Piston<br>corer                     | 0                                              | 153<br>(2)    | 78<br>(1)      | 68<br>(1)    | 75<br>(1)       | 0             | 0           | 243<br>(3)                         | 0                   | 0           | 617<br>(8)   |
| Foerst<br>sampler                   | 44                                             | 41            | 26             | 41           | 16              | 23            | 31          | 48                                 | 0                   | 0           | 270          |
| Snapper<br>sampler                  | 1                                              | 0             | 1              | 2            | 0               | 0             | 0           | 3                                  | 0                   | 18          | 25           |
| Dipper                              | 0                                              | 0             | 0              | 0            | 0               | 0             | 0           | 0                                  | 9                   | 0           | 9            |
| Pick                                | 0                                              | 0             | 0              | 0            | 0               | 0             | 0           | 0                                  | 4                   | 0           | 4            |
| Total                               | 60<br>(1)                                      | 342<br>(7)    | 164<br>(3)     | 295<br>(11)  | 159<br>(4)      | 91<br>(2)     | 145<br>(5)  | 507<br>(10)                        | 13                  | 30<br>(3)   | 1806<br>(46) |

Figures in parentheses indicate number of cores.

114°00'

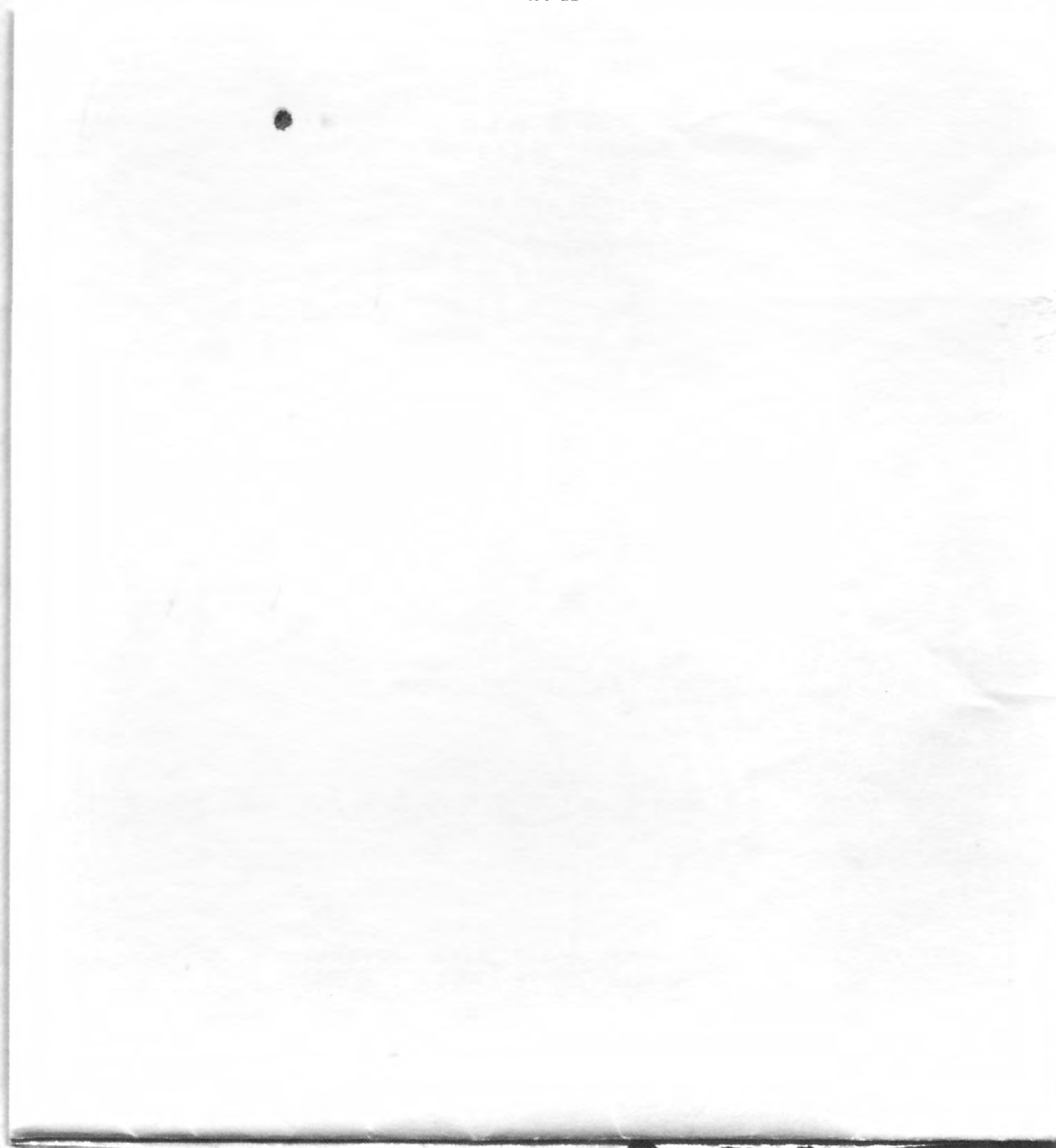
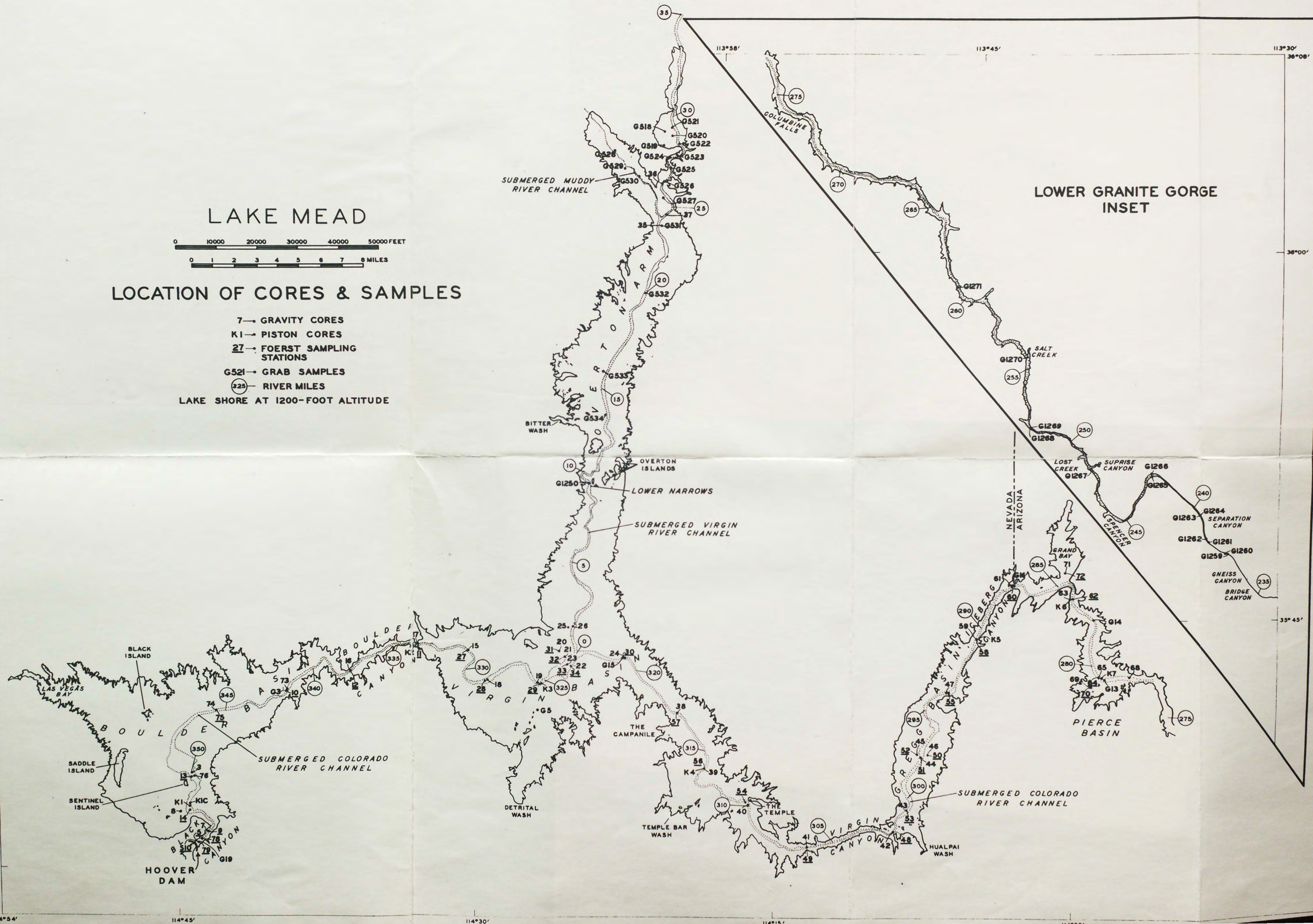


FIGURE 9

MAP SHOWING THE LOCATION OF CORES AND SAMPLES FROM THE  
SEDIMENT ACCUMULATED IN LAKE MEAD

River-miles along the submerged Colorado River channel are measured downstream from the U. S. Geological Survey concrete gage well opposite the mouth of the Paria River, Arizona. River-miles along the inundated Virgin River channel are measured upstream from its former junction with the Colorado River.







filling of the reservoir, limited the depth of penetration, 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, table 2) was reached by the coring equipment at river-mile 283.6<sup>2</sup> in the lower part of Pierce Basin.

#### Gravity Cores

Most of the cores were obtained with a gravity corer (fig. 10), 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.

The chief disadvantage of the gravity corer is the shortening of the core caused by sidewall friction between the sediment and the tube liner, and by the resistance of the material to being pushed aside or downwarped at the bottom of the tube. Emery and Dietz have demonstrated that

---

<sup>2</sup> River-miles along the former Colorado River channel are measured from the U. S. G. S. concrete gage wall opposite the mouth of the Paria River, Arizona.





FIGURE 10

GRAVITY CORER BEING ASSEMBLED FOR ITS TRIP  
INTO THE ACCUMULATED SEDIMENT

Weighted shaft is at the top of a 90-foot tube which is  
suspended in the water.

in a deposit which increases in density as a function of 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.

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 foot to 31.0 feet. The recovery ratios ranged from 24.6 to 57.7 percent, and averaged 35.5 percent, as shown in table 2. The ratios of core length to penetration depth are plotted in figure 11. A best-fit visual line drawn through these points shows that the relationship between core length and penetration depth is approximately linear. This relationship has been used in adjusting the positions of samples from the cores to their estimated depths in situ.

#### Piston Cores

Toward the end of the field period a new type of coring device was constructed by the U. S. Geological Survey and used at Lake Mead. This instrument, known as a piston corer, was adapted by W. O. Smith from a similar

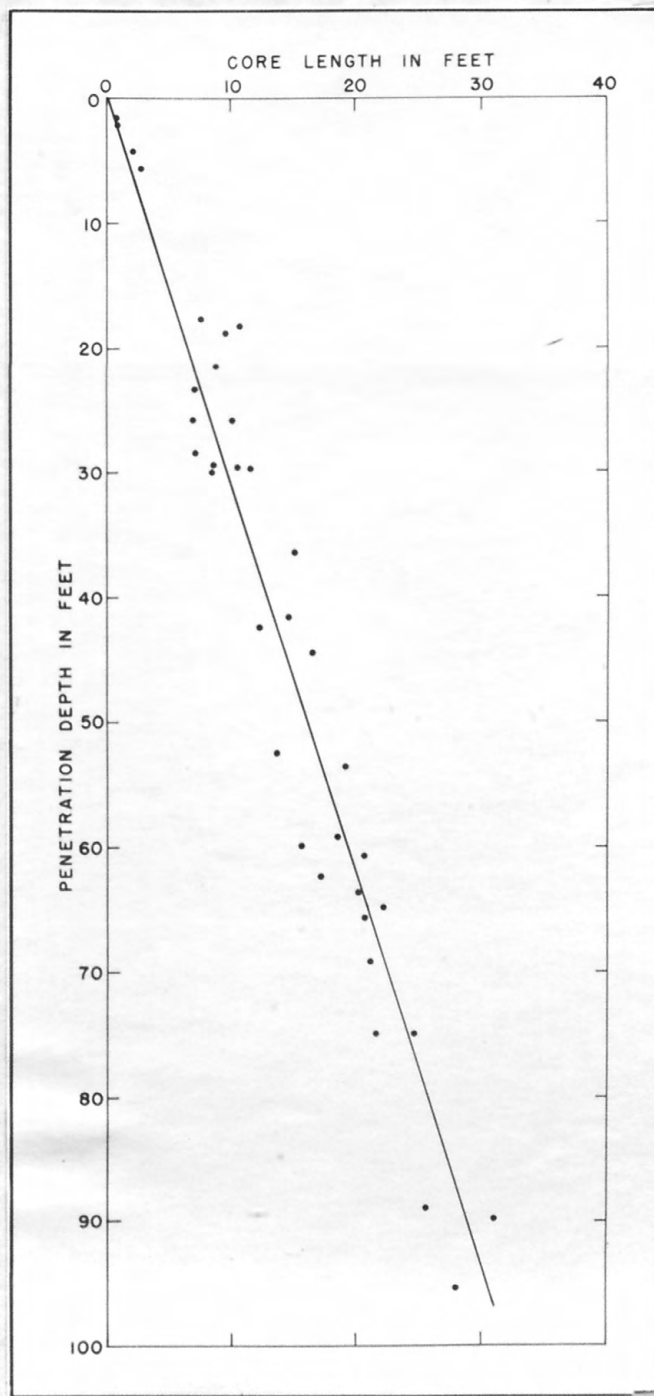


FIGURE 11

RELATION OF CORE LENGTH TO PENETRATION DEPTH  
FOR GRAVITY CORE-SAMPLER



TABLE 2

41

Penetration depths and core lengths  
obtained by gravity core sampler

| Core number | Penetration depth in feet | Core length in feet | Percent recovery |
|-------------|---------------------------|---------------------|------------------|
| 3           | 72.0                      | 31.0                | 43.1             |
| 7           | 90.0                      | 31.0                | 34.4             |
| 8           | 18.2                      | 10.5                | 57.7             |
| 13          | 53.7                      | 19.0                | 35.4             |
| 16          | 65.0                      | 22.0                | 33.8             |
| 17          | 60.7                      | 20.5                | 33.8             |
| 18          | 52.7                      | 13.5                | 25.6             |
| 19          | 46.5                      | 14.5                | 31.2             |
| 20          | 28.5                      | 7.0                 | 24.6             |
| 21          | 23.5                      | 7.0                 | 29.8             |
| 22          | 42.5                      | 12.1                | 28.5             |
| 23          | 36.7                      | 15.0                | 40.9             |
| 24          | 29.7                      | 11.5                | 38.7             |
| 25          | 5.8                       | 2.0                 | 34.5             |
| 26          | 18.8                      | 9.5                 | 50.5             |
| 35          | 4.5                       | 2.1                 | 46.7             |
| 36          | 5.7                       | 2.9                 | 50.9             |
| 37          | 2.1                       | 1.0                 | 47.6             |
| 38          | 41.8                      | 14.5                | 34.7             |
| 39          | 21.2                      | 8.8                 | 41.5             |
| 40          | 26.0                      | 10.0                | 38.5             |
| 41          | 43.5                      | 17.7                | 40.7             |
| 42          | 59.1                      | 18.2                | 30.8             |
| 43          | 29.7                      | 10.5                | 35.4             |
| 44          | 29.5                      | 8.5                 | 28.8             |
| 45          | 30.0                      | 8.2                 | 27.3             |
| 46          | 17.8                      | 7.5                 | 42.1             |
| 47          | 65.8                      | 20.5                | 31.2             |
| 59          | 63.8                      | 20.0                | 31.3             |
| 61          | 89.1                      | 25.5                | 28.6             |
| 63          | 95.5                      | 28.0                | 29.3             |
| 65          | 26.0                      | 6.8                 | 26.2             |
| 68          | 2.0                       | 1.0                 | 50.0             |
| 69          | 75.0                      | 24.5                | 32.7             |
| 71          | 69.3                      | 21.0                | 30.3             |
| 73          | 60.0                      | 15.5                | 25.8             |
| 74          | 62.5                      | 16.0                | 25.6             |
| 76          | 75.0                      | 21.5                | 28.7             |

Average = 35.5



device designed by Kullenberg (1941). 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 sediment to 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 to being pushed aside or downwarped. As a result, the cores are considerably longer than those taken by the gravity device. If the hydrostatic pressure is great enough, cores equal in length to the depth of penetration can be obtained.

Because of its late arrival, time did not permit extensive use of the piston corer. The eight cores obtained with this instrument were extremely useful, however, 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 3, 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, representing a range in recovery ratios of 70.2 percent to 143.1 percent. The low

| Core<br>number | Penetration<br>depth, feet | Core length,<br>feet | Percent<br>recovery |
|----------------|----------------------------|----------------------|---------------------|
|----------------|----------------------------|----------------------|---------------------|

|     |      |      |       |
|-----|------|------|-------|
| K1  | 70.5 | 49.5 | 70.2  |
| K1a | 70.0 | 75.0 | 107.1 |
| K2  | 68.0 | 51.0 | 75.0  |
| K3  | 43.5 | 43.5 | 100.0 |
| K4  | 43.5 | 43.5 | 100.0 |
| K5  | 76.5 | 69.0 | 90.2  |
| K6  | 79.0 | 70.5 | 89.2  |
| K7  | 25.5 | 36.5 | 143.1 |

Penetration depths and core lengths  
obtained by piston core sampler

TABLE 3

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 insufficient to overcome the internal sidewall friction between the sediment and the coring tube. Low hydrostatic pressure appears to be the most probable explanation for the observed shortening of cores K5 and K6. The high recovery ratios of cores K10 and K7 resulted from failure of the tube to penetrate the sediment to its full length. The material in excess of that penetrated was forced into the bottom of the tube at the depth of maximum penetration.

With the exception of cores K5 and K6, where shortening was caused by inadequate hydrostatic pressure, only minor adjustments in the positions of the samples in the core tube were required to obtain their approximate depths in situ. Physical properties of the gravity core samples, corrected for depth in place, correspond closely with the physical properties of piston core samples taken at the same locations.

#### Forst Samples

Samples of sediment in suspension, and in the soft upper layers of the accumulated material west of river-mile



279.3, were obtained with a Foerst sampling bottle. This instrument, designed originally for collecting river water samples, required a few modifications for sampling of the soft mud in Lacc Head. Consequently, the Foerst sampling bottle used in these investigations differs slightly from the original model. It consists essentially of an open lucite cylinder with rubber stoppers mounted at both ends. A heavy brass weight attached to the top stopper is suspended below the cylinder to drag the instrument through fairly viscous 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. Therefore, only the bottom 4 inches of each sample were saved for laboratory analysis.

Foerst samples were collected at 35 stations, 32 of which have the same field locations as the gravity cores (fig. 9). 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. Good correspondence between the physical properties of Foerst samples and gravity core samples was observed throughout their range of overlap.

Immediately behind Hoover Dam, (river-mile 354.6), the accumulated sediment was too fluid to be retained by 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.

The Foerst sampler was also used extensively in measuring the depth to the interface between the lake water and the accumulated sediment, and in providing information on the nature of that interface. Measurements to the level of the sediment surface 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 about 3 feet. Except for a few periods when the bottom of the eastern part of the lake was masked by turbidity currents, the sediment-water interface was sharp and distinct as illustrated in figure 12.

#### Grab Samples

Samples of the sediment surface in the Overton Arm,

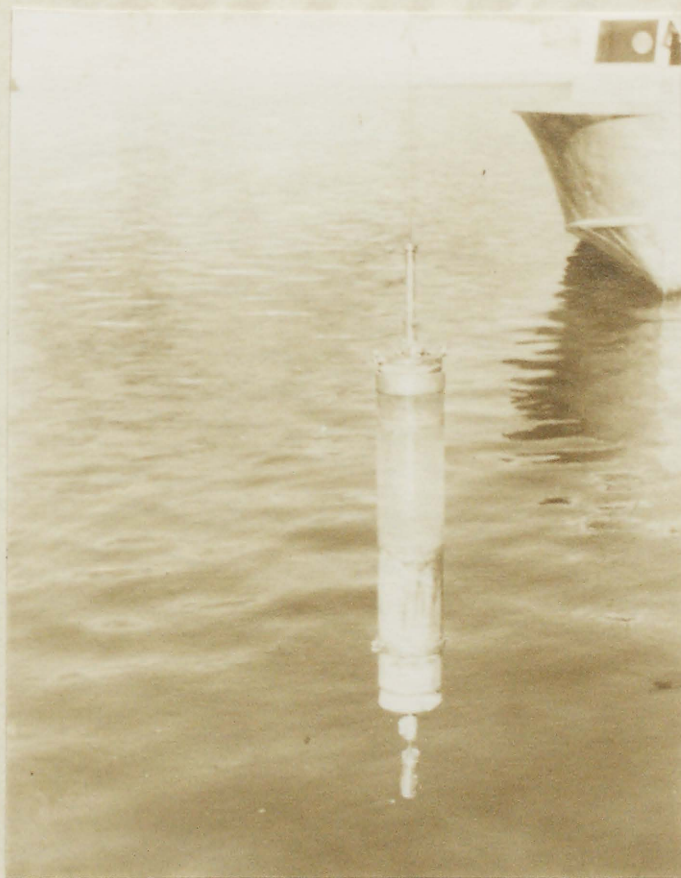


FIGURE 12

MODIFIED FOREST SAMPLER CONTAINING SAMPLE FROM THE SEDIMENT  
SURFACE, SHOWING THE SHARPNESS OF THE WATER-SEDIMENT  
INTERFACE AT THE BOTTOM OF THE LAKE

Photograph by F. C. Ames



and a few samples of the original lake bottom in areas of non-deposition were obtained with a snapper-type bottom sampler (fig. 13) designed by LaFond and Dietz (1948). In the Lower Granite Gorge samples from the subaqueous part of the deposit were collected with a dipper, and the sub-aerial part of the deposit was channel sampled with a geologist's pick.

#### Miscellaneous Observations

Although the collection of cores and samples from the accumulated sediment received the greatest emphasis, a number of other minor studies were undertaken. These included the measurement of vertical temperature gradients in the sediments, and photography of the lake bottom in a few areas of critical interest. In areas having only a thin layer of sediment penetration measurements were made to determine its thickness. Numerous water samples collected in conjunction with the chemical and physical limnology investigations, carried out jointly by the U. S. Geological Survey and the U. S. Navy Electronics Laboratory, were analyzed for their suspended sediment. These measurements, together with the results of the limnology studies (Howard, 1952; Anderson and Pritchard, 1952) provided considerable information on the effectiveness of turbidity currents as agents of sediment transportation.



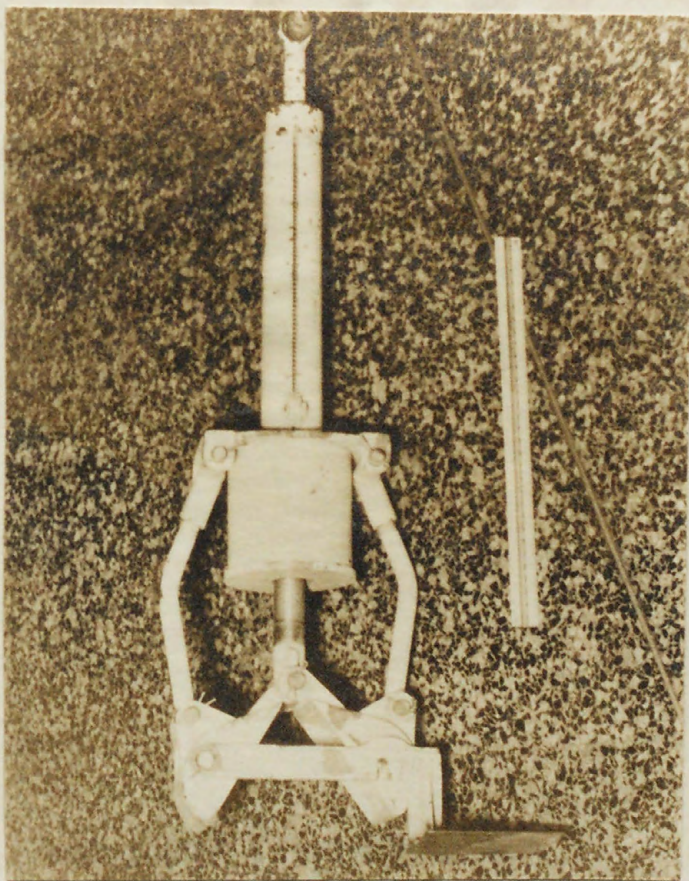


FIGURE 13

SNAPPER TYPE BOTTOM SAMPLER  
U. S. Bureau of Reclamation photograph

### Laboratory Studies

Laboratory studies of samples and cores began in the spring of 1948, in space provided by the U. S. 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, approximately 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 of 7½ piston core samples were determined 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 determination by the writer of the organic content and calcium carbonate content of several selected samples, bacteriological and biochemical studies by F. D. Sisler (1952) of the Scripps Institution of Oceanography, and analyses by the U. S. Bureau of Mines of gas occurring in the sediment. The U. S. Bureau of Mines has also investigated the sediment for its ceramic



qualities and other commercial uses. Chemical, X-ray, and spectrographic analyses of a number of samples were made in the geochemical laboratories of the U. S. Geological Survey at Washington, D. C. In addition, Mr. George Tchilingirian of the University of Southern California has investigated the sediment for its usefulness as a drilling fluid. The results of these various special analyses are presented in the discussion of the characteristics of the accumulated sediment in a later part of this report.

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. The sample is then allowed to dry in an oven at a temperature of  $105^{\circ}$  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 amount of water contained in the pore spaces of the sample, and the water content may be computed from the formula:

$$W. C. = 100 \left( \frac{W_w - W_d}{W_w} \right),$$

where W. C. is the water content in percent,  $W_w$  is the weight of the wet sediment 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:

$$M = 100 \left( \frac{W_a - W_d}{W_a} \right),$$

where M is the air-dry moisture content in percent,  $W_a$  is the weight of the air-dry sediment 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. 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 (Sherman, 1951) where the air-dry moisture content ranges from 0.1 percent for medium sand to about 6.0 percent for clay that has a median particle diameter of 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 Krumbein and Pettijohn (1938, pp. 501-502). Relatively large samples, weighing from 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 approximately 12 hours before the final weighings were made.

A total of 117 specific gravity measurements were made of 72 samples, selected from widely separated positions. Duplicate analyses of 45 of the samples show that the error 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 which are described in the following pages.

#### Density, Porosity, and Specific Weight

As an introduction to the discussion of laboratory determinations the reader should know what is meant by the terms "density", "porosity", and "specific weight", as used in this report. The following paragraphs include definitions, as well as the methods used for determination of these physical characteristics.

Density is the ratio of the weight of the sediment and 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. However, they 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 sediments, 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:

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

in which  $W_w$  equals the weight of water saturated sample in grams,  $V_{wa}$  is the volume in cc of water driven off by oven drying,  $W_d$  is the weight of oven-dried sample in grams, and  $sg$  is the specific gravity of grains.

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

In the other samples the porosity was computed from the formula:

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

where  $V_{wa}$  is the original water volume in cc as determined by oven-drying,  $W_d$  is the weight of the dried sample in grams, and  $sg$

is the specific gravity of the mineral grains.

Specific weight is the ratio of the weight of the solid mineral particles to the volume of the water-saturated sediment. This ratio is not expressed in metric units, but in pounds per cubic foot because of engineering needs. All formulas for its computation, therefore, include a conversion factor of 62.43. In the 74 piston-core samples the specific weight was determined directly as the weight of the oven-dried sample divided by the volume of the water-saturated sample and multiplied by 62.43.

For other samples the specific weight was computed by the formula:

$$S_w = \frac{62.43 W_d}{V_{wa} + \frac{W_d}{SG}}$$

where  $S_w$  is the specific weight in pounds per cubic foot and other factors have been identified above.

#### Corrections for Gas in Samples

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. However, the gas in the sample occupies a much larger volume at the surface than at its true depth in situ. When

samples from the accumulated sediment are raised to the surface they experience a pressure change which is equal to the difference between the pressure in situ 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 situ. 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 volume of gas in situ did not exceed 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 direct measurements of these physical properties have been corrected for gas expansion.

#### Gas Volume In Situ

The percentage volume of gas contained in the sediment in situ has been obtained by the following formula:

$$G = \frac{V_w - (V_{wa} + V_d)}{V_w} \times \frac{100}{P_g}$$

where G is the percent gas volume in situ,  $V_w$  is the volume of the water-saturated sample in cc at atmospheric pressure,  $V_{wa}$  is the volume of interstitial water in cc,  $V_d$  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.

#### Grain Size Distribution

Because of the considerable amount of time required for particle-size determinations of fine-grained sediments, only 300 samples were analyzed. However, these were selected from widely distributed positions, both geographically and in depth, and are considered, therefore, to be representative of the accumulated sediment as a whole.

#### Methods

Sand and gravel samples 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 grain-size distribution of silt and clay samples is given here.

The method consisted of weighing a sufficient amount of the water-saturated sample to provide approximately 10 grams of solid mineral particles for pipette analysis. The exact total 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 time-consuming 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 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 hexameta-phosphate ( $\text{NaPO}_3$ )<sub>6</sub>, buffered to a pH of 9 as suggested by Tyner (1934) and diluted with 200 cc of distilled water, was added to the sample, which was then 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, and brought up to a volume of 1000 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 4. 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 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 1 liter graduate was agitated for 5 minutes, after which the suspended particles were allowed to settle. According to Stoke's 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 relationship the depths to which limiting particle sizes will travel during a given time may be computed. 25 cc samples of the suspended sediment were withdrawn from these selected depths at measured time intervals. The limiting diameters chosen for

TABLE 4

Combined Udden<sup>1</sup>- Wentworth<sup>2</sup> size classification

| Grade size limits<br>(Diameters in microns) <sup>3</sup> | Name             |
|----------------------------------------------------------|------------------|
| Larger than 256,000                                      | Boulder          |
| 256,000 - 64,000                                         | Cobble           |
| 64,000 - 4,000                                           | Pebble           |
| 4,000 - 2,000                                            | Granule          |
| 2,000 - 1,000                                            | Very coarse sand |
| 1,000 - 500                                              | Coarse sand      |
| 500 - 250                                                | Medium sand      |
| 250 - 125                                                | Fine sand        |
| 125 - 62                                                 | Very fine sand   |
| 62 - 31                                                  | Coarse silt      |
| 31 - 16                                                  | Medium silt      |
| 16 - 8                                                   | Fine silt        |
| 8 - 4                                                    | Very fine silt   |
| 4 - 2                                                    | Coarse clay      |
| 2 - 1                                                    | Medium clay      |
| 1 - 0.5                                                  | Fine clay        |

1 Grade size divisions smaller than 62 microns follow Udden's classification.

2 Grade size divisions larger than 62 microns follow Wentworth's classification.

3 1 micron = .001 millimeter.



the analyses of the Lake Mead samples correspond to the diameters smaller than 62 microns shown in table 4. Withdrawals at the limiting diameter of 0.5 micron were made, however, only for samples with 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 represents the amount of sediment contained in the coarse silt grade, 62-31 microns.

The true limiting diameters differ slightly from those shown in table 4 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 a function 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 grains, but no correction has been applied for the variation of particle shape from that of a true sphere.

In addition to these analyses, the particle sizes of five silt and clay samples, showing a considerable range in texture, were measured in untreated lake water. The results of these analyses are presented in a later discussion on flocculation of particles.

#### Presentation of Data

The data obtained from the sieve and pipette analyses were plotted as cumulative curves, an example of which is shown in figure 14. Attempts were made to measure the diameters of particles as fine as 0.25 micron, but the results were erratic and un dependable. It was concluded that the dimensions of clay particles less than about 0.4 micron in diameter (corrected for grain density and temperature of the settling medium) could not be measured accurately by the pipette method. Krumbein and Pettijohn (1938, p. 101) and others have also concluded that particles finer than approximately 0.5 micron in diameter no longer obey Stoke's law, but behave rather as a colloidal suspension. This explanation accounts for the incompleteness of the curve shown in figure 14, which is typical of most of the cumulative curves for silt and clay samples from

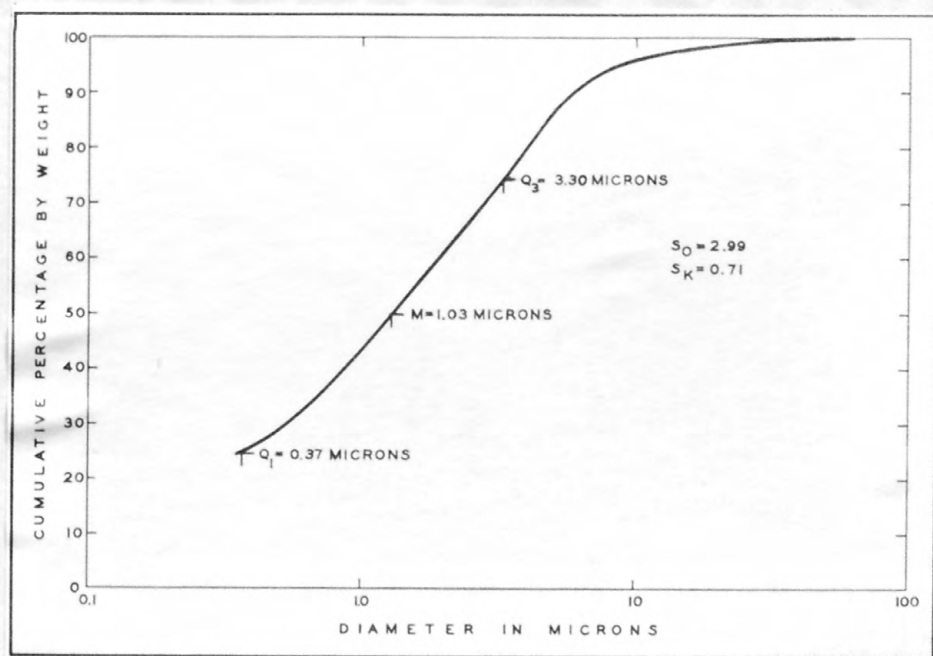


FIGURE 14

TYPICAL CUMULATIVE SIZE-FREQUENCY CURVE FOR SILT AND CLAY  
SAMPLES FROM THE SEDIMENT ACCUMULATED IN LAKE MEAD

The median diameter, first quartile, third quartile,  
sorting coefficient, and skewness coefficient are designated  
by  $M$ ,  $Q_1$ ,  $Q_3$ ,  $S_0$ , and  $S_k$  respectively. (Sample 266 from  
gravity core 16 in Boulder Canyon)

Lake Head.

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 as shown in table 5.

Values of the statistical constants employed by Trask (1932, pp. 67-76), namely, the median diameter and the coefficients of skewness and sorting were also determined.

The median diameter indicates the mid-point by weight of the size distribution as determined from the cumulative curves. The coefficient of sorting is a statistical measure of the uniformity in size of the sediment particles, and is defined as:

$$S_o = \sqrt{\frac{Q_1}{Q_3}}$$

where  $S_o$  is the coefficient of sorting,  $Q_1$  is the minimum diameter making up less than 25 percent of the sample, and  $Q_3$  is the minimum diameter making up less than 75 percent of the sample. As the coefficient of sorting approaches unity the more perfect is the sorting. Trask has described samples having a coefficient of sorting less than 2.5 as



TABLE 5

Size classification as used in this report

| Grain size limits<br>(Diameters in microns) | Name                             |
|---------------------------------------------|----------------------------------|
| Greater than 4,000                          | Gravel                           |
| 4,000 - 1,000                               | Very coarse sand<br>and granules |
| 1,000 - 250                                 | Medium and coarse<br>sand        |
| 250 - 62                                    | Fine sand                        |
| 62 - 4                                      | Silt                             |
| 4 - 1                                       | Medium and coarse<br>clay        |
| Less than 1                                 | Fine clay                        |

as being well-sorted and samples having a coefficient of sorting greater than 4.5 as being poorly sorted.

The dissymmetry of the size distribution curve, namely 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:

$$S_k = \frac{Q_1 - Q_3}{M}$$

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; 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. 14) 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 consisted of particles smaller than 0.5 micron. In these samples the quartiles making up less than 25 percent of the samples could not be obtained from the cumulative curves, and it has been impossible to determine

sorting and skewness coefficients.

## CHARACTERISTICS OF THE ACCUMULATED SEDIMENT

The sediment 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. These are referred to in this report as the Colorado delta and the Virgin delta respectively. Figure 15 shows the areal distribution of the deltas and their relationship to the submerged river channels. The vertical distribution and surface features are also denoted by 18 sections across the deltas at selected positions throughout the reservoir. Frequent reference to these cross-sections will be made in the following discussion of the accumulated sediment.

### Distribution

#### Colorado Delta

Most of the sediment brought into Lake Mead has been supplied by the Colorado River and has accumulated 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, have been



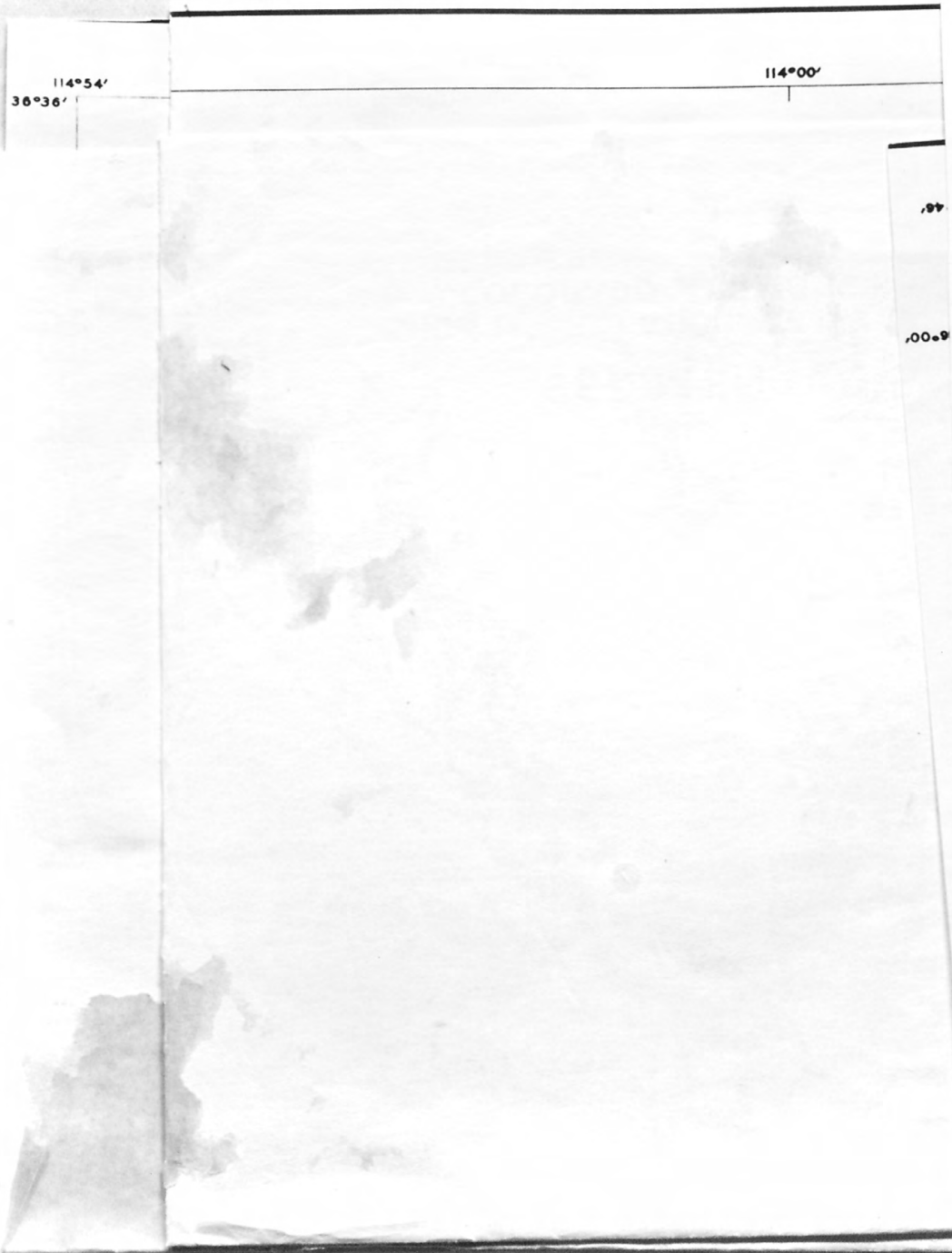
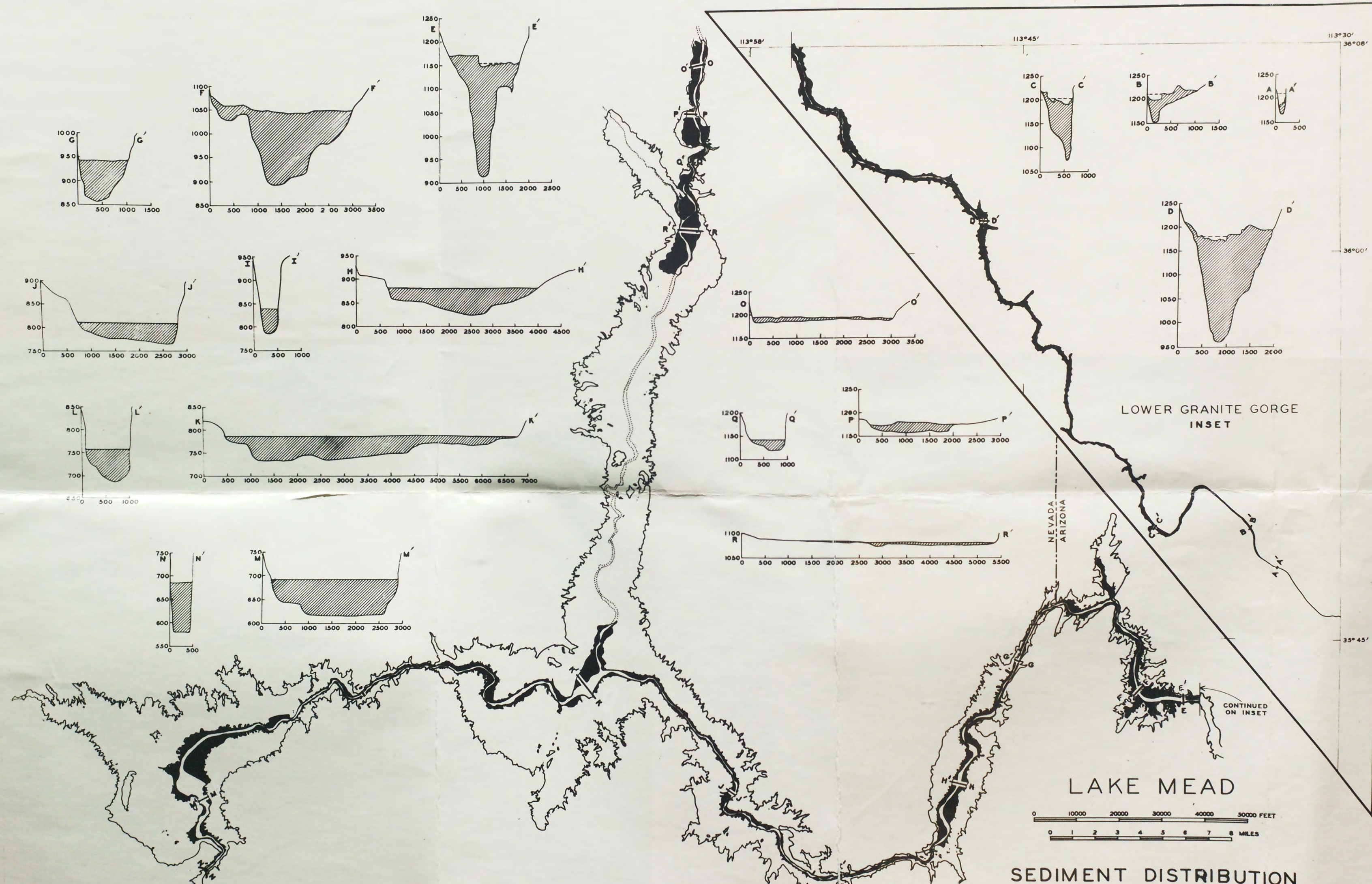


FIGURE 15

MAP AND CROSS-SECTIONS SHOWING THE DISTRIBUTION OF  
SEDIMENT ACCUMULATED IN LAKE MEAD





LAKE SHORE AT 1200 FEET  
CROSS SECTION VERTICAL SCALE IN FEET ABOVE  
MEAN SEA LEVEL - HORIZONTAL SCALE IN FEET  
VERTICAL EXAGGERATION X10

### LAKE MEAD SEDIMENT DISTRIBUTION

SHOWING RELATION OF SEDIMENT TO SUBMERGED  
COLORADO AND VIRGIN RIVER CHANNELS



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 depositing sediment continuously along its course. Several turbidity currents, carrying vast quantities of sediment, have traversed the entire length of the reservoir, 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 figure 15, 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 approximately 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 which is higher than the average lake level (approximately 1,170 feet altitude). As shown by sections A-A' to B-B' (fig. 15), the Colorado delta progressively increases in thickness from Bridge Canyon to river-mile 277.8, where it attains a maximum thickness of 270 feet. Topset beds cover 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 the Lower Granite Gorge.

Although some of the topset beds in the Lower Granite Gorge are above the average operating level of the reservoir (approximately 1,170 feet altitude) and in some places above the level of the permanent spillway crest (1,205.4 feet altitude), the delta in its present stage of development does not extend upstream from the eastern end of the reservoir at river-mile 235.

West of river-mile 277.3 the delta lies entirely beneath the average lake surface (approximately 1,170 feet altitude), and is confined to the region of the submerged Colorado River channel. Foreset beds make up the surface of the delta east of river-mile 277.3, but from that point to Hoover Dam, a distance of about 75 miles, the delta surface is composed of bottomset beds.

In the canyon areas of the lake, steep walls bound the sediment on either side, but in the intervening basins the delta spreads out over the terraces that flank 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





FIGURE 16

ENTRANCE OF THE COLORADO RIVER INTO  
PIERCE BASIN IN NOVEMBER 1948

Note sharp contact between lake and river where the turbid water plunges down along the lake bottom. The 1948 terrace just below the water surface may be seen to the right. U. S. Bureau of Reclamation photograph.



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 the Virgin Basin, where the bottomset beds of the Colorado delta fill the lower  $2\frac{1}{2}$  miles of the Virgin River valley to the same level as the sediment in the central part of the Virgin Basin (fig. 15). 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 river-mile 279.2, 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  $1\frac{1}{2}$  miles north of the thalweg at river-mile 284.6, is almost 50 feet above the level of the sediment in the thalweg.

Sections P-P' to N-N' (fig. 15) 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 river-mile 314.1 (section J-J') midway between the mouth of Virgin Canyon and the 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 P-P') this part of the deposit attains a maximum thickness of 155 feet. Immediately behind Hoover Dam (section R-R') 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, and the Virgin delta, is, of course, very much smaller than the Colorado delta. As shown in figure 15, the Virgin delta occupies only the upper 14 miles of the Gorton 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 is apparently composed similarly of topset, foreset, and bottomset beds. At its northern end, or apex, at river-mile 35.8<sup>3</sup> the delta has a thickness of less than 1 foot; the thickness increases to a maximum of 22 feet at river-mile 27.4 (section Q-Q', fig. 15), and then decreases in thickness to less than 1 foot at its lower end at river-

---

<sup>3</sup> River-miles along the Virgin River are measured upstream from its junction with the Colorado River prior to 1935.



mile 21.4.

Between the toe of the Virgin delta and the Lower Narrows of the Overton Arm (river-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.

The accumulation of sediment along the thalwegs of the Colorado River and Virgin River, and its absence in other parts of the lake, is indicated by many lines of evidence. Both the acoustical sounding records and numerous line soundings in all parts of the lake outside of the thalweg areas agree with the topography of the original lake bottom except in a few areas affected by landslides. Sounding weights and various oceanographic instruments that were lowered to the bottom, showed no evidence of sediment accumulation beyond the limits of the channels and their

associated flood plains and terraces: In the thalweg areas these instruments were generally covered with a thick coating of mud, but elsewhere no such coating was observed. Furthermore, underwater photographs of the bottom outside of the channel areas (fig. 17) show that the vegetation which grew on the reservoir floor prior to inundation has not been buried 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 non-deposition.

#### Deposits at the Mouths of Minor Tributaries

Muddy Creek and other small tributaries to Lake Mead have undoubtedly supplied some sediment, but 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 Hualpai Wash show no evidence of sediment accumulation in these areas. Samples from the inundated Muddy Creek channel 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





FIGURE 17

UNDERWATER PHOTOGRAPH OF THE BOTTOM OF LAKE MEAD BEYOND THE  
\* MARGIN OF THE COLORADO DELTA NORTH OF RIVER-MILE 341

Note that vegetation on the original reservoir floor has  
not been buried by sediment. Approximate area, 9 square feet;  
water depth, 351 feet. U. S. Navy photograph in March 1949.



tributaries, or by slumping directly into the lake. Examples of sediment that is probably of local origin are described near Detrital Wash and the Temple in a later section of this report. 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.

### Physiography of the Deltas

#### Colorado Delta

##### Topset Beds

The topset beds that make up the surface of the Colorado delta in the 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, when 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. It appears, therefore, that the average upstream slope of the topset beds is not affected much by short period changes in level due to alternate scour and fill.

Channel characteristics.—As shown by annual profiles of the Colorado delta surface (fig. 18), the average gradient of the Colorado River channel in the 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 by the U. S. Bureau of Reclamation (1941, 1947), whereas the 1948 profile, showing considerable detail, is based on soundings during the 1948-49 survey. These profiles represent the approximate position of the delta surface at the end of each calendar year.

In constructing the profiles, 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 figure 18 differ slightly in some places from the altitudes of the water-sediment interface as initially recorded. Because of inadequate data, the

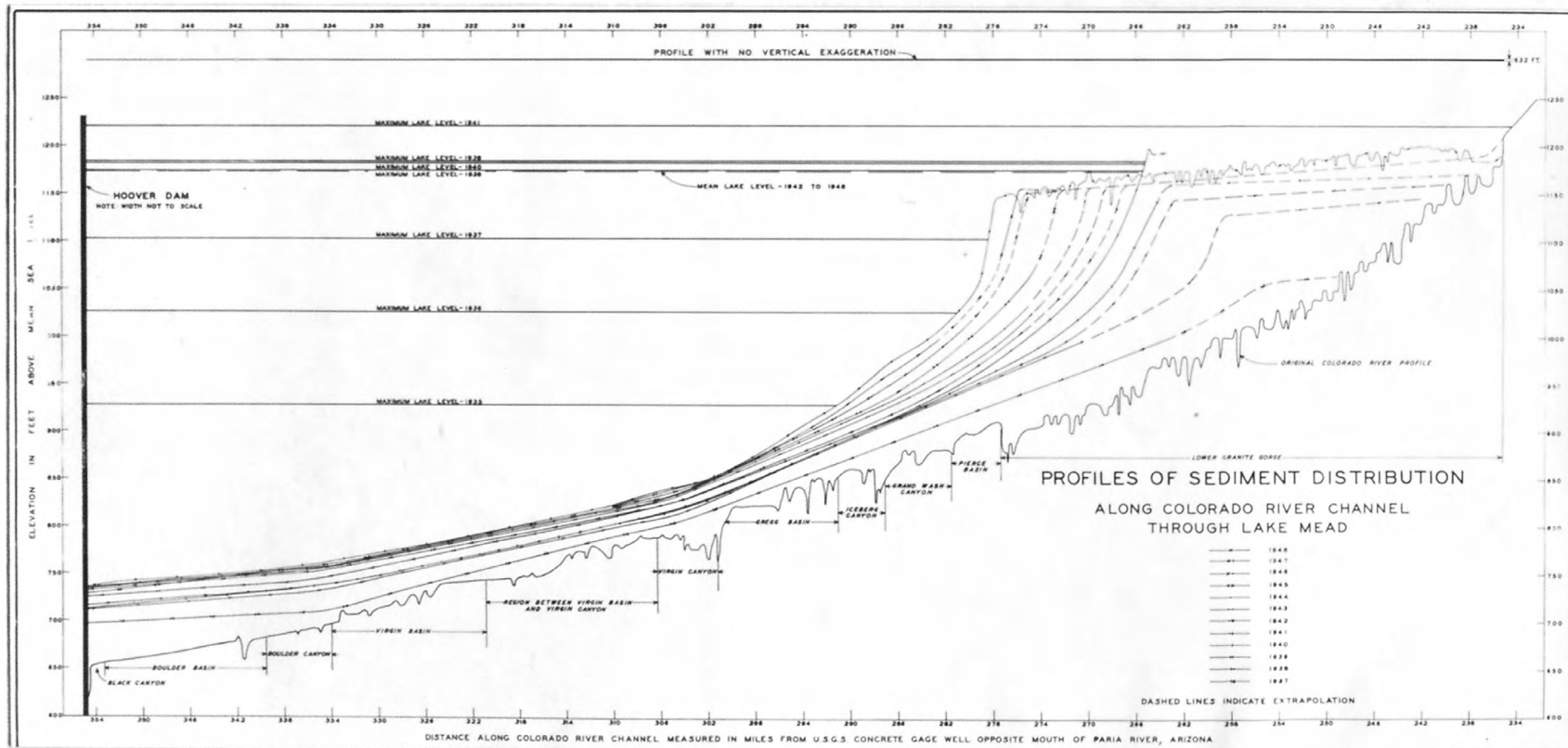


FIGURE 18

ANNUAL PROFILES OF THE COLORADO DELTA ALONG THE THALWEG OF THE COLORADO RIVER  
1937-1947 profiles are based on U. S. Bureau of Reclamation data



profiles in the 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 the 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', fig. 15) 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 portion of the canyon. The width of the Lower Granite Gorge at the surface of the topset beds 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' (fig. 15), the width of the 1948 channel ranged from 200 feet to 600 feet. This is a two to three fold increase over the width of the former channel in the bottom of the

canyon.

With its lesser slope and greater width, the Colorado River in the Lower Granite Gorge has assumed the characteristics of a mature stream, in contrast to the vigorous young stream that formerly flowed along the narrow V-shaped notch at the bottom of the gorge. The 1948 Colorado River channel throughout most of its length follows a meandering course which conforms in general to the winding plan of the Lower Granite Gorge. The convex sides of its meanders extend several feet above the water surface, whereas the concave sides stand at considerably lower levels and in some places are cut back to the bare rock walls of the Lower Granite Gorge. Large eddies, formed where the river changes its course abruptly, commonly have cut deep holes in the channel. As shown in figure 18, the 1948 channel is characterized by numerous bars and holes, similar to those of the buried Colorado River channel. In the Lower Granite Gorge the Colorado River, like other meandering streams, is continuously changing its course in response to variations in river currents, sediment load, and water discharge.

Terraces, levees, and marginal depressions.- 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 have been mostly removed by undercutting or reduced to only thin remnants plastered against the canyon walls. Tributary canyons of the Lower Granite Gorge have been dammed by these natural sediment barriers, behind which shallow depressions have formed at the margins of the delta surface. Water discharged by a number of the tributaries has been captured in the depressions, thus forming lakes or ponds of clear water effectively isolated from the turbid water of the Colorado River (fig. 19). The sediment embankments across the mouths of some of the larger side canyons have been subsequently breached by water discharged from their tributaries, probably during flash floods. Most prominent among these are Spencer Canyon, Surprise Canyon, and Reference Point Canyon. However, the embankments across the mouths of other large tributary canyons, notably Separation Canyon, Hellsdiver Canyon, and Salt Creek Canyon, are still intact.

At the time of the 1948-49 survey the terrace that was most extensive, most nearly continuous, and most prominent from the river was obviously 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





FIGURE 19

MARGINAL LAKE RESULTING FROM DAMING OF TRIBUTARY BY  
NATURAL LEVEES IN THE SUBAERIAL PART OF THE COLORADO DELTA

Higher terrace and natural levee, covered by vegetation,  
were probably formed during 1941. The 1948 terrace appears  
in the foreground. Photograph taken at river-mile 264 in  
March 1949.

July to 1,155 feet in December and 1,150 feet in March 1949. The resulting terrace is continuous from Bridge Canyon to the mouth of the Colorado River in Pierce Basin. As shown in figure 15, the 1948 terrace ranges in altitude from 1,213 feet at river-mile 239.5 (section B-B') to 1,170 feet in Pierce Basin (section E-E').

In the eastern part of the Lower Granite Gorge, the 1948 terrace is composed almost entirely of cross-bedded 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 overlies the cross-bedded sand of the 1948 terrace. 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 (fig. 20).

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), are conical in shape, with openings at the bottom through which gas escapes to the surface (figs. 21 and 22). The pits are about 2 feet to 10 feet in diameter at the surface and 1 to 4 feet deep. The diameter of the gas vent at the bottom of





FIGURE 20

CLOSE-UP VIEW OF THE 1948 TERRACE BEING CUT BACK BY THE  
COLORADO RIVER IN PIERCE BASIN

Columns of cross-bedded sand capped by a mud-cracked  
layer of clayey silt are plunging into the turbulent river  
below. Photograph taken in March 1949.



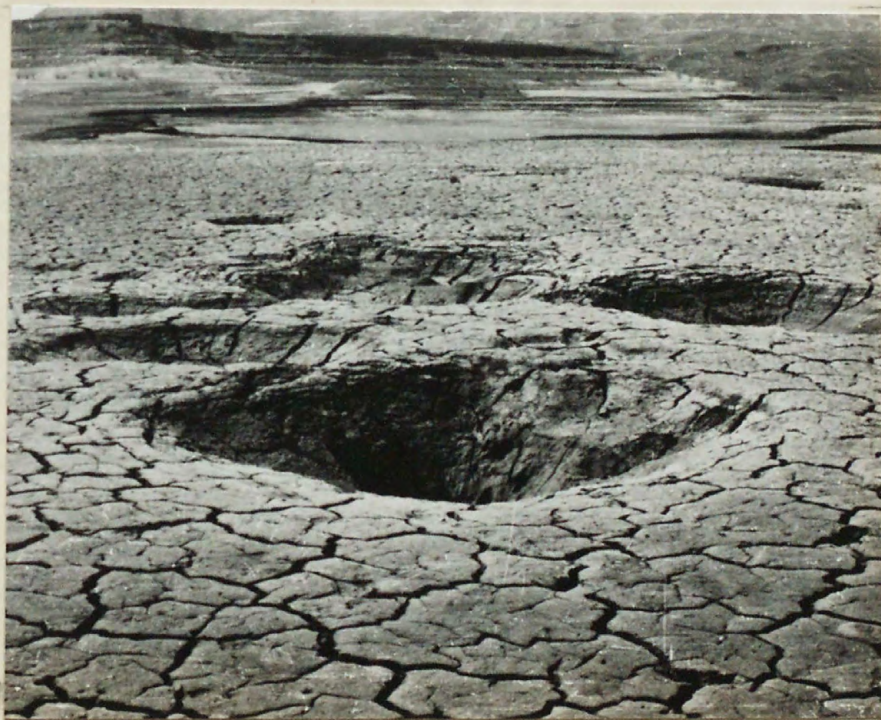


FIGURE 21

GAS PITS IN THE 1948 TERRACE NEAR THE COLORADO DELTA FRONT  
Large pit in the foreground is about seven feet in diameter.





FIGURE 22

CLOSE-UP VIEW OF ONE OF THE LARGE GAS PITS SHOWING  
THE CIRCULAR ORIFICE AT THE BOTTOM OF THE PIT  
THROUGH WHICH GAS ESCAPES TO THE SURFACE

each pit ranges from one-half inch 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 foreset and topset members.

Along most of its length the 194 terrace has extremely little relief (fig. 23). Natural levees superimposed on its surface generally rise only 1 to 2 feet above the terrace level although locally they are 4 to 5 feet high. In the narrow eastern end of the Lower Granite Gorge the levees commonly abut abruptly against the canyon walls, but in the western part of the Gorge and in the eastern end of Pierce Basin, the levees are parallel to the channel and as much as 200 feet from the canyon walls. Between the levees and the canyon walls are numerous small depressions that range 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 its way through the 1948 terrace to the lake. This drainage resulted in the cutting of deep narrow clefts tributary to the incised channel of the





FIGURE 23

UPSTREAM VIEW OF THE 1948 TERRACE IN WHICH THE  
COLORADO RIVER HAS ENTRENCHED ITSELF

The higher vegetation-covered terrace and natural levees  
in the background were probably formed during 1941. Photo-  
graph taken at river-mile 264 in March 1949.

Colorado River. These are particularly prominent in the eastern part of Pierce Basin near the delta front, where they provide excellent exposures of the cross-bedded structure of the topset beds.

East of Colorado River-mile 267.5 another terrace about 25 feet above the 1948 terrace can be clearly identified. This higher terrace is discontinuous, and ranges in altitude from 1,226 feet at river mile 239.5 to 1,198 feet at river-mile 267.5. It was probably formed during the summer of 1941 when the lake surface reached an altitude of 1,220 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' (fig. 15). Upstream from river-mile 239.5, the higher terrace has been removed in most places during subsequent periods of flood.

Superimposed on the higher terrace along its outer margins are well-developed natural levees which rise 2 to 5 feet above the terrace. These are best preserved where they cross the mouths of tributary canyons as shown in sections B-B' and D-D' (fig. 15). Like the terrace upon which they rest, the levees were probably formed during the high lake stage of 1941.

Annual profiles of the delta surface support the dating of these high terrace remnants and levees. As shown



in figure 18, the topset beds in 1941 extended only as far west as river-mile 266, which corresponds closely with the western terminus of the higher terrace and its superimposed levees. Since the topset beds in the western part of the Lower Granite Gorge were not formed until after 1941, the higher terrace and levees are absent in this region.

Extending downstream from the western terminus of the 1941 terrace (river-mile 267.5) to river-mile 270.5 are isolated remnants of another terrace that is intermediate in altitude between the 1941 terrace and the 1948 terrace. Spotty remnants of this and possibly other terraces are also visible upstream from river-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 the high lake stages of 1942, 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. 2). All terraces developed prior to 1941 have evidently been buried by the 1941 terrace which was formed when the lake reached its all-time high (1,220 feet altitude). Similarly, the terraces developed during 1945, 1946, and 1947 have been buried by the 1948 terrace.

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 developed at the time of the latest high lake stage, and subsequently entrenched. The delta deposits during years of exceptionally high lake stage, such as 1941, may persist as terraces for several years, but they too will eventually be buried.

#### Foreset Beds

The foreset beds that make up the delta front, in Pierce Basin, dip sharply beneath the lake surface for a distance of about  $1\frac{1}{2}$  miles from the river mouth (river-miles 277.8 to 279.3) where they grade into the gently sloping bottomset beds (fig. 24). Near its southern margin the delta front ranges in slope from about 300 feet per mile near the top to less than 25 feet per mile near the foot, and averages about 100 feet per mile.

In contrast, the slope of the delta front in its central and northern portions has been greatly modified by turbidity currents flowing over its surface. As shown in figure 24, this part of the delta front is traversed by a narrow valley, the axis of which extends into the mouth of the Colorado River. At the foot of the delta front the valley broadens out onto the gently sloping surface of the

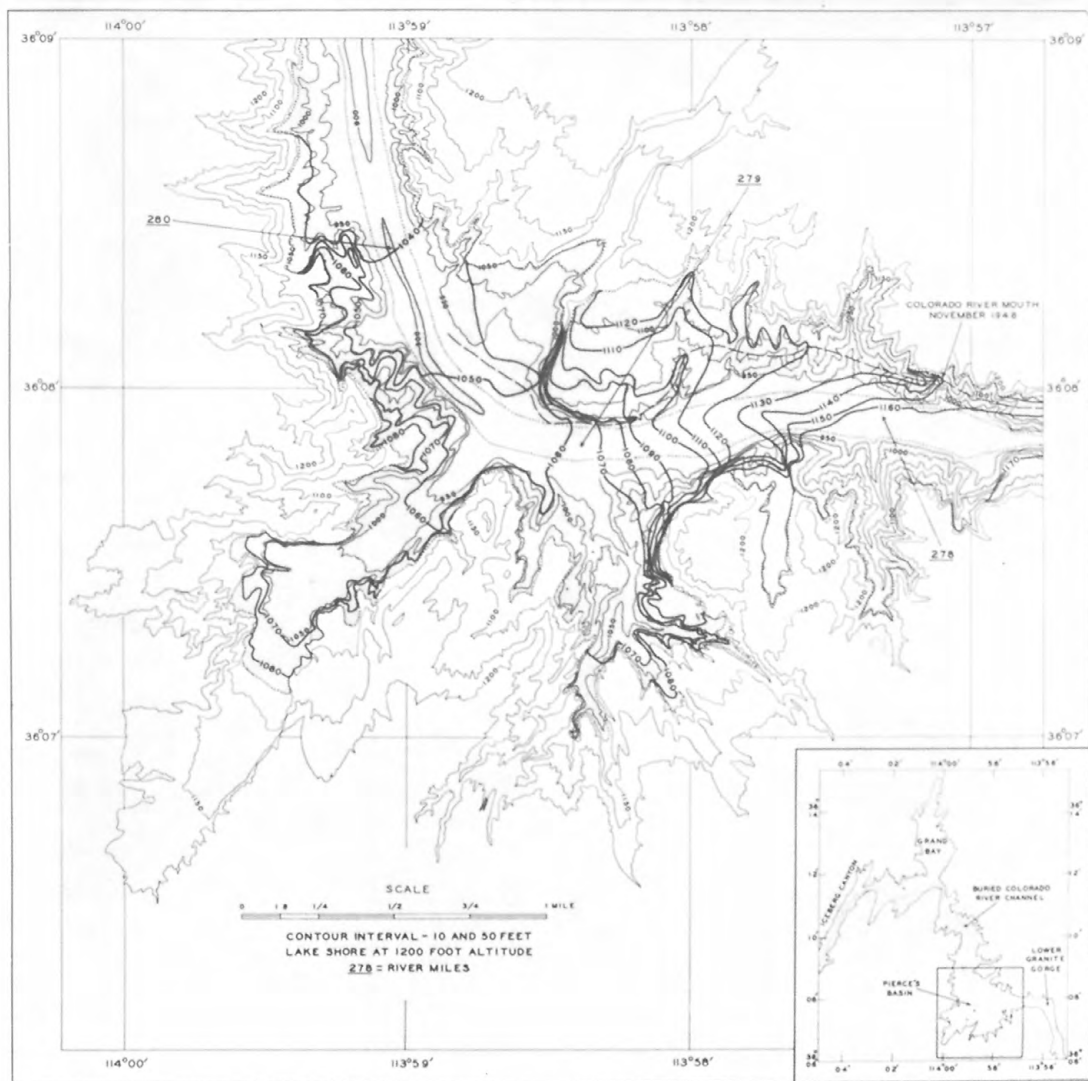


FIGURE 24

## TOPOGRAPHIC MAP OF PIERCE BASIN

Pre-Lake Mead topography is shown by light 50-foot contours, and the topography of the accumulated sediment (shaded area) is shown by heavy 10-foot contours. Pre-Lake Mead topography in unshaded area has not changed. The channel of the Colorado River prior to inundation is denoted by the light dotted lines, and the axis of the valley traversing the foreset beds is shown by a dashed line.

bottomset beds. The average slope of the delta front measured along the valley axis is about 55 feet per mile. It is not known whether this valley represents active erosion by turbidity currents or merely a lower rate of deposition at the center of the currents where velocities are higher. 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 is 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 figure 18, there is 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 to compaction, but the chief controlling factor appears to be the basining effect of Hoover Dam. As noted previously, the bottomset beds in 1948 increased from a minimum thickness of 45 feet at river-mile



31½ to 106 feet at the dam. If Hoover Dam had been constructed several hundred miles downstream, the thickness of the bottomset beds west of river-mile 31½ should have continued to decrease, which would have resulted in a somewhat greater slope of these beds. Above river-mile 31½, it may be postulated that the declivity is that of a delta built into a lake of "infinite extent". Below this position, 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 averages only 1.2 feet per mile.

Figure 18 also shows that the position of minimum sediment thickness, which denotes the eastern limit of basining effect, has migrated progressively farther uplake. In 1937, the position of minimum thickness was at river-mile 33½ near the head of Boulder Canyon, and in 1938 it regressed to river-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 (river-miles 306-31½).

In transverse section the sediment surface along most of its length is essentially level, the deposit at the sides extending only a few feet above the center elevation (fig. 15). However, within 5 miles of the delta front, the margins of the sediment are as much as 25 feet above the sediment surface along the thalweg, as illustrated in section F-F', (fig. 15).

One of the most striking features in this region is the continuation of the channel that traverses the delta front (fig. 24). The channel is bordered on both sides by underwater ridges which in section F-F' (fig. 15) rise about 5 feet above the center of the channel. The ridges are, 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 the Lower Granite Gorge.

West of river-mile 283 the difference between side and center elevations is generally less than 2 feet, but even in this region marginal ridges may 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 has formed across the mouth of Grand Bay at its intersection with the submerged Colorado River channel. Although field

evidence is inconclusive, there is 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 (river-mile 345 to 347) stands 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 the Lower Granite Gorge. Like the underwater "levees" and marginal depressions bordering the "levees", 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 stream flow, 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 being 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 flowing 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 immediately over the bottom was encountered as far west as river-mile 318, or nearly to the eastern end of the Virgin Basin.

#### Virgin Delta

Except for their lower relief, the surface features of the Virgin delta are generally similar to those of the Colorado deltas. Topset beds make up the surface of the upper 8 miles (Virgin River-mile 35.8 to 27.4) of the Virgin delta, over which the Virgin River flows to its entrance into Lake Mead. They have an average 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 river-mile 30.2 the surface of the topset beds is above the mean lake level of approximately 1,170 feet, but between river-miles 30.2 and 27.4 the topset beds are exposed only at low lake stages. A break in slope at altitude 1,140 feet marks 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 wide. 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. Along most of its length the Virgin River channel is flanked by one well-defined terrace which is 3 to 7 feet above the river channel (sections O-O' and P-P', fig. 15). Bordering the channel and superimposed on the terrace are broad natural levees that stand only 1 to 2 feet above the terrace level. The levees, in turn, are flanked by slight depressions in the delta surface which generally are less than 5 feet deep.

The surface of this part of the Virgin delta is composed chiefly of cross-bedded sand, but between river-miles 30.2 and the delta front at river-mile 27.4, the sand is overlain by a layer of soft clayey silt 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 form the delta surface between river-miles 27.4 and 26.7. These have an average downstream

slope of 29 feet per mile. South of river-mile 26.7 the surface is composed of bottomset beds with an average declivity of 14 feet per mile. At the toe of the delta (river-mile 21.4) the bottomset beds grade into the profile of the former Virgin River channel. As noted previously, however, a thin layer of silt and clay, ranging from a few tenths of a foot to about 2 feet in thickness, has accumulated, at least in isolated patches, between the toe of the Virgin delta and the Lower Narrows (river-mile 9.3) of the 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 the Overton Arm.

As shown by sections Q-Q' and R-R' (fig. 15), the bottomset beds are 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 have been filled to the level of the sediment in the channel. The most prominent example of tributary filling occurs at river-mile 25.0, where the bottomset beds of the Virgin delta extend almost one-half mile into the lower part of theuddy Creek valley, (fig. 15). 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 Lake Mead Delta

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 here until it is high enough to be affected by river currents; additional sediment is carried to the edge of this platform and dropped into the deeper still-water body to form the foreset beds; finer material is carried still farther out into the still water and there forms the bottomset beds; still other material may be deposited on the platform as topset beds; as deposition continues, the gradient of the stream is modified, and some sediment may be deposited upstream from the original mouth. Thus the delta grows outward in the still-water body by deposition of foreset and bottomset beds; by its deposition of topset beds it grows upward and also projects into the original channel of the stream that provides the source material.

The growth of the deltas in Lake Mead is necessarily more complex than that of streams debouching into an ocean

or into a lake having relatively constant level. During the first 6½ years of the lake history the point at which the river entered still water migrated from the Boulder Basin to Bridge Canyon in the Lower Granite Gorge (a distance of more than 100 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 altitude 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 the Lower Granite Gorge.

A general idea of the growth of the Colorado delta from 1937 to 1948 may be obtained from the profiles of figure 18, but there is no similar information concerning the development of the Colorado delta during its earliest stages. Prior to the 1948 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 course of the 1948 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 gaging station. Some of the cores obtained during the 1948 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.

The question as to the age of the sediments may be answered by reference to the 1935 Soil Conservation Service topographic maps which generally depict the reservoir floor prior to sedimentation. A difficulty here is that flooding and delta deposition began in some areas prior to the surveys for these maps. The topography of Black Canyon and Boulder Basin, as portrayed by the maps of 1935, was taken from the Brock and Weymouth surveys of 1930 (Brown, 1941, p. 387), 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 plane-table data in the Virgin River valley and with sections across the Colorado River channel. The photographs, plane-table survey, and river cross-sections upstream from Pierce Basin were all obtained prior to inundation.

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, even though these sections were made within a period of a few days to three weeks after inundation. Accumulation of sediment in these early days of flooding was enough between the time of inundation and the time of survey in some areas to cause appreciable discrepancies between the aerial photographs and the cross-section data. In compiling the maps, corrections were applied to obtain the approximate topography of the channel prior to inundation, but the sediment accumulated in the channel along much of its length was evidently too thin to be detected by this means and has probably been included as part of the pre-Lake Mead topography.

#### Growth in February and March 1935

During the first two weeks (February 1-15, 1935) after Hoover Dam was closed, 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. 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 at most only a few inches thick.

The lake level remained at about 700 feet altitude from February 15 to April 1. The mouth of the Colorado River during this time was located near the head of Boulder Canyon, 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, doubtless 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. According to Grever and Howard (1938), turbid water was discharged from the diversion tunnel near the bottom of the

dam in the latter part of February 1935 and again in March and April 1935. Apparently the sediment carried by the currents 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, fig. 9) 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 underlying the fine-grained bottomset beds was encountered at a depth 83 feet which corresponds closely with the thickness of accumulated sediment determined by comparison of the 1943 topography with 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 sand layer only a few inches thick deposited in the channel during its flooding in February 1935.

At the head of Boulder Canyon, sand (cores 17 and K2, fig. 9) was encountered at depths of 55 to 60 feet below the sediment surface and 5 to 10 feet above the buried Colorado River channel as portrayed by the Soil Conservation Service maps. Although the pre-Lake Mead channel topography in this area was not mapped until after its inundation, it seems reasonable to suppose that this relatively thick accumulation of sediment was detected and that appropriate corrections were applied to obtain 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 from February 1 to April 1, 1935. This layer probably consists of incipiently developed topset and foreset beds deposited at the mouth of the Colorado River as it receded upstream in response to the rising lake water. 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. 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 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 an altitude of 925 feet in July, and then remained relatively constant until April 1936. Between July 1935 and April 1936 the Colorado River entered the lake in Pierce Basin near river-mile 276, about 30 miles upstream from Hoover Dam. The river mouth at this time was about 2 miles east of the river entrance in 1948, but the channel near the river mouth 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 river as it regressed upstream from April to 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. 402), 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 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 course of 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 approximately 1,000 acre-feet. Assuming that this material is 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 1 to June 30, 1935) this estimate appears somewhat low. According to Howard (1947, p. 41), a total of  $87\frac{1}{2}$  million tons of sediment were carried in suspension by the Colorado River during this period past the Grand Canyon gaging station, of which about  $1\frac{1}{2}$  million tons was carried through the reservoir and dam by turbidity currents (Grover and Howard, 1938).

From studies of the texture and specific weight of the accumulated sediment (reported in later sections of this paper) it seems reasonable to assume that at least 50 percent ( $43\frac{1}{2}$  million tons) of this load is made up of sand, which when accumulated in the reservoir has an average specific weight of 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-sized particles exceeded 50 percent of the total on most days, particularly on the days when the river was

carrying the greatest sediment loads. 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 regressed 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. This deposit of sand, like that underlying the bottomset beds in the western part of the lake, 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

From April 1936 to July 1937 the lake rose in two successive stages from an altitude of 910 feet to an altitude of 1,100 feet. The first rise (April-July 1936) brought the water surface to an altitude of 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 regressed 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 river-mile 255, and in July 1937 the river entered the lake near river-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 regressed 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 river-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 the 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 (river-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 (fig. 18), the contact between the bottomset beds and the overlying foreset and topset beds accumulated in the eastern part of the lake from 1937 to 1948 may be projected as illustrated in figure 25. 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 the Lower Granite Gorge, and it is impossible to verify the accuracy of this division. However, a number of drill cores extending to maximum

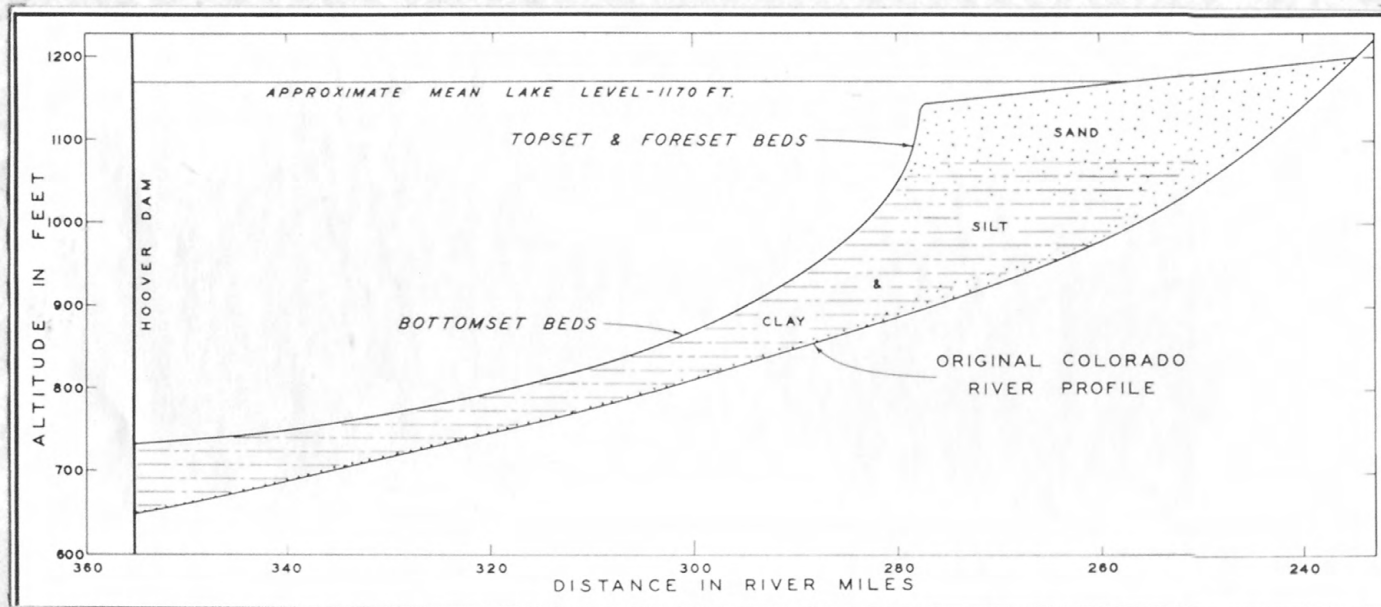


FIGURE 25

STRUCTURAL SECTION OF THE COLORADO DELTA SHOWING RELATION OF BOTTOMSET BEDS  
(DASHED LINES) TO TOPSET AND FORESET BEDS (DOTTED)

sediment depths of 75 feet, were taken in the eastern part of the Lower Granite Gorge (river-mile 236.3 to 240.1) by the Bureau of Reclamation in 1941 and 1942. Logs of these cores, as recorded by Murdock (1942), show that the total thickness of the accumulated sediment in this region consists of sand and silt, with only a small amount of gravel near the bottom of the buried Colorado River channel. This suggests that the delta in the eastern part of the Lower Granite Gorge is composed wholly of topset and foreset beds, confirming the interpretation shown in Figure 25.

The Lower Granite Gorge portion of the Colorado delta did not begin its development until the water level of the reservoir reached an altitude of approximately 1,100 feet in July 1937. Since that date the lake surface has 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 1941 this portion of the delta occupied the entire Lower Granite Gorge from Bridge Canyon downstream about 43 miles to the delta front in Pierce Basin.

In the same period many tens of feet of silt and clay accumulated in the bottomset beds which extend to Hoover Dam. These beds in the western part of the lake provide a thick cover over the portion 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 in 1948 of the Colorado delta along the thalweg is indicated by figure 25. Because of inadequate data it is impossible to make an accurate division between the topset and foreset beds at the bottom of the channel and the overlying bottomset beds. Consequently, the contact shown in figure 25 is purely diagrammatic. In the eastern part of the Lower Granite Gorge, the delta is made up entirely of topset and foreset beds which 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 very thin section of topset and foreset beds. The bottomset beds in this area have been accumulating continuously since the area was first inundated by the lake. 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 in this area, three (cores 3, 16, and 76, fig. 9) terminated in compact silt and clay at distances of 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, and it is likely that the sand was contributed by this source. The slumping of sand into the channel also accounts for the limited penetration in this area. This sediment from local sources constitutes a negligible proportion of the total deposited in Boulder Basin.

In the Virgin Basin, ten cores (15, 18-23, 25-26, and K3, fig. 9) extended to within less than 5 feet of the pre-Lake Mead bottom as portrayed by the Soil Conservation Service maps. Core 24 fell about 13 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 from 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 bottom 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 bottom.

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 (cores 19, 22, 23 and K3, fig. 9) 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 753 feet, corresponding to the 1939 sediment level near the intersection of Detrital Wash with the Colorado River channel (river-mile 323-325, fig. 13), and may have been derived from the scour of Detrital Wash near its



entrance into Lake Mead (Gatewood, 1945), probably during extreme floods in 1939. The lower sand layer is at altitude 755 feet, and may have been deposited in 1939; 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 of the accumulated sediment comes from the Colorado River and has been deposited in bottomset beds of the Colorado delta.

Between the eastern end of the Virgin Basin (river-mile 320) and the foot of the delta front in Pierce Basin (river-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 sediment thickness; this core (core K, fig. 9) was made up entirely of silt and clay from the bottomset beds. The other cores (cores 38-41) 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 slumping of sand and coarse silt 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 (fig. 26).

In Virgin Canyon and Gregg Basin only two of eight cores (cores 45 and 46, fig. 9) 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 (42-44, 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. Cores 60 and 71 (fig. 9) show that 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 ranges in thickness from about 100 feet to 150 feet.



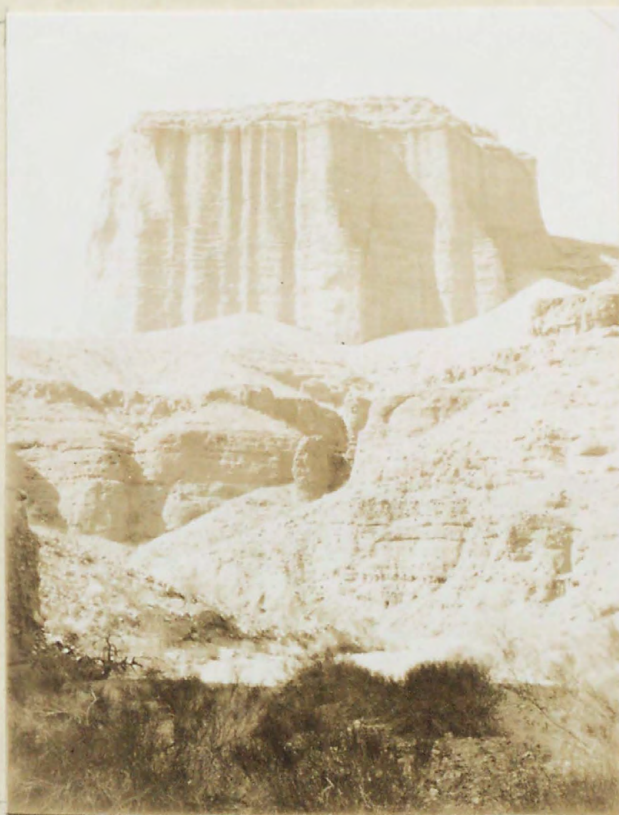


FIGURE 26

## THE TEMPLE IN 1934 (UPPER) AND 1948 (LOWER)

The talus cone and underlying cliff shown in upper photograph were subsequently covered by Lake Mead. Note the fresh landslide scars on the face of the Temple in 1948. Upper photograph by C. R. Longwell.



The maximum sampling depths (cores 61, 63 and K6) range from 79 feet to 95 feet, equivalent to the lengths of the longest coring tubes used in Lake Mead. Thus, the depth of penetration was limited by the lengths of the core tubes, not by compact sand or consolidated layers of silt and clay in the lower part of the channel. 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 surface 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. For example, core 68 taken near the head of the delta front extended only 2 feet into the hard sand of the foreset beds. On the other hand, cores 65 and K7 taken near the foot of the delta front, reached depths of about 23 feet. These cores 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 further, its thickness is not known, but it suggests an inter-fingering 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 topset and foreset beds exposed in Pierce Basin and the 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 topset and foreset beds.

#### Virgin Delta

The Virgin delta did not begin its development until the early part of May 1935, when the rising water of Lake Mead reached the junction of the Virgin and Colorado Rivers. Prior to this 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 1 to July 1, 1935, the lake flooded the lower 12 miles of the Virgin River valley (Overton Arm), and the mouth of the Virgin River regressed rapidly upstream to its intersection with Bitter Wash, about 3 miles north of the Lower Barrows, where it remained essentially

stationary until April 1936. With the second rise in lake stage (April-July 1936) the mouth of the Virgin River moved northward to river-mile 19.5 where it again became stationary until March 1937. Following 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.

It seems probable that sedimentation in the Virgin River channel during this early period of reservoir filling progressed in much the same fashion as in the Colorado River channel, the coarser particles being dropped 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 during this period was evidently very small. The 1918 topography of the lower 21 miles of the Virgin River valley shows 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 transgress the lower 2½ miles of the Virgin River valley. On the other hand, bottom samples and penetration measurements between Virgin River 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 the 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 the 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 the three cores (35, 36, and 37, fig. 9) obtained between the toe of the Virgin delta (river-mile 21.4) and the foot of the delta front (river-mile 26.7), core 35 is the only one that penetrated the full thickness of the accumulated sediment. At this position (river-mile 23.7) the delta consisted of 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 lake bottom, although it is possible that some of the sand may have accumulated in the Virgin River channel during the filling of the reservoir.

At river-miles 24.5 and 26.1 the delta is about 10 feet thick, but only the upper few feet could be penetrated. Core 37 at river-mile 24.5 reached a depth of only 1 foot, and core 36 at river-mile 26.2 extended about 5 feet into the delta. These cores show that the upper part of the delta is made up of layers of silt and clay; the hard compact character of the lower part of the delta, which could not be penetrated, suggests that it consists chiefly of layers of sand. The sand layers are interpreted as topset and foreset beds that accumulated near the mouth of the Virgin River when it remained essentially stationary in the vicinity of river-mile 26.0 from July 1927 to April 1938. The overlying layers of silt and clay are interpreted as bottomset beds which 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 river-mile 26.7. The surface or near-surface layers of this part of the delta are made up chiefly of hard sand which could not

be penetrated by the coring device. Between river-mile 26.7 and 30.2, samples and penetration measurements show that the upper few inches of the delta are 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 1943. Immediately below the soft surface layer are layers of hard sand and coarse silt, which, as observed by Frank B. Ames (personal communication), are exposed at the delta surface north of river-mile 30.2. These sand layers are regarded as topset and foreset beds, the division being made at river-mile 27.4, where the delta profile steepens from 10.7 feet per mile to 24 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 out over the bottomset beds that make up the delta surface south of river-mile 26.7.

#### Physical Properties

The Lake Mead deltas are made up almost entirely of particles of sand, silt, and clay. The sand particles have been deposited at or near the mouths of the Colorado and Virgin Rivers and are confined, therefore, to the topset and foreset 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 graded geographically, 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 a soft, ooze-like consistency.

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

#### Texture and Stratification

##### Topset and Foreset Beds

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 the Lower Granite Gorge the active channel deposits are made up chiefly of medium and coarse sand with small

amounts of gravel, whereas the levees and terraces consist of cross-bedded fine sand. Locally the upper layers of the terraces and levees have been reworked by the wind, thus producing a veneer of well-rounded, frosted sand grains upon the river embankments in many places. Surface material in the depressions behind the natural levees is 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 the 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 the western part of the gorge and the eastern part of Pierce Basin is capped by a layer of poorly sorted silt and clay that accumulated in the slack water that covered this area during the high lake stage of 1948. However, the sediment immediately beneath this layer, as well as the sediment in the channel, is made up chiefly of 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 stream gravel both in the active

channel and in the natural levees. Samples from the topset beds show that gravel is present only in the easternmost 2 miles of the reservoir (river-miles 235 to 237), and that it is confined to the center of the channel. Although no cores were obtained from this portion of the delta during the 1948 survey, cores taken in 1941 and 1942 by Murdock (1942) show that sand and silt constitute practically the entire thickness of the delta east of river-mile 240 and that only small amounts of gravel are 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 composed of gravel.

The horizontal grading of the delta materials is shown clearly in a longitudinal section (fig. 27). The sediment particles at the surface range in median diameter from 22.5 millimeters at river-mile 237.3 to less than .001 millimeter (1 micron) at river-mile 354.6. It is interesting 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 (fig. 27), 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



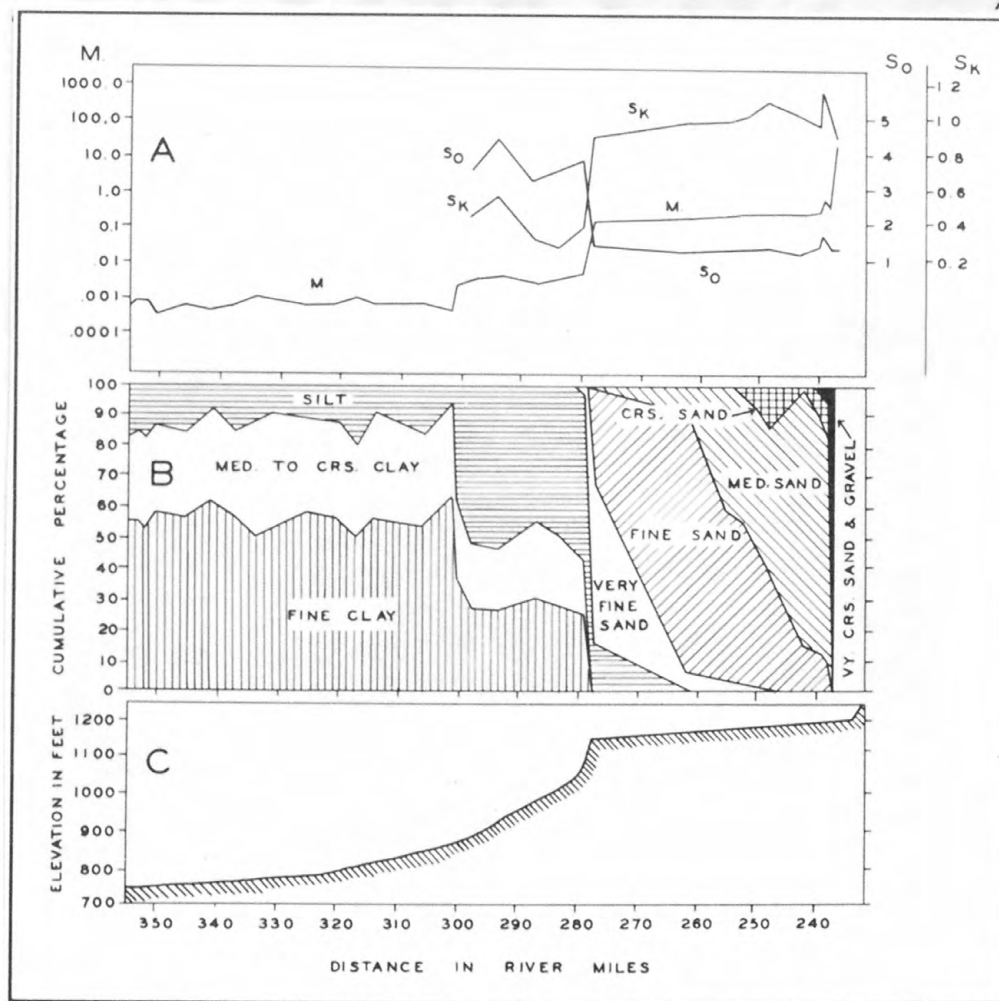


FIGURE 27

TEXTURAL CHARACTERISTICS OF THE SURFICIAL DEPOSITS  
OF THE COLORADO DELTA ALONG THE THALWEG

(A)  $S_k$  = coefficient of skewness,  $S_o$  = coefficient of sorting, and M = median diameter in millimeters: (B) Cumulative percentage graph showing the size distribution of various sediment components: (C) Longitudinal profile of the Colorado delta.

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 to estimate the contact between the bottomset beds and the overlying topset and foreset beds in the Lower Granite Gorge (fig. 25). The contact shown on figure 25 does not account for 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 27 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. This relationship suggests that the velocities of the Colorado River turbidity currents 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 east of river-mile 30.2 (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 suggest, 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 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, the topset and foreset beds south of river-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 one of these samples (9520, fig. 7) 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) with 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 river-mile 30.2, but according to Frank C. Ames (personal communication), who investigated this part of the delta, they are made up predominantly of sand with a minor amount of silt.

#### Bottomset Beds

The bottomset beds of the Colorado delta are composed of stratified silt and clay and because of their high water content, they are exceedingly soft and jelly-like. Only samples of the most deeply buried layers are solid enough that they do not 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 them a sponge-like appearance.

Textural variations in the bottomset beds are small in transverse section when compared to those in longitudinal

and vertical section. Between river-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, but west of river-mile 285.0 the textural variations in transverse section are extremely small. 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.

Particle-size variations in longitudinal section are well illustrated by figure 27. The median particle diameter grades from 6 microns at river-mile 279.3 to less than 1 micron at Hoover Dam. The relationship 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 28. The comparatively large vertical variations in median diameter above Virgin Canyon (river-mile 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. It seems probable that the coarser elements were carried by relatively high velocity currents, whereas the finer particles were transported by currents of

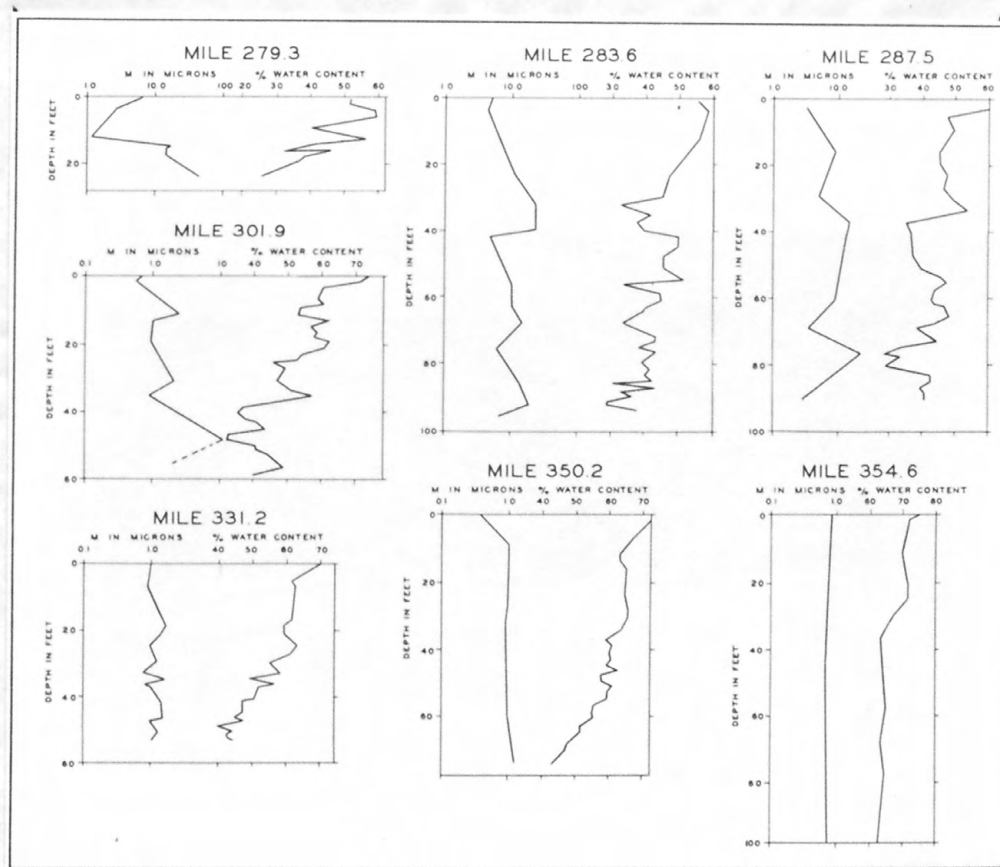


FIGURE 28

TYPICAL VERTICAL SECTIONS OF THE BOTTOMSET BEDS  
OF THE COLORADO DELTA, SHOWING THE VARIATIONS  
IN WATER CONTENT AND MEDIAN PARTICLE SIZE  
Median diameter in microns, water content in percent by  
weight.



low velocity. West of river-mile 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.

Although the textural variations are not large, the bottomset beds do have a distinct stratification. 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 (fig. 29); or by an unusually high percentage of gas cavities (fig. 30).

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 travelled through the lake may account for our inability to trace the individual layers of the bottomset

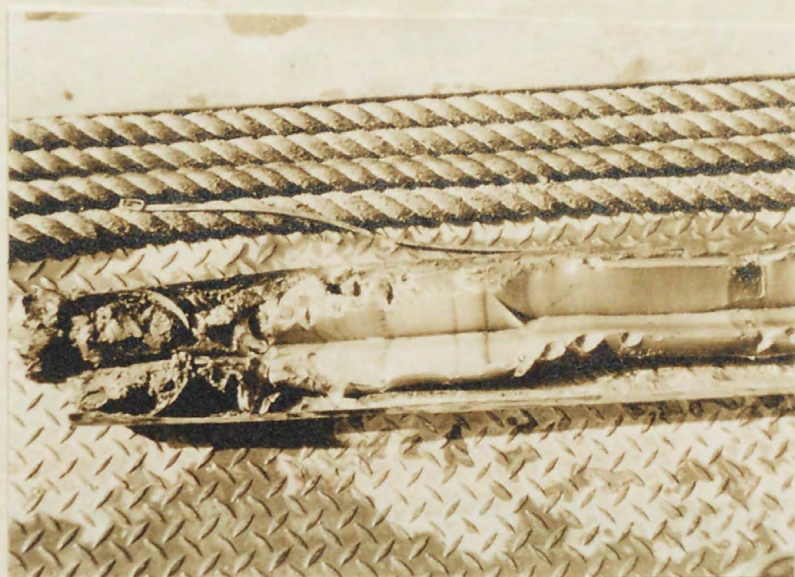


FIGURE 29

SECTION OF CORE FROM THE BOTTOMSET BEDS OF THE  
COLORADO DELTA, SHOWING THIN BLACK ORGANIC  
LAYERS AND JELLY-LIKE CHARACTER OF THE MATERIAL  
Length about 3 feet

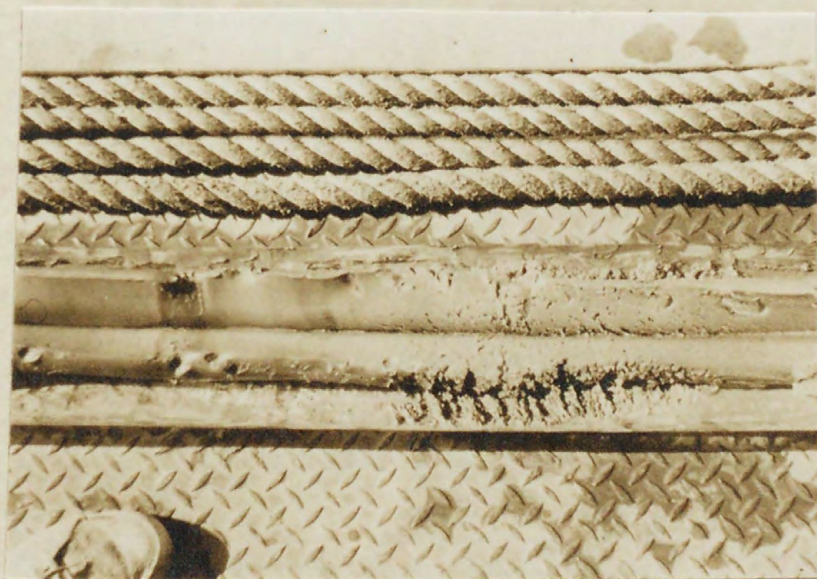


FIGURE 30

CORE SECTION IMMEDIATELY ABOVE THAT SHOWN IN FIGURE 29  
Porous layer (right) illustrates the abundance of gas  
cavities in some strata. Length about 3 feet.



beds for any great distance.

The texture of the bottomset beds, as reported above, is based on grain size analyses made in a fully dispersed medium where the individual particles behave as discrete units. Duplicate analyses of a few samples made in untreated lake water show, however, that the silt and clay of the bottomset beds are flocculated, and as would be expected, the finest material exhibits the greatest degree of flocculation (table 6). It is evident from these analyses that the silt and clay particles have settled to the bottom as flocculated masses, not as discrete units.

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 the surface of the Virgin delta, the median particle diameter of the bottomset beds ranges from 4.2 microns near the foot of the delta front (river-mile 26.7) to about 2.5 microns near the southern end of the delta (river-mile 21.4). South of river-mile 21.4



TABLE 6

Comparison of the median particle diameters of samples from the bottomset beds of the Colorado delta as determined by analyses in a dispersed medium and in untreated lake water.

| Sample number | Position in river miles | Sediment depth in feet | Dispersed <sup>1</sup> medium | Untreated <sup>2</sup> lake water    |
|---------------|-------------------------|------------------------|-------------------------------|--------------------------------------|
|               |                         |                        | Median diameter in microns    | Effective median diameter in microns |
| 14            | 282.3                   | 0                      | 5.0                           | 13.0                                 |
| 16            | 287.5                   | 0                      | 7.0                           | 11.5                                 |
| 67            | 350.1                   | 71.6                   | 0.50                          | 10.0                                 |
| 19            | 354.5                   | 0                      | 0.90                          | 11.0                                 |

1 Sediment dispersed with 0.896 gram of sodium hexametaphosphate,  $(\text{NaPO}_3)_6$ , per liter of suspension.

2 Salinity of untreated lake water approximately 700 parts per million.

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 river-mile 15.1. This thin layer was identified as far south as river-mile 9.3, but the sample (G1250, fig. 9) from this location is not representative because of contamination with sand from the bottom of the channel. The downstream 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 the 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 which 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 (fig. 9), the texture of the bottomset beds between river-miles 26.7 and 23.7 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 river-mile 279.3.

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 the 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 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 more than 80 percent of the wet weight of the accumulated sediment, or greater than 70 percent when expressed in terms of porosity. As additional layers are deposited on top of those in place, the solid particles of the buried material pack together more tightly, thus driving out part of the interstitial water. The water content and porosity of the accumulated sediment 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 sediments. This relationship 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. Expressed in terms of volume, 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 23.

The water content in all sections decreases with increasing depth, and where the texture changes, the water content is inversely proportional to the median diameter. Sections at river-miles 279.5, 283.6, 287.5, and 301.9 show many inversions due to abundant textural changes in this portion of the delta. The correlation would doubtless be more evident if all samples had been analyzed both for particle size and water content; size analyses require so much time, however, that they were made only of samples with the most significant textural changes. At river-miles 331.2 and 350.2, however, textural changes are fewer and smaller, and the water content inversions are less pronounced. Immediately above Hoover Dam (river-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 river-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 31. At river-mile 345.9 in Boulder Basin, where the bottomset beds are high in interstitial water and only weakly consolidated, 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 river-miles 324.3 in Virgin Basin and 295.5 in Gregg Basin can also be distinguished, but with greater difficulty. The closeness of the record between the upper and lower traces at river-miles 324.3 and 295.5 results from the greater consolidation and lower water



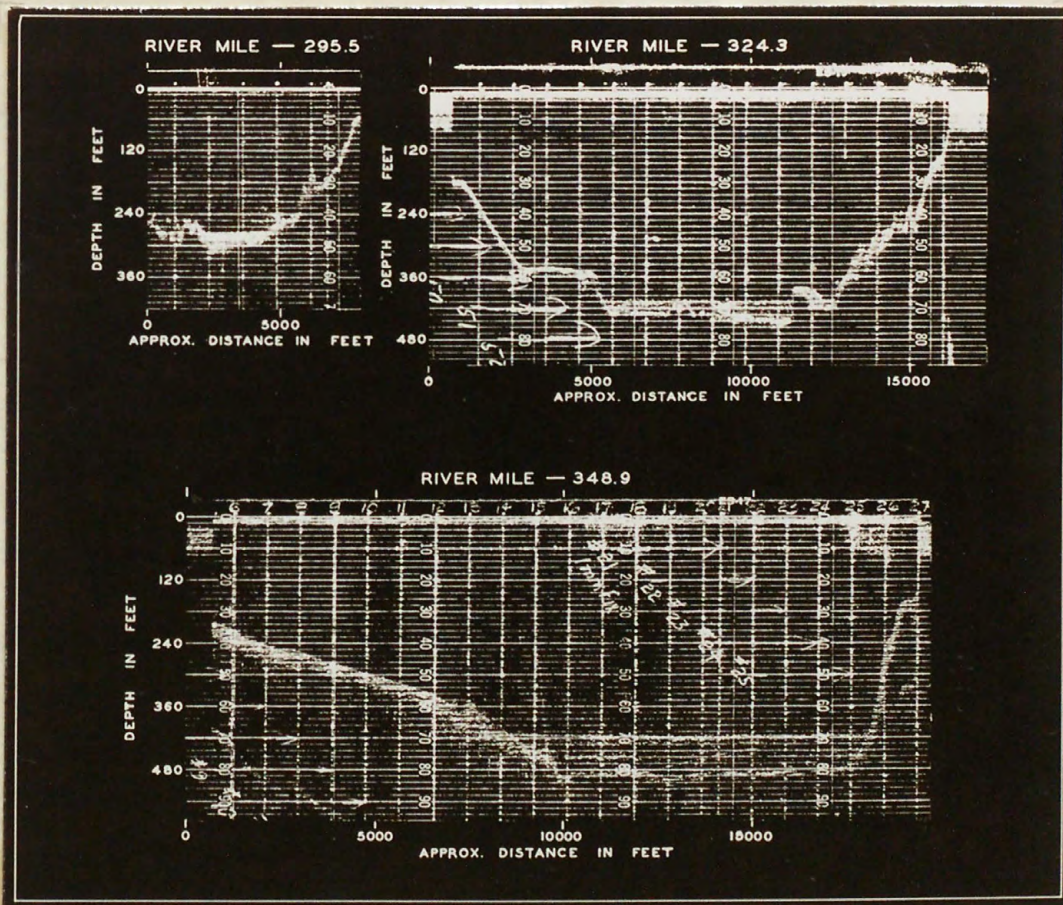


FIGURE 31

FATHOGRAMS ACROSS THE BOTTOMSET BEDS OF THE COLORADO  
 DELTA SHOWING THEIR INCREASE IN CONSOLIDATION  
 UPSTREAM FROM HOOVER DAM

Upper horizontal trace shows the surface of the bottomset  
 beds, whereas the lower trace delineates the topography of  
 the pre-Lake Mead bottom.



content of the bottomset beds in these areas. Owing to the still greater consolidation of the bottomset beds east of river-mile 295.5, the sound was completely absorbed before it reached the bottom of the buried Colorado River channel. Consequently, bathograms east of river-mile 295.5 show only the surface of the bottomset beds.

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 percent to 62 percent, and the porosity ranges from 63 percent to 82 percent. In contrast, the water content of the surface layers of the Colorado delta bottomset beds ranges from 47 percent to 75 percent, and the porosity ranges from 71 percent 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 (fig. 9) taken at Virgin River-mile 26.1, 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 percent to 59.3 percent.

#### Specific Weight

Because of its limited application in most geological studies, specific weight is not commonly 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 a particularly useful quantity for it provides a relatively simple method of obtaining the total weight of the solid mineral particles deposited in the reservoir.

Direct specific weight determinations were made of only a few samples because of the difficulty in obtaining material of known volume and the complications caused by the expansion of gas in the samples. As a result, the specific weight of most samples has been determined indirectly by the method outlined in an earlier section of this report. The values of specific weight, as determined by this method, have not been corrected for the volume of gas in situ, but from measurements of the quantity of gas

in 74 samples from widely separated positions, the maximum error in the specific weight determinations is estimated at less than 1 percent.

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

If the accumulated material is of uniform texture, 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, however, 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.

Both the horizontal and vertical variations in the specific weight of the Colorado delta are illustrated in figure 32. This diagram clearly shows that the specific weight of the topset and foreset beds exposed at the delta surface above river-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 39 feet at river-mile 283.6 and the other from the same depth at river-mile 350.1. The sample at river-mile 283.6 has a median particle diameter of 22.0 microns and a specific weight of 62.1 pounds per cubic foot. In contrast, the sample at river-mile 350.1 has a median diameter of 0.7 micron and a specific weight of 32.5 pounds per cubic foot.

In the deeper layers of the bottomset beds that could not be sampled, the specific weight has been obtained by linear extrapolation of specific weight data from higher

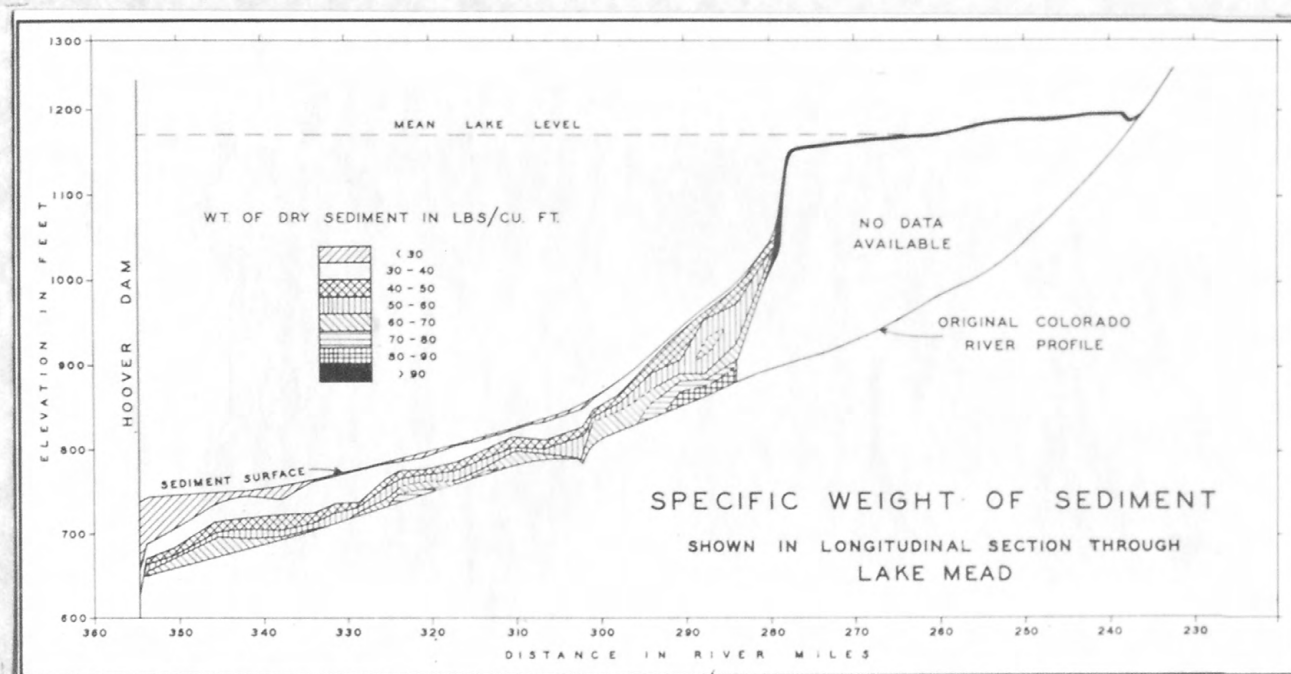


FIGURE 32

SPECIFIC WEIGHT OF THE SEDIMENT ACCUMULATED IN THE COLORADO DELTA ALONG THE THALWEG  
Dashed lines indicate extrapolation

levels. These extrapolations are denoted in figure 32 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 the 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 the Lower Granite Gorge is 93.8 pounds per cubic foot, whereas the average extrapolated 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. 25) and the volume of sediment suggest, however, that the sand of the 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 consolidation or 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 superimposed 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 characteristic of all depths.

This conclusion is supported by specific weight measurements of a few 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 the 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 samples collected from the surface of the topset and foreset beds.

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 62.5 pounds per cubic foot near the delta front to 39.6 pounds per cubic foot at the lower end of the delta. As shown by core 36 (fig. 9), where the Virgin delta bottomset beds are thickest, the specific weight ranges from 41.7 pounds per cubic foot at the surface to 63.7 pounds per cubic foot at a depth of about 5 feet. The specific weight of the uppermost bottomset beds of the Colorado delta ranges from 50 to 18 pounds per cubic foot.

#### Gas Content

The occurrence of a considerable amount of gas in the sediments of the Colorado delta is indicated both by abundant gas pits on the exposed terrace near the delta front and by a great number of unconnected gas cavities in cores from the bottomset beds. An analysis (table 7) by the U. S. Bureau of Mines' Petroleum and Oil-Shale Experiment Station at Laramie, Wyoming, shows that the gas issuing from the conical-shaped pits of the delta surface



TABLE 7

Gas from the Colorado delta

Analysis by Petroleum and Oil-Shale Experiment Station,

U. S. Bureau of Mines, Laramie, Wyoming

|                               | Percent      |
|-------------------------------|--------------|
| Methane, $\text{CH}_4$        | 78.0         |
| Nitrogen, $\text{N}_2$        | 16.3         |
| Oxygen, $\text{O}_2$          | 4.8          |
| Argon, $\text{A}_2$           | 0.4          |
| Carbon dioxide, $\text{CO}_2$ | 0.5          |
|                               | <u>100.0</u> |

is composed principally of methane, some nitrogen and oxygen, and small amounts of argon, and carbon dioxide. Inasmuch as the nitrogen, oxygen, and argon are in roughly the same proportions as they are in air, it was thought initially that air had been introduced during the collection of the sample. F. B. Sisler (personal communication) has suggested, however, on the basis of his study of the bacteriological and biochemical properties of the Lake Mead sediments, that the small amount of oxygen, nitrogen, and argon may indicate a natural aeration of the sediment in situ. Methane and carbon dioxide, on the other hand, are being produced by the biochemical decomposition of organic matter in the bottomset beds (Sisler, 1952).

Except for the small amount of argon, the gas contained 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, and are extremely numerous in some layers. The 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 bottommost 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 pressure. To obtain an estimate of the average gas content in situ, 74 samples of measured volume were collected from the bottommost beds of the Colorado delta. These samples were obtained from widely distributed localities, both laterally and vertically, and are considered, therefore, to be representative of the Colorado delta bottommost beds as a whole. The volume of gas contained in the sediment in situ was calculated as outlined in the discussion of laboratory methods.

At atmospheric pressure the gas volume may be as much as 12 percent of the volume of the water-saturated sediment, but the maximum gas content in situ is only 2 percent. In vertical section the gas content does not vary systematically, but in longitudinal section 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 seven vertical sections, ranges from 1.1 percent at river-mile 283.5 to 0.3 percent at river-mile 351.2 (fig. 33). The average of all determinations is 0.6 percent, which is probably



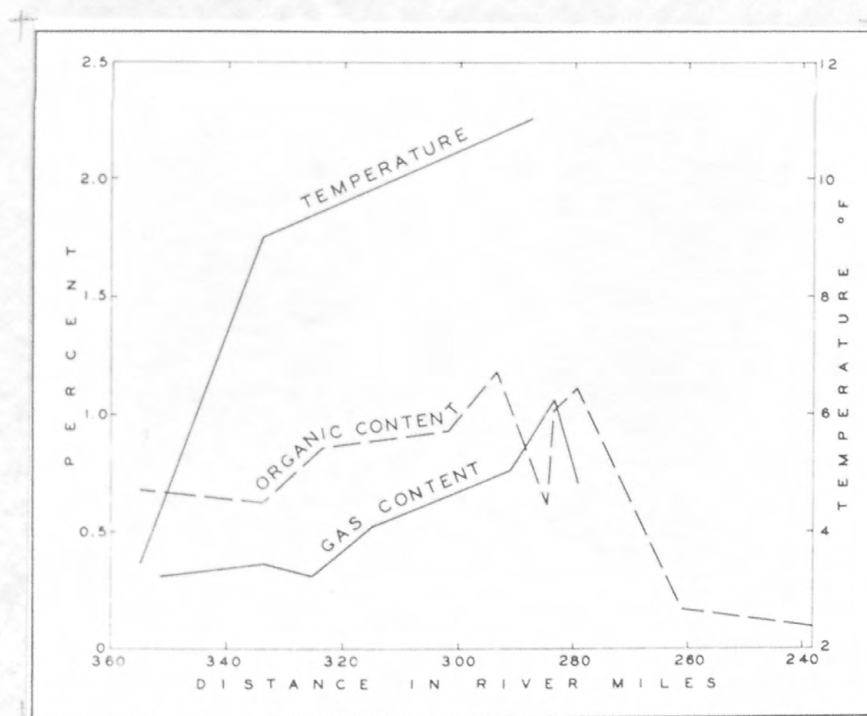


FIGURE 33

RELATION OF GAS CONTENT, ORGANIC CONTENT, AND TEMPERATURE GRADIENT IN LONGITUDINAL SECTION THROUGH THE COLORADO DELTA

Values of organic content and gas content are averages of samples from each of several vertical sections. Temperature gradient represents temperature increase in the upper 40 feet of the accumulated sediment.

representative of the average gas content of the bottomset beds west of the Colorado delta front.

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

No measurements were made of the gas content of the Virgin delta bottomset beds, but from visual inspection of cores, gas cavities are not nearly so prominent as they are in the bottomset beds of the Colorado delta.

#### Sediment Temperature

One of the most striking features of the bottomset beds of the Colorado delta is their extremely high temperatures. Measurements taken by the U. S. Bureau of Reclamation (1941, 1947) since the summer of 1937 show that the surficial layers of the bottomset beds are commonly more than 5° F. warmer than the overlying lake water with which they are in contact. This high temperature is not a local phenomenon, but a general condition of the bottomset beds wherever they are exposed on the lake bottom. Prior to the 1948 survey temperature measurements were confined chiefly to the lake water and to the surficial layers of the

bottomset beds. Only spotty measurements were available from the deeper sediment layers.

In order to obtain the temperatures of the deeper sediments, a mud bathythermograph, specially designed and constructed by the U. S. 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 modification 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 hysteresis caused by mud clinging to the instrument. By lowering this instrument at a rate less than 3 feet per minute, hysteresis was reduced and 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 (river-mile 333.9) and Iceberg Canyon (river-mile 227.5) the bathythermograph was stopped by compact sediment at depths of 42 feet and 45 feet respectively. The results of these measurements (fig. 3h) show that the temperature of the



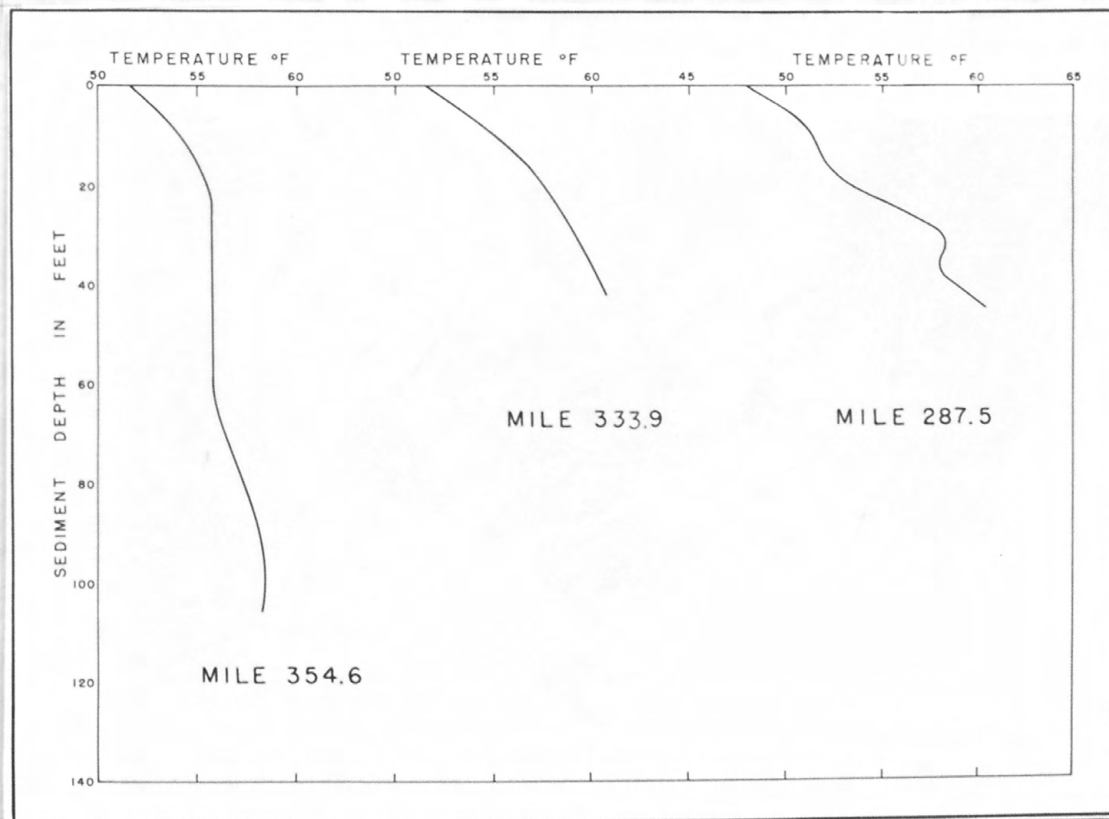


FIGURE 34

VERTICAL DISTRIBUTION OF TEMPERATURE IN THE BOTTOMSET  
BEDS OF THE COLORADO DELTA

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  $0.28^{\circ}$  F. per foot at river-mile 287.5 to  $0.07^{\circ}$  F. per foot at river-mile 354.6. The traces at river-miles 287.5 and 354.6 show a distinct temperature stratification.

Apparently, the high temperature of the bottomset beds has extremely little effect on the temperature of the overlying lake water. The numerous measurements taken by the U. S. Bureau of Reclamation, as well as those obtained during the course of the 1948 survey, show no evidence of heating of the lake water near its contact with the bottomset beds. The change in temperature at the water-sediment interface is abrupt. This does not imply that there is no transfer of heat from the bottomset beds to the lake water, but it does suggest that what heat is transferred is distributed rapidly throughout the water mass.

Probably a great number of factors have contributed to the heating of the bottomset beds of the Colorado delta, but since there has been no study of the heat budget, they cannot be evaluated quantitatively. From the limited data available it appears, however, that biochemical processes have been chiefly responsible for the observed heating.

According to Sisler (1952), the concentration of bacteria in the bottomset beds is about the same as that found in raw sewage. Furthermore, he has demonstrated by laboratory experiment that the bacteria, in their oxidation of organic matter, are capable of raising the temperature of the sediment by about  $2^{\circ}$  F. in a period of only 3 weeks.

There is evidence also that part of the observed heat may be attributed to the initially high temperature of the sediment when it was deposited in the bottomset beds. Records of the U. S. Bureau of 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, in March 1939 a flow of turbid water about  $4^{\circ}$  F. warmer than the overlying lake water was detected at the bottom of the reservoir as far west as Boulder Canyon. Probably the temperature of some other flows has been correspondingly high, but there are no records of them. A similar high temperature of turbid water flowing along the bottom of Elephant Butte Reservoir has been recorded by Flock (1934).

Radioactivity of the sediments as a possible source of heating was found to be negligible. According to Sisler (1952) the maximum energy liberated as heat from radioactivity was less than  $10^{-10}$  calories per minute per gram.



He has further estimated that the average heat energy would probably be a hundred or a thousand times less than this maximum estimate.

Geothermal heat and hot springs have been suggested as other possible sources from which the bottomset beds may have derived part of their heat. The geothermal gradient near Hoover Dam has been estimated at about  $.013^{\circ}$  F. per foot (U. S. Bureau of Reclamation, 1950). 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. Bureau of Reclamation, 1950). 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.

The steep temperature gradients in the bottomset beds of the Colorado delta suggest that their thermal conductivity is extremely low. However, this factor, as well as all other factors that influence the heat budget of the bottomset beds, needs to be evaluated quantitatively before

any clear understanding of this anomalous heating can be obtained.

### Chemical Properties

Chemical, spectrographic, and clay-mineral analyses have been made of a relatively few samples, carefully 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. Likewise, 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 by the geochemical laboratories of the U. S. Geological Survey. Of these, seven were obtained from the Colorado delta and one from the Virgin delta. The samples from the Colorado delta include representative material from the topset, foreset, and bottomset beds, but the sample from the Virgin delta is representative only of the bottomset beds.

The results of these analyses (table 8) show that the

TABLE 8

Chemical analyses of samples from the sediment accumulated in Lake Mead, in percent.

| Location of sample, river-mile              | Colorado delta |              |                |       |       |       |       | Virgin delta   |
|---------------------------------------------|----------------|--------------|----------------|-------|-------|-------|-------|----------------|
|                                             | Tonset beds    | Foreset beds | Bottomset beds |       |       |       |       | Bottomset beds |
|                                             | 255.5          | 277.9        | 287.5          | 297.7 | 306.2 | 325.3 | 345.4 | 15.8           |
| Sample number                               | G1270          | 1037         | 937            | 698   | 634   | 332   | 1176  | G533           |
| Depth below sediment surface                | 0              | 1            | 58             | 13    | 42    | 18    | 30    | 0              |
| SiO <sub>2</sub>                            | 91.7           | 80.4         | 55.7           | 55.2  | 56.4  | 52.1  | 47.0  | 45.4           |
| Al <sub>2</sub> O <sub>3</sub>              | 1.6            | 5.2          | 12.2           | 13.0  | 15.4  | 17.2  | 14.8  | 14.2           |
| Fe <sub>2</sub> O <sub>3</sub> <sup>1</sup> | 1.8            | 1.0          | 4.0            | 4.0   | 4.9   | 5.2   | 4.6   | 4.8            |
| MgO                                         | 0.22           | 0.75         | 2.8            | 3.0   | 2.6   | 3.0   | 3.7   | 4.3            |
| CaO                                         | 1.4            | 3.6          | 7.4            | 7.6   | 5.1   | 5.0   | 9.2   | 9.8            |
| Na <sub>2</sub> O                           | 0.46           | 0.75         | 0.90           | 0.76  | 0.69  | 0.48  | 0.48  | 0.66           |
| K <sub>2</sub> O                            | 0.79           | 2.0          | 2.4            | 2.4   | 2.6   | 2.6   | 2.6   | 2.8            |
| TiO <sub>2</sub>                            | 0.32           | 0.24         | 0.59           | 0.72  | 0.70  | 0.64  | 0.58  | 0.58           |
| P <sub>2</sub> O <sub>5</sub>               | 0.05           | 0.07         | 0.18           | 0.17  | 0.17  | 0.16  | 0.18  | 0.20           |
| MnO                                         | 0.02           | 0.02         | 0.08           | 0.06  | 0.08  | 0.06  | 0.08  | 0.10           |
| Ignition <sup>2</sup>                       | 1.1            | 5.1          | 13.0           | 13.2  | 12.2  | 14.0  | 16.6  | 17.3           |
| Total                                       | 99.5           | 99.1         | 99.2           | 100.1 | 100.8 | 100.4 | 99.8  | 100.1          |

<sup>1</sup> Total Fe expressed as Fe<sub>2</sub>O<sub>3</sub><sup>2</sup> Includes loss due to oxidation of FeO



composition of the topset beds of the Colorado delta differs markedly from the composition of the bottomset beds. The foreset beds of the Colorado delta (sample 1037) are intermediate in composition between that of the topset and bottomset beds, but more like the topset beds. The bottomset beds of the Colorado and Virginia deltas are notably similar in composition. The topset beds of the Colorado delta (sample G1270) are made up almost entirely of  $\text{SiO}_2$ , whereas the bottomset beds (samples 937, 698, 634, 332, and 1136) have an average  $\text{SiO}_2$  content of only about 50 percent. Of the major constituents,  $\text{Al}_2\text{O}_3$ ,  $\text{Fe}_2\text{O}_3$ ,  $\text{MgO}$ ,  $\text{CaO}$ , and  $\text{K}_2\text{O}$  are much more abundant in the bottomset beds. Likewise, the minor elements,  $\text{Na}_2\text{O}$ ,  $\text{TiO}_2$ ,  $\text{P}_2\text{O}_5$ , and  $\text{MnO}$ , are appreciably higher in the bottomset beds than in 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 consist chiefly of hydrous aluminum silicates and hydroxides of iron and aluminum, as shown by lower silica content, the appreciable quantities of  $\text{Al}_2\text{O}_3$ ,  $\text{Fe}_2\text{O}_3$ ,  $\text{MgO}$ , and  $\text{K}_2\text{O}$ , and the 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

samples contain only one-half the sodium and one-fourth the  
 the Mississippi river silt, except that the Colorado delta  
 from the Colorado delta is of the same order as that of  
 states that the element composition of the silt and clay  
 for presentation in table 9. Mr. A. J. Wiers, the analyst,  
 their general similarity the analyses have been averaged  
 Mississippi river silt as comparison standards. Owing to  
 D. C., using both prepared soil samples and a sample of  
 laboratories of the U. S. Geological Survey in Washington,  
 delta were analyzed spectrographically by the Geochemical  
 six samples from the bottomest beds of the Colorado  
 Spectrographic Analyses

only one-half the sodium concentration of the average shale.  
 the Lakehead delta contain about twice the calcium and  
 only notable differences are that the bottomest beds of  
 average composition of shales (Clarke, 1924, p. 30). The  
 Colorado and Virgin deltas corresponds closely with the  
 wise, the composition of the bottomest beds of both the  
 the calcium concentration shown in Clarke's average. Like-  
 except that it has one-fourth the aluminum and about twice  
 position of river sands listed by Clarke (1924, p. 307)  
 Colorado delta is remarkably similar to the average com-  
 The composition of the sand in the topset beds of the  
 aluminum silicates.

TABLE 9

171

Spectrographic analysis of samples from the  
bottomset beds of the Colorado delta<sup>1</sup>

A. T. Myers, analyst

| Constituent                    | Percent |
|--------------------------------|---------|
| Major                          |         |
| SiO <sub>2</sub>               | 80.0    |
| Al <sub>2</sub> O <sub>3</sub> | 10.0    |
| Fe <sub>2</sub> O <sub>3</sub> | 05.0    |
| CaO                            | 04.0    |
| K <sub>2</sub> O               | 03.0    |
| MgO                            | 03.0    |
| Minor                          |         |
| Na <sub>2</sub> O              | 00.5    |
| TiO <sub>2</sub>               | 00.5    |
| P <sub>2</sub> O <sub>5</sub>  | 00.5    |
| MnO                            | 00.05   |
| ZrO <sub>2</sub>               | 00.05   |
| BaO                            | 00.05   |
| NiO                            | 00.005  |
| CuO                            | 00.005  |
| Cr <sub>2</sub> O <sub>3</sub> | 00.005  |
| V <sub>2</sub> O <sub>5</sub>  | 00.005  |
| PbO                            | 00.0005 |
| Trace                          |         |
| Sr                             |         |
| Y                              |         |

1 Average for six samples.

2 The first significant digit in the percentage composition is denoted by X. For example, the percentage of SiO<sub>2</sub>, shown as 80.0 percent, indicates that the material contains between 10 and 90 percent SiO<sub>2</sub>. Additional elements, Ag, As, Au, Be, Bi, Cd, Co, Ge, In, La, Mo, and Zn were looked for but not found.



copper concentration found in the Mississippi River silt.

#### Clay Minerals

Clay-mineral analyses were made of four samples from the bottomset beds of the Colorado delta by George Tchilingirian of the University of Southern California. He reports (Tchilingirian, 1951) 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 Wrix, Dietz, and Bradley (1949, pp. 1805-1806), 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 alkalimeter method outlined by Trask (1932, p. 97). The results of these analyses (table 10) show that the sand of the topset and foreset beds contains much less calcium carbonate than does the silt and clay of the bottomset beds. The calcium carbonate content of the topset and foreset beds ranges from 2.3 percent to 6.4 percent and averages 4.6 percent. In contrast, the calcium carbonate

TABLE 10  
Calcium carbonate and organic matter in selected samples from  
the Colorado delta

| Location,<br>river-mile | Sample<br>no. | Sediment<br>depth, ft. | Median diam-<br>eter, microns | CaCO <sub>3</sub> ,<br>percent | Organic matter,<br>percent <sup>1</sup> |
|-------------------------|---------------|------------------------|-------------------------------|--------------------------------|-----------------------------------------|
| <u>Tonset beds</u>      |               |                        |                               |                                |                                         |
| 238.1                   | G1261         | 0                      | 377.0                         | 5.2                            | 0.10                                    |
| 260.9                   | G1271         | 0                      | 187.0                         | 2.3                            | 0.17                                    |
| <u>Foreset beds</u>     |               |                        |                               |                                |                                         |
| 277.9                   | 1036          | 0                      | 105.0                         | 6.4                            | 0.14                                    |
| <u>Bottomset beds</u>   |               |                        |                               |                                |                                         |
|                         | 1038          | 1                      | 5.6                           | 18.5                           | 1.31                                    |
|                         | 1073          | 28                     | --                            | 18.4                           | 1.00                                    |
| 279.3                   | 1064          | 48                     | --                            | 12.2                           | 1.17                                    |
|                         | 1083          | 73                     | --                            | 16.1                           | 1.05                                    |
|                         | 1084          | 75                     | 0.9                           | 16.5                           | 1.09                                    |
|                         | 1017          | 2                      | --                            | 14.9                           | 0.66                                    |
| 279.35                  | 1015          | 9                      | --                            | 17.5                           | ---                                     |
|                         | 1024          | 15                     | 17.4                          | 17.4                           | 1.72                                    |
|                         | 1027          | 24                     | 45.0                          | 13.2                           | 0.99                                    |
|                         | 967           | 12                     | --                            | 17.6                           | 0.80                                    |
| 283.6                   | 988           | 71                     | --                            | 17.8                           | 1.41                                    |
|                         | 1003          | 93                     | --                            | 13.1                           | 0.87                                    |
| 284.5                   | 1121          | 63                     | 47.0                          | 17.7                           | 0.32                                    |
|                         | 1125          | 68                     | 1.5                           | 19.7                           | 0.92                                    |
|                         | 742           | 2                      | --                            | 17.0                           | 1.12                                    |
| 293.6                   | 750           | 31                     | --                            | 17.7                           | 1.16                                    |
|                         | 783           | 63                     | --                            | 18.6                           | 1.26                                    |
|                         | 657           | 5                      | --                            | 17.1                           | 1.12                                    |
| 301.9                   | 657           | 37                     | --                            | 13.1                           | 0.93                                    |
|                         | 670           | 59                     | --                            | 16.1                           | 0.78                                    |
|                         | 376           | 7                      | --                            | 18.5                           | 0.73                                    |
| 323.7                   | 409           | 23                     | --                            | 17.4                           | 1.05                                    |
|                         | 420           | 36                     | --                            | 16.5                           | 0.80                                    |
| 325.3                   | 338           | 26                     | --                            | 10.2                           | 1.27                                    |
|                         | 281           | 7                      | --                            | 15.8                           | 0.99                                    |
| 333.9                   | 242           | 35                     | 1.3                           | 12.1                           | 0.12                                    |
|                         | 304           | 56                     | --                            | 16.4                           | 0.78                                    |
| 341.6                   | 1162          | 57                     | 1.2                           | 14.9                           | 0.39                                    |
|                         | S10-1C        | 0                      | 0.8                           | 13.7                           | 0.66                                    |
| 354.6                   | S10-2C        | 44                     | 0.6                           | 16.2                           | 0.80                                    |
|                         | S10-3C        | 99                     | 0.7                           | 15.7                           | 0.58                                    |

<sup>1</sup> Organic carbon determined by chromic acid reduction, multiplied by 1.7.

content of the bottomset beds ranges from 10.7 percent 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 river-mile 279.3.

Although the high calcium carbonate content of the bottomset beds is clearly related to their fine texture, the percentage of calcium carbonate in individual samples does not vary systematically as a function of grain size. For example, sample SIO-1C with a median diameter of 0.3 micron has about the same calcium carbonate content as sample 1029 with 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 calcium carbonate analyses have been made of samples from the Virgin delta. However, the high calcium concentration in the Virgin delta bottomset beds (table 8) suggests that the calcium carbonate content of the Virgin delta is of the same order as that of the Colorado delta.

The total weight of sediment in the topset and



foreset beds of the Colorado delta (reported in a later section of this paper) is 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 Dr. Wilson Orr (personal communication) 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 by Dr. E. Vale Dawson (personal communication) of the Allan Hancock Foundation as the genus, Spyrosira.

The quantity of calcium carbonate in the accumulated sediment, however, is far greater than can be accounted for

by precipitation from the lake. Howard (1952), in his study of changes in the chemical properties of the Colorado River water as it passes through Lake Mead, observed that some dissolved solids are lost by precipitation in the lake and that others are gained by solution of soluble salts from the reservoir boundary. From consideration of the total inflow and outflow, plus the amount of water stored in the reservoir, he computed the net gain and loss of dissolved solids during the 14 year interval from 1935 to 1948. According to these computations, about 9 million tons of calcium carbonate and 1 million tons of silica were precipitated. In terms of the total weight of dry sediment (2,014,400,000 tons) that has accumulated in Lake Mead during this same period, the amount of calcium carbonate precipitated is 0.45 percent and the silica precipitated is 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, pp. 132-133) of the suspended load of the Colorado River in the delta at the head of the Gulf of California. According to his 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 along with the inorganic particles in the Lake Mead delta. Some organic matter is also contributed to the sediment by fresh water algae and sub-aerial 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 the changing lake level, 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, 1935). Organic matter is, of course, composed of oxygen, hydrogen, nitrogen, and

other constituents in addition to carbon, but Trask (1932, pp. 18-19) and others have found a fairly constant relation between organic carbon and total organic content. On the basis of this relation the organic contents of the samples, shown in table 10, were determined 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 the 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 in Pierce Basin at river-mile



279.3 to 6.68 percent at Hoover Dam (Fig. 33).

#### Biochemical Properties

The high temperature and considerable quantity of gas in the bottomset beds of the Colorado delta suggested immediately the need for a thorough investigation of the biochemical properties of the accumulated sediment. At the request of the U. S. Geological Survey, the Microbiology Division of the Scripps Institution of Oceanography kindly agreed to undertake this investigation, the results of which have been reported by Sisler (1952). No attempt will be made to review in detail the results of Sisler's work, but a resume of his major findings, particularly as they relate to the heating of the sediment and to the production of gas, will be given here.

The bacteriological and biochemical properties reported herein are based on the analyses of three samples (samples S10-10, 20, and 30, table 10) from the bottomset beds of the Colorado delta immediately upstream from Hoover Dam. These samples were obtained from depths of 0.5, 46, and 99 feet below the sediment surface. The samples near the sediment surface contained at least 7 million bacteria per gram (wet weight), and the deeper samples contained 6 million bacteria per gram. In contrast, the overlying lake water near its contact with the bottomset beds contained

only 100 bacteria per gram. The total counts of bacteria in the bottomset beds approximate those found in raw sewage, whereas the water immediately overlying the bottomset beds is as free from bacteria as unpolluted well water.

The various groups of bacteria are rather uniformly distributed throughout the vertical section except for the anaerobic bacteria which show the highest concentration at the greatest depth. The abundance of bacteria in the bottomset beds corresponds closely to the bacteria population in surficial layers of marine and other fresh-water sediments, but unlike the Lake Mead sediments, the number of bacteria in marine and fresh-water sediments drops off sharply with increasing depth.

To demonstrate the effect of bacterial activity on heating of the sediments, Sisler placed the samples in insulated containers and allowed them to stand in a constant temperature bath for periods of 3 to 4 weeks. The results of this experiment showed that the bacteria, even in this short period, raised the temperature of the sediment by about 2° Fahrenheit. Since the containers were not perfect insulators, Sisler observed that this rise in temperature under controlled conditions probably represents only a small fraction of the potential.

During the course of the biochemical studies, it was

noted that a considerable quantity of gas was evolved from the samples. In order to determine the composition and rate of gas production, 1 quart of sterile mud and 1 quart of raw mud were placed in sealed containers and incubated at 22° C. for two days. At the end of this period the gas overlying the samples was analyzed. The results of these analyses show that no gas was evolved from the sterile sample, but that 25 ml of methane and a small amount of carbon dioxide were produced by the sample of raw mud.

This informative study of the biochemical properties gives ample proof that the bacteria in the bottomset beds of the Colorado delta are chiefly responsible for the production of gas and that they have contributed substantially to the heating of the sediment.

In an attempt to apply the results of Sisler's studies to the bottomset beds as a whole, the longitudinal variations in organic content, gas content, and temperature gradient have been plotted on the same graph (fig. 33). 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; and conversely, where the organic content is low, the temperature gradient and gas content are, in general, low.

Since the number of bacteria in sediments is controlled largely by the amount of organic material (Zobell, 1939), we would logically expect that the largest bacteria population would be concentrated where the organic material is most abundant. Furthermore, it would be expected from the results of Sisler's studies that the gas content and heating of the sediment would be highest where the bacteria are most numerous. Although it seems likely that bacterial activity accounts chiefly for the relationship between organic content, gas content, and heating of the sediment, possible proof of this relation will require a more intensive study of biochemical properties of the Lake Mead sediments than was possible during the 1948 survey.

#### Amount of Sediment

The amount of sediment accumulated in Lake Mead may be expressed either in terms of volume or weight. The sediment volume is the space occupied by the accumulated material, which includes both the solid constituents and the interstitial water. The sediment weight, however, includes only the solid particles.

#### Volume

In December 1948, the sediment accumulated in Lake Mead had a total volume of 1,426,000 acre-feet, of which 1,420,000 acre-feet was stored below the level of the permanent spillway crest (1,205.4 feet altitude). If all



this volume were confined to an area of 1 square mile it would form a block some 2,220 feet, or almost one-half mile, in height. When compared with the capacity of Lake Mead, however, the total volume of sediment is less impressive. It has reduced the original water storage capacity (28,794,000 acre-feet) of the reservoir below the level of the permanent spillway crest by only about 5 percent.

To determine the areal distribution of sediment volume, the lake has been divided into eight areas (fig. 35), and the volume of sediment in each area has been computed separately (Ames and Kennon, 1952). In these computations, the volumes of sediment between successive 10-foot contours were determined individually, and the total volume in each of the eight selected areas was obtained by summation of the 10-foot increments. These areas conform in general to the major geographic divisions of the lake and divide the accumulated sediment insofar as practicable into similar sedimentary units. For example, area 1 is the Boulder Basin where the finest and least consolidated material has accumulated, and area 7 is the Lower Granite Gorge where the sediment is made up predominantly of firmly packed sand.

The results of these computations (table 11) show that the Colorado Delta (areas 1-7) contains 97.6 percent of the total volume of sediment, whereas the Virgin delta

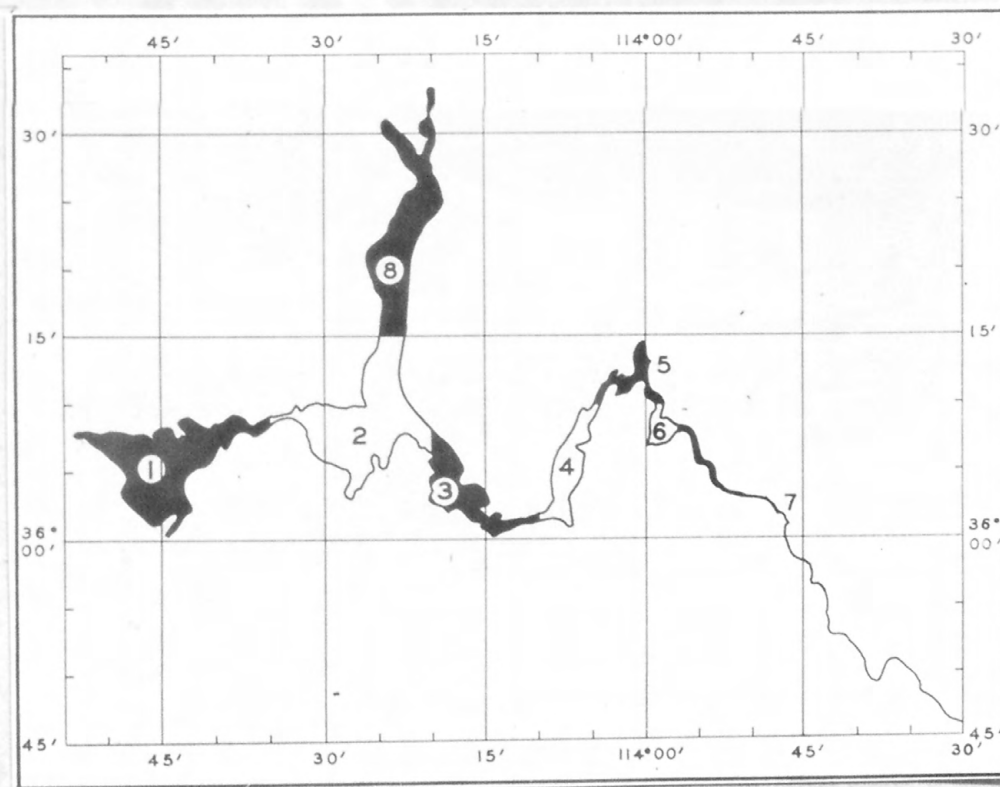


FIGURE 35

LAKE MEAD OUTLINE MAP SHOWING THE LOCATION OF THE  
EIGHT AREAS FOR WHICH SEPARATE SEDIMENT VOLUME  
COMPUTATIONS HAVE BEEN MADE

TABLE 11

## Sediment in individual areas

| Area No. | Area                       | Volume    |                  | Weight           |                  | Mean specific Weight<br>lbs/cu. ft. | Median particle diameter<br>microns |
|----------|----------------------------|-----------|------------------|------------------|------------------|-------------------------------------|-------------------------------------|
|          |                            | Acre-feet | Percent of total | Millions of tons | Percent of total |                                     |                                     |
| 1        | Boulder Basin <sup>1</sup> | 295,000   | 20.7             | 219              | 10.9             | 34.1                                | .95                                 |
| 2        | Virgin Basin <sup>1</sup>  | 142,000   | 10.0             | 123              | 6.1              | 39.8                                | 1.25                                |
| 3        | Temple Bar Area            | 59,000    | 4.1              | 54               | 2.7              | 41.9                                | 1.40                                |
| 4        | Gregg Basin                | 114,000   | 8.0              | 122              | 6.1              | 49.4                                | 2.45                                |
| 5        | Grand Bay                  | 97,000    | 6.8              | 111              | 5.5              | 52.3                                | 6.60                                |
| 6        | Pierce Basin               | 144,000   | 10.1             | 214              | 10.6             | 68.2                                | 25.0                                |
| 7        | Lower Granite Gorge        | 541,000   | 37.9             | 1,113            | 55.3             | 94.5                                | 150.0                               |
| 8        | Overton Arm                | 34,000    | 2.4              | 57               | 2.8              | 78.4                                | 49.0                                |
| Total    |                            | 1,426,000 | 100.0            | 2,014            | 100.0            | 64.9 <sup>2</sup>                   | 46.0 <sup>2</sup>                   |

1 Includes part of Boulder Canyon (see figure 35)

2 Weighted average

(area 8) contains only 2.4 percent. The greatest volume of sediment in the Colorado delta has accumulated in the Lower Granite Gorge (area 7), and the Boulder Basin (area 1) contains more than twice as much sediment as the Virgin Basin (area 2).

### Height

### Total Weight

To obtain the total weight of the solid mineral particles, the volume of sediment in each 10-foot increment of altitude was multiplied by its average specific weight. These weight-increments were then added together to obtain the total weight of solid mineral particles in each of the eight selected areas. As mentioned previously, the specific weight of the sediment accumulated in the Lower Granite Gorge and the eastern part of Pierce Basin (area 7 and part of area 6) has been obtained largely from extrapolation of specific weight data from surface layers of this part of the deposit and from the bottomset beds west of the Colorado delta front. Owing to insufficient sediment data from the topset and foreset beds of the Virgin delta, the specific weight of the sediment accumulated in area 2 has also been derived in part by extrapolation. However, in areas 1-5 little extrapolation has been required.

The results of these computations (table 11) show that 2.014 billion tons of sediment have accumulated in Lake



head during the 14 year interval, 1935-1948. Of this total, 97.2 percent is contained in the Colorado delta (areas 1-7), and 2.8 percent in the Virgin delta (area 8). The greatest weight of material has been deposited in the Lower Granite Gorge (area 7) where 55.3 percent of the total has accumulated. A further estimate based on delta structure reveals that approximately 50 percent of the total weight of sediment in the Colorado delta (areas 1-7) is contained in the topset and foreset beds and that about 50 percent has accumulated in the bottomset beds. Because of inadequate data, no attempt is made to estimate the relative quantities of material in the topset, foreset, and bottomset members of the Virgin delta.

A comparison between the weight and volume of sediment in each of the selected areas is presented in table 11. More than 55 percent of the total weight of sediment has been deposited in the Lower Granite Gorge (area 7), but its volume is only 37.9 percent of the total volume of accumulated sediment. In contrast, only 10.9 percent of the total weight of sediment has been deposited in the Boulder Basin (area 1), but it has a volume of almost 21 percent of the total. This comparison further illustrates the variations in compaction of the water-saturated sediment owing to differences in the physical properties of the solid

particles and to the depth of sediment burial.

#### Mean Specific Weight

The mean specific weight of the sediment in each of the eight selected areas is also given in table 11 based on the volume and weight computations. According to these calculations, the average specific weight of all the sediment accumulated in Lake Mead is 64.9 pounds per cubic foot. The sediment in the Virgin delta (area 8) averages 78.4 pounds per cubic foot, whereas the material in the Colorado delta (areas 1-7) averages only 64.6 pounds per cubic foot. The higher average specific weight of the Virgin delta may be related, at least in part, to its smaller percentage of fine constituents. As noted previously, the bottomset beds of the Virgin delta are considerably coarser than the bottomset beds of the Colorado delta. This has given them a lower porosity and higher specific weight than the bottomset beds of the Colorado delta. The considerable extrapolation required in estimating the weight and volume of the topset and foreset beds of the Virgin delta may also have contributed to the difference in the average specific weights.

#### Median Particle Size

To obtain a quantitative estimate of the average size distribution of the constituent particles, size data

for samples from each of the eight selected areas have been averaged separately. In the Lower Granite Gorge and the eastern part of Pierce basin where data are inadequate, it has been assumed that the deeply buried topset and foreset beds have about the same texture as the surface layers and that the bottomset beds are similar in texture to the bottomset beds that have been sampled in Pierce Basin. Likewise, in the absence of adequate data, the sediment accumulated in the Virgin delta topset and foreset beds has been extrapolated largely from size analyses of samples from the topset and foreset beds of the Colorado delta. Owing to the general textural similarity of the topset and foreset beds of the Virgin and Colorado deltas, it seems probable that no great error has resulted from this extrapolation.

The results of these computations (fig. 36) show that the median particle diameter of the sediment in the Colorado delta decreases progressively from the eastern end of the lake (area 7) to the Boulder Basin (area 1) and that the median particle diameter of the Virgin delta (area 8) is about twice that of the sediment accumulated in Pierce Basin (area 6).

Table 11 shows that the median particle diameter of the sediment in each of the eight selected areas increases directly with the mean specific weight.

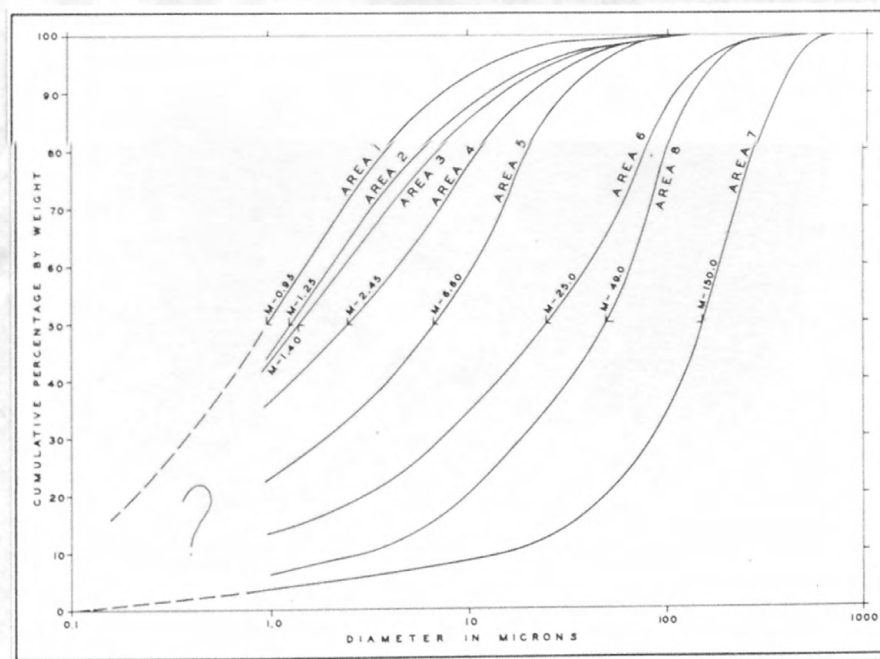


FIGURE 36

CUMULATIVE CURVES SHOWING THE ESTIMATED AVERAGE  
 SIZE DISTRIBUTION OF THE ACCUMULATED SEDIMENT  
 IN EACH OF THE EIGHT SELECTED LAKE AREAS  
 The median diameter for each curve is shown in microns.



In figure 37, the average textural characteristics of the material in several of the areas have been combined and weighted so as to provide an estimate of the average size distribution of various parts of the accumulated sediment. For example, the curve for areas 1-8 shows that the median particle diameter of all the sediment accumulated in Lake Mead is about 46 microns. Similarly, the curve for areas 1-7 shows a median particle diameter of 41 microns for the material of the Colorado delta. The median diameter of the silt and clay particles of the Colorado delta bottom-set beds (areas 1-5) is, in contrast, only 1.65 microns. The median diameter in areas 1-6 is larger than that in areas 1-5 owing to the inclusion of sand from the topset and foreset beds in the eastern part of Pierce Basin.

Except for small amounts of material contributed by ephemeral tributaries and by slumping of the reservoir walls, practically all of the material in the Colorado delta (areas 1-7) has been carried into the lake by the Colorado River. The cumulative curve for areas 1-7 (fig. 37) is, therefore, an estimate of the average size distribution of the total load of sediment carried into Lake Mead by the Colorado River during the 14 year interval, 1935-1948. This curve shows that the average sediment load of the Colorado River during this period has been made up of

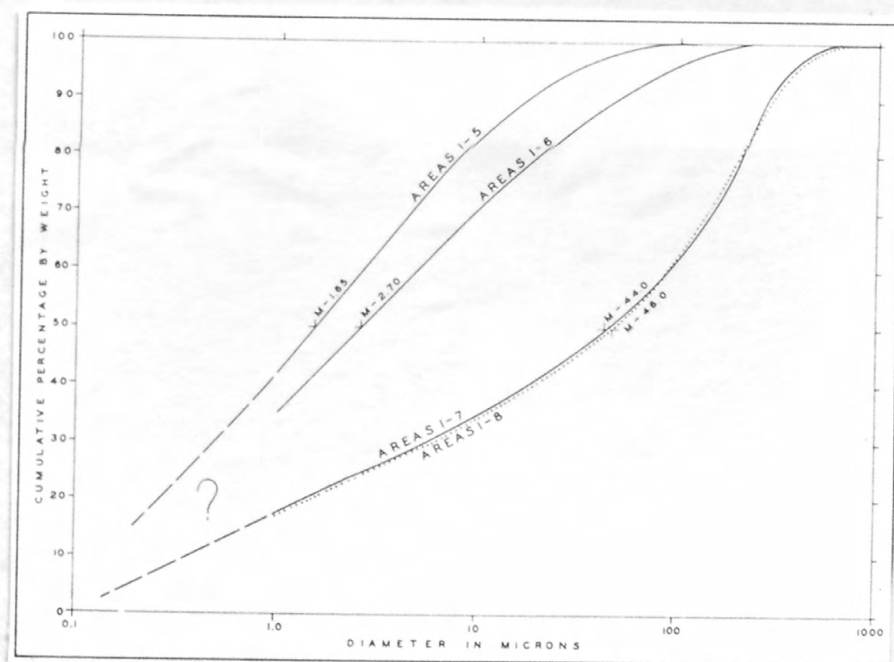


FIGURE 37

CUMULATIVE CURVES SHOWING THE ESTIMATED AVERAGE  
SIZE DISTRIBUTION OF THE SEDIMENT ACCUMULATED  
IN SEVERAL OF THE LAKE AREAS COMBINED

The median particle diameter for each curve is shown in  
microns.

approximately 45 percent sand ( $> 62$  microns), 27 percent silt ( $4-62$  microns) and 28 percent clay ( $< 4$  microns). The most striking feature of this distribution is the virtual absence of coarse components. Only 1 percent of the material consists of particles greater than 500 microns in diameter, that is, coarse sand or larger grains.

The results of numerous size determinations of the suspended particles carried by the Colorado River and its tributaries in the drainage basin upstream from Lake Mead have been reported by Howard (1947, pp. 150-158), but no composite analysis of the size distribution of the total load has yet been attempted. From inspection of the individual analyses, however, it appears that most of the material deposited in the Colorado delta could have been carried in the suspended load. Certainly, the lack of coarse stream gravel and the small amount of coarse sand in the Colorado delta indicate that the quantity of material transported along the bed of the river is not great.

#### Average Chemical Composition

From the sediment weight and chemical data presented in the preceding pages, a further estimate may be made of the mass chemical composition of the sediment accumulated in the Colorado delta. Because of inadequate chemical data from the sediment of the Virgin delta, no attempt will be

made to estimate its average composition. The method used in estimating the average composition of the Colorado delta corresponds closely to the method of estimating the average particle-size distribution.

One sample from each of the seven delta subdivisions (areas 1-7, fig. 35) was chemically analysed, the results of which are reported in table 8. In areas 1-5, where the Colorado delta is made up almost entirely of bottomset beds, it is assumed that the chemical composition of each sample is representative of the total weight of sediment in the area from which it was obtained. However, in areas 6 and 7, where the delta is made up of topset, foreset, and bottomset beds, this assumption is not valid. Chemical data in these areas are available only for samples 1037 and G1270, table 8) from the topset and foreset beds. It seems a fair assumption, however, that the bottomset beds in areas 6 and 7 are similar in composition to the bottomset beds in area 5 (sample 937, table 8). On the basis of this assumption an estimate has been made of the average chemical composition of the total sediment in areas 6 and 7. The average chemical analyses of the sediment in the seven lake areas were then combined and weighted so as to provide an estimate of the average chemical composition of all of the sediment in the Colorado delta. The results of these computations are



presented in table 12.

Since practically all of the sediment in the Colorado delta has been supplied by the Colorado River, the analysis shown in table 12 is an estimate of the average chemical composition of the total load of sediment carried into Lake Mead by the Colorado River during the 14 year period, 1935-

1948.

A comparison of this analysis with Clarke's composite analysis of 235 samples from the Mississippi delta (Clarke, 1924, p. 509) shows a marked similarity in the composition of the Colorado and Mississippi deltas. The only notable differences are in concentrations of calcium, sodium, and potassium. The Colorado delta contains about twice as much calcium, one-half the sodium, and about three-fourths of the potassium concentration of the Mississippi delta.

#### Potential Economic Use

With the thought that the sediment accumulated in Lake Mead might be a resource, instead of a liability, the exceedingly fine material in the bottomest beds of the Colorado delta was investigated for its possible uses in the ceramic and petroleum industries.

Tests of the ceramic properties of the sediment were made by Mr. T. A. Klinefelter of the U. S. Bureau of Mines who states that the clay of the bottomest beds is of the

TABLE 12

Estimated average chemical composition of the sediment  
accumulated in the Colorado delta<sup>1</sup>

| Constituent                                 | Percent    | Composite of<br>235 samples from<br>Mississippi delta <sup>2</sup> |
|---------------------------------------------|------------|--------------------------------------------------------------------|
| SiO <sub>2</sub>                            | 72.5       | 69.96                                                              |
| Al <sub>2</sub> O <sub>3</sub>              | 7.6        | 10.52                                                              |
| Fe <sub>2</sub> O <sub>3</sub> <sup>3</sup> | 3.0        | 3.47                                                               |
| MgO                                         | 1.6        | 1.41                                                               |
| CaO                                         | 4.4        | 2.17                                                               |
| Na <sub>2</sub> O                           | 0.60       | 1.51                                                               |
| K <sub>2</sub> O                            | 1.66       | 2.30                                                               |
| TiO <sub>2</sub>                            | 0.46       | .59                                                                |
| P <sub>2</sub> O <sub>5</sub>               | 0.12       | .18                                                                |
| MnO                                         | 0.05       | .06                                                                |
| Ignition <sup>4</sup>                       | <u>7.5</u> | <u>          </u>                                                  |
| Total                                       | 99.5       | 92.2                                                               |

1 Weighted average of samples 332, 634, 698, 937, 1037, 1176, and G1270 (table 8).

2 See Clarke, 1924, p. 509.

3 Total Fe expressed as Fe<sub>2</sub>O<sub>3</sub>.

4 Includes loss due to oxidation of FeO.

montmorillonite (non-swelling bentonite) type as determined by x-ray patterns and physical properties. The ceramic tests were confined, therefore, to oil bleaching and heat treatment. The results of these analyses show that there is some possibility of using the Lake Mead clay in decolorizing or clarifying fats and oils. However, the clay would require activation by leaching in acid before it could be used for this purpose. There is also a possibility that the clay could be used as a catalyzer for oil cracking, but no test for this property has yet been made.

The chief potentiality of the Lake Mead sediment would be as a bloating clay for use in the manufacture of light weight cements, building brick, and other construction materials. When flash heated to a temperature of  $2100^{\circ}$  F., the Lake Mead clay increased from three to four times in volume, forming a fine blast with small though somewhat uneven vesicles or blebs. The specific weight of the blast ranges from 19 pounds per cubic foot to 24 pounds per cubic foot which is well within the commercial range of bloating clays. At lower temperatures the product would be somewhat heavier and stronger. Most of the commercial products range in weight from 45 to 55 pounds per cubic foot, chiefly because lighter blasts at temperatures of  $1,800^{\circ}$  F. to  $2,200^{\circ}$  F. cannot be produced from most clays used for this

purpose. Hence, the Lake Mead material would be unusually good as bloating clay although it would require care in handling in the kilns because of its somewhat narrow bloating range. As determined by slow heating (100° F. per hour), bloating of the Lake Mead clay occurs between temperatures of 2,000° F. to 2,200° F..

The suitability of the material as a drilling fluid was investigated by Mr. George Tchilingarian (1951) of the University of Southern California, who found that it fails to meet the specifications of the petroleum industry. The viscosity and filtration loss of drilling muds prepared with the Lake Mead clay are too high to compete with fresh-water clays currently used for this purpose.



## TRANSPORTATION OF SEDIMENT BY TURBIDITY CURRENTS

### Definition

In view of the variety of terms that have been used synonymously with turbidity current, and the various ways that these terms have been defined, it seems desirable at the outset to define the term, turbidity current, as used in this paper. Johnson (1939, p. 27) first introduced the name, turbidity current, as a synonym for density current (Daly, 1936) and suspension current (Stetson and Smith, 1938). Turbidity currents are currents produced by fine-grained sediment in suspension. Water charged with fine suspended particles is denser than clear water of the same temperature and salinity, and because of its greater density, the water with suspended sediment will flow beneath less dense clear water. If, for example, a river carrying an appreciable amount of suspended sediment enters a quiet, clear body of water of the same temperature and salinity, the turbid water will plunge beneath the mass of clear water and travel by gravity along the floor of the standing body of water. Bell (1942a) has appropriately referred to this type of turbidity current as an underflow.

In nature, however, the temperature and salinity of a standing body of water are seldom the same from top to

bottom. The oceans as well as most lakes have a distinct stratification in both temperature and salinity, the lower layers commonly being colder and more saline than the upper layers. Since water increases in density with decrease in temperature (to 39° F.) and increase in salinity, the lower strata are denser than the upper strata. In some cases the density of turbid river water entering a lake is greater than the density of the upper lake layers but not as great as the density of the lower strata. Under these conditions the turbid river water sinks beneath the lake surface and flows on one of the lower water layers of higher density. This type of turbidity current has been termed an interflow by Bell (1947a).

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

Most definitions of turbidity currents (Daly, 1936; Johnson, 1939; Stetson and Smith, 1938, and Kueneen and Migliorini, 1950) require that they have a higher density

than the water at the surface of the lake, and, consequently, do not include the type of turbidity current referred to as overflow. Bell (1926), however, broadly defines a density current as a gravity flow of liquid or gas through, under, or over a fluid of approximately equal density. He uses the phrase, "of approximately equal density", to exclude specific types of gravity flows that are not truly density currents. A river flowing beneath air has been cited by Bell as an example of a gravity flow that does not meet the requirements of a density current because of the very great difference between the density of water and air. When referring solely to movement of water masses in relation to each other, however, there is no need for including Bell's concept "of approximately equal density."

Bell's definition of a density current, when applied to water masses, includes all currents which are produced by differences in density. Some of them are produced solely by differences in temperature or salinity, whereas others may originate, at least in part, from differences in their amount of suspended sediment. The type of density current in which suspended sediment accounts for part of the difference in density is referred to in this paper as a turbidity current. Thus, a turbidity current may be rather simply defined as a gravity flow of turbid water through,

under, or over water of different density. Part of the difference in density is produced by suspended sediment, but suspended sediment is not always the dominant factor. In the overflow type of turbidity current the lower density is due to higher temperature or lower salinity, or both. Similarly, in the interflow or underflow type of current suspended sediment may not account in some cases for as great a part of the higher density as does lower temperature or higher salinity.

#### Relation to River Discharge and Lake Stratification

Turbidity currents are developed at the mouths of both the Colorado and Virgin Rivers, and they have transported a tremendous quantity of silt and clay to the deeper parts of the lake. Because the Virgin River turbidity currents are of relatively minor significance and because they have not been studied intensively, the present discussion will be concerned primarily with the Colorado River currents.

Turbidity currents are always present near the mouth of the Colorado River, but only rarely do they flow the entire length of the lake. The three types of currents designated above as overflow, interflow, and underflow all occur in Lake Mead, but underflow is by far the dominant and most important type.



### Overflows

Overflows occur only during the late spring and early summer (usually from late April to early July) when the incoming river water is lighter than the water at the surface of the lake. The inflow during this period is derived principally from the rapid melting of snow in the upper Colorado River basin and represents the maximum discharge for the year. The temperatures of the river water and the lake surface water are approximately the same, but the salinity of the inflowing water is much lower than that of the lake water (Anderson and Pritchard, 1952). The river in this period commonly carries a high proportion of sand grains, and these coarse particles are deposited in the topset and foreset beds of the Colorado delta. Thereafter, the inflowing water, even with the sediment remaining in suspension, has a density lower than that of the lake. Hence, the turbid river water spreads out over the lake surface, rapidly at first and then progressively more slowly as the overflow continues downlake.

Owing to these lower velocities and to the mixing of the overflow with the denser lake water, a large part of the sediment is dropped from suspension during the first few miles of travel. The rapid settling of the suspended sediment and the mixing of the overflow with the underlying

basin. The suspended sediment in this section ranged from  
 of the overflow was detected in the center of the Virgin  
 tations are observed. In May 1968 the westernmost boundary  
 are littered with logs, but further west no such accumu-  
 of the Virgin Basin, the cover and gently sloping beaches  
 they eventually become stranded along the shoreline. Most  
 (late April to early July) they are carried downstream where  
 any near the river mouth, but during periods of overflow  
 carried into the lake by the Colorado River remain station-  
 debris along the lake shore. During most seasons, loss  
 elution is supported by the distribution of logs and other  
 dam (U. S. Bureau of Reclamation, 1961, 1967). This con-  
 of the Virgin Basin and they apparently never reach the  
 entrance. However, the turbid overflows seldom extend west  
 surface a perceptibly turbid appearance far from the river  
 reservoir, enough may remain in suspension to give the lake  
 settles out of the overflows in the eastern part of the  
 Although a considerable amount of suspended sediment  
 0.110 percent near the bottom of the lake.  
 creased progressively from 0.013 percent at the surface to  
 into lake head. The proportion of sediment by weight in-  
 10 miles downlake from the entrance of the Colorado River  
 made in May 1968 at river-mile 287.5, which was then about  
 lake water is well-illustrated by a series of observations

0.007 percent at the lake surface to 0.006 percent at the bottom.

Bell (1942a, pp. 30-31) has illustrated by laboratory experiment that particles dropped from an overflow, upon approaching the bottom, may continue to travel in a downstream direction as an underflow. Because of the difficulty in distinguishing movement of a thin layer of very fluid sediment over the bottom of a lake, there is no direct evidence that this type of flow occurs in Lake Mead. On the other hand, it is evident from the distribution of the accumulated sediment (fig. 15) that small underflows must take place along the steep side slopes of the submerged channel of the Colorado River. If minor underflows of this type were not active in Lake Mead, the sediment that is dropped from overflows would be expected to be accumulated over a great part of the lake bottom. Investigations of the accumulated sediment show, however, that essentially all of the sediment brought into the lake by the Colorado River turbidity currents has accumulated in the region of the submerged Colorado River channel, and that no appreciable amount of sediment from this source has accumulated in other areas of the lake bottom. It seems probable, therefore, that the sediment dropped from the overflows in the shallow lake areas travels along the bottom until it comes to rest

in the deep submerged channel of the Colorado River. There is no evidence whether the material, upon reaching the submerged channel, continues to move as an underflow in a downlake direction.

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

#### Interflows

Interflows are apparently of minor significance compared to overflows and underflows. Anderson and Pritchard (1952) report that interflows during 1948 were most prominent in August and September, and that during this period the temperatures of the river and the lake surface water were about the same, but the salinity of the incoming water was considerably greater than the salinity of the lake surface layer. However, the density of the river water, even with its dissolved and suspended load, was not as great as that of the colder water at the bottom of the lake. Under these conditions the turbid river water sinks through the light surface layer and spreads out at intermediate depth over the denser water, thus conforming to the definition of an interflow. Although the high salinity of



such interflows can be identified for a considerable distance downlake, the suspended sediment readily settles to the bottom near the river entrance.

#### Underflows

Underflows are the dominant and most important currents transporting sediment into Lake Mead. Whenever the density of the inflow is greater than the density of the lower lake layers, the turbid water plunges beneath the lake surface and travels downlake along the submerged channel of the Colorado River. In late spring and summer, overflows and interflows are periodically replaced by underflows, but during fall and winter there is a continuous movement of turbid water along the lake bottom. Water discharged by the Colorado River from October to April is colder and more saline than the deep water in the eastern part of the lake. Owing to these factors and to its suspended sediment, the muddy river water sinks rapidly beneath the clear lake water and travels along the submerged Colorado River channel.

During this period the division between the turbid river water and the clear lake surface is sharp and distinct as shown in figure 16, and is commonly marked by a raft of logs carried into the lake by the Colorado River. This line of demarkation, known as a convergence, denotes a downstream

movement of water at the bottom of the lake and an upstream movement of water at the surface. The debris collects at the line of zero surface velocity where the opposing surface currents meet.

Most underflows do not reach the western part of the lake, but at least 12 conspicuous underflows have travelled along the old Colorado River channel from the river mouth to Hoover Dam. Of this number, 11 occurred during the first 7 years of reservoir operation (1935-1941) when the lake was from 70 to 120 miles long. The only other major flow of turbid water to reach the dam arrived in the fall of 1947 when the distance between the river mouth and the dam was about 78 miles. Although these extensive currents are comparatively rare, they have transported a tremendous quantity of sediment great distances from the head of the lake.

The first three major underflows arrived at Hoover Dam during 1935 when the lake was from 70 to 90 miles long (Grover and Howard, 1938). Prior to May 1, 1936, water was discharged through a diversion tunnel located near the bottom of the lake; consequently, the arrival times of these currents were easily detected by the appearance of turbid water in the Colorado River channel downstream from the dam. Grover and Howard have shown that these underflows were

related to large increases in the quantity of suspended sediment carried by the Colorado River past the Grand Canyon gaging station located 265 miles upstream from Hoover Dam and that the arrival of the underflows at the dam followed the increases in the suspended sediment load at the Grand Canyon station by about 6 days. Furthermore, they were able to relate the increased load of suspended sediment to flash floods on the Little Colorado and San Juan Rivers that enter the Colorado River upstream from the lake.

Since the closure of the diversion tunnel in 1936, the arrival times of turbid underflows at Hoover Dam are less accurately known. There is no record of underflows reaching the dam during 1936 and the early part of 1937, but by June 1937, measurements by the U. S. Bureau of Reclamation (1941, p. 20) indicate that the diversion tunnel through which water was previously discharged, had been covered by about 10 feet of sediment. Thus it appears that the flow of turbid water through the lake was probably as prominent during this period as in 1935.

From June 1937 to December 1946 monthly measurements of the sediment level at the bottom of the lake near the dam were made by the Bureau of Reclamation (1941, 1947). These data (fig. 38) clearly reveal the periods during which conspicuous flows of turbid water have reached Hoover

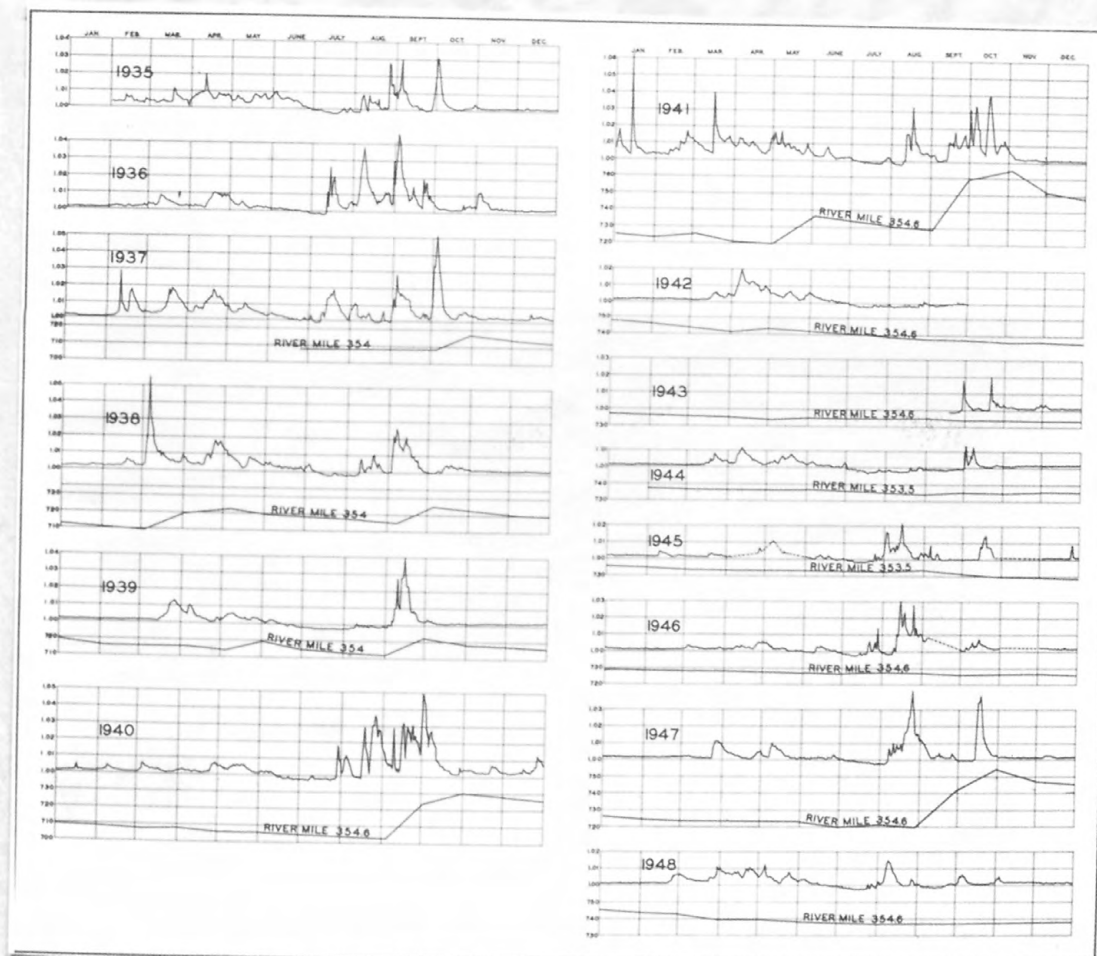


FIGURE 38

RELATION BETWEEN COMPUTED DENSITY OF THE COLORADO RIVER  
WATER AT THE GRAND CANYON GAGING STATION AND THE  
ARRIVAL OF TURBID UNDERFLOWS AT THE DAM

Upper curves show density (in grams per cubic centimeter) of incoming Colorado River water at the Grand Canyon station. Lower curves show altitude of water-sediment interface (in feet above mean sea level) at the bottom of Lake Mead near Hoover Dam. The sampling station designated as river-mile 354.6 is located 200 feet above the dam. Stations at river-miles 354 and 353.5 are located 0.6 and 1.1 miles, respectively, upstream from the dam.



Dam. The periods of underflow are marked by a rapid rise in the level of the water-sediment interface behind the dam, and conversely, the intervals between periods of underflow are marked by a lowering of the sediment surface due to compaction (Gould, 1951).

Also shown in figure 38 are the approximate daily densities of the incoming river water during the 14-year period from 1935 to 1948. These densities have been computed from measurements of temperature, salinity, and suspended sediment of the Colorado River as recorded at the Grand Canyon gaging station. The method used in computing these densities is outlined by Rubey (1938), who states that densities computed by this method probably have an average error of about 0.0003 gram per cubic centimeter. In the computations the density of the suspended solids was taken as 2.67 as determined by direct measurement, rather than the assumed value of 2.60 used by Rubey. In the absence of temperature data prior to September 30, 1936, it has been assumed that the temperature varied in about the same manner as in 1939, which appears to be a representative year.

The density of the water entering the main body of Lake Mead after the coarser sediment particles have been deposited in the Lower Granite Gorge and Pierce Basin, is

undoubtedly somewhat lower than the density of the water passing the Grand Canyon gaging station. However, it seems a fair assumption that the daily variations in the amount of sediment still in suspension when the turbid river water enters the lake are roughly in the same proportion as the variations in the suspended sediment content of the Colorado River at the Grand Canyon gaging station. Of course, these variations are not synchronous owing to the time required for water to flow from the Grand Canyon station to the head of Lake Mead. Computations by Rubey (1938) indicate that the time required for water to travel from the Grand Canyon station to the eastern end of the lake ranges from 1 to  $4\frac{1}{2}$  days. The shorter travel times occur during periods of floods, whereas the longer travel times correspond to periods of extremely low discharge.

The data presented in figure 36 clearly show that the rises in the sediment level behind Hoover Dam follow the peak water densities of the Colorado River at the Grand Canyon station. A considerable lag may be expected between the appearance of high density water at the Grand Canyon station and the rise in the sediment level behind the dam, because of the time required for the high density water to travel from the Grand Canyon station to Hoover Dam. This travel time does not account, however, for the total time

separation of the curves in figure 36. Observations of the sediment level behind the dam are made only once each month, and it is possible, therefore, that the time of arrival of turbid underflows at the dam may be missed by as much as 30 days.

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

move may also determine their distance of penetration into the lake, but density appears to be the dominant factor.

#### Velocity, Density, and Thickness

One of the most striking features of the underflows is their low velocity. Bell (1942b) has estimated that the average velocity of one of the underflows reaching the dam in 1935 was approximately 0.83 foot per second. Similarly, records since 1937 (U. S. Bureau of Reclamation, 1941, 1947) show that the average velocities of the later currents were generally about 0.5 foot per second and commonly as low as 0.3 foot per second. These records also indicate that the underflows travel much more rapidly over the steeper, upper parts of the delta than over the flatter, lower portions. Mean velocities of 1.0 foot per second are common near the river mouth where the turbid water plunges down the face of the delta front, but by the time these currents reach the flat floor of the Boulder Basin, their velocities are less than 0.25 foot per second and are commonly too low for measurement.

Underflows are confined to the submerged channel of the Colorado River and are generally only a few feet thick. Between the entrance of the river in 1948 and the mouth of Iceberg Canyon (a distance of about 11 miles), abundant mixing of the muddy inflow and the lake water takes place



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

In late November 1948, the underflow of muddy water extended to the east side of the Virgin Basin. Observations of this current showed a very sharp interface between the muddy flow at the bottom of the lake and the clear water above. The average thickness of the underflow west of Iceberg Canyon was about 3 feet and its density ranged from approximately 1.001 at the top to about 1.200 at the bottom. In figure 39 the typical vertical distribution of density of the November 1948 underflow is shown in a section taken at the mouth of Virgin Canyon. The marked increase in density near the bottom of the underflow probably represents a division between material that is still in motion and that which has been recently deposited, but as this contact is somewhat transitional, it has been denoted in figure 39 as a gradational zone.

#### Amount of Sediment and Distance of Travel

In a previous section of this report it has been estimated that approximately 50 percent of the total weight of sediment accumulated in the Colorado delta is contained in the fine-grained bottomset beds. Practically all of this material has been transported by turbidity currents.

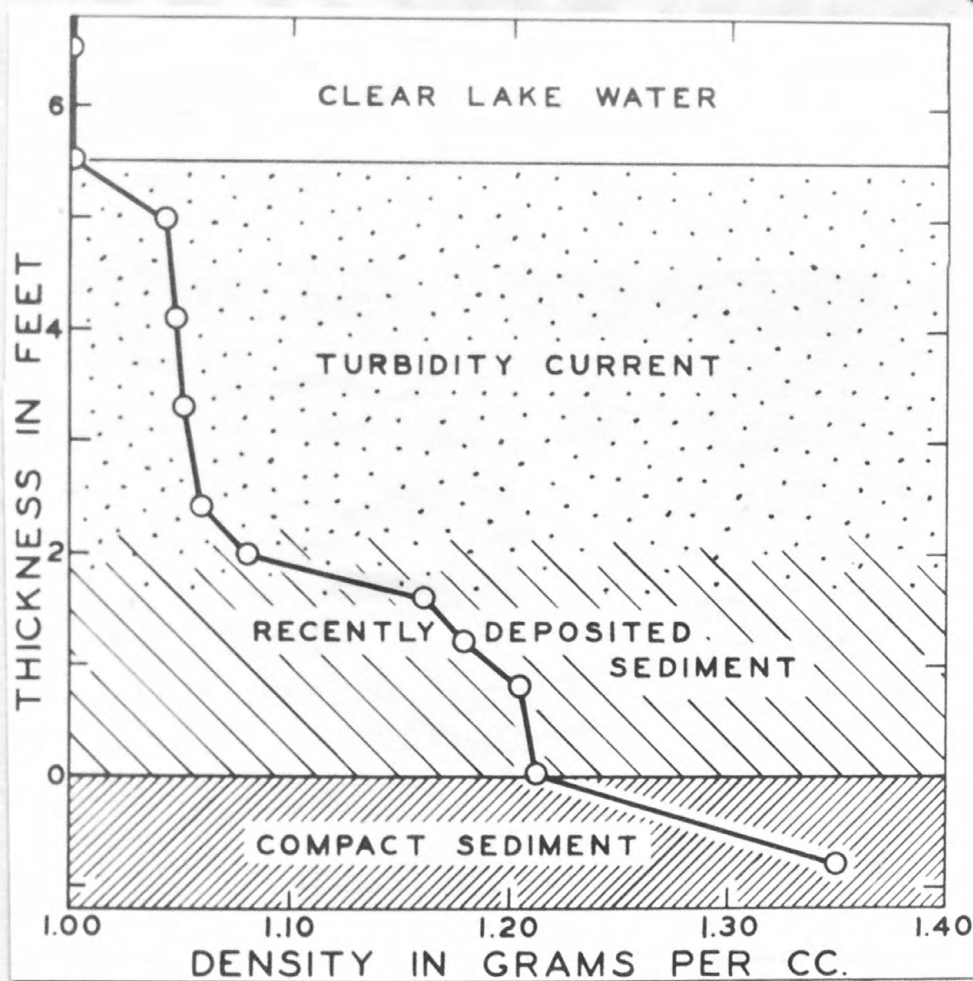


FIGURE 39

DISTRIBUTION OF DENSITY IN VERTICAL SECTION  
OF THE NOVEMBER 1948 UNDERFLOW

Section is located at the mouth of Virgin Canyon (Colorado River-mile 301.9). Thickness of the underflow is measured in feet above the compact sediment layer at the bottom of the lake.

developed at the mouth of the Colorado River. Cores from the bottomset beds provide no information as to the relative quantities of material that have been transported into the lake by the three types of turbidity currents; overflows, interflows, and underflows. It is clear, however, from investigations of the U. S. Bureau of Reclamation (1941, 1947) that most of the sediment in the Boulder Basin has been transported by underflows. Interflows have never been identified in this region and overflows rarely extend west of the Virgin Basin.

In figure 40, the percentage distribution of sediment transported by the Colorado River turbidity currents has been plotted against the distance from the eastern end of the reservoir at Bridge Canyon measured along the buried Colorado River channel. This figure shows that about 80 percent of the sediment carried by the Colorado River turbidity currents has accumulated on the reservoir floor at a distance of more than 43 miles from the head of the reservoir and that 23 percent has accumulated at a distance of more than 100 miles. Owing to the advance of the delta front into the lake, it is not known precisely how far this material has been transported. It is known, however, that most of the sediment in Boulder Basin has been transported at least 70 miles before finally coming to rest. These

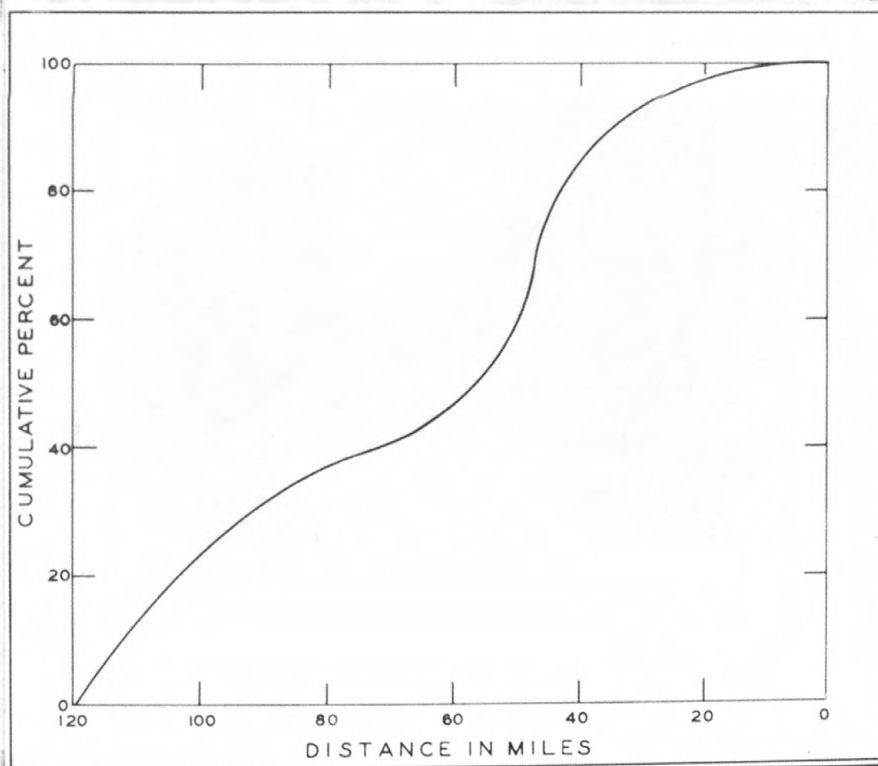


FIGURE 40

PERCENTAGE DISTRIBUTION OF SEDIMENT TRANSPORTED  
BY TURBIDITY CURRENTS IN RELATION TO DISTANCE  
FROM THE EASTERN END OF THE RESERVOIR  
MEASURED ALONG THE BURIED COLORADO RIVER CHANNEL



long-ranging flows of turbid water could, in all probability, have continued for many more tens of miles if Lake Mead had been large enough.

#### Change in Slope and Width of the Channel

The sediment accumulated in the Colorado delta has reduced the average slope of the former Colorado River channel from 5 feet per mile to about 3 feet per mile (fig. 18). The greatest reduction in slope occurs in the Boulder Basin where the declivity of the sediment surface is less than 1 foot per mile. As shown in figure 18 this reduction in slope took place prior to 1942 when the Boulder Basin received most of its sediment. The width of the channel was also greatly increased during this period because of the rapid rate of sedimentation. As the continued underflow of turbid water is controlled in part by the slope and cross-sectional area of the channel, it is possible that this early reduction in slope and the increased width of the channel may be partly responsible for the decreased flow of turbid water into the western part of the lake since 1942 (fig. 38). However, periods of high density inflow, which are generally associated with extensive underflows, have occurred only rarely in recent years, and this condition may have been more effective in limiting the distance that underflows have travelled.

### Size of Suspended Particles

Assuming that the deeply buried bottomset beds in the Lower Granite Gorge are similar in texture to the bottomset beds west of the Colorado delta front, we can obtain a fair estimate of the average size distribution of the particles transported by the Colorado River turbidity currents. According to this estimate (areas 1-5, fig. 37) the suspended particles have an average median diameter of 1.65 microns (in dispersed state) and consist of 67 percent clay (smaller than 4 microns), 32 percent silt (4 to 62 microns) and less than 1 percent sand (larger than 62 microns).

Even though the range in size of the sediment particles is small, the bottomset beds are horizontally graded, the coarsest particles being deposited near the river mouth and the finest at the greatest distance from the source. This relationship is illustrated in figure 36 where the size characteristics of samples from each of the seven subdivisions of the Colorado delta have been combined and averaged so as to give a composite size distribution curve for each of the divisions. Curves for areas 1 through 5 show the gradation in particle size of material transported by turbidity currents, whereas the curves for areas 6 and 7 include sand and coarse silt that have not been

transported by turbidity currents.

As mentioned previously, the sediment in the bottom-set beds of the Colorado delta in its natural condition does not settle out as discrete particles, but as flocculated masses which are from 2 to 20 times larger than the individual grains (table 6). Similar studies of suspended sediment in the Lake Mead underflows (Sherman, unpublished manuscript) and in the Colorado River (Crover and Howard, 1938) show that the material also travels in a flocculated state.

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

#### Virgin River Turbidity Currents

The Virgin River turbidity currents, although of little quantitative significance, are worthy of brief mention. Essentially all of the sediment carried into the lake by the Virgin River has accumulated in the upper 14 miles of the Overton Arm, and it is apparent that most of

the Virgin River turbidity currents have extended only a short distance into Lake Mead. However, there is evidence that some underflows of turbid water have travelled through most if not all of the inundated Virgin River channel.

Our knowledge of these extensive currents is based entirely on data obtained at the Lower Narrows, located 9.3 miles upstream from the former junction of the Virgin River and the Colorado River. Records obtained by the U. S. Bureau of Reclamation (1941, 1947) at this station show that suspended silt and clay particles were present in the former Virgin River channel from January to March 1938 and again from June to September 1938. From January 1939 to February 1940, the suspended sediment had disappeared completely as shown by the presence of clear water in contact with the sandy bottom of the channel. Thus, it appears that essentially no sediment was permanently deposited from these early underflows as they moved through the Lower Narrows.

Again in March 1940 suspended sediment appeared in the bottom of the channel at the Lower Narrows, but in contrast to the earlier underflows, some of the sediment was deposited. Samples taken by the U. S. Bureau of Reclamation in June 1940 showed that the bottom material was composed of sand, silt, and clay particles, indicating that a very thin layer of silt and clay had been deposited



on top of the sand of the inundated channel. Records obtained once or twice each year since June 1940 show that suspended sediment has appeared periodically in the submerged channel between 1942 and 1947. During 1948 suspended sediment was observed in the channel at the Lower Narrows in April, but by January 1949 it had disappeared. The suspended sediment at the Lower Narrows commonly appears prior to the period of Colorado River overflows, and the Virgin River is evidently its source.

Part of the suspended sediment that moves along the former Virgin River channel has probably been derived from the Colorado River overflows. During the late spring and summer of 1943 the overflow of turbid water from the Colorado River extended northward from the Virgin Basin into the Overton Arm, indicating that at least part of the suspended sediment that has been observed in the old Virgin River channel has been dropped from the Colorado River overflows.

A layer of silt and clay ranging from a few tenths of a foot to about 2 feet thick has accumulated in the bottom of the inundated Virgin River channel between the toe of the Virgin delta and the Lower Narrows. This is regarded as an incipient extension of the bottomset beds of the Virgin delta into the deeper parts of the Overton Arm. Whether

or not this thin layer of accumulated sediment represents the total amount of material carried by the extensive Virgin River turbidity currents is not known. However, it is certainly possible that some of the sediment may have been carried along the entire length of the old Virgin River channel and deposited in the bottomset beds of the Colorado delta in the area of the former junction of the Colorado and Virgin Rivers.

## EROSION IN THE RESERVOIR

Although Lake Mead is predominantly a site for aggradational processes, there are also numerous evidences of the effects of erosion. Some of these effects are conspicuous to the casual observer, and some may have an appreciable bearing on the storage capacity of the reservoir, or upon the quality of the stored water. The effects of erosion are abundantly reflected by small-scale sliding and slumping of steep-sided headlands, cutting of terraces, and solution of gypsum and other salines in the basin areas of the lake. A considerable amount of erosion has also resulted from the scour of Detrital Wash near its entrance into Lake Mead. The submarine channel in the delta deposits may also be evidence of erosion by turbidity currents.

Slumping of the lake boundary occurs both above and below the water surface, but in only a few places has it been sufficient to produce any notable change in the configuration of the lake. Most of the material moved by landslides and wave action is redistributed within the reservoir itself. However, in a few localities, weakly cemented or highly jointed materials, standing many tens of feet above the water surface, have slumped into the

lake, and this has resulted in a slight reduction in reservoir capacity. On the other hand, a large percentage of the salines dissolved from the reservoir floor are carried out of the lake in solution, resulting in a slight increase in storage capacity. These changes were too small, however, to be measured quantitatively in the 1946 survey.

#### Landslides

Small-scale landslides may be seen along the shore in practically all parts of the lake, but the largest and most prominent slides are in Virgin Canyon and the southeast part of Gregg Basin near Hualpai Wash (east and south of Colorado River-mile 301). The most striking of these (fig. 41) is in the highly jointed gneiss and schist of pre-Cambrian age (Longwell, 1936, pp. 1404-1406) which forms the north wall of Virgin Canyon near its mouth. According to E. T. Schenk (personal communication) of the U. S. Bureau of Mines Experimental Station in Boulder City, Nevada, this large mass of rock began its movement during the early stages of reservoir filling. Sliding was evidently initiated by lubrication of argillaceous materials on the joint planes of the rock as the reservoir filled. Because the high-water mark (denoted by the white precipitate on the canyon wall) is not displaced, it is





FIGURE 41

LANDSLIDE ON THE NORTH WALL OF  
VIRGIN CANYON NEAR ITS MOUTH

The 1941 high water mark, which stands about 65 feet above the lake surface, has not been displaced. Photograph taken in February 1948.

apparent that all movement ceased before July 1941.

The slides in the southeastern part of Gregg Basin occur in the Hualpai limestone and its associated siltstone and clay members of possible Pliocene age (Longwell, 1936, pp. 1429-1432). Like the Virgin Canyon slide, movement was probably initiated by lubrication of clayey joint surfaces as the lake level rose. The greatest amount of sliding in this region occurred after 1941 as shown by the considerable displacement of the high water mark on the reservoir wall.

According to Sharpe's (1938, pp. 65-66) classification, the landslides in the Virgin Canyon and Gregg Basin are of the slump variety. The largest of the Gregg Basin slumps (figures 42-44) is typical of others in the region. Movement has taken place on a spoon-shaped surface concave toward the slip, and the slumped material has moved as a unit with a pronounced backward rotation (figure 43). At the apex (figures 42, 43) the movement is chiefly vertical, but at the sides (figure 44) there is a marked horizontal component. In a few of the slides, movement has taken place on a series of closely-spaced parallel surfaces, thus giving them a terraced or stepped appearance, also characteristic of slumps.

There is little evidence of sliding and slumping of





FIGURE 42

VIEW OF A PROMINENT LANDSLIDE ON THE EAST SIDE OF  
GREGG BASIN NEAR THE MOUTH OF HUALPAI WASH  
U. S. Bureau of Reclamation photograph in March 1949.





FIGURE 43

NORTHWARD VIEW NEAR THE APEX OF THE SAME  
LANDSLIDE SHOWN IN FIGURE 42

Note the clayey character of the material on the slip plane. Downslumped block on the left has been rotated backwards as shown by the steep dip of the bedding and the inclination of the vegetation. U. S. Bureau of Reclamation photograph in March 1949.





FIGURE 44

SOUTHWARD VIEW OF THE LANDSLIDE SHOWN  
IN FIGURES 42 AND 43

The displacement of the 1941 high water mark, denoted by a line of drift wood above the terraced area, shows that most of the movement has taken place since 1941. U. S. Bureau of Reclamation photograph in March 1949.

the reservoir floor below the average lake level (approximately 1,170 feet altitude). Closely spaced profiles of the bottom topography reveal only two slumps of any considerable size, both in the Boulder Basin. From inspection of the geologic map of Lake Mead (Longwell, 1936, pls. 2 and 21), it is clear that both slides occurred in the poorly consolidated Chemehuevi formation of Pleistocene age. The larger one extends from the shoreline on the north side of the Boulder Basin to the submerged Colorado River channel between river-miles 341.0 and 343.5. Sand and coarse silt contributed by this slumping were detected at a depth of about 40 feet in the bottomset beds of the Colorado delta, thus indicating that the slide occurred early in the history of the reservoir.

The smaller subaqueous slide occurred between river-miles 351.5 and 352.0, where material from the Chemehuevi formation has slumped into the channel area south of Sentinel Island. In a few other places, notably between the east side of the Virgin Basin and the mouth of Virgin Canyon, sand and coarse silt, slumped from the adjacent reservoir walls, were detected in cores from the bottomset beds of the Colorado delta. The slumps in this area were too small, however, to be revealed by underwater soundings.

In addition to the landslides caused by lubrication,



a number of small slides have resulted from wave undercutting and caving. These slides may be seen in many areas of the lake. They are best developed near the head of Las Vegas Bay, along the east side of the Overton Arm, and between Virgin Canyon and the east side of the Virgin Basin. In these areas undercutting and caving have been confined to weakly cemented clastics of the Muddy Creek formation which, according to Lea, well (1936, pp. 1419-1429), may be of Pliocene age.

At the head of Las Vegas Bay, excavation of weak silt and clay strata has allowed large blocks of the overlying breccia to give way (fig. 45). Similarly, in the Overton Arm and near the mouth of Temple Bar Wash prominent headlands of poorly consolidated clastics of the Muddy Creek formation have been sharply truncated by wave action and caving (fig. 46). The high level of undercutting in figures 45 and 46, suggests that most of the slumping in these areas occurred during the high lake stages of 1941 and 1942.

#### Wave-Cut Terraces

In most areas of the lake, the shore is only moderately sloped and is not subject to serious caving or slumping. Erosion in these areas is confined to the cutting of terraces in the easily eroded basin formations. Wave-cut



FIGURE 45

SHORELINE CHANGES ON THE NORTH SIDE OF LAS VEGAS BAY  
RESULTING FROM UNDERCUTTING AND CAVING OF WEAKLY  
CEMENTED CLASTICS OF THE MUDDY CREEK FORMATION  
U. S. Bureau of Reclamation photograph, 1949





FIGURE 46

TRUNCATION OF STEEP-SIDED HEADLANDS OF THE MUDDY CREEK  
FORMATION ALONG THE SHORE OF LAKE MEAD SOUTHWEST OF  
COLORADO RIVER-MILE 315

Photograph taken in February 1948

terraces occur at practically all altitudes between the 1,150 and 1,220-foot contours, the approximate range in lake level from 1941 to 1948, but they are best preserved at altitudes of 1,200 feet to 1,220 feet, which are seldom reached by the water surface. At lower altitudes, the terraces are not well-developed owing to modification by frequent changes in lake stage. The terraces range in width from a few inches to several feet depending on the type of rock, the altitude and configuration of the shore, and the relation of the shore to the prevailing wind direction.

Wave action has also been effective in truncating the tops of small islands and shoals in Las Vegas Bay. These prominences, composed of weakly cemented cobbles, have been cut as much as 30 feet below their original levels, as shown by comparison of the 1948 topography with the pre-Lake Mead topography. In other areas where islands and shoals are composed of more durable materials, no such bevelling was observed. In general the effects of wave action, though conspicuous, are insignificant insofar as reservoir storage is concerned.

#### Solution

Erosion of the reservoir floor by solution is of particular interest owing to the considerable quantities of

gypsum and other salines exposed in the broad basins of the lake. According to Longwell (1936, pp. 1419-1429) and others, the greatest concentration of gypsum occurs in the Muddy Creek formation which makes up a large part of the reservoir floor in the Virgin Basin, Overton Arm, and the northern part of the Boulder Basin. He reports the occurrence of gypsum and anhydrite beds with a total exposed thickness of 400 to 500 feet in the southern part of the Virgin Basin, and layers of pure gypsum about 25 feet thick in Las Vegas Bay. Gypsiferous clay and silt beds of the Muddy Creek formation are also prominent in these areas. The other soluble salts of the Muddy Creek formation are not nearly as extensive as the gypsum. According to Longwell, rock salt and other salines occur only locally in the Virgin Basin and Overton Arm.

The soluble outcrops have been covered by the lake in most places, but in a few localities they are exposed along the shore or in near-shore reefs and low-lying islands. The most extensive areas are in the southern part of the Virgin Basin, where the shore and offshore islands consist almost entirely of thick beds of gypsum and anhydrite. From inspection of these beds (fig. 47) and other gypsum outcrops, such as that shown in figure 48, it is clear that solution is locally effective in eroding the





FIGURE 47

SOLUTION AND TERRACING OF GYPSUM REEFS  
AND LOW-LYING ISLANDS ON THE SOUTH SIDE  
OF THE VIRGIN BASIN NEAR THE MOUTH OF DETRITAL WASH  
U. S. Bureau of Reclamation photograph, November 1948.





FIGURE 48

SOLUTION CAVITIES IN INTERSTRATIFIED SILTSTONE  
AND GYPSUM BEDS OF THE MUDDY CREEK FORMATION  
IN LAS VEGAS BAY

U. S. Bureau of Reclamation photograph, May 1949.

reservoir boundary. Solution appears to be confined, however, to the surface layers of the soluble material, and it has not yet produced any appreciable change in configuration of the lake either along the shore or below the water surface.

Calculations based on Howard's (1952) data on chemical changes of the Colorado River water during its storage in Lake Mead, show that approximately 13.6 million tons of material has been dissolved from the reservoir bed and banks from 1935 to 1949. Of this total, 10 million tons has remained in solution, thus increasing the concentration of dissolved solids in the lake water and in the water discharged from Hoover Dam. This increased concentration is made up chiefly of sulfate with smaller amounts of calcium, sodium, potassium, and chloride. The remaining 3.6 million tons consists of calcium which has combined with carbonate and precipitated in the lake.

The large quantities of calcium and sulfate that have been dissolved from the reservoir boundary show that solution of gypsum is considerably greater than the solution of rock salt, represented by the smaller amounts of sodium, potassium, and chloride. Rock salt is much more soluble than gypsum, and its smaller contribution to the gain in dissolved solids probably results from its limited exposures.

According to the Bureau of Reclamation (1950), the total exposed area of salt outcrops on the reservoir floor prior to inundation was only 22 acres. Subsequent covering of some of these outcrops by the sediment accumulated from 1935 to 1948 has reduced their areal dimensions still farther.

Assuming that gypsum, anhydrite, and other salines dissolved from the reservoir boundary have an average density of 2.50, we can obtain a reasonable estimate for the rate of solution. According to this estimate, the total volume of salines taken into solution from 1935 to 1948 is 4000 acre-feet, and the average annual rate of solution is 285 acre-feet. If the total volume of dissolved material were confined to an area of 1 square mile, it would form a layer about 7.4 feet thick.

Earlier estimates by the Bureau of Reclamation (1950) predicted that a maximum of 330 acre-feet of rock salt would be dissolved from the reservoir during its first year of operation (1935) and that the annual rate of solution in subsequent years would be reduced to about half that value. On the other hand, these early estimates predicted that gypsum would undergo no appreciable solution. The estimate based on chemical changes in the lake water suggests, however, that the solution of rock salt has been somewhat less



than that predicted by the Bureau of Reclamation and that the solution of gypsum and anhydrite has been of considerably greater significance.

Unlike the material eroded by landslides and wave action, most of the salines taken into solution are permanently removed from the reservoir in the water discharged at the dam.

#### Erosion of the Delta Surface

There is no evidence of erosive forces acting upon the lower part of the delta; a feature brought out by the hydrographic survey in 1948 was the remarkable smoothness and regularity of the surface formed by the bottomset beds. On the other hand, the uppermost part of the delta is periodically subject to erosion.

There remains that part of the delta in the vicinity of the delta front, which is approximately the locus of maximum deposition. A channel in this area has been described briefly but it deserves further consideration here, because with further study it may constitute evidence of erosion by turbidity currents. This channel (fig. 24) is clearly defined from river-mile 277.8 to river-mile 279.5; it is generally 300 to 1,000 feet wide, and has a maximum depth of about 25 feet below the average delta front at river-mile 278.6.



Nothing is known of the history of this channel except that it was there in 1948. It is not known whether some such channel developed early in the history of delta deposition, and if so, whether it has shifted from side to side as the delta grew. Nor is it known whether it maintains approximately the same form at all times, or is filled during periods of peak sediment deposition, or is scoured more deeply under certain conditions of inflow.

## RATE OF SEDIMENTATION

### Estimate Based on Total

#### Weight of Sediment Accumulated in Lake Mead

An estimate of the rate of sedimentation may be readily obtained from the total weight of sediment accumulated in Lake Mead during the 14 year interval, 1935-1948. As determined in a preceding section of this report, approximately 2,014 million tons of sediment were deposited in the reservoir during this period. Thus, the average annual rate of sedimentation is estimated at 144 million tons. As indicated earlier, most of the material in the Colorado delta and the Virgin delta has been supplied by the Colorado and Virgin Rivers, respectively. Consequently, a further estimate may be made of the mean annual load of detrital material carried into the lake by each of these rivers. According to this estimate, the mean annual contribution of the Colorado River is 140 million tons, whereas that of the Virgin River is only 4 million tons.

### Comparison with Estimate Based on

#### Stream Gaging Measurements

It is interesting to compare the above estimate of the mean annual load of sediment supplied by the Colorado River with suspended load measurements obtained by the U. S. Geological Survey at the Grand Canyon gaging station.

According to Thomas (1952) approximately 1,995 million tons of suspended sediment were carried past the Grand Canyon station during the interval from 1935 to 1948. This is equivalent to a mean annual load of about 142 million tons, or approximately 2 million tons more than the estimated average annual deposition of sediment from the Colorado River in Lake Mead during the same period. No estimate is made of the average annual suspended load of the Virgin River, because of the short period of record.

Such close agreement between the mean annual suspended load of the Colorado River and the average annual rate of sedimentation in the Colorado delta is indeed striking. However, the material carried as bed load has not been included in the measurement of sediment passing the Grand Canyon station, whereas it is included in the estimate of the amount of sediment accumulated in the Colorado delta. If the quantity of sediment carried in the bed load is appreciable, we would expect the total amount of sediment in the Colorado delta to be somewhat greater than the total suspended load passing the Grand Canyon station. Since this is not the case, it appears that the bed load of the Colorado River is extremely small, and that practically all of the sediment supplied by the Colorado River is carried in suspension. Thomas (1952) has cited many lines of

evidence which indicate that the bed load of the Colorado River upstream from Lake Mead is not great. Similarly, the absence of significant quantities of coarse constituents in the Colorado delta suggests a small bed load.

The correspondence between the mean annual suspended load of the Colorado River and the average yearly rate of sedimentation in the Colorado delta also support Thomas's conclusion that nearly all of the sediment carried into Lake Mead by the Colorado River passes the Grand Canyon station. In other words, the quantity of material supplied by ungaged tributaries entering the Colorado River and Lake Mead between the Grand Canyon station and Hoover Dam is very small.

The relative accuracy of the estimated sedimentation rates based on the amount of sediment in the Colorado delta and on stream gaging measurements cannot be evaluated quantitatively. In the stream gaging measurements, it has been assumed generally that the sediment concentration during one period of the day is representative of the entire day (Howard, 1947, pp. 2-7). This undoubtedly has introduced some error in the computation of daily loads, particularly during periods of rapid change in river discharge. Additional errors have probably resulted from the failure of sampling instruments to obtain completely representative



samples of the suspended load and from the use of estimated concentrations during periods when no measurements were obtained. Failure to consider the bed load of the river (although it is evidently quite small) has undoubtedly led to further error in the estimate of the rate of sedimentation based on stream gaging measurements.

The rate of sedimentation estimated from the total weight of sediment accumulated in the Colorado delta is also subject to error. Small errors have undoubtedly been introduced by assuming that cores obtained along the central part of the delta are representative of the entire cross-sections. However, the chief source of error probably lies in the considerable extrapolation required in estimating the total weight of sediment in the thick part of the Colorado delta east of the delta front.

Although none of these possible errors can be evaluated quantitatively, the close correspondence of estimates of the rate of sedimentation obtained by such widely differing methods suggests that the estimates are of the right order of magnitude.

## SEDIMENTATION IN RELATION TO RESERVOIR UTILIZATION

One of the chief problems in the operation and maintenance of the reservoir is the loss of water storage resulting from the accumulation of sediment. As shown in a preceding section of this report, the sediment accumulated in 14 years has reduced the water-storage capacity of the reservoir below the permanent spillway crest (1,205.4 feet altitude) from 28,794,000 acre-feet in 1935 to 27,271,000 acre-feet in 1948, a decrease of 4.9 percent. The usable storage at the permanent spillway level, however, diminished only 815,000 acre-feet, or about 3.2 percent of the 1935 usable capacity. If it could be assumed that the rate of sedimentation and storage loss would continue the same in the future, and that the capacity of the reservoir for storing sediment were the same as its capacity for storing water, the maximum life expectancy of Lake Mead could be calculated quite readily: about 20 times 14 years, or 280 years. However, neither of these assumptions is valid. The rate of storage depletion cannot be expected to remain constant owing to the future compaction of the accumulated sediment and also to any future changes in the rate of sedimentation. Likewise, the reservoir's water-storage capacity is considerably different from its sediment-storage capacity, because the upper surface for water must be

essentially horizontal, but the sediment surface never can be. It is the purpose of this section to attempt an evaluation of these factors and to obtain a reasonable estimate of the future rate of storage depletion and the life expectancy of the reservoir.

Sediment-Storage Capacity Above  
the Permanent Spillway Level.

It is a popular fallacy that the capacity of a reservoir to store sediment is the same as its capacity to store water. Stevens (1946), for example, in estimating the life expectancy of Lake Mead assumed that the sediment-storage capacity is equal to the water-storage capacity at the permanent spillway level. This assumption would require, as pointed out by Mackin (1928, p. 497), that when the delta front reaches the dam the river will transport its detrital load from the head of the reservoir to the delta front on a surface of no slope. It is obvious that such a condition could not exist and that when the reservoir is filled the sediment surface must slope downstream toward the dam. The sediment-storage capacity of the reservoir is, therefore, considerably greater than its water-storage capacity. For Lake Mead, the difference between the water and sediment-storage capacities is equal to the volume between the level surface (water level) at the altitude of the permanent spillway crest and the sloping sediment

surface that will extend upstream from the dam when the reservoir becomes filled with sediment.

In a previous discussion of the characteristics of the Colorado delta, it was shown that the topset beds over which the Colorado River flows have an average slope of about 1.25 feet per mile and that this slope has remained essentially constant since the inception of Lake Mead. The highest topset beds near Bridge Canyon are as much as 65 feet above the average lake level (approximately 1,170 feet altitude), and 15 feet above the highest level yet attained by the lake, but they do not, in their present stage of development, extend upstream from the eastern end of the reservoir. Whether or not the slope of the topset beds will remain the same in the future is not known, but some idea of its possible trend may be obtained from consideration of delta development in a more advanced stage at Elephant Butte Reservoir on the Rio Grande.

According to Eakin (1939, pp. 90-99), the topset beds near the head of Elephant Butte Reservoir at San Marcial, New Mexico grew about 10 feet in thickness between 1916 and 1935. Blaney (1936) reports that since 1918 sedimentation has occurred progressively farther upstream from Elephant Butte Reservoir, and by 1934 had extended a distance of about 150 miles along the Rio Grande. At La



Joya (50 miles upstream from the reservoir) the river bed was raised 7 feet during this period, and at Albuquerque (100 miles upstream and 500 feet above the spillway level) a rise of 2 to 4 feet was detected. Hupp (1946) has shown that the lower 15 miles of this aggradation is due to the extension of delta topset beds upstream from the head of Elephant Butte Reservoir and that about 48 percent of the total load of sediment supplied by the Rio Grande during the interval from 1936 to 1941 was deposited in these beds. The net effect of this up-valley extension of the delta is to increase the gradient of the topset beds over which the Rio Grande flows to its entrance in Elephant Butte Reservoir. This gradual steepening is in accord with Mackin's (1943, pp. 496-498) observation that a delta in its more advanced stages of development tends to parallel the gradient of the stream channel over which it has been deposited, provided that the original stream was at grade.

The pre-Lake Mead gradient of the Colorado River in the Lower Granite Gorge was as much as 7 feet per mile, but in view of the very great thickness of unconsolidated sediments in the canyon section before the creation of Lake Mead, it seems almost certain that the river was not at grade. The average gradient of the river below Yuma, Arizona is about 1 foot per mile, and the slope of the

Colorado delta in the Gulf of California, containing sediment comparable to that now accumulating in Lake Mead, is of the same order of magnitude. The average slope of the natural channel from Hoover Dam to the Gulf is about 1.7 feet per mile.

Although the observations of delta growth in Elephant Butte Reservoir furnish some qualitative information of value in considering the future development of the Colorado delta in Lake Mead, essential quantitative data are lacking. If we assume, however, that the slope of the topset beds in 1948 (1.2 feet per mile) is fairly representative of the slope that will be attained when the reservoir becomes filled, an estimate may be made of the sediment-storage capacity above the permanent spillway level.

In figure 49, the sloping surface of the Colorado delta topset beds has been projected so as to extend from the permanent spillway crest at Hoover Dam to its upstream intersection with the Colorado River channel. By operation of the spillway gates, water can be stored in the lake to a level 16 feet above the permanent crest, and in 1948 the controlled capacity above that crest was 2,450,000 acre-feet. It is anticipated, however, that the gates will be used for no more than temporary storage and that the sediment surface will be graded to the level of the permanent

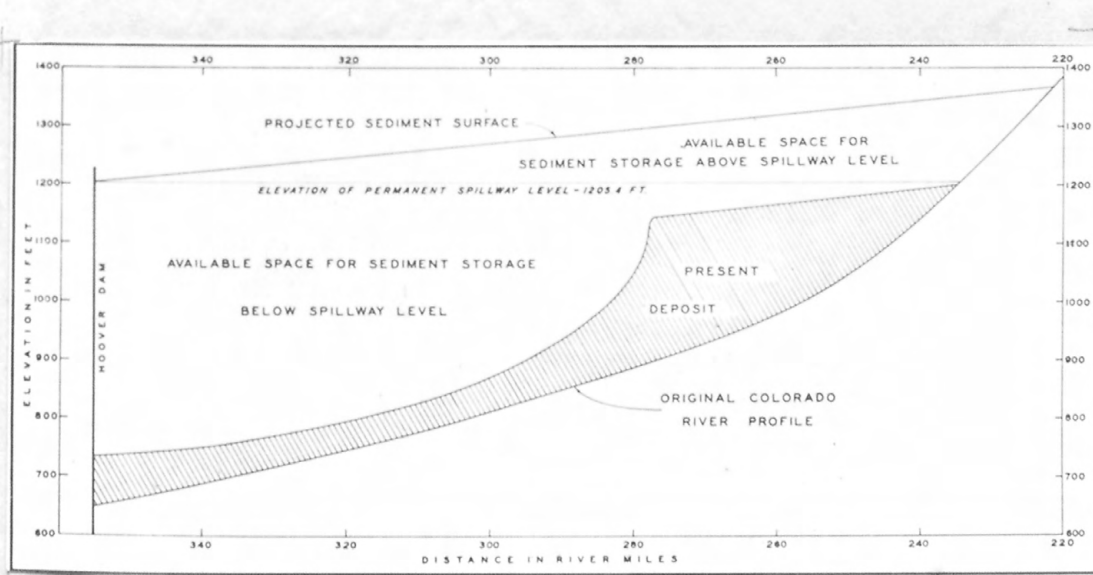


FIGURE 49

DIAGRAMMATIC REPRESENTATION OF THE SURFACE OF THE SEDIMENT  
ACCUMULATED IN LAKE MEAD WHEN FILLED TO THE PERMANENT  
SPILLWAY CREST AT HOOVER DAM

crest.

On the basis of the above assumptions, the sloping surface in figure 49 delineates the upper limit of the accumulated sediment when the reservoir will become filled. As shown by this diagram, the topset beds at the original eastern end of the reservoir (river-mile 235) will rise to an altitude of about 1,350 feet, or 145 feet above the permanent spillway level. The topset beds will then intersect the old Colorado River profile at river-mile 221.5, about 13.5 miles upstream from the original head of the reservoir and at an altitude of 1365 feet.

Computations of the volume between the surface at spillway level and the sloping surface of the topset beds, based on planimeter measurements of the areas enclosed by contours of the two surfaces, show that the sediment-storage capacity above the permanent spillway level is about 6,900,000 acre-feet, almost 25 percent of the storage capacity below the permanent spillway level. The total sediment-storage capacity is estimated, therefore, as of the order of 35,700,000 acre-feet.

This estimate of sediment-storage capacity is necessarily oversimplified owing to the lack of quantitative data on the complex interrelations of factors governing stream aggradation. It has been assumed, for example, that



the long, narrow arms of the reservoir will be filled to the level of the sediment in the main body of the lake, whereas it is possible that the sediment level in these regions may be lower than that of the main part of the delta. Furthermore, it has been necessary to assume that the Overton Arm, which extends northward from the central part of the lake, will be filled to the level of the delta surface in the Virgin Basin. If such deposition does occur, a considerable quantity of detrital material must be supplied to this region by future distributaries of the Colorado River. The quantity of sediment transported into Lake Mead by the Virgin River alone is not sufficient to fill this part of the reservoir during the period that will be required to fill the main body of the lake.

#### Sediment Compaction

Sediment compaction has an extremely important bearing on the rate of depletion of water-storage volume and on the life expectancy of the reservoir. The sediment accumulated in Lake Mead consists of two major types of material; namely, the sand of the topset and foreset beds, and the silt and clay of the bottomset beds. It has been shown that the compaction of sand is probably insignificant, and consequently can be neglected. The potential compaction of silt and clay, however, is large.

The degree to which silt and clay sediments are compacted is related primarily to their depth of burial and to the size, shape, and sorting of their constituent particles. In order to obtain an average empirical relation between these various factors, the water content-depth data of all cores from the bottomset beds of both the Colorado and Virgin deltas were plotted, and a best-fit visual curve was drawn. This curve (fig. 50) shows an approximately linear relation between decrease in water content and depth of burial of the bottomset beds.

Although this curve furnishes reasonably accurate compaction data throughout a depth interval of 95 feet, it alone does not afford an adequate basis for estimating the compaction of the material at greater depths after the reservoir has become filled with sediment. By the use of Hedberg's (1936) porosity data for fine-grained sediments, however, it is possible to extend the water-content curve obtained from the Lake Mead cores to considerably greater depths as illustrated in figure 50. In this extension, the lower 30 feet of the curve based on the Lake Mead cores has been disregarded owing to considerations discussed below.

In the analysis of the individual cores it was noted that the samples near the original reservoir bottom were considerably lower in water content than samples from the

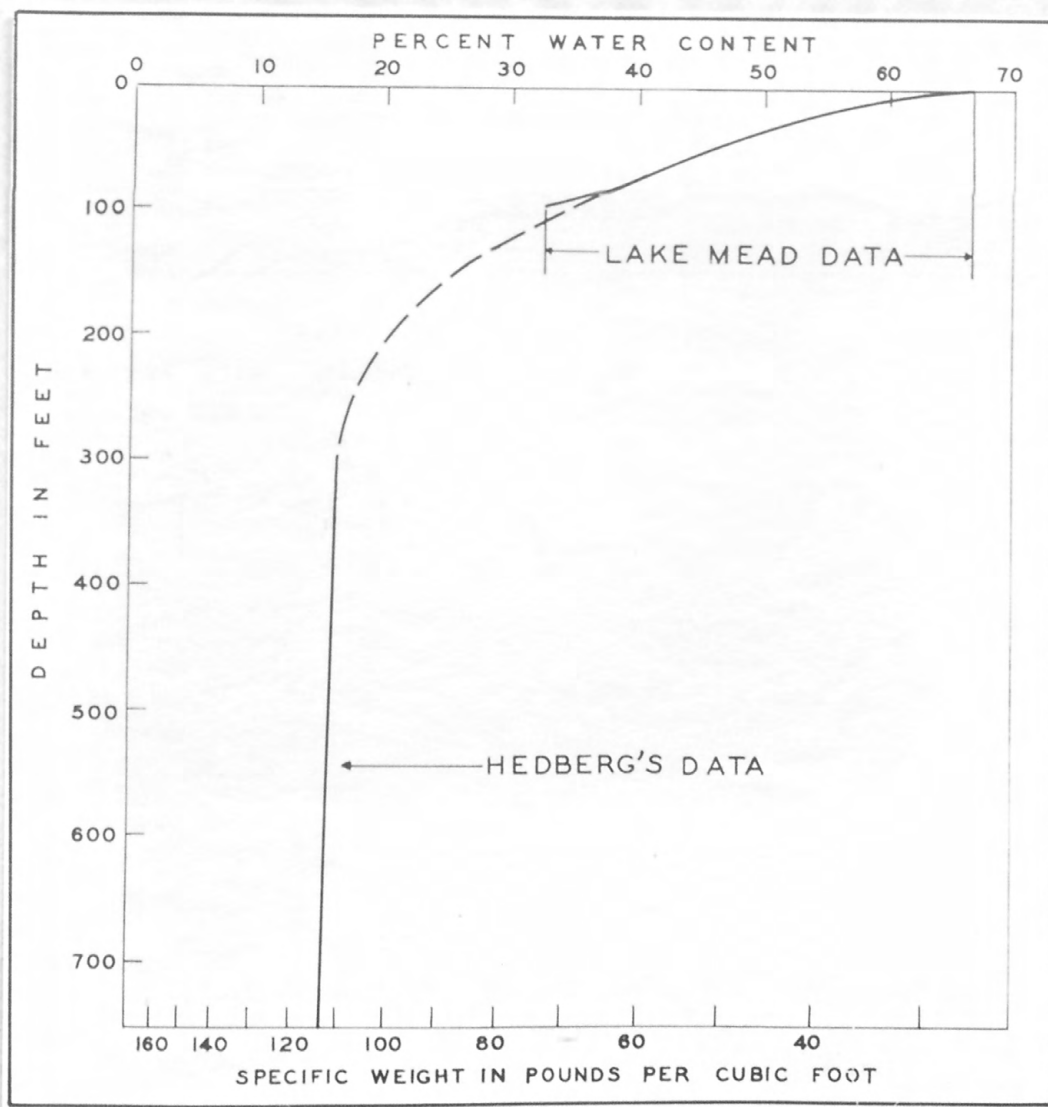


FIGURE 50

WATER CONTENT AND SPECIFIC WEIGHT OF SILT AND CLAY  
Dashed line indicates interpolation.

same sediment depth at nearby locations, but at higher levels above the original bottom. An excellent example of this relation is afforded by two samples from the bottomset beds of the Colorado delta in the southern part of the Boulder Basin. One sample from a sediment depth of 16 feet, and only 1 foot above the original reservoir floor, has a water content of about 47 percent, whereas the other sample from the same sediment depth, but at a distance of about 66 feet above the original reservoir bottom, has a water content of 64 percent. The first sample was obtained near the margin of the delta where the bottomset beds are only 17 feet thick, whereas the other sample was obtained from the central part of the delta where the bottomset beds are about 82 feet thick.

A possible explanation for the low water content of the sediment near the original reservoir floor may be found by consideration of the mechanism of compaction in a very thin layer of sediment which we will assume is located midway between the top and bottom of the accumulated material. When this thin layer is subjected to increased pressure from above, such as would result from additional sediment loading, some of the interstitial water is forced from the material into the overlying strata. At the same time, this increment receives water that is driven from the



interstices of the sediment below. However, the inflow of water into this thin layer is less than the outflow; thus the water content of the layer under consideration is reduced.

Let us now assume that another increment of sediment is located at the same depth as in the example above, but that it is in contact with the original reservoir bottom. When subjected to increased loading, some of the interstitial water will be forced out of this sediment layer, as in the example above, but owing to the low compactibility of the original reservoir bottom, there will be little if any squeezing out of water from below. As a result, the water content of this layer in contact with the original bottom is considerably less than that of a similar layer located at mid-depth. A lower water content in these basal layers of sediment would also occur if the underlying materials were relatively impermeable, so that their saturation proceeded slowly and continued after deposition of some sediment, causing drainage from these basal layers, a condition similar to that postulated by Emery and Kittenberg (1952, p. 761), and others to account for abnormally rapid compaction.

Theoretically, the water content in the sediment at all levels would be reduced to some extent owing to the low

compactibility of the original reservoir floor. Only in a sediment accumulation of infinite thickness would this effect be entirely eliminated. In Lake Mead the marked reduction in water content appears to be appreciable only in about the lower 10 feet of the bottomset beds; but because of their variable thickness, the water-content values in figure 50 appear to be significantly lower in the bottom 30 feet of the curve. Consequently, they are not considered representative and have been omitted in the interpolation of the curve to greater depths.

Returning now to the portion of the water content-depth curve based on Hedberg's data (fig. 50), one cannot be certain that these values are strictly applicable to the silt and clay accumulated in Lake Mead. For example, it is not known what effect time has on the compaction of sediments. Hedberg's determinations were obtained from clay and shale strata that have been buried for a great length of time, compared to the few centuries that the earliest Lake Mead sediments will have been buried when the reservoir becomes entirely filled. Supposedly, the sediments examined by Hedberg have had sufficient time for the forces of compaction to reach approximate equilibrium, but we do not know whether the Lake Mead silt and clay will attain a comparable state of compaction during the life of the

reservoir. Furthermore, Hedberg gave no precise information as to the size, shape, and sorting of the constituent sediment particles, and there is the possibility that the texture of the material investigated by him differs significantly from the texture of the Lake Mead silt and clay. Because of the close relationship between texture and compaction, any significant difference in texture would produce a corresponding change in compaction.

Assuming, however, that a few hundred years is sufficient for the compaction of sediments to reach a state of equilibrium with the weight of the overburden, and that the sediment investigated by Hedberg does not differ significantly in texture from the silt and clay accumulated in Lake Mead, it is possible to apply the part of the water content-depth curve constructed from Hedberg's data to the Lake Mead sediments.

It is unfortunate that no further compaction data are available in the critical range between depths of 75 feet (the lower limit of the Lake Mead observations) and 290 feet (the shallowest observational depth reported by Hedberg). Continued observation in Lake Mead will eventually provide specific information for this zone about which very little is yet known. For the present, the interpolated portion of the water content-depth curve,

together with the upper few hundred feet of the curve constructed from Hedberg's data, is considered, however, to provide reasonably reliable compaction data for deeply buried layers of silt and clay accumulated in Lake Mead when it becomes entirely filled with sediment. The accumulated sediment at the time of reservoir filling will attain a maximum thickness of about 575 feet immediately upstream from Hoover Dam.

#### Pattern of Sedimentation in the Future

From the preceding considerations of sediment-storage capacity and compaction an attempt will now be made to trace the probable future pattern of sedimentation in Lake Mead and to predict when this pattern will critically affect the normal functions of the reservoir.

The gates through which water can be discharged from the reservoir are at three levels. The uppermost of these are the spillways with their permanent crest at 1,205 feet altitude. The gates at the two lower levels are situated in the four intake towers immediately uplake from Hoover Dam. The sill of the uppermost gates is at an altitude of 1,015 feet, 310 feet above the 1943 sediment surface and 415 feet above the original floor of the reservoir. The sill of the lower gates is at an altitude of 895 feet, 160 feet above the 1943 sediment surface and 265 feet above the



original lake bottom at the intake towers. These are the outlets through which all water for generating power and supplying water to downstream users is normally discharged.

All water stored below the 895-foot level is, of course, in dead storage. When water was first impounded behind Hoover Dam, the dead storage space measured 3,223,000 acre-feet, but by January 1949 it had been reduced by the accumulation of sediment to 2,620,000 acre-feet, or by 18.7 percent. Whenever the dead storage space becomes completely filled with sediment it will be necessary either to discharge great quantities of sediment to downstream areas or to close the lower gates and allow them to become covered. Loss of the dead storage space will thus mark the first critical stage in reservoir filling. Similarly, the filling of the reservoir to the levels of the upper outlet sill and permanent spillway crest will denote, respectively, the second and third critical stages. In the following discussion, predictions of the amount and distribution of sediment that will have accumulated in the reservoir at the three critical stages will be attempted. The time required to reach these stages is discussed in a later section of this report.

#### Complete Filling

On the basis of foregoing considerations it is

possible to obtain a reasonable estimate of the amount of sediment that will be required for the reservoir to become completely filled; that is, the stage when the sediment accumulation will intersect the dam at the altitude of the permanent spillway crest. Data have been presented which indicate that a total of 2 billion tons of dry sediment has been deposited in Lake Mead during the 14-year period, 1935-48. This quantity is taken as a convenient unit of measurement for discussion of the future accumulation of sediment in Lake Mead. It has also been shown (fig. 37) that this material consists of approximately 45 percent sand, and 55 percent silt and clay. The total load of sand, therefore, is 900 million tons, and the total load of silt and clay is 1,100 million tons. There is no assurance that the Colorado River will continue to carry sediments similarly proportioned in particle size. The geologic history of the Chemehuevi formation (Longwell, 1936) shows that it has not done so in the past, but instead has carried a considerable amount of gravel. Such changes recorded in geologic history, however, may require thousands of years. For the few centuries under discussion in the following paragraphs, it is assumed that the size distribution will be similar to that in the 2-billion ton sample accumulated prior to the 1948 survey.

Further data on the physical properties of the sediment suggest that compaction of the sand is insignificant, but that the silt and clay undergo considerable compaction as their depth of burial increases (fig. 50). It is desirable, therefore, to consider the sand and fine constituents independently.

Using a mean specific weight of 93.8 pounds per cubic foot for sand, we find that the total sediment-storage capacity (35,700,000 acre-feet) has been reduced 441,000 acre-feet by the first 2 billion tons of sediment brought into the reservoir. Since it is assumed that the sand will experience no further compaction, the sand in each 2-billion ton unit will reduce the total sediment-storage capacity by an equivalent amount.

The rate of sediment-storage depletion resulting from the accumulation of silt and clay is not constant, but will become progressively less because of increased compaction during the filling of the reservoir.

In order to obtain the rate of sediment storage reduction resulting from the accumulation of silt and clay, we must first determine the total weight of sediment that will be stored in the reservoir when it becomes entirely filled. This can be accomplished by use of the sediment compaction data shown in figure 50 and the sediment-storage

capacity curve presented in figure 51.

In the following determinations, it is assumed that the pattern of sedimentation during the period 1935-1948 will continue in the future; that is, the sand will be deposited in the topset and foreset beds, and the silt and clay will accumulate in the bottomset beds. When the reservoir becomes entirely filled with sediment, the sand will then overlies the silt and clay. In figure 51 it is estimated that the available sediment-storage space above the permanent spillway level is equally distributed above and below an altitude of 1,240 feet, and this is the level to which the sediment compaction data in figure 50 have been referred. For example, water contents at depths of 0 feet and 200 feet in figure 50 correspond to altitudes of 1,240 feet and 1,040 feet, respectively, in figure 51.

To obtain the weight of silt and clay accumulated in the reservoir when it becomes filled with sediment, the volumes of silt and clay in successive 50-foot increments of altitude (fig. 51) were multiplied by their average specific weights as determined from figure 50. Since it is assumed (above) that the silt and clay will make up the lower part of the deposit, these computations have been made from the lake bottom to increasing altitudes. The total weight of silt and clay (table 13) was then obtained by summation of



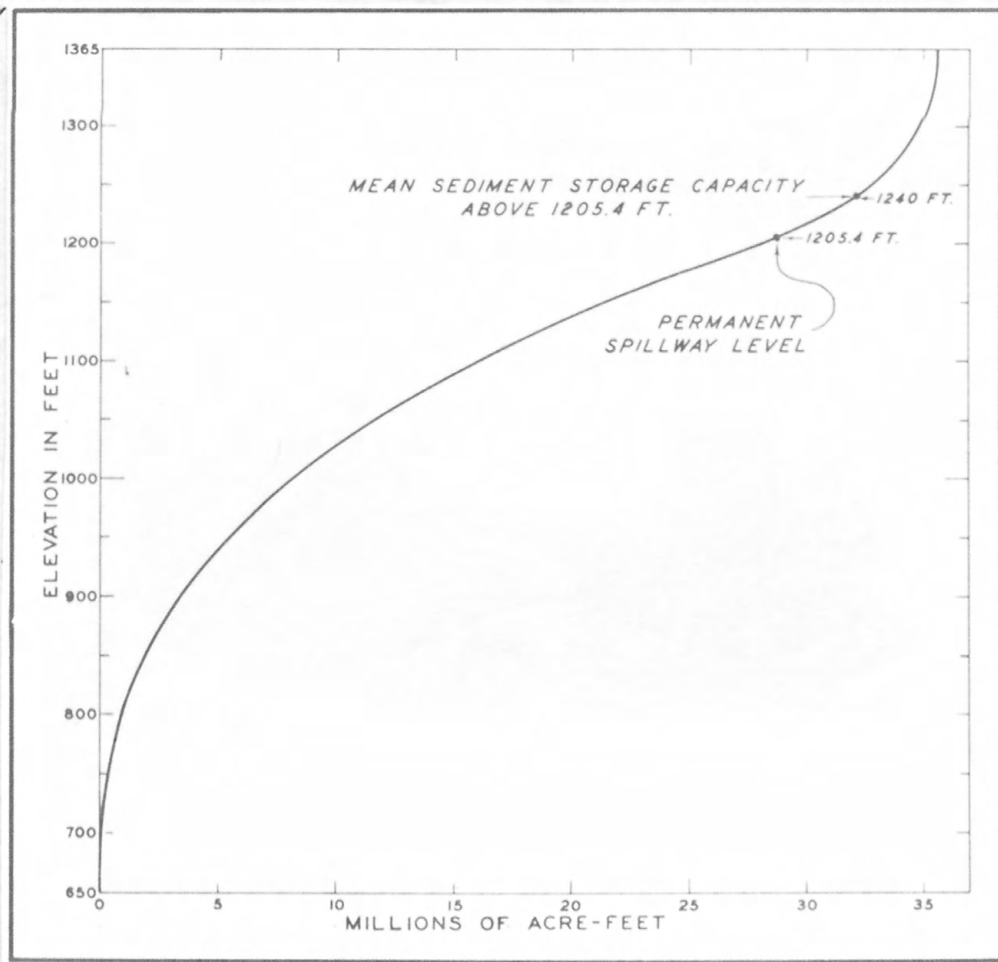


FIGURE 51

CURVE SHOWING THE ESTIMATED SEDIMENT STORAGE CAPACITY  
OF LAKE MEAD WHEN THE ACCUMULATED SEDIMENT REACHES  
THE ALTITUDE OF THE PERMANENT SPILLWAY AT HOOVER DAM

TABLE 13

Estimated weight, volume and specific weight of the sediment in Lake Mead when it becomes filled.

| Sediment type    | Weight, millions of tons | Volume, acre-feet | Mean specific weight, lbs./cu. ft. |
|------------------|--------------------------|-------------------|------------------------------------|
| Silt and clay    | 41,100                   | 19,250,000        | 98.0                               |
| Sand             | 33,600                   | 16,450,000        | 93.8                               |
| Silt, clay, sand | 74,700                   | 35,700,000        | 96.1                               |

the 50-foot weight increments. The results of these computations are presented in graphic form in figure 52.

The weight of sand accumulated in the reservoir when it becomes filled with sediment can be computed in the same manner as the weight of silt and clay, except that compaction need not be considered. In these computations, we have used a mean specific weight of 93.8 pounds per cubic foot for the accumulated sand as determined in a preceding section of this report. Since it is assumed that the sand will be confined to the upper layers of the deposit, the weight of sand in each 50-foot increment of depth has been computed from the altitude of maximum sediment storage (fig. 51) to decreasing altitudes. The total weight of sand (table 13) was then obtained by summation of the 50-foot weight increments. The results of these computations are plotted on the same graph as the silt and clay data (fig. 52).

Near the level of contact between the sand and the underlying silt and clay, the increments of altitude were reduced to 10 feet, and a graphic method was employed to determine precisely the total weights of the sand and the silt and clay constituents. This procedure resulted, also, in a more precise determination of the altitude of contact between the silt and clay and the overlying sand. As shown

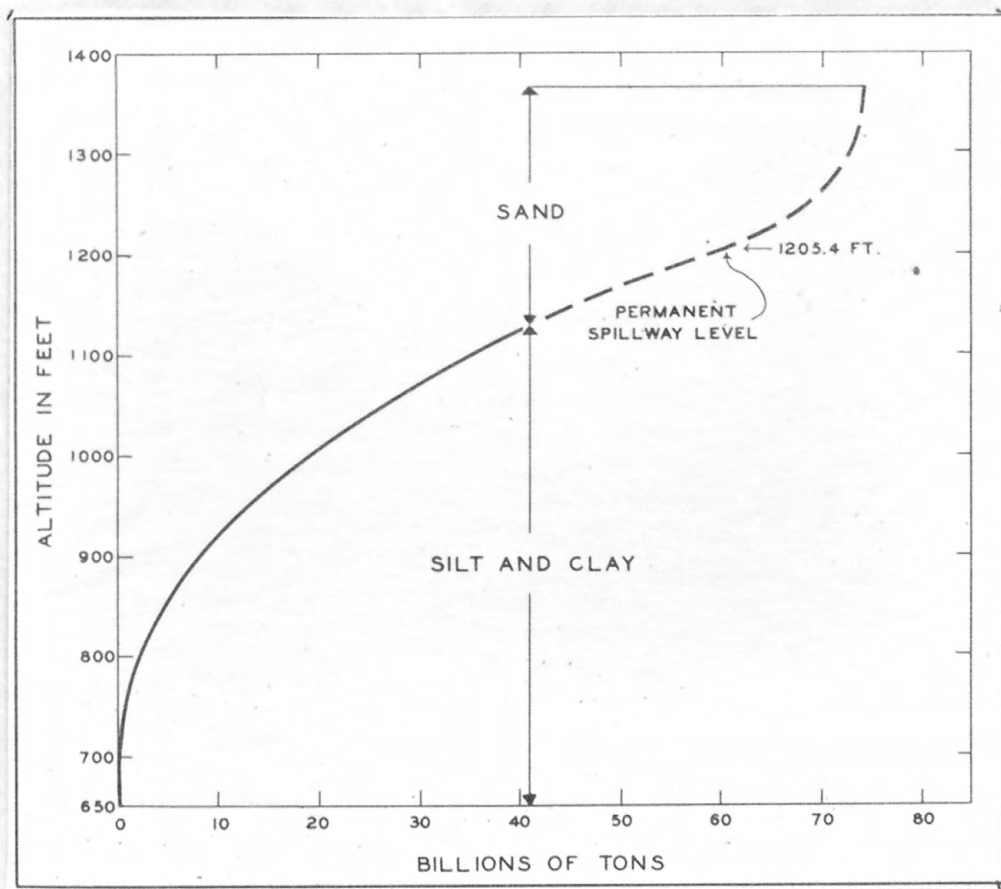


FIGURE 52

CUMULATIVE CURVE SHOWING THE ESTIMATED WEIGHT OF SEDIMENT  
AND OF COARSE AND FINE COMPONENTS WHEN THE RESERVOIR  
IS FILLED WITH SEDIMENT



in figure 52, most of the silt and clay will be stored below an altitude of 1,130 feet, and most of the sand will be stored above this altitude. Other quantitative results of these computations are given in table 13. Further calculations based on this table show that the average rate of reduction in total sediment storage space during the time required to fill the reservoir is 956,000 acre-feet for each 2-billion ton unit. Of this volume, sand will occupy 441,000 acre-feet and silt and clay will occupy 515,000 acre-feet.

#### Half-Way Point in Reservoir Filling

It appears that the usefulness of the reservoir will not be materially impaired until its water-storage capacity at the level of the permanent spillway crest is reduced to about 13,000,000 acre-feet, the average annual flow into Lake Mead from 1935 to 1948. This would be slightly less than half of the original water-storage capacity at that level.

Admittedly, a major attribute of Lake Mead today is its capability for holdover storage: with a capacity more than twice the average inflow it can accumulate water during years of high runoff, and release it during subsequent years of low runoff, thus furnishing a relatively

constant supply during wet and dry years. Under the terms of the Colorado River Compact of 1922 and the Treaty of November 1945 between the United States and Mexico, however, only 8,250,000 acre-feet of water is yet allocated definitely to the Lower Basin, for which Lake Mead constitutes the prime regulating body. A capacity of 13,000,000 acre-feet, therefore, would represent an amount more than 50 percent greater than the annual use in the Lower Basin on the basis of present allocation. Furthermore, the usable storage at that time may be considerably greater than 13,000,000 acre-feet because of ground-water storage provided by alternate saturation and drainage of the delta sands as the reservoir level rises and falls. The controlled storage in Lake Mead can also be increased substantially by raising the spillway gates at Hoover Dam.

In order to obtain an estimate of the sediment accumulation when the water-storage capacity is reduced to approximately 13,000,000 acre-feet, the following assumptions are made: (1) the average water level of the reservoir will be maintained at or near the altitude of the permanent spillway crest (1,205.4 feet) by raising the spillway gates during months of peak inflow; (2) a proportionate amount of the total volume of sediment stored above the permanent spillway crest at the time the reservoir

becomes filled with sediment will be deposited above spillway level each year; (3) the total weight of sediment will be made up of 45 percent sand and 55 percent silt and clay; (4) the mean specific weight of sand will remain the same (93.8 pounds per cubic foot) as in 1948; and (5) the mean specific weight of silt and clay will increase according to the relation shown in figure 50 from 51.6 pounds per cubic foot (the mean specific weight of silt and clay accumulated in Lake Mead from 1935 to 1948) to 93.0 pounds per cubic foot (the estimated mean specific weight of silt and clay when the reservoir becomes completely filled with sediment), and this increase will be proportional to the ratio between the sediment volume (1,426,000 acre-feet) in 1948 subtracted from the sediment volume at any future time and the sediment volume in 1948 subtracted from the ultimate sediment volume of 35,700,000 acre-feet when the reservoir becomes entirely filled with sediment.

The volume of sediment that will be stored in the reservoir when its water-storage capacity is reduced to 13,000,000 acre-feet can be evaluated readily from assumptions (1) and (2). The volume of sediment below spillway level is equal to the difference between the original reservoir capacity below spillway level (28,794,000 acre-

feet) and the space still available for water storage (13,000,000 acre-feet). The amount of sediment stored below spillway level would therefore be 15,794,000 acre-feet, or about 55 percent of the original reservoir volume below the permanent spillway level. According to assumption (2) the volume of sediment accumulated above the spillway level will be 55 percent of the total space (6,900,000 acre-feet) available for sediment storage above the spillway level, or 3,800,000 acre-feet. The total volume of sediment that will be stored in the reservoir at the time the water storage space is reduced to 13,000,000 acre-feet is estimated, therefore, at 19,600,000 acre-feet.

With this estimate of sediment volume the mean specific weight of the silt and clay accumulation may be determined as outlined in assumption (5).

According to figure 50 the mean specific weight of silt and clay (51.8 pounds per cubic foot) accumulated in Lake Mead from 1935 to 1948 is the same as the specific weight of a layer of silt and clay buried to a depth of 50 feet. Similarly, the estimated mean specific weight (98.0 pounds per cubic foot) of the silt and clay accumulation when the reservoir becomes filled with sediment is the same as the specific weight of a layer covered by 200 feet of overburden. The mean specific weight increases not only



with depth of burial, but also with the volume of sediment. According to assumption (5), the increase in the mean specific weight of silt and clay resulting from increased depth of burial will be proportional to the increase in sediment volume. For example, when the mean specific weight of the silt and clay becomes the same as the specific weight (79.0 pounds per cubic foot) of a layer at a depth of 125 feet (midway between the 50 foot and the 200 foot layers, fig. 50), the volume of accumulated sediment will increase by half of the difference between the ultimate sediment volume (35,700,000 acre-feet) and the volume of sediment (1,426,000 acre-feet) accumulated from 1935 to 1948, or by 17,137,000 acre-feet.

The 17,600,000 acre-feet of sediment that will be stored in the reservoir when its water-storage capacity is reduced to 13,000,000 acre-feet represents an increase of 16,174,000 acre-feet over the volume of sediment accumulated from 1935 to 1948. According to the method outlined above, it is estimated that the silt and clay accumulated in the reservoir at the half-way point will have a mean specific weight of 80.0 pounds per cubic foot.

From assumptions (3) and (4) above, the total weight of the sediment accumulated in the reservoir when its water storage capacity is reduced to 13,000,000 acre-feet can be

computed by the following equations:

$$(1) \quad W_T = \frac{21.78 S_S (V_T - V_F)}{.45}$$

$$(2) \quad W_T = \frac{21.78 S_F V_F}{.55}$$

where  $W_T$  is the total weight of the accumulated sediment in tons,  $S_S$  is the mean specific weight of the sand fraction,  $V_T$  is the total volume of the accumulated sediment in acre-feet,  $V_F$  is the volume of the silt and clay fraction in acre-feet, and  $S_F$  is the mean specific weight of the silt and clay fraction. The numerical factor, 21.78, is used for converting pounds to tons and acre-feet to cubic feet; the numerical values, .45 and .55, are proportions of the total weight of sediment made up by the sand fraction and the silt and clay fraction, respectively.

Solving equation (2) for  $V_F$  in terms of  $W_T$  and substituting this value in equation (1), we find that  $W_T$ , the total weight of sediment accumulated in the reservoir when the water-storage capacity is reduced to 13,000,000 acre-feet, is 36.6 billion tons. Further computations show that the sand fraction will have a volume of 8,100,000 acre-feet and a weight of 16.5 billion tons. The silt and clay

fraction will occupy a volume of 11,500,000 acre-feet and weigh 20.1 billion tons. The mean specific weight of the total accumulation will be 85.7 pounds per cubic foot.

Of the 8,100,000 acre-feet of sand, 3,800,000 acre-feet will be deposited above the altitude (1,205.4 feet) of the permanent spillway crest. The 4,300,000 acre-feet of sand to be deposited below spillway level would be enough to fill all of the original water-storage space below that level in the Lower Granite Gorge, Pierce Basin, Grand Bay, Iceberg Canyon, Gregg Basin, and the upper 3 miles of Virgin Canyon. Even without any accumulation of bottomset beds in these areas, the top of the delta front at the half-way point in filling of the reservoir must advance at least to river-mile 300, about 25 miles downlake from its position in Pierce Basin in 1943.

Assuming that the topset beds maintain an average slope of about 1.2 feet per mile as at present, the 1943 delta surface in the Lower Granite Gorge and Pierce Basin would be buried under about 69 feet of additional material, of which 35 feet would result from increasing the average water level in the reservoir from 1,170 feet to 1,205 feet, and the remainder (34 feet) would be accounted for by up-building of the topset beds at a rate of 1.2 feet for each mile of advance of the delta front. The highest delta

deposits at this time would be 8 miles upstream from Bridge Canyon rapids (which will then be covered by sediment) at altitudes as high as 1,300 feet, or about 95 feet above the altitude of the permanent spillway crest. These deposits are included in the 3,800,000 acre-feet of accumulation above the spillway level.

The silt and clay fraction, as estimated above, will amount to 11,500,000 acre-feet, and it will accumulate in the bottomset beds. If this material were to form a level surface in the lowest parts of the reservoir west of the delta front (river-mile 306) it would rise to an altitude of 1,070 feet, a distance of 25 feet above the altitude (1,045 feet) of the sill of the upper gates.

It is obvious, however, that in order for turbidity currents to transport the detrital load to the lowest parts of the reservoir, the bottomset beds must have a downlake slope. To obtain a reasonable estimate of this slope, let us consider the declivity of the subaqueous delta surface in 1948 and the space available for sediment storage in the lowest parts of the reservoir west of the top of the delta front (river-mile 306) at the half-way point. As pointed out earlier, there was a marked reduction in declivity of the 1948 delta surface beginning in the vicinity of Virgin Canyon and extending to Hoover Dam, and it was shown that



this decreased slope was related to a progressive thickening of the bottomset beds toward Hoover Dam. Both the decreased slope and the delta thickening were ascribed to the basining effect of the dam.

An analysis of volume capacities shows that this basining effect at the half-way point must extend approximately the same distance uplake from the dam as it did in 1948 and that the slope of this part of the delta cannot be greater than the average slope (1.2 feet per mile) of the bottomset beds in Boulder Basin in 1948, which is the best available example of basining effect. Calculations based on volume capacities and an assumed slope of 1.2 feet per mile show that the bottomset beds at the half-way point would extend to river-mile 300 where they would rise to an altitude of 1,100 feet. Assuming that the delta front maintains its 1948 slope of about 55 feet per mile, the surface of the bottomset beds would grade into the topset beds at about the same position as in 1948; that is, 105 feet below the altitude of the top of the delta front and 2 miles downlake. The bottomset beds at the dam would then rise to an altitude of 1,044 feet, only 1 foot below the sill of the upper gates. The available capacity below this assumed slope of 1.2 feet per mile is just sufficient to store the 11,500,000 acre-feet of silt and clay accumulated in the reservoir at

the halfway point.

If a slope greater than 1.2 feet per mile is used in these calculations, it is found that the capacity is not sufficient to store the 11,500,000 acre-feet of silt and clay. For example, the capacity below a surface with a slope of 1.8 feet per mile extending from an altitude of 1,100 feet at the face of the delta front and intersecting the dam at an altitude of 1,010 feet is only 10,000,000 acre-feet of the 11,500,000 acre-feet required. Likewise, the capacity below a surface with a subaqueous slope of 5.8 feet per mile, which is slightly greater than the average subaqueous slope of the delta in 1943, is only 10,000,000 acre-feet. The inadequacy of the reservoir for storing the 11,500,000 acre-feet of silt and clay below these greater slopes is caused by the irregular distribution of available storage space west of river-mile 306. At the half-way point, the upper one-quarter of the subaqueous profile where the sediments are thickest will be confined to the Virgin Canyon-Temple Bar area (river-miles 306-317), but this part of the reservoir cannot possibly store a corresponding volume of the 11,500,000 acre-feet of silt and clay to be deposited west of the delta front. To obtain adequate space it is necessary to utilize considerable portions of Virgin Basin and Boulder Basin where greater storage capacity

is available. The assignment of sufficient quantities of sediment to these areas requires a slope of not greater than 1.2 feet per mile.

For many years the accumulation of bottomset beds will continue in the portion of the reservoir east of Virgin Canyon, in the area over which the delta front will have advanced when the reservoir is half-filled with sediment. Some of the space in these upper areas will thus be preempted by bottomset beds, so that the topset beds and foreset beds must advance further downlake than would be estimated on the basis of basin capacities alone. Assuming that 20 percent or 860,000 acre-feet of the capacity below spillway level in the upper basins were occupied by bottomset beds, the top of the delta front would have to advance over the underlying bottomset beds to river-mile 317 at the eastern end of Virgin Basin. Using a 1.2 feet per mile slope for the profile west of the delta front, we find that the bottomset beds would intersect the intake towers at an altitude of 1,025 feet, or about 20 feet below the upper sill.

In summary, the filling of Lake Mead will have reached the half-way point when the sediment accumulation becomes 13 times as great as the amount brought into the lake between 1935 and 1943. At that time the topset,

Foraset, and underlying bottomset beds will fill all of the reservoir east of Virgin Basin and extend into that basin. The bottomset beds at the dam will reach almost to the level of the upper gates. The water-storage capacity (not including ground-water storage) will be about 13,000,000 acre-feet below the permanent spillway crest, comprising about 4,500,000 acre-feet in Boulder Basin, 500,000 acre-feet in Boulder Canyon, 5,000,000 acre-feet in Virgin Basin and 3,000,000 acre-feet in Overton Arms. The total storage can be increased to about 14,900,000 acre-feet by raising the spillway gates.

#### Filling to the Bill of the Lower Gates at the Intake Towers

Following the general procedure outlined in the preceding pages, it is now possible to obtain a reasonable estimate of the amount of sediment required for the sediment surface at the intake towers to reach the lower gates (695 feet altitude). In this estimate it is assumed that the lower 46 miles (extending from river-mile 308 at the mouth of Virgin Canyon to river-mile 354 at Hoover Dam) of the delta profile will exhibit basining effect and that this part of the profile will have a slope of 1.2 feet per mile. With the lower end of this sloping plane intersecting the dam at the level of the lower gates, the upper end will rise



to an altitude of 950 feet at river-mile 308. Uplake from this position it is assumed that the subaqueous profile will have the same slope as the upper part of the 1940 subaqueous profile relative to the position of the delta front. It is assumed, also, that the average slope of the subaerial part of the delta (topset beds) east of the delta front will remain at 1.2 feet per mile as in 1948 and that the water level in the reservoir will be maintained approximately at the altitude of the permanent spillway crest.

Based on these assumptions, the delta front at this stage of reservoir filling will have progressed to the mouth of Iceberg Canyon at river-mile 290, about 12 miles downlake from its position in Pierce Basin in 1948. The sediment accumulated in the reservoir at this stage will have a total volume of 8,400,000 acre-feet which will be comprised of 3,000,000 acre-feet of sand and 5,400,000 acre-feet of silt and clay.

The sand fraction will be deposited, of course, as topset and foreset beds east of the delta front. Of the total volume of sand, 1,400,000 acre-feet will be deposited below an altitude of 1,205 feet, and 1,600,000 acre-feet will be deposited above this altitude. Assuming that the topset beds will maintain their present slope of 1.2 feet per mile, the 1948 delta surface in Pierce Basin and the

Lower Granite Gorge would be buried by approximately 49 feet of additional material, of which 35 feet would result from increasing the water level in the reservoir from 1,170 feet to 1,205 feet, and the remainder (14 feet) would result from upbuilding of the topset beds at a rate of 1.2 feet for each mile of advance of the delta front. The topset beds at this stage would extend about 6 miles upstream from Bridge Canyon rapids where they would rise to a maximum altitude of 1,280 feet, or 75 feet above the altitude of the permanent spillway crest.

Of the 5,400,000 acre-feet of silt and clay, 500,000 acre-feet will underlie the accumulation of sand east of the delta front. This part of the silt and clay fraction comprises the bottomset beds in the area over which the delta front will have progressed at this stage in reservoir filling. The remaining 4,900,000 acre-feet of silt and clay will make up the bottomset beds extending from the foot of the delta front to Hoover Dam.

At a mean specific weight of 93.6 pounds per cubic foot, the sand will have a total weight of 6.1 billion tons. Further calculations, based on the method outlined in the discussion of the half-way point, show that the silt and clay will have a mean specific weight of 62.6 pounds per cubic foot and a total weight of 7.4 billion tons. The

entire accumulation will have a mean specific weight of 73.6 pounds per cubic foot and a total weight of 13.5 billion tons.

In summary, the sediment level at the intake towers will have reached the altitude of the lower gates when the total accumulation becomes about 7 times as great as the amount brought into the lake from 1935 to 1948. At that time the reservoir east of Gregg Basin will be completely filled with sediment, but abundant storage space will still be available in the western part of the reservoir. The water-storage capacity below the permanent spillway crest will be about 22,000,000 acre-feet, comprising 6,300,000 acre-feet in Boulder Basin, 800,000 acre-feet in Boulder Canyon, 8,000,000 acre-feet in Virgin Basin, 3,300,000 acre-feet in Overton Arm, 2,000,000 acre-feet in the Temple Bar area, 300,000 acre-feet in Virgin Canyon, and 1,300,000 acre-feet in Gregg Basin. By raising the spillway gates, the total storage can be increased to about 24,100,000 acre-feet.

#### Terminal Slope and Residual Storage

In the foregoing discussion of the various stages of reservoir filling it has been assumed that all of the sediment transported into Lake Mead will be deposited in the lake and that none will be discharged through the intake gates or spillway tunnels of Hoover Dam. If the intake gates are used for discharging sediment through the dam, however, it seems likely that the reservoir will never

become entirely filled with sediment but will eventually reach a terminal stage when all the sediment transported into the lake will be discharged through the intake gates and spillway tunnels of Hoover Dam. At this stage the reservoir will be almost completely filled with sediment. There will remain, however, a very small space still available for water storage. This space is referred to in this paper as residual storage, and the slope of the sediment surface underlying the residual storage space is referred to as the terminal slope.

As estimated previously, the sediment surface at the dam will rise to the level of the lower gates when the accumulation becomes about 7 times as great as in 1948. Even before this time, however, turbidity currents carrying an appreciable quantity of suspended sediment may be expected to override intermittently the sill of the lower gates. Use of these gates may then be abandoned so as to avoid passing great quantities of suspended sediment to the small reservoirs (Lake Mohave and Havasu Lake) downstream from Hoover Dam unless some method is developed for passing sediment through them also.

Although use of the lower gates may be abandoned at this time, the upper gates will still be capable of discharging clear water until they too begin to be engulfed in



sediment. According to a previous estimate, this stage will be reached when the reservoir becomes approximately half-filled with sediment, or when the total accumulation becomes approximately 13 times as great as in 1948. At that time the delta front will be near the eastern end of Virgin Basin, about 37 miles uplake from the dam, and the sediment surface at the dam will be only a few feet below the sill of the upper gates.

Probably some sediment will have to be passed through the upper gates before this stage is reached, but the following considerations indicate that the quantity will be small. As noted earlier, the suspended sediment entering the lake during most of the year travels downlake along the bottom of the reservoir. In consequence, the upper water strata are generally clear and uncontaminated by suspended sediment. However, when the Colorado River is in flood (usually from late April to early July), the turbid water spreads out over the lake surface and travels for a considerable distance downlake. In May 1948 the western limit of the turbid surface flow was detected in the center of Virgin Basin about 48 miles west of the river entrance. Thus we may expect that some suspended sediment will be discharged during late spring and early summer through the upper outlet gates prior to the half-way point in reservoir

filling when the distance between the dam and the Colorado River entrance will be reduced to only 37 miles.

Measurements during the high spring inflow of 1948 show that the average suspended sediment concentration in the upper lake layers at a distance of more than 20 miles from the river entrance was only about 0.003 percent. Using this value for the suspended sediment concentration and assuming the water discharged through the upper gates will average 30,000 cfs during this period of high spring inflow (3 months are used in these computations), a total of 580,000 tons of sediment will be discharged annually through the upper gates. This is only 0.4 percent of the average annual weight of sediment accumulated in Lake Mead from 1935 to 1948. It may be concluded, therefore, that the sediment discharged through the upper outlet gates will initially be in small quantities and limited to the period of spring floods. However, as the sediment surface approaches the upper gates at the half-way stage in reservoir filling, some of the turbidity currents flowing along the bottom of the reservoir will overtop them and result in the passage of progressively larger quantities of sediment through the dam.

At this time consideration and evaluation of a number of factors will be required by those responsible for

operation of Lake Mead and the control of the Colorado River. As mentioned in the discussion of the lower gates, the passage of large amounts of sediment through the dam will destroy the usefulness of downstream reservoirs, unless some provision is made for passing sediment through them. On the other hand, if the upper gates are abandoned and the reservoir allowed to become entirely filled with sediment, all the sediment carried into the lake will then be discharged downstream through the spillway tunnels. This, of course, will also result in the filling of downstream reservoirs, but at a somewhat later date.

Still another factor must be considered. If the upper gates are permanently closed to avoid discharging large quantities of sediment downstream, the power output of Hoover Dam will be suddenly and totally curtailed. On the other hand, if the upper gates are used for discharging sediment, Hoover Dam can continue indefinitely a large proportion of its average annual output of electrical energy.

The question as to whether the dam could pass large quantities of sediment requires consideration of a number of factors, the most important of which appear to be the following:

1. The maximum water discharge capacity of the upper outlet gates when the lake surface is at an

altitude of 1,205.4 feet.

2. The maximum sediment particle size that can be physically passed by the power-plant turbines.
3. The abrasive effects of sedimentary debris on the power-plant turbines and appurtenant structures.

Messrs. Vetter and Stanley (personal communication), of the U. S. Bureau of Reclamation Office of River Control at Boulder City, Nevada, give their evaluation of these factors:

The maximum discharge which could be passed through the upper gates by power units now operating or under installation and outlet needle valves, with a forebay level of 1,205.4 feet, is approximately as follows:

|                                          |             |
|------------------------------------------|-------------|
| Through power units                      | 33,500 cfs  |
| Through 12 lower tunnel<br>needle valves | 41,200 cfs  |
| Through 11 canyon wall<br>needle valves  | 41,800 cfs  |
|                                          | <hr/>       |
| Total                                    | 116,500 cfs |

In view of the outlet capacity listed above, it is apparent that all the flood inflow, except during short peaks of extreme floods, could physically be passed without use of the spillways.

The present sediment inflow to Lake Mead could be passed through the power-plant turbines, although some increase in turbine wear would result and more frequent repairs would be necessary. Gravel, of course, would cause excessive wear, but particles of the size now entering the lake could be passed, if necessary.



On the basis of this competent appraisal there seems to be no question that most of the sediment and water delivered to Lake Mead could be passed through the upper gates by the power-plant turbines and outlet needle valves. Only during short peaks of extreme floods would use of the spillways be required.

If sediment is intentionally and regularly passed through the upper gates, it is of interest to speculate briefly on the possible course of sedimentation as the reservoir passes into its terminal stage, the stage when all of the sediment transported into Lake Mead will be discharged through Hoover Dam. Even before the level of the sediment surface at the intake towers reaches the sill of the upper gates, it seems probable that a considerable quantity of fine silt and clay transported by turbidity currents along the bottom of the reservoir will be discharged through the dam.

The coarser particles, principally sand, will continue presumably to accumulate in the topset and foreset beds, and part of the silt and clay will accumulate in the upper reaches of the bottomset beds. In this way, the delta front will continue its advance down the lake, but at a diminishing rate owing to the passage of progressively larger quantities of sediment through the upper gates.

The amount of sediment discharged through the upper gates must necessarily increase because of the reduced distance between the river entrance and the dam and because of the downlake displacement of the steeper parts of the delta profile. The lower, flatter part of the delta profile, which resulted chiefly from the basining effect of Hoover Dam, will increase in declivity, approaching the slope of a delta built into a lake of "infinite extent". These factors will result, of course, in a steeper average slope of the subaqueous delta surface, which will increase the velocity and sediment transporting power of turbidity currents moving along the bottom of the reservoir. In other words, the sediment that formerly accumulated on the flatter part of the delta surface will be discharged through the upper gates.

As the steeper portions of the delta are displaced toward the dam, the average slope of the subaqueous delta surface will become progressively greater. Eventually, an average slope will be attained that is great enough to provide a sufficient velocity for the transportation through the upper outlet gates of all the sediment delivered to Lake Mead. This slope is referred to as the terminal slope.

Owing to the lack of quantitative data and to an incomplete understanding of the interrelations of factors

governing transportation of sediment through reservoirs, it is possible to predict the nature of the terminal slope only in a very general way. It seems reasonable to assume that the terminal slope will not be less than 55 feet per mile, which was the average slope of the Colorado delta front in 1948 (measured along the axis of the valley traversing the foreset beds). That slope in 1948 was apparently in equilibrium with the bottom velocities then prevailing in its vicinity. As the reservoir nears its terminal stage, however, the velocity at the bottom may be expected to increase appreciably. Part of this increase will result from the limited capacity of the reservoir at its terminal stage, which during times of flood at least, will require a considerable increase in the discharge of water through the upper gates. A further increase in the bottom velocity may be expected in the narrow constriction of Black Canyon upstream from Hoover Dam. Presumably, this increase in velocity will provide a terminal slope somewhat steeper than the declivity of the Colorado delta front in 1948, but there is no reasonable basis for estimating with any precision the amount of steepening to be expected. Consequently, it is assumed that the terminal slope will be the same as the average declivity (55 feet per mile) of the delta front in 1948.

If the lake is maintained at the level of the permanent spillway crest (1,205.4 feet altitude), the terminal slope will intersect the upper gates at the intake towers when the Colorado River entrance is only about 3 miles uplake from Hoover Dam. Since it is assumed that all the sediment entering the reservoir in its terminal stage will be discharged through the dam, a small space will still be permanently available for water storage. This space, as previously mentioned, is referred to as residual storage.

In order to obtain an estimate of the residual storage capacity, the terminal slope assumed above was used as a basis for constructing a hypothetical topographic map of the reservoir floor at its terminal stage. As shown in figure 53, a contour interval of 10 feet was used. The areas enclosed by the contours were measured by planimeter, and the volumes between adjacent contour surfaces were computed. According to these computations, the reservoir at its terminal stage will have a residual storage capacity of 64,700 acre-feet, or only 0.22 percent of the initial storage capacity (28,794,000 acre-feet) of Lake Mead at the altitude of the permanent spillway crest (1,205.4 feet). Expressed in other terms, the reservoir in its terminal stage will hold only 0.43 percent of the average annual inflow (13,000,000 acre-feet) to Lake Mead during the



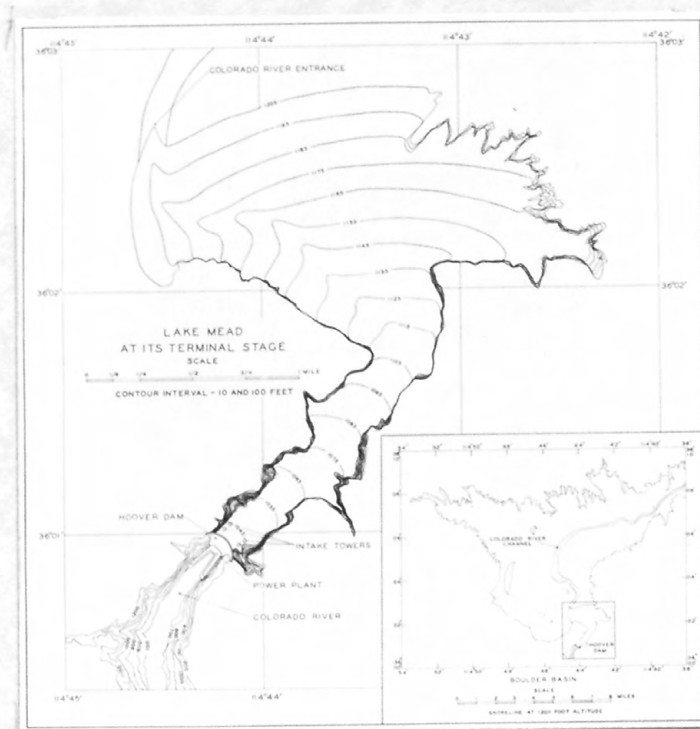


FIGURE 53

DIAGRAMMATIC MAP SHOWING THE BOTTOM TOPOGRAPHY OF  
LAKE MEAD AT ITS TERMINAL STAGE

The relation of the lake at its terminal stage to the  
Boulder Basin appears in the inset.

14-year period, 1935-1948.

During December, January, and February, when the flow into the lake averages less than 7,000 cfs the reservoir will be capable of storing the total quantity of water discharged during a period of about 6 days. In May and June, however, when the flow averages about 50,000 cfs, the holdover storage will be reduced to the total quantity of water flowing into the reservoir in only 16 hours. During this period and especially at times of peak discharge, when the flow sometimes exceeds 100,000 cfs, the spillway gates may be raised to provide some regulation of the river flow. At the terminal stage these gates can increase the water-storage capacity by about 250,000 acre-feet, which can be used for some measure of flood control, but will be inadequate for seasonal regulation for downstream users. Hoover Dam will still be capable of producing large quantities of electrical energy.

Lest this section become too distressing for the reader, it should be pointed out that these last days of Lake Mead are far in the future -- beyond the life span of anyone now living, or even of anyone born during the next century. The estimation of the time required to reach these end stages is reserved for the next section, but here it may be concluded that in order to complete its life

cycle, Lake Mead must acquire about 37 times as much sediment as it received during the first 11 years of its existence.

#### Life of the Reservoir

In the preceding section, the three critical stages of reservoir filling have been discussed in terms of weight of the accumulated sediment. Assuming that no sediment will be discharged through the dam, it has been estimated (p. 285) that the sediment surface at the intake towers will reach the lower gates (895 feet altitude) when the total sediment accumulation reaches 13.5 billion tons and that the sediment surface will approach the upper gates (1,045 feet altitude) at the half-way point when the accumulation totals 36.6 billion tons. The weight of the total accumulation when the sediment surface reaches the permanent spillway crest (1,205 feet altitude) is estimated at 74.7 billion tons. The time required to reach these stages depends not only upon the weight of sediment but also upon the rate of sedimentation and on other natural and developmental factors which are discussed below.

#### Rate of Sedimentation, 1935-48

Based on the 2.014 billion tons of sediment that have accumulated in Lake Mead from 1935 to 1948, the average annual rate of sedimentation has been estimated (p. 284)

at 144 million tons. This value is in close accord with an estimate for the same period based on stream gaging measurements at the Grand Canyon station (p. 245).

If we could assume that this rate of sedimentation would remain the same in the future, we could conclude that approximately 520 years would be required for the reservoir to become completely filled and that the sediment surface at the intake towers would rise to the lower gates in about 95 years and to the upper gates in 255 years.

It is clear, however, from a study of historical sediment and water discharge records in the drainage basin tributary to Lake Mead and from records (Schulman, 1945) of long-period climatic changes in this region that the average annual rate of sedimentation from 1935 to 1948 has probably been less than that which may be expected during the remaining life of the reservoir. Obviously, any change in the rate of sedimentation will result in a corresponding change in the estimated life of Lake Mead.

#### Rate of Sedimentation, 1926-43, Based on Suspended Sediment Records at the Grand Canyon Station

Computations based on Hosard's (1947) and Thomas' (1952) estimates show that average annual load of suspended sediment passing the Grand Canyon station in the 23-year period, 1926-43, was 175 million tons or about 23 percent



greater than the mean annual load (11.2 million tons) during the 14-year interval, 1935-48. Since the mean annual load of sediment passing the Grand Canyon station during this 14-year period agrees favorably with the estimated average annual rate of sedimentation (11.4 million tons) in Lake Mead, it seems a reasonable assumption that this value of 175 million tons would also correspond very closely to the average annual load of sediment reaching the Lake Mead area during the 23-year period, 1926-48.

Rate of Sedimentation, 1911-48, Based on  
Suspended Sediment Records at Yuma, Arizona

Further qualitative knowledge of the amount of sediment removed from the drainage basin tributary to Lake Mead during a longer period may be obtained from suspended sediment records (U. S. Bureau of Reclamation, unpublished data) taken continuously at Yuma, Arizona, since 1911. The Yuma records from 1935 to 1948, of course, cannot be used since most of the sediment carried by the Colorado River during this period has been deposited in Lake Mead. The Yuma records prior to the closure of Hoover Dam indicate, however, that the mean annual suspended load passing Yuma between 1911 and 1925 was about 38 percent greater than in the period, 1926-34. The total quantity of suspended sediment discharged at Yuma during any given year has always

been smaller than that which passes the Grand Canyon station: the annual sediment load recorded at Yuma between 1925 and 1934 varied from 36 to 78 percent of the annual suspended load recorded at the Grand Canyon station. Nevertheless, the sediment records at the two stations show the same general trend. Both high and low values at the Grand Canyon station are reflected by corresponding high and low values at Yuma, but there is no constant relation between the total quantity of sediment discharged at the two stations during any given year.

Even though the records are not directly comparable, the high sediment loads recorded at Yuma from 1911 to 1925 suggest a greater rate of sediment movement by the Colorado River in those years than in the period, 1926-48. Computations based on these records indicate that the rate of sediment transport into the Lake Mead area during the 38-year interval, 1911-48, may possibly have been of the order of 230 million tons, about 60 percent greater than the average annual flow of sediment into Lake Mead from 1935 to 1948.

#### Rate of Sedimentation, 1897-1948, Based on

#### Water and Sediment Records at the Grand Canyon Station

A further estimate of the average annual load of suspended sediment removed from the tributary drainage basin

for a longer historical period may be obtained from a comparison of the annual runoff and the annual suspended load carried by the Colorado River past the Grand Canyon station. In figure 54 the suspended sediment load is plotted against the total runoff at the Grand Canyon station for each year from 1926 to 1947. The visual best-fit curve drawn through these points provides a reasonable basis for estimating the average annual suspended load at the Grand Canyon station if the average annual runoff is known.

From records of the U. S. Geological Survey and the U. S. Bureau of Reclamation (1946, p. 281) the mean annual water discharge at the Grand Canyon station from 1897 to 1943 is estimated at 14,600,000 acre-feet. Referring to figure 54 this suggests that the average annual suspended load passing the Grand Canyon station during this period has been approximately 200 million tons. If we assume that the mean annual sediment load at the Grand Canyon station is about the same as the average rate of sedimentation in Lake Mead (as shown by the 1948 survey), we find that the estimated average yearly rate of sedimentation during the 52-year period, 1897-1943, is about 39 percent greater than the 14-year average (144 million tons) from 1935 to 1948.

Rate of Sedimentation, 1298-1945, Based on  
Tree-Ring Studies in the Tributary Drainage Basin

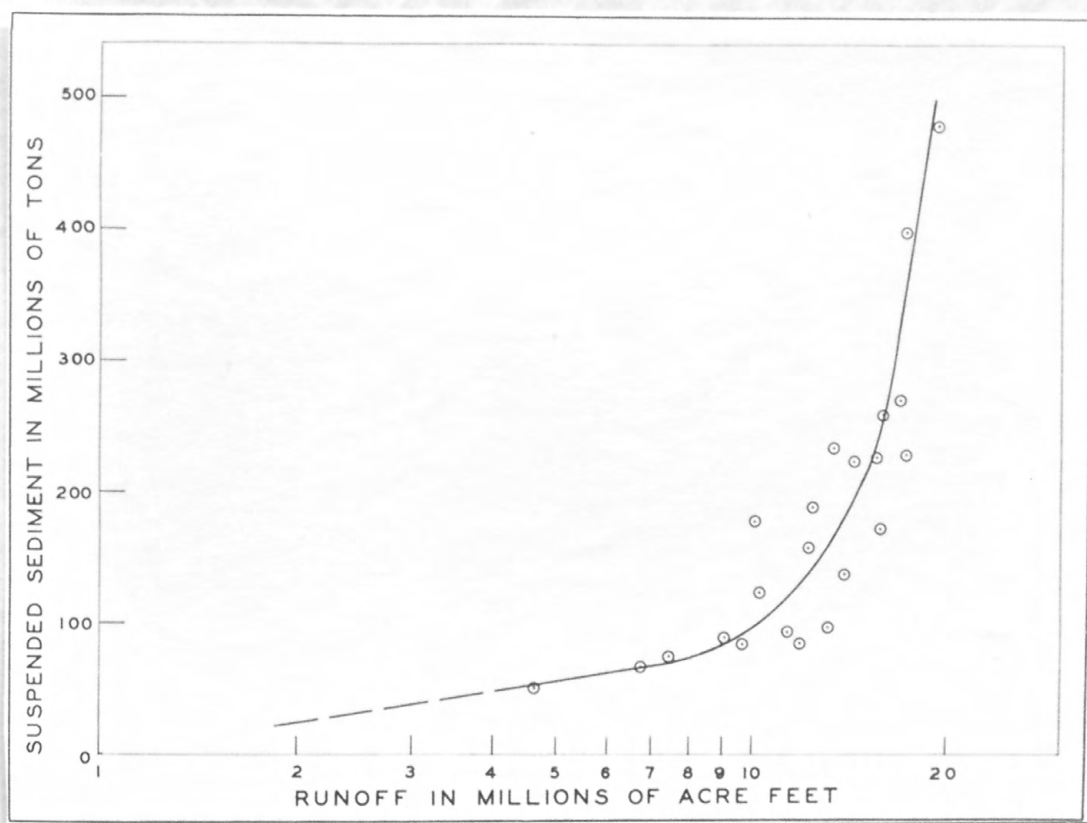


FIGURE 54

RELATION BETWEEN ANNUAL RUNOFF AND SUSPENDED SEDIMENT AT  
THE GRAND CANYON GAGING STATION FROM 1926 TO 1947  
Water and sediment values are for the water year begin-  
ning October 1 and ending September 30.



Using Schulman's (1945) results from tree-ring investigations in the tributary basin we can obtain an independent estimate of the average rate of sediment transport into the Lake Mead area during the past several hundred years. According to Schulman, there is general agreement between rainfall, runoff, and tree growth in the basin during the period for which rainfall and runoff data are available. By tree-ring dating methods he has concluded that the growth index of the Douglas fir during the interval, 1887-1945, has varied considerably from the mean for the 658-year period, 1288-1945. He reports that the growth index in 1887-1905 was 18.1 percent less than the 658-year average, whereas during the interval, 1906-30, it was 16.1 percent above the long-term average. From 1931 to 1940 the growth index was 19.7 percent below the average, but was near normal during the interval, 1941-45. Since there is correspondence between the tree-growth index and runoff in the 50 years of contemporaneous records, we can conclude that the runoff in the past several centuries has also probably experienced the same general fluctuations as the tree-growth.

Extrapolation of these results, together with available runoff records, suggests that the average annual virgin stream flow (undepleted by artificial diversion for

irrigation and commercial uses) at the Grand Canyon station during the past 658 years has been about 15,800,000 acre-feet. Owing to present-day irrigation development and exportation of water from the basin, the average virgin stream flow is reduced by approximately 2,300,000 acre-feet annually (U. S. Bureau of Reclamation, 1946). It is estimated, therefore, that the long-period average annual discharge at the Grand Canyon station (as modified by present-day runoff depletion) is about 13,500,000 acre-feet, or 1,100,000 acre-feet less than the average annual discharge (14,600,000 acre-feet) between 1897 and 1942. Referring again to figure 54, we find that the estimated long-period mean annual sediment load passing the Grand Canyon station is about 165 million tons. If we assume that this value represents the approximate yearly rate of sediment transport into the Lake Mead area for the past 658 years, we find that the long-period average annual rate of sedimentation is about 15 percent greater than that estimated for the 14-year period, 1935-48.

#### Estimates of Life Expectancy Based on Sedimentation Rates

One of the most illuminating features of the preceding estimates of annual sedimentation rates is their great variability, ranging from 144 million tons for the

14-year period, 1935-48, to 230 million tons for the 38-year interval, 1911-48. On hasty inspection it might be concluded that the 163 million ton estimate for the 658-year interval, 1288-1945, would be the most reliable for future predictions because it covers the longest period. However, even this appears to be hazardous because it assumes that the climatic conditions of the past 6½ centuries will apply generally to a comparable period in the future. Little is known about the irregularities of long-term climatic periods measured in centuries, but it seems almost certain they are no more uniform than short climatic periods measured in years or decades.

Figure 55, based on the various estimated rates of sedimentation discussed in the preceding pages, shows the time in years that will be required for the sediment accumulation to reach the three critical stages of reservoir filling. Based on the minimum average annual sedimentation rate (144 million tons), the sediment surface at the intake towers will intersect the lower gates (895 feet altitude) in about the year 2030 A.D., 95 years from the time that Hoover Dam was closed in 1935. The half-way point in reservoir filling when the sediment at the intake towers approaches the upper gates (1,045 feet altitude) will be reached in 2190 A.D., and complete filling will occur in

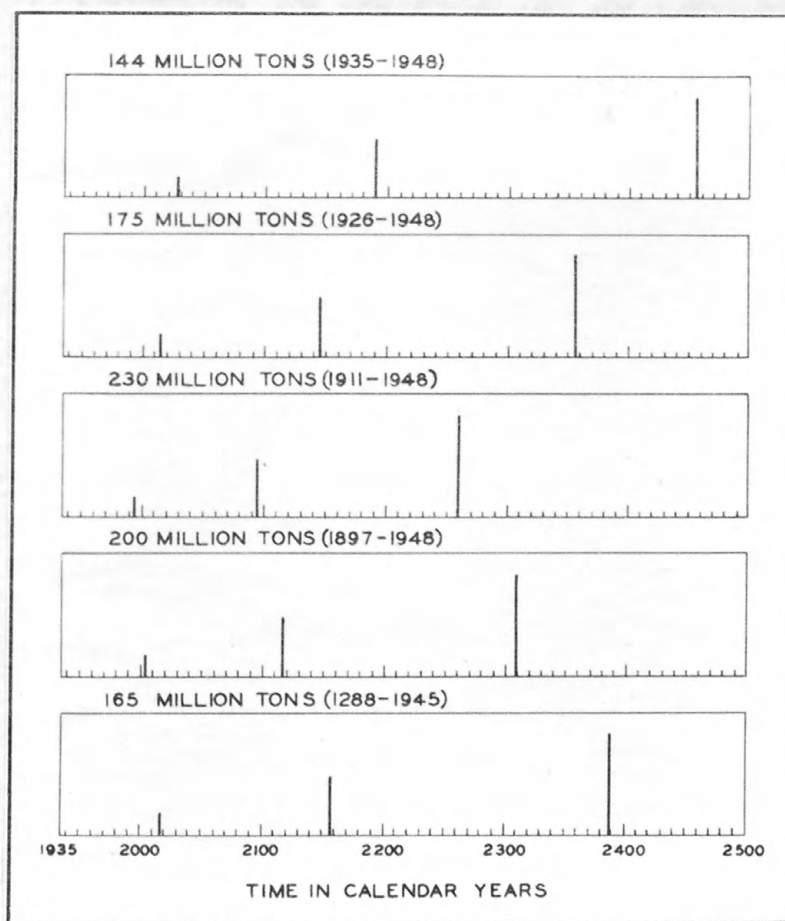


FIGURE 55

GRAPH SUMMARIZING THE SEVERAL ESTIMATES OF TIME WHEN THE SEDIMENT SURFACE AT HOOVER DAM WILL REACH THE LOWER INTAKE GATES (895 FEET ALTITUDE), THE UPPER INTAKE GATES (1,045 FEET ALTITUDE), AND THE PERMANENT SPILLWAY CREST (1,205 FEET ALTITUDE)

The estimated rate of sedimentation used in each determination appears above the diagram to which it applies. The heights of the vertical lines are proportional to the altitudes of the intake gates and spillway crest which they represent.



2455 A.D., 520 years after the closure of Hoover Dam. Using the maximum estimated annual rate of sedimentation (230 million tons), the three critical stages in reservoir filling, listed in the same order as above, will be reached in 1995 A.D., 2045 A.D., and 2260 A.D. Calculations based on the three other estimated rates of sedimentation give values intermediate between these two extremes (fig. 35).

#### Modification by Future Natural and Developmental Factors

In the preceding discussion of the life of Lake Mead, it has been assumed that all of the sediment carried into the lake would be deposited there and that none would be discharged through the dam. However, if sediment is regularly and intentionally passed to downstream areas, as discussed on pp. 288-296, the life of Lake Mead will be greatly increased, perhaps by several centuries. In fact, according to the concept of terminal slope and residual storage pp. 285-297, it seems unlikely that the reservoir will ever become completely filled with sediment. The reservoir at this stage will be relatively ineffective, of course, as a regulatory body, but Hoover Dam will still be capable of producing large quantities of electrical energy.

It has been further assumed in the discussion of the life of Lake Mead that no significant regulatory storage

will be in operation in upstream areas. However, it seems almost certain that Glen Canyon and other large regulatory reservoirs will be constructed long before Lake Mead reaches its terminal stage or even before the usefulness of Lake Mead in controlling the flow of the Colorado River begins to be materially impaired.

In its plans for the development of the tributary drainage basin, the U. S. Bureau of Reclamation (1946) has numerous reservoirs and dam sites under consideration. With the construction of any one of these, the life of Lake Mead will be increased because all future reservoirs upstream would have to be filled with sediment prior to the filling of Lake Mead. It seems probable, therefore, that a great part of the water-storage capacity will be available for many centuries longer than the estimates shown in Figure 55 which are based on the assumption that no future regulatory storage would be in operation upstream.

#### RATE OF EROSION FROM THE TRIBUTARY DRAINAGE BASIN

The quantitative measurements of the sediment accumulated in Lake Mead provide a basis for estimating with considerable accuracy the average rate of erosion from the tributary drainage basin during the 14-year period, 1935-1948. Most of the weathering products are carried from the basin in the detrital load of the Colorado River and its tributaries, and since the closure of Hoover Dam in 1935, this material has accumulated in Lake Mead. The 2 billion tons of sediment deposited in Lake Mead from 1935 to 1948 is, therefore, a measure of the total amount of stream-transported detritus removed from the tributary drainage basin during this period.

According to Howard (unpublished data), 134,200,000 tons of dissolved solids were carried in the Colorado River as it passed through Grand Canyon from February 1935 to September 1948. Considering the amounts carried by the Virgin River, Muddy Creek, and other minor tributaries, the total dissolved load brought into Lake Mead during the 14-year period, 1935-1948, is probably of the order of 160,000,000 tons. The total weight of material carried from the tributary drainage basin in solution and as stream-transported detritus during this interval is estimated, therefore, at about 2.16 billion tons. No data are

available on the amount of material removed by wind action, but it seems probable that the sediment transported in this fashion is negligible compared to the amount of material removed by other agencies.

Using the above value for the total weight of material removed and a value of 2.67 for the specific gravity of the mineral particles, we can obtain a reasonable estimate of the average rate of erosion from the basin from 1935 to 1948.

The rate of erosion may be expressed either in terms of soil or in terms of unweathered rock. According to Lutz and Chandler (1946, p. 250) the mean porosity of average soils is about 50 percent. The average porosity of all types of unweathered rock in the basin, however, is very difficult to estimate. Average shale, for example, has a porosity of about 13 percent (Pettijohn, 1949, p. 277), but the unconsolidated and semiconsolidated sediments which are widely distributed in the basin probably have porosities ranging to more than 35 percent. Even crystalline rocks have an appreciable porosity due to joints and other fractures. Solution cavities in limestones, and gas vesicles in basalt and other lava flows give a considerable porosity to these types of rocks. For this estimate an arbitrary assignment of 15 percent for the mean porosity of



unweathered rock in the basin is probably not unreasonable.

Assuming an average soil porosity of 50 percent, calculations indicate that a layer of soil with an average thickness of 0.133 inch has been removed from the 168,000 square miles of the tributary drainage basin during the 14-year interval, 1935-1948. If this rate of erosion were to continue in the future, a layer of soil with an average thickness of 1 foot would be removed every 1,260 years. Expressed in terms of unweathered rock with an estimated porosity of 15 percent, we find that the tributary drainage basin has been reduced in altitude by an average of about 0.078 inch from 1935 to 1948. At this rate, the average lowering of the basin by erosion would be approximately 1 foot every 2,150 years.

The 74 billion tons of sediment required to fill the reservoir completely would represent the erosion products from a soil layer averaging 4.9 inches thick over the entire tributary basin. However, we may be sure that the rate of erosion will be far from uniform over the basin. Judging by the history of the past century, we may expect that between now and the date when the reservoir is full of sediment, the erosion in some parts of the basin will be negligible, and in others will be measured in tens of feet.

Records of suspended sediment in streams indicate

these inequalities in sediment production and therefore in the rates of erosion in various parts of the basin (Thomas, 1952). The network of sediment-gaging stations is enough to indicate that the drainage basin tributary to Lake Mead (figure 1) could be divided approximately into halves, consisting of (1) headwater areas in Colorado, Wyoming and northern Utah, which commonly contribute more than three-fourths of the water but less than one-fourth of the sediment to Lake Mead; and (2) arid areas in New Mexico, Nevada, Arizona, and southern Utah which produce less than one-fourth of the water but most of the sediment carried into the lake. Assuming a similar contrast in sediment production in the future, the filling of Lake Mead would be accomplished by erosion averaging nearly 8 inches in the arid areas but only slightly more than 2 inches in the headwater half of the drainage basin.

## RELATION TO STREAM PROCESSES IN THE LOWER COLORADO RIVER

The closure of Hoover Dam in 1935 has produced widespread changes in the regimen of the lower Colorado River. The tremendous load of detritus that was formerly carried from the Upper Colorado River Basin to the Colorado delta at the head of the Gulf of California, has since accumulated in Lake Mead. Likewise, the seasonal floods resulting from the melting of snow or from short periods of intense rainfall in the Upper Colorado River Basin have been eliminated from the lower Colorado River.

In response to these changes, the lower Colorado River since 1935 has been undergoing a new stage in its development. Owing to the loss of sediment in Lake Mead, the water discharged from Hoover Dam has an increased capacity for recharging its detrital load, and this capacity is satisfied by scouring of the channel downstream from the dam. According to Stanley (1950, p. 10), the suspended sediment load passing Yuma, Arizona during the first 3 years (1935-38) after the closure of Hoover Dam was almost equal to that carried at any given discharge prior to 1935. However, owing to the control of the river by Hoover Dam, the average discharge during this period was a great deal lower than in previous years when the river was flowing in

its natural state. As a result, the average annual suspended load passing Yuma (U. S. Bureau of Reclamation, unpublished data) from 1935-38 was only about 9 percent of the average annual load before the closure of Hoover Dam. This material was not derived, however, from the Upper Colorado River Basin as in previous years, but rather from scour of the channel between Hoover Dam and Yuma, Arizona.

With the construction of Parker Dam and Imperial Dam (see fig. 1) in 1938, the channel has been eroded in some sections and aggraded in others. As reported by Stanley (1950), the bed of the Colorado River in the 26-mile section below Hoover Dam was lowered from 5 to 11 feet between 1935 and 1946, and its gradient was increased from 1.7 to about 2.0 feet per mile. Since 1938 this material has accumulated in Havasu Lake behind Parker Dam and in the channel between Havasu Lake and Needles, California.

Erosion of similar magnitude has also taken place downstream from Parker Dam and Imperial Dam. Below Parker Dam the channel has been scoured for a distance of about 100 miles, and downstream from Imperial Dam, scouring action has extended several miles below the International Boundary. The sediment removed from the river bed south of Parker Dam has accumulated in the 55-mile section of the channel upstream from Imperial Dam, whereas the sediment



arced below Imperial Dam has been carried into the lower reaches of the Colorado delta. The accumulation of sediment behind the dams downstream from Hoover Dam has greatly reduced the rate of sedimentation in the Colorado delta in recent years. Judging from the suspended load passing Tuma (U. S. Bureau of Reclamation, unpublished data), the average annual supply of sediment to the Colorado delta from 1942 to 1948 was only 31 percent of that carried into the delta from 1935 to 1941 and less than 3 percent of the average annual load prior to the closure of Hoover Dam in 1935.

There has been considerable speculation as to the possible effect of this reduced rate of sedimentation on the development of the Colorado delta. Sykes (1937, p. 174) has predicted that the growth of the delta as a major phenomenon would be terminated, whereas others have suggested that compaction, subsidence, and erosion would cause a general lowering of the delta surface. No published account of the changes in the Colorado delta is yet available, but according to J. F. Frieckin (personal communication) of the International Boundary and Water Commission at San Diego, California, there is no evidence of any appreciable change in delta characteristics since the closure of Hoover Dam.

## SUMMARY AND CONCLUSIONS

Lake Mead, created in 1935 by the construction of Hoover Dam on the Colorado River, is the site of deposition of most of the sediment that formerly accumulated in the Colorado delta at the head of the Gulf of California. During the 14 year period, 1935-48, approximately 1,426,000 acre-feet, or almost one-half cubic mile of sediment has accumulated in Lake Mead. This has reduced the total water-storage capacity below the altitude of the permanent spillway crest by about 5 percent.

With the exception of minor amounts of material contributed by local slumping of reservoir walls, practically all of the sediment has been supplied by the Colorado and Virgin Rivers. This material forms two deltas, one built by the Colorado River, and the other, much smaller, built by the Virgin River. The Colorado delta extends the entire length of the lake, a distance of 120 miles measured along the submerged course of the Colorado River, whereas the Virgin delta is restricted chiefly to the upper 14 miles of the inundated Virgin River valley (Overton Arm of Lake Mead). These deltas do not spread out over the vast reaches of the lake bottom, but are confined, rather, to the deep submerged channels of the Colorado and Virgin Rivers and

to their associated floodplains and terraces. As a result, they are long, narrow, and sinuous, in marked contrast to the broad fan or delta-shape characteristic of most deltas. Of the total volume of sediment, more than 97 percent is in the Colorado delta, whereas less than 3 percent is in the Virgin delta.

In structure, the Lake Mead deltas are similar to those formed in other lakes, being composed of topset, foreset, and bottomset beds and of particles which grade from coarse to fine with increasing distance from the river mouths. The topset and foreset beds are made up principally of sand, dropped near the entrances of the rivers into the quiet lake water. In contrast, the bottomset beds are made up of silt and clay carried into the lake by turbidity currents.

During the 14-year period, 1935-48, the topset and foreset beds of the Colorado delta progressed several tens of miles out over the bottomset beds. As a result, the eastern 43 miles of the lake occupying the narrow Lower Granite Gorge of the Grand Canyon has been filled with sediment. The surface of this part of the delta is made up of topset beds over which the Colorado River flows to its entrance in Pierce Basin.

In response to this filling, the Colorado River in

the eastern 43 miles of the Lower Granite Gorge has assumed the characteristics of an older, more mature stream, much in contrast to the vigorous, young stream that formerly flowed in the narrow V-shaped notch at the bottom of the gorge. The channel in 1943, as compared with the former channel at the bottom of the gorge, has been reduced in slope from an average of 7.0 feet per mile to only 1.2 feet per mile, and its average width has increased from about 300 feet to more than 600 feet.

Because of extreme fluctuations in river discharge and changes in lake level, the topset beds are being re-worked 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 fall and winter, however, when the lake level is falling, the river cuts down through the deposit in order to maintain its gradient to the subsiding lake level, and topset beds become deeply dissected. As a result of these processes, the river is flanked by terraces and natural levees, and beyond the levees are delta-flank depressions and marginal lakes, effectively isolated from the main current in the channel.

Downstream from the river mouth, the foreset beds dip sharply beneath the lake surface for a distance of about 2 miles where they grade into the gently sloping bottomset



beds that extend to Hoover Dam, 75 miles to the west. Unlike the sand of the topset and foreset beds which is deposited directly by the river, the silt and clay of the bottomset beds are deposited by turbidity currents, several of which have traversed the entire length of the lake.

In Lake Mead, three types of turbidity currents are recognized: (1) overflow, (2) interflow, and (3) underflow. Overflow, as the name implies, refers to the flow of turbid river water out over the lake surface. Similarly, interflow refers to the flow of muddy river water at some intermediate depth, and underflow refers to the movement of sediment-laden river water along the bottom of the lake. The type of flow at any given time is dependent on the relative densities of the river water and the lake water.

Of the three types of turbidity currents, underflow is by far the dominant and most important type. From October to April when the incoming water is denser than the lake water, there is a continuous flow of turbid water along the bottom of the lake. During other times of the year when overflows or interflows prevail, an increase in the suspended sediment load of the Colorado River may cause them to be replaced by underflows. From the distribution of sediment in Lake Mead, it is evident that the sediment dropped from overflows and interflows has accumulated in

the area of the submerged Colorado River channel, and it is possible that even this material has moved as an underflow after reaching the channel area. Most underflows do not reach the western part of the lake, but when the incoming water contains a very large amount of suspended sediment, the underflow of turbid water extends the entire length of the lake, depositing sediment continuously along its course. These currents and the inundated Colorado River channel along which they travel account for the exceptional length and extreme narrowness of the Colorado delta.

The bottomset beds in the western part of the lake are essentially level in cross-section, but in the eastern part they are traversed by a broad channel along which turbidity current underflows move. At the borders of the channel are underwater "levees" which rise from 2 to 5 feet above the general sediment level. The "levees", in turn, are flanked by slight depressions near the margins of the delta. The marked resemblance of these features to the natural levees and marginal depressions in the sub-aerial part of the delta suggests that turbidity current underflows conform to the same mechanical principles as stream flow.

The physical and chemical properties of the bottomset beds are markedly different from those of the topset and

foreset beds. An estimate of the average size distribution of particles in the bottomset beds of the Colorado delta reveals that they have a median diameter of less than 2 microns and consist of 67 percent clay (<4 microns), 32 percent silt (4-62 microns), and less than 1 percent sand (>62 microns). In contrast, the particles in the topset and fohset beds are made up principally of sand with an estimated median diameter of about 150 microns. Because of their great amount of interstitial water, the bottomset beds are soft and jelly-like. Only samples from the most deeply buried layers are solid enough so that they do not flow under their own weight. On the other hand, the sand of the topset and fohset beds is hard and firmly packed.

Studies of the mass chemical properties of the Colorado delta reveal that the bottomset beds are made up chiefly of hydrous aluminum silicates and hydroxides of iron and aluminum, whereas the topset beds consist predominantly of detrital fragments of quartz. Likewise, the fohset beds are made up chiefly of quartz, but they are slightly higher in hydrous silicates and hydroxides than the topset beds. With the exception of aluminum and calcium the composition of the topset beds is similar to the average composition of river sands. The sand of the topset beds contains one-fourth the aluminum and about twice the

calcium concentration in the average river sand. Similarly, the composition of the bottomset beds corresponds closely with the average composition of shales. The only notable differences are the higher concentration of calcium and the lower concentration of sodium in the bottomset beds. They contain about twice the calcium and only one-half the sodium concentration in the average shale. The estimated average composition of all the sediment in the Colorado delta corresponds closely with the average composition of samples from the Mississippi delta. The chief differences are the higher concentration of calcium and the lower concentration of sodium in the Colorado delta.

Most of the calcium in the Colorado delta occurs as calcium carbonate. The calcium carbonate content of the bottomset beds averages 16.1 percent, whereas that of the topset and foreset beds averages 4.7 percent. The average calcium carbonate content of the entire Colorado delta, is about 10 percent. Of the total amount of calcium carbonate, 5 percent has been precipitated from the lake water and 95 percent has been carried into the lake in the detrital load of the Colorado River. Most of this material, as shown by its concentration in the bottomset beds, is of silt and clay size.

The organic matter in the Colorado delta is also



concentrated in the bottomset beds. The content of organic material in the bottomset beds averages 0.93 percent whereas that of the topset and foreset beds averages only 0.14 percent. The considerable amount of organic matter in the bottomset beds has given rise to a large bacteria population which approximates that found in raw sewage. As a result of bacterial activity, an appreciable amount of gas (chiefly methane) is being produced from the decomposition of organic matter. Bacterial activity also appears to be chiefly responsible for an anomalous heating of the bottomset beds. However, this contribution to sediment heating cannot be determined quantitatively until all other factors that influence the heat budget have been evaluated.

The total weight of mineral particles deposited in Lake Mead from 1935 to 1948, together with the total weight of dissolved solids (160,000,000 tons) transported into the lake during this interval, provides a rather accurate estimate of the rate of erosion from the drainage basin tributary to Lake Mead. According to this estimate, a layer of soil with an assumed porosity of 50 percent and an average thickness of 0.113 inch has been removed from the basin from 1935 to 1948. If this rate were to continue in the future, a layer of soil with an average thickness of 1 foot would be removed every 1200 years. Expressed in terms

of unweathered rock with an assumed porosity of 15 percent, the entire area (168,000 square miles) of the tributary basin would be lowered by erosion approximately 1 foot every 2150 years. This estimate is based on the assumption that the rate of production of soil and rock mantle by weathering processes is keeping pace with the rate of removal. There is evidence which suggests, however, that the rate of removal may be exceeding the rate of production.

The physical, chemical, and physiographic properties of the Virgin delta have not been studied intensively, but from the limited data available, they appear to be generally similar to those of the Colorado delta. Turbidity currents which have been so essential to the development of the Colorado delta have also played a prominent role in the development of the Virgin delta.

Based on the analyses of 46 cores and more than 300 samples, the total weight of solid mineral matter accumulated in Lake Mead from 1935 to 1948 is estimated at 2,014,400,000 tons. This is equal to an average annual sedimentation rate of 144,000,000 tons or an average daily rate of almost 400,000 tons.

In applying the results of the sediment studies to the problem of reservoir utilization, the probable future pattern of sedimentation has been analyzed in terms of the

following three critical stages of reservoir filling: (1) the rise of the sediment surface at the intake towers to the level (895 feet altitude) of the lower intake gates, (2) the half-way point in reservoir filling when the sediment at the intake towers approaches the upper gates (1,045 feet altitude), and (3) complete filling when the sediment surface at the dam rises to the level (1,205 feet altitude) of the permanent spillway crest. The total weights of sediment that will have accumulated at these stages, listed in the same order as above, are 13.5 billion tons, 36.6 billion tons, and 74.7 billion tons. The time required to reach these various stages depends not only upon the weight of sediment, but upon its rate of supply and other natural and developmental factors. Estimates of the average annual rate of sedimentation, based on the amount of sediment accumulated in Lake Mead from 1935 to 1948, records of stream flow, and historical climatic data, range from 144 million tons to 230 million tons. Estimates of the life of Lake Mead, based on these sedimentation rates range from 325 years to 520 years from the time that Hoover Dam was closed in 1935.

These estimates are based on the assumption that all of the sediment carried into Lake Mead will be deposited there and that none will be discharged through Hoover Dam.

However, if sediment is regularly and intentionally passed to downstream areas, it seems likely that the reservoir will never become completely filled, but will eventually reach a terminal stage when all of the sediment supplied to the lake will be discharged through the dam. The reservoir at this stage will be relatively ineffective as a regulatory body, but Hoover Dam will still be capable of producing large quantities of electrical energy.

It has been further assumed in those estimates of the life of Lake Mead that no significant regulatory storage will be in operation in upstream areas. However, it seems almost certain that other large regulatory reservoirs will be constructed in the tributary drainage basin long before Lake Mead reaches its terminal stage or even before its usefulness as a regulatory body is materially impaired. These reservoirs would have to be filled with sediment prior to the filling of Lake Mead. Hence, it appears that a large part of the water storage capacity of Lake Mead will be available for many centuries longer than the few centuries estimated on the assumption that no regulatory storage would be in operation upstream.



## REFERENCES

- Allison, L. E., 1935, Organic soil carbon by reduction of chromic acid: Soil Sci., vol. 40, no. 4, pp. 311-320.
- Ames, F. C., and Kennon, F. W., New area-capacity tables for Lake Mead: in Final report of the Lake Mead sedimentation survey, U. S. Geol. Survey Prof. Paper (in press).
- Anderson, E. R., and Pritchard, D. W., 1952, Physical limnology of Lake Mead: in Final report of the Lake Mead sedimentation survey, U. S. Geol. Survey Prof. Paper (in preparation).
- Bell, E. S., 1942a, Stratified flow in reservoirs and its use in the prevention of silting: U. S. Dep't. Agr. Misc. Pub. 491, 46 pp..
- \_\_\_\_\_, 1942b, Density currents as agents for transporting sediment: Jour. Geology, vol. 50, pp. 512-547.
- Blaney, H. F., 1936, Discussion of "The silt problem": Am. Soc. Civ. Eng. Trans., vol. 101, p. 266.
- Brown, C. S., 1941, Mapping Lake Mead: Geog. Rev., vol. 31, pp. 385-405.
- Carder, D. S., 1945, Seismic investigations in the Boulder Dam area, 1940-1944, and the influence of reservoir loading on local earthquake activity: Seismol. Soc. America Bull., vol. 35, pp. 175-192.
- \_\_\_\_\_, and Small, J. B., 1948, Level divergencies, seismic activity, and reservoir loading in the Lake Mead area, Nevada and Arizona: Am. Geophys. Union Trans., vol. 29, pp. 767-771.
- Clarke, F. W., 1924, The data of geochemistry: U. S. Geol. Survey Bull. 770, 841 pp..
- Daly, R. A., 1936, Origin of submarine "canyons": Am. Jour. Sci., ser. 5, vol. 31, no. 186, pp. 401-420.
- Dutton, C. W., 1882, Tertiary history of the Grand Canyon District: U. S. Geol. Survey Mon. 2, 262 pp..

## REFERENCES (cont'd)

- Eakin, H. H., 1939, Silting of reservoirs: U. S. Dept. Agr. Tech. Bull. 524, rev. by C. E. Brown, 168 pp..
- Emery, K. O., and Dietz, R. S., 1941, Gravity coring instrument and the mechanics of sediment coring: Geol. Soc. America Bull., vol. 52, pp. 1685-1714.
- \_\_\_\_\_, and Rittenberg, S. C., 1952, Early diagenesis of California basin sediments in relation to origin of oil: Am. Assoc. Petroleum Geologists Bull., vol. 36, pp. 735-806.
- Fenneman, N. M., 1931, Physiography of the western United States, New York, McGraw-Hill, 534 pp..
- Flock, L. H., 1934, Records of silt carried by the Rio Grande River and its accumulation in Elephant Butte Reservoir: Am. Geophys. Union Trans., 15th Ann. Mtg., pt. 2, pp. 455-473.
- Gatwood, J. S., 1945, Floods of September 1939 in Colorado River Basin below Boulder Dam: U. S. Geol. Survey Water-Supply Paper 957A, pp. 1-39.
- Gould, H. R., 1951, Some quantitative aspects of Lake Mead turbidity currents: Soc. Econ. Paleontologists and Mineralogists, Sp. Pub. no. 2, pp. 34-52.
- Grim, E. S., Dietz, R. S., and Bradley, W. F., 1949, Clay mineral composition of some sediments from the Pacific Ocean off the California coast and the Gulf of California: Geol. Soc. America Bull., vol. 60, pp. 1785-1808.
- Grover, H. C., and Howard, C. S., 1938, The passage of turbid water through Lake Mead: Am. Soc. Civ. Eng. Trans., vol. 103, pp. 720-732.
- Happ, S. C., 1946, Discussion of "Future of Lake Mead and Elephant Butte Reservoir": Am. Soc. Civ. Eng. Trans., vol. 111, p. 1298.
- Hedberg, H. S., 1936, Gravitational compaction of plays and shales: Am. Jour. Sci., ser. 5, vol. 31, pp. 241-267.

## REFERENCES (cont'd)

- Howard, C. S., 1947, Suspended sediment in the Colorado River, 1925-41: U. S. Geol. Survey Water-Supply Paper 998, 165 pp..
- \_\_\_\_\_, 1952, Chemical limnology of Lake Mead: in Final report of the Lake Mead sedimentation survey, U. S. Geol. Survey Prof. Paper (in preparation).
- Ives, J. C., 1861, Report upon the Colorado River of the west, pt. I, U. S. Govt. Printing Office, Washington, 131 pp..
- Johnson, D. W., 1939, The origin of submarine canyons, Columbia Univ. Press, New York, 126 pp..
- Jones, A. E., 1944, Earthquake magnitudes, efficiency of stations, and perceptibility of local earthquakes in Lake Mead: Seismol. Soc. America Bull., vol. 34, pp. 161-173.
- Krumbein, W. C., and Pettijohn, F. J., 1938, Manual of sedimentary petrography, New York and London, D. Appleton Century Company, 549 pp..
- Kuenen, Ph. H., and Migliorini, C. I., 1950, Turbidity currents as a cause of graded bedding: Jour. Geology, vol. 58, pp. 91-127.
- Kullenberg, B., 1947, The piston core sampler: Svenska Hydrografisk-Biologiska Kommissionens Skr., Tredje Serien, Hydrografi, Band 2, Häfte 2, 46 pp..
- Lafond, E. C., and Dietz, R. S., 1948, New snapper-type sediment sampler: Jour. Sedimentary Petrology, vol. 18, no. 1, pp. 34-37.
- LaRue, E. C., 1925, Water power and flood control of the Colorado River below Green River, Utah: U. S. Geol. Survey Water-Supply Paper 556, 176 pp..
- Lee, W. T., 1908, Geologic reconnaissance of a part of western Arizona: U. S. Geol. Survey Bull. 352, 96 pp..

## REFERENCES (cont'd)

- Longwell, C. R., 1928, Geology of the Muddy Mountains, Nevada with a section through the Virgin Mountains to the Grand Wash Cliffs, Arizona: U. S. Geol. Survey Bull. 798, 152 pp..
- \_\_\_\_\_, 1936, Geology of the Boulder Reservoir floor, Arizona-Nevada: Geol. Soc. America Bull., vol. 47, pp. 1393-1476.
- Lutz, H. J., and Chandler, R. F., 1946, Forest soils, New York, John Wiley and Sons, 514 pp..
- Mackin, J. H., 1948, Concept of the graded river: Geol. Soc. America Bull., vol. 59, pp. 463-512.
- Maxon, J. H., 1940, Gas pits in non-marine sediments: Jour. Sedimentary Petrology, vol. 10, no. 3, pp. 142-145.
- Mead, T. C., and Carder, D. S., 1941, Seismic investigations in the Boulder Dam area in 1940: Seismol. Soc. America Bull., vol. 31, pp. 321-324.
- Menard, H. W., and Ludwick, J. C., 1951, Applications of hydraulics to the study of marine turbidity currents: Soc. Econ. Paleontologists and Mineralogists, Sp. Pub. no. 2, pp. 2-13.
- Murdock, J. H., 1942, Unpublished reports in the files of the U. S. Bureau of Reclamation.
- Pettijohn, F. J., 1949, Sedimentary rocks, New York, Harper and Brothers, 526 pp..
- Powell, J. W., 1875, Exploration of the Colorado River of the West, U. S. Govt. Printing Office, Washington, 291 pp..
- Ransome, F. L., 1923, Geology of the Boulder Canyon and Black Canyon dam sites on the Colorado River, Unpublished report in the files of the U. S. Geol. Survey.
- \_\_\_\_\_, 1930, Salt deposits of the Virgin valley, Nevada, Unpublished report in the files of the U. S. Bureau of Reclamation.



## REFERENCES (cont'd)

- Rubey, W. W., 1938, Discussion of "The passage of turbid water through Lake Mead": Am. Soc. Civ. Eng. Trans., vol. 103, pp. 763-767.
- Schulman, E., 1945, Tree-ring hydrology of the Upper Colorado River Basin: Univ. Ariz. Bull., vol. 16, no. 4, 51 pp..
- Sharpe, C. F. S., 1938, Landslides and related phenomenon; a study of mass movements of soil and rock, New York, Columbia Univ. Press, 136 pp..
- Shaw, H. W., 1913, The mud lumps at the mouths of the Mississippi: U. S. Geol. Survey Prof. Paper 85, pt. 3, 27 pp..
- \_\_\_\_\_, 1914, Gas from mud lumps at the mouths of the Mississippi: U. S. Geol. Survey Bull. 541-A, pp. 19-22.
- Sherman, Irving, 1951, A rapid substitute for textural analysis: Jour. Sedimentary Petrology, vol. 21, pp. 173-177.
- Sisler, F. D., 1952, Bacteriology and biochemistry of Lake Mead sediments: in Final report of the Lake Mead sedimentation survey, U. S. Geol. Survey Prof. Paper (in preparation).
- Spurr, J. B., 1903, Descriptive geology of Nevada south of the fortieth parallel and adjacent portions of California: U. S. Geol. Survey Bull. 208, 229 pp..
- Stanley, J. W., 1950, Retrogression in the lower Colorado River after 1935: Am. Soc. Civ. Eng. Proc., vol. 76, separate no. 28, 12 pp..
- Stetson, H. C., and Smith, J. F., 1938, Behavior of suspension currents and mud slides on the continental slope: Am. Jour. Sci., ser. 5, vol. 35, no. 205, pp. 1-13.
- Stevens, J. C., 1946, Future of Lake Mead and Elephant Butte Reservoir: Am. Soc. Civ. Eng. Trans., vol. 111, pp. 1242-1254.

## REFERENCES (cont'd)

- Sykes, Godfrey, 1937, The Colorado delta: Am. Geol. Soc., Sp. Pub. 19, 193 pp..
- Tchilingarian, George, 1951, Possible use of Lake Mead clay and marine mud in the oil well drilling fluids: Research Paper, Dept. of Geology, Univ. of Southern California, 19 pp.
- Terzaghi, C. E., 1925, Principles of soil mechanics, elastic behavior of sand and clay: Eng.-News Record, vol. 95, pp. 987-990.
- Terzaghi, Karl, and Peck, R. B., 1948, Soil mechanics in engineering practice, New York, John Wiley and Sons, 566 pp..
- Thomas, H. E., 1952, The tributary drainage basin: in Final report of the Lake Mead sedimentation survey, U. S. Geol. Survey Prof. Paper (in preparation).
- Trask, P. D., 1932, Origin and environment of source sediments of petroleum, Houston, Gulf Publishing Company, 323 pp..
- Tyner, E. H., 1939, The use of sodium metaphosphate for dispersion of soils for mechanical analysis: Soil Sci. Soc. America Proc., vol. 4, pp. 106-113.
- Udden, J. A., 1914, Mechanical composition of clastic sediments: Geol. Soc. America Bull., vol. 25, pp. 655-744.
- U. S. Bureau of Reclamation, 1939, Stress studies for Boulder Dam: Boulder Canyon Project final reports, pt. V, Bull. 4, 286 pp..
- \_\_\_\_\_, 1941, Lake Mead density current investigations, vols. I-II, 453 pp..
- \_\_\_\_\_, 1946, The Colorado River, 295 pp..
- \_\_\_\_\_, 1947, Lake Mead density current investigations, vol. III, pp. 454-904.

## REFERENCES (cont'd)

- \_\_\_\_\_, 1950, Geological investigations: Boulder Canyon Project final reports, pt. III, Bull. 1, 232 pp..
- Sentworth, C. K., 1922, Grade and class terms for clastic sediments: Jour. Geology, vol. 30, pp. 377-392.
- Wheeler, O. M., 1875, Report upon United States geographical and geological explorations west of the one-hundredth meridian, vol. III, pt. I, U. S. Govt. Printing Office, Washington, 187 pp..
- \_\_\_\_\_, 1889, Report upon United States geographical surveys west of the one-hundredth meridian, vol. I, U. S. Govt. Printing Office, Washington, 780 pp..
- Kobell, C. K., 1932, Bacteria in marine sediments: In Recent marine sediments, Am. Assoc. Petroleum Geologists, pp. 416-427.

5664<sup>i</sup>







USGS LIBRARY - RESTON



3 1818 00083528 8