DEPARTMENT OF THE INTERIOR
Hubert Work, Secretary

U. S. GEOLOGICAL SURVEY
George Otis Smith, Director

Water-Supply Paper 556

WATER POWER AND FLOOD CONTROL

OF

COLORADO RIVER BELOW GREEN RIVER, UTAH

BY

E. C. LARUE

WITH A FOREWORD BY

HUBERT WORK

SECRETARY OF THE INTERIOR

WASHINGTON
GOVERNMENT PRINTING OFFICE
1925

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FOREWORD

By Hubert Work
Secretary of the Interior

The Department of the Interior is authorized to investigate, through the Geological Survey, and report on the natural resources of the country, including minerals of various kinds and sources of water available for use in irrigation, the development of water power, industrial processes, and municipal supplies. The whole task is enormous and necessarily must be accomplished in parts. The endeavor is made to so plan the investigations that information will be available as needed, and the results accomplished are being used extensively as a basis for the safe and sane development of the public domain and for the classification of Government lands with respect to their entry and use under the public-land laws. This work will be completed only when all our natural resources have been examined and the map of our country is made to show their location, magnitude, and value.

Congress has recently provided in the Temple Act for a program of mapping which is designed to complete the topographic map of the country in 20 years. In the interest of economy and efficiency it is planned in connection with this program to make such detail surveys of rivers and of dam, reservoir, and power sites as to afford an adequate topographic basis for comprehensive plans for controlling and utilizing the water resources of the country. This topographic basis must be supplemented by adequate records of river discharge and engineering and geologic investigations.

Study of water resources must of necessity anticipate by many years the needs of development, because surface streams vary widely in their discharge, and safe and economical design of hydraulic structures must be based on records showing maxima, minima, and average yields of rivers over long periods. In wise anticipation of the utilization of Colorado River, the Geological Survey began many years ago to collect records of discharge of the river and its tributaries, and as funds were available it has made surveys of stretches of river in this basin to show sites for possible reservoirs, water-power plants, and diversion dams, routes for canals, and the location of irrigable lands. The information thus collected has been published in the Survey reports and maps and particularly within the last few years has been largely utilized in the formulation of projects for the control and development of the resources of Colorado River, which constitute perhaps the greatest undeveloped asset of several States.

Maps showing the topography of the canyons and gorges, the position of the rapids, and especially the sites for dams that would be valuable either for the creation of storage reservoirs or for the development of water power have also recently been published.

The most urgent needs of development relate to flood control, in order that lives and property on the lower river may not be subjected to the annual menace of destruction. I am concerned for the future of the people who are menaced by floods inadequately controlled, and I entertain a lively sense of the necessity and the importance of conserving this magnificent potential natural resource for the great waiting territory that is to be directly benefited, for the benefits will also extend to the United States as a whole.

The Colorado River basin has been under observation, survey, and study and has formed the subject of reports to Congress since the end of the Civil War. The program of investigations initiated by the Geological Survey is now substantially completed. Maps of Colorado River and its tributaries are available from the headwater region to the Mexican boundary, and records of stream flow in the basin have been placed on a sound, continuing basis. When a modest program of preliminary drilling at apparently favorable dam sites shall have been completed, the time will have arrived when the Government should decide on at least the main features of a comprehensive plan of development by which this great river, now a natural menace, may be converted into a national resource.

INTRODUCTION

By Nathan C. Grover

Colorado River is one of the remarkable rivers of the world in its value for irrigation and water power. It combines in proper sequence for complete use a large quantity of water, great concentrations of fall, reservoir sites for the control of flow, sites for power plants, and several million acres of irrigable land below the stretch where power may be developed. The Columbia also may be used largely for both water power and irrigation, but no other river on this continent affords such enormous opportunities for this double use of its water.

The drainage basin of the Colorado covers 244,000 square miles, or one-thirteenth of the area of the United States, situated in seven States. The river flows also through the Republic of Mexico, and its waters are used for irrigation in that country. As its resources, which constitute the most important undeveloped asset of this great region, will play an important part in the growth of several States in agriculture, industry, population, and wealth, the problems of their development are of interstate and international interest.

The most urgent need of the basin is flood protection for cities, towns, and large irrigated areas near Yuma and in the Imperial Valley. Property values exceeding $100,000,000 and the prosperity of many thousand people on both sides of the international boundary are seriously menaced. As Colorado River carries its burden of silt to the Gulf of California it is constantly building up its bed across the delta, making necessary a corresponding periodic increase in the height of the levees built to confine it. The flood menace is therefore increasing yearly, and the maintenance of the levees is becoming more difficult and costly as time goes on.

Colorado River and its upper tributaries rise in the mountains of Wyoming, Colorado, and Utah, where precipitation, especially in the form of snow, is heavy. The valleys of its upper tributaries have an excellent climate that is well adapted to agriculture and industry and that combines with beautiful scenery to make the region attractive for the building of homes.

The irrigable lands in these valleys have in part been irrigated, cities and towns have been built, and a substantial and well-justified development of the region is under way. Additional irrigation in this upper portion of the basin will deplete to some extent the present flow of water in the canyon or power section of the river and in the lower part of the basin, where the largest arid areas are situated. Of the many sites available for constructing water-power plants a few of small capacity have been utilized and others will be developed as the population and financial resources of the region increase. The utilization of water-power sites does not decrease the water supply of the river except through the increased evaporation caused by the added water surface exposed to the action of the sun and air in new storage reservoirs built as essential parts of the power plants. There are therefore good reasons why the development of the upper basin and the utilization of the available water supply for both power and irrigation should be protected and encouraged by all proper means.

The canyon section of the river offers the second largest concentration of water-power sites in the United States and the third largest on this continent. Its only superiors in this respect are the St. Lawrence and Columbia River basins. These rivers also are international, and the greater part of the potential power of the St. Lawrence is in Canada. The equalization of the flow of St. Lawrence River is accomplished naturally by the Great Lakes. An equally effective control of the flow of the Colorado is possible by means of reservoirs, for which nature has furnished sites of great capacity. The value of the power sites in Colorado River may therefore be greatly increased by building reservoirs at or near the upper end of the stretch of great fall, whereby the erratic natural flow of the river, ranging between flood discharges of more than 200,000 second-feet and low-water discharges of less than 3,000 second-feet, may be converted to a discharge that will be nearly uniform over a period of years. Dam sites have been discovered and surveyed in the canyon section that make possible the utilization of the whole fall or any part of it that may be desired.

The part of the basin situated below Black Canyon has relatively small power possibilities but has great areas of fertile land that may be made productive by irrigation. The distribution throughout the year of the needs for water for agriculture are, however, different from those for power. Consequently the conversion of the river from one of widely varying flow into one of uniform discharge through the canyon section in the interest of power development will not fully serve the requirements of irrigation, for which a reservoir below the canyon section is desirable to re-regulate the flow in accordance with the seasonal needs of growing crops. Here again nature has favored the region by affording opportunities for building reservoirs to reconvert the flow needed for the best utilization of the water-power resources in the canyons into the flow needed for full use in the irrigation of the arid lands of the lower basin.

The need for further agricultural development in the Colorado River basin will increase gradually, while the demand for electric energy in the basin and in regions outside the basin but within economic transmitting distance will increase more rapidly. It would not be economical, however, to proceed with a program of development that is greatly in advance of actual requirements. Such a program would be unwise because uneconomical and would surely result in losses of invested capital. It is important also that any developments, whenever or wherever made, shall conform to a rational scheme for the full development of the river that will not needlessly sacrifice head available for power or unnecessarily waste water by evaporation from reservoir surfaces.

Although there has never been satisfactory navigation in Colorado River it has been traversed by steamboats from the Gulf of California to the old town of Callville, at the lower end of Boulder Canyon. The navigation was not great in amount even before railroads were built in this region, but at that time it was of much local importance. Since the construction of the railroads navigation has been continued as needed for the erection and operation of works along the river, but its relative importance in the general development of the region has decreased. The greatest obstructions to navigation have been the shifting sand bars in the stretch of river below the canyons and the dangerous rapids in the canyons. The erection of dams for storage and power will provide safe access by boat to certain parts of the canyon section of the river that are now inaccessible except at great expense and danger. For example, a dam in Glen Canyon will make easily accessible by motor boat 150 to 200 miles of river above, including besides Glen Canyon the wonderful Rainbow Bridge and many beautiful canyons of tributary streams. The construction of an automobile road from a trunk-line railroad to some point on the backwater of such a dam would open up one of the most attractive tourist areas on the continent and would make accessible a region of beauty unsurpassed anywhere in the world. Other dams would create longer or shorter stretches of slack water and would open to tourists corresponding parts of the river and canyons. Such slack water would not impair the beauty of the canyons, as its depth would generally be little if any more than sufficient to cover the débris at the base of the cliffs, and nowhere would any appreciable part of the beautiful canyon walls be submerged. By thus providing for navigation the Grand Canyon, which surpasses in beauty the noted fiords of Norway, would be made easily accessible and would attract to our western country many travelers who now go to Europe for recreation.

As would be expected in the study of problems involving a region so large and so diverse in its needs, there are many opposing views and conflicting interests. It is not to be expected that sufficient information has now been collected to serve as a basis for the settlement of all questions that may arise. Indeed, some of them can be finally adjusted only as development progresses, because the details of the necessary information can only then be known. It is of prime importance, however, to have available the essential facts to serve as a guide in outlining the broad lines of development and policy that should be adopted, at least tentatively, before initial large developments are made.

The question of public or private ownership and operation of the projects involving the development of power has been little discussed openly in connection with Colorado River, although it has had a controlling effect on the attitude of many people. Federal control of the floods of a large river has been recognized as good public policy. Similarly the financing and building of irrigation works and, in connection therewith, the construction of large storage reservoirs for regulating the flow of rivers have for more than 20 years been accepted as proper governmental activities. The possibility of extending such activities into the business of financing, constructing, and perhaps operating large hydroelectric power plants in a field that has heretofore been occupied almost exclusively by privately owned public-utility companies, operated under governmental regulation, opens up a big question of policy, on which there are sure to be sharp and honest differences of opinion. These differences may delay the construction of large power dams and power plants, but they should not be permitted to delay the urgently needed protection against the flood menace.

The Geological Survey has collected records of discharge of some of the tributaries of Colorado River for many years, but it is only within the last five years that the establishment and maintenance of satisfactory gaging stations on Colorado River itself have been possible. Such stations are now operated at Lees Ferry above Paria River, in the Grand Canyon above Bright Angel Creek, and at Topock below the Atchison, Topeka & Santa Fe Railway bridge. The Geological Survey and later the Bureau of Reclamation have collected records of flow for many years at Yuma. All these records have been utilized in the preparation of the estimates of flow at the several sites for reservoirs and power plants.

The Geological Survey has also made available in maps and profiles the results of surveys of more than 1,800 miles of Colorado River and its tributaries, including the river itself from Grand Junction, Colo., to the Mexican boundary, the Green from Green River, Wyo., to its mouth, and the San Juan from Bluff, Utah, to its junction with the Colorado.

Mr. La Rue, the author of this report, had previously prepared the first comprehensive report on the utilization of Colorado River, published in 1916 by the Geological Survey as Water-Supply Paper 395. Prior to the writing of that report he had investigated and prepared unpublished reports on many power and irrigation projects in the basin and had seen most of the accessible regions within its borders. Since that report was written he has worked almost continuously on projects within the basin. He has made boat trips, including canyon sections, as follows: In 1914 from Green River, Wyo., to Horseshoe Canyon, Utah, 75 miles; in 1914 from Moab, Utah, down Colorado River to the mouth of Green River and thence up Green River to the town of Green River, Utah, 181 miles; in 1915 from Hite, Utah, through Glen Canyon of Colorado River to Lees Ferry, Ariz., 162 miles; in 1921 from Green River, Utah, down Green River to its mouth and thence through Cataract and Glen canyons of Colorado River to Lees Ferry, Ariz., 332 miles; in September, 1922, from Halls Crossing, Utah, through Glen Canyon to Lees Ferry, Ariz., 120 miles; in October, 1922, from Boulder Canyon to Needles, Calif., 122 miles; in October and November, 1922, from Boulder Canyon to Yuma, Ariz., 344 miles; in 1923 from Lees Ferry, Ariz., through the Grand Canyon to Needles, Calif., 456 miles; in September and October, 1924, from Flour Sack Rapids, in lower Grand Canyon, to Needles, Calif., 191 miles.

When making these boat trips in company with the party of topographic engineers, Mr. La Rue has been charged with the responsibility of selecting the dam sites and supervising the survey of such sites. He has therefore first-hand knowledge of the problems of the basin, which has been supplemented by careful study, continued over many years, of the data relating to the control and utilization of the river. He has taken more than a thousand photographs to show the many interesting features of the canyons, especially the dam sites and the river and canyon walls near them. A few of these photographs have been used to illustrate this report; others are on file in the Washington office, where they may be studied by those who are interested.

The Geological Survey is not attempting to promote any particular project but is endeavoring to collect and make available the information needed as the basis for outlining a proper scheme for full development of the river and for selecting the site for first development. It recognizes the fact that the final choice of any project will represent a compromise of conflicting interests, in which many factors—engineering, economic, and perhaps political—must be evaluated and given proper weight. The Survey hopes that this report, which contains the latest compilation of data relating to the water supply of the basin and the results of all surveys of sites for reservoirs and power dams, may aid in the solution of these important problems.

WATER POWER AND FLOOD CONTROL OF COLORADO RIVER BELOW GREEN RIVER, UTAH

By E. C. La Rue

SYNOPSIS OF REPORT AND GENERAL CONCLUSIONS

The purpose of this report is to present the facts regarding available water supply and all known dam sites on Colorado River between Cataract Canyon, Utah, and Parker, Ariz., and to show the relative value of these dam sites. To determine the relative value of the dam sites, a comprehensive plan of development for Colorado River below the mouth of Green River is presented that will provide for the maximum practicable utilization of the potential power, maximum preservation of water for irrigation, effective elimination of the flood menace, and adequate solution of the silt problem. This plan, which is preliminary and is offered by the writer to show the basis for his conclusions relative to flood control, irrigation, power development, and silt storage, contemplates the construction of 13 dams making available 3,383 feet of head for the development of power and a maximum of 42,000,000 acre-feet of storage capacity for the control of floods, equalization of flow, and storage of silt.

The water supply estimated to be available in 1922,[1] with storage, is equivalent to a uniform flow of 19,300 second-feet at Lees Ferry, 22,600 second-feet at the lower Black Canyon site, and 22,100 second-feet at Parker. Under future conditions the flow in and below the Grand Canyon[2] will be reduced. When development in the upper basin is completed and the canyon section and lower river are developed as is suggested in this report, the average annual flow is estimated at 12,000 second-feet at Lees Ferry, 14,440 second-feet at the lower Black Canyon site, and 13,940 second-feet at Parker.

[1] The figures given in this report relating to available water supply are based on an analysis of the records of stream flow for years prior to and including 1922. The run-off at Lees Ferry for the year 1923 was about 16,800,000 acre-feet and for 1924 about 11,600,000 acre-feet. The mean annual flow at Lees Ferry for the period 1895–1922, corrected for past depletion due to irrigation in the upper basin, was 14,400,000 acre-feet. The average annual flow during the years 1923 and 1924 was 14,200,000 acre-feet. It is therefore reasonable to assume that for all practical purposes the estimates of available water supply given in this report may be used as applicable in 1925.

[2] The United States Geographic Board on February 4, 1925, defined the Grand Canyon as "extending from the mouth of Paria River and Lees Ferry to Grand Wash Cliffs." The Grand Canyon is 278 miles long and at one place is 13 miles wide and nearly 6,000 feet deep.

Under the plan suggested and with the water supply estimated to be available in 1922, 4,350,000 continuous horsepower may be developed. Ultimate development in the upper basin will deplete the water supply to some extent and thereby reduce this figure to about 3,420,000 continuous horsepower. Under an annual load factor of 60 per cent, the aggregate installed capacity of the plants would be 5,743,000 horsepower. This may be taken as the ultimate power capacity of Colorado River below Green River, Utah, after all demands for water in the upper basin have been satisfied. The location by States of the undeveloped power just referred to is shown in the following table:

Undeveloped water power on Colorado River below an elevation of 4,050 feet[a]

Power site	Utah	Arizona	Nevada	California
Cataract Canyon	672,000			
Glen Canyon	491,300	65,700		
Marble Gorge		362,000		
Mineral Canyon		588,000		
Ruby Canyon		495,000		
Specter Chasm		392,000		
Havasu		387,000		
Bridge Canyon		1,090,000		
Devils Slide		317,000		
Hualpai Rapids		433,400	4,600	
Lower Black Canyon		187,500	187,500	
Parker		35,000		35,000
	1,163,000	4,353,000	192,000	35,000

[a] The figures given in the table represent the capacity of the sites in horsepower under a 60 per cent load factor, with maximum use of water in the upper basin. If a power site lies in two States the power capacity of such site has been credited to the States in proportion to the fall in the river that is utilized in each State.

In order to obtain a maximum use of the water for power and provide for the most complete use of the water for irrigation, it will be necessary to utilize a reservoir site below the mouth of Green River and above Grand Canyon to regulate the flow in the interest of power development, and another reservoir site below all large power sites to prevent floods on the lower river and re-regulate the flow in the interest of irrigation.

If full use is made of the water in the upper basin, the water supply of the lower Colorado will not be sufficient to serve even the portion of the irrigable land below Parker in and adjacent to the basin that lies within the United States. If the irrigable land on the delta in Mexico is also to be served and if 2,000 second-feet of water is reserved to furnish a domestic water supply for the cities of southern California the annual deficiency in water supply will be more than 5,000,000 acre-feet, and in that event about 1,250,000 acres of irrigable land must remain dry.

The preceding data show the magnitude and the limits of the Colorado River project. As the amount of land that can be irrigated and the amount of power that can be developed are limited by the available water supply, it follows that the most beneficial comprehensive plan of development will be one that precludes an unnecessary waste of water. The plan here suggested is based on the results of accurate surveys of the water supply and of the topography above water level in the river. Prior to final decision on any comprehensive plan of development it is essential that the conditions under water at the dam sites be also fully explored. Each dam built on the river should form a unit of the adopted plan of development.

COOPERATION AND ASSISTANCE

The work of surveying the 186-mile section of Glen Canyon was carried on in cooperation with the Southern California Edison Co. This company also cooperated with the Geological Survey in the work of surveying six additional dam sites below Diamond Creek.

The Geological Survey has been able to maintain gaging stations on lower Colorado River because the greater part of the expense has been borne by the States of Arizona and California, the Bureau of Reclamation, the Imperial Valley Irrigation District, the Southern California Edison Co., the Federal Power Commission, the city of Los Angeles, the United States Weather Bureau, and the Palo Verde irrigation district.

In connection with the preparation of this report, the author feels greatly indebted to George F. Holbrook, assistant engineer, who made most of the studies of stream-flow records and assisted in determining the relative value of the dam sites; to Dr. Raymond C. Moore, for his report on the geology at dam sites in Grand Canyon; and to Herman Stabler and other engineers for valuable suggestions.

TOPOGRAPHY AND CLIMATE

The Colorado River basin is naturally divided into three parts which are topographically different. The southwestern part is in general but little above the level of the sea, though isolated mountains rise here and there to elevations of a few thousand feet. The central part is a great plateau region which has a general elevation of 5,000 to 8,000 feet. This part is bounded on the east and west by ranges of high mountains, and most of it is cut by deep gorges and canyons. The northern part of the basin is bounded on the east by the Rocky Mountains, which rise to elevations of more than 14,000 feet; on the north by the Wind River Mountains, in Wyoming, which reach 13,700 feet or more; and on the west by the Wasatch Mountains, in Utah, which reach altitudes exceeding 13,000 feet.

The differences in the topographic features of the basin at once suggest great differences in the climate. In the southwestern desert region the average annual precipitation ranges from 1.5 to 8 inches and the temperature from about 32° in the winter to 120° in the summer. In the central part of the basin the average annual precipitation ranges from about 10 inches over most of the plateau area to about 30 inches in the higher mountains, and although temperatures of 100° are not uncommon during the summer, the winter temperatures in exposed places drop below zero. The northern part of the basin, which includes the major areas of high mountains, has a mild summer climate but very severe winters. Temperatures of 30° below zero are not uncommon, and the annual precipitation ranges from less than 10 inches along Green River to as much as 60 inches along the Continental Divide.

The differences above set forth explain why 76 per cent of the annual discharge of Colorado River at Yuma originates in that part of the basin above and including Green River.

FACTORS AFFECTING HYDRAULIC STRUCTURES

ICE

At Green River, Wyo., monthly mean temperatures as low as 18° F. have been recorded. At Green River, Utah, about 100 miles north of the Cataract Canyon power site, the lowest monthly mean temperature has been 23° to 24°, and the daily minimum −32°. At Hite, Utah, which is on Colorado River 23 miles below the Cataract Canyon power site, the minimum temperature has been 7° and there has been an average of 102 days yearly with temperature below 32°. These data indicate that considerable ice would form in the forebay above a dam built in Cataract Canyon. However, it is not likely that the ice would interfere with the operation of a power plant. The ice would form at a time when the discharge of the river is low and would probably disappear before the period of spring and summer floods. It is not likely that ice would be carried over the spillway or over the top of an overflow dam or would subject the dam to great pressure.

The next important dam site on Colorado River is situated 4 miles above Lees Ferry, Ariz., 186 miles downstream from Cataract Canyon. This site is 3,127 feet above sea level. Here the summers are hot and dry and the winters are mild, with temperatures usually well above freezing. However, the following record[3] shows that Lees Ferry has experienced at least one very severe winter.

[3] From the journal of A. W. Ivins, Salt Lake City, Utah.

On the 8th of January, 1878, I left St. George in company with Erastus B. Snow, our destination being northern Arizona and New Mexico, where we were to do missionary work among the Pueblo and Navajo Indians. * * * We found the river (at Lees Ferry) frozen over for the first time since people had lived there. A short distance above the ferry and a few hundred yards below there are rapids, and the water was free from ice, but the still water above the lower rapids was frozen over from bank to bank.

The ice was not considered safe, but after sounding it we decided to cross. We had about 1,200 pounds of loading on our wagon. We unhitched the team, tied a rope to the end of the tongue, and the two of us easily pulled the wagon to the south bank. We then led the horses over singly. There being no feed for the horses at the river, Brother Snow went on with the team to Navajo Springs.

* * * Some of the cattle we were obliged to throw down and hog tie and drag them across. The ice was so smooth that a man could drag an animal over without trouble.

On the 20th * * * the ice was cracked from shore to shore; I could reach my hand down to running water in many places, but it was about 2 feet thick and it held until we were all safely across.

I crossed the river on the ice 32 times. There were many of the travelers who absolutely refused to go on the ice, and I was obliged to take their outfits over for them. On the 21st we were all safely at Navajo Springs, away from the treacherous river, and that night prayers of thanksgiving went up from many hearts. * * *

About the 10th of January, 1866, James M. Whitmore and Robert McIntire were killed by Navajo Indians near Pipe Springs. Just such a period of cold weather prevailed at that time. The militia who went in pursuit of the Indians suffered greatly because of the intense cold, which followed a heavy snowstorm. The Indians drove off a flock of sheep which belonged to Whitmore, as well as some horses and cattle. I understood from reports current among the Indians when I visited them later that they crossed these sheep on the ice at the Crossing of the Fathers, above Lees Ferry. It is certain that they reached their own country with the sheep, and I do not think a sheep could possibly swim the river, the only way they could cross at that time except on the ice.

On January 15, 1925, the river again had an ice cover at Lees Ferry sufficiently thick to support loaded animals, and Indians rode their ponies and drove their pack mules across the river on the ice.

At the Redwall dam site, in Marble Gorge, 30 miles below Paria River, the flowage line of the reservoir would be at an elevation of about 3,108 feet above sea level. No doubt some ice would form in the reservoir every winter, but it seems reasonable to believe that at no time would the ice cause trouble at the proposed dam. The ice would disappear before the period of summer floods, and it is not likely that any ice would be carried over an open spillway or over the crest of a dam of the overflow type.

It is not expected that ice would cause trouble at any dam site in the Grand Canyon. Little if any ice would form in the Boulder Canyon reservoir. At the dam site in Mohave Canyon, 427 feet above sea level, hydraulic works may be built without fear of trouble from ice.

FLOODS

In the design of any hydraulic structure to be installed in Colorado River provision should be made to take care of the flood flow of the river.

The stream-flow records, which extend back about 30 years, indicate that the maximum flood in Cataract Canyon has been about 150,000 second-feet, and at Lees Ferry about 200,000 second-feet. Gage readings and traditional evidence, however, show that a flood of still greater magnitude occurred in 1884. On July 4, 1884, a gage reading of 18.5 feet was recorded by the United States Weather Bureau at Fruita, Colo. The Geological Survey has maintained a gaging station at this point for many years. By extending the rating curve for the gaging station at Fruita, Robert Follansbee, district engineer of the Geological Survey at Denver, has estimated that the flow of the Colorado at Fruita July 4, 1884, was about 125,000 second-feet. It may be reasonable to assume that at this time Green River was discharging 100,000 second-feet. This would indicate that the flood of 1884 reached a stage of 225,000 second-feet in Cataract Canyon.

Jerry Johnson, who was living at Lees Ferry in 1884, relates how he rescued his cat, which was marooned by the flood and resting uncomfortably in the forks of an apple tree. As he waded out to get the cat, the height of the water on the trunk of the tree was well impressed on his mind. Assisted by Mr. Johnson, an engineer of the Geological Survey ran a line of levels from the apple tree and determined the probable height of the flood of 1884 with reference to the gage now installed at Lees Ferry. By extending a well-defined rating curve for the Lees Ferry gaging station, it was found that the flood of 1884 may have reached a stage of about 250,000 second-feet. This determination, though subject to some uncertainties, was accurate enough for the purpose it was intended to serve, as the probable error was no greater than is inherent in flood estimates. With this estimate as a basis for the flood peak, daily gage readings obtained at Yuma in 1884 by the Southern Pacific Co. were used to show the total flow of Colorado River at Yuma. These studies indicate that in 1884 the discharge of Colorado River at Yuma exceeded 100,000 second-feet for 57 days and that the annual run-off was about 32,000,000 acre-feet.

The highest discoverable water marks found near the mouth of Bright Angel Creek, when referred by G. C. Stevens, hydraulic engineer, of the Geological Survey, to an extension of a well-defined rating curve at that place, indicate a probable maximum discharge there of at least 250,000 second-feet. Water-lodged drift, evidently undisturbed for many years, about 8 miles below the mouth of Diamond

Creek, when compared with the stage at the same place of the flood of September, 1923, indicates a probable discharge of 200,000 to 220,000 second-feet.

Under present conditions hydraulic works to be built in Cataract Canyon should be designed with sufficient spillway capacity to take care of a flood of at least 250,000 second-feet. At Lees Ferry such works should be safe against floods of 250,000 to 300,000 second-feet, but a dam could be operated in such a way as to take care of the flood peak by means of storage in the reservoir, and in that case it would not be necessary to provide a spillway capacity of 300,000 second-feet.

The preceding statements would apply to the first dam built on Colorado River below the mouth of Green River. If ten dams were built on the main stream below the mouth of Green River, the sites being developed in their order going upstream, their cost would be a maximum. It would be necessary to take care of the annual floods during the construction of each dam, and it would also be necessary to provide a spillway capacity of 300,000 second-feet for the site near Lees Ferry and each dam below it. If the first dam were built at the site near Lees Ferry and made sufficiently high to control the floods, then each dam lower on the river could be built at a greatly reduced cost. In addition to the reduction in the cost of the dams, the amount of power that could be developed below Lees Ferry would be more than doubled.

LOGS AND DÉBRIS

During flood periods Colorado River carries a large amount of driftwood. In the flood of September, 1923, hundreds of logs 20 to 30 feet long and 2 to 3 feet in diameter passed through the Grand Canyon. At all hydraulic structures on the river some provision should be made to take care of the drift.

SILT

An exhaustive study of the silt problem of Colorado River, made by R. B. Dole,[4] showed that the average annual silt load carried by the river at Yuma is equivalent to about 80,000 acre-feet of compacted silt, such as would be deposited on the bottom of a reservoir. The Bureau of Reclamation, as indicated in the statement below,[5] estimates the average annual silt content of Colorado River at Yuma as 105,000 acre-feet.

Silt sampling at Yuma has been carried on continuously by the Bureau of Reclamation since 1909, with over 5,000 determinations to date. A silt determination is made at practically every gaging for discharge. A quart sampler is

[4] U. S. Geol. Survey Water-Supply Paper 395, pp. 218-226, 1916.

[5] Weymouth, F. E. (chief engineer, Bureau of Reclamation), unpublished report on problems of the Colorado River basin, vol. 4, p. 72, February, 1924.

attached to a sounding weight and filled by opening a valve. These samples are taken at the top, middle, and bottom of the stream at three different locations across the stream. After allowing sufficient time for settlement to clear the liquid, the sediment is dried and weighed. To determine the relation between weight and volume for silt, 20 samples of deposited silt were obtained with a 3-inch copper tube at various points on the river in the vicinity of Yuma. These determinations indicate:

Silt volume=water volume×percentage of silt by weight×0.727. The specific gravity of the Colorado River silt has been found to average 2.60, and the average weight of wet silt in place 86 pounds per cubic foot.

Silt content of Colorado River at Yuma

	Discharge at Yuma in acre-feet	Silt content in acre-feet	Silt volume in percentage of total	Yuma flow from Gila River in acre-feet
1909-1916	146,700,000	1,000,043	0.68	8,450,000
1917	20,611,000	89,062	.43	1,150,000
1918	13,145,000	59,831	.45	330,000
1919	10,272,000	68,333	.66	740,000
1920	21,446,000	122,829	.57	800,000
1921	19,454,000	111,948	.57	478,000
1922	17,091,000	95,407	.56	673,000
Average (1909-1922)			.62	

The maximum silt content was found to be present with a discharge of 26,000 second-feet. This is also the minimum discharge at which the mean velocity of the stream reached 6 feet per second, which is exceeded but little with higher discharge.

With an average flow at Yuma of 17,000,000 acre-feet at the present time and an average silt content of 0.62 per cent by volume, the annual load of silt brought to the delta region by the Colorado and Gila averages 105,000 acre-feet, or 170,000,000 cubic yards.

The mean of silt measurements taken when no water was entering from Gila River gave an average content of 0.7 per cent by weight for the period 1909-1916, inclusive. This corresponds to a mean content of 0.51 per cent by volume. If the diversions at Laguna dam were added to Yuma flow and complete desilting assumed at Laguna, the silt percentage could be decreased from 0.51 per cent to 0.49 percent. As the Colorado River valleys between Yuma and Boulder Canyon are being raised very slowly, if at all, it may be concluded that the silt content at Boulder is the same as at Laguna dam.

With the construction of reservoirs on the tributaries above Boulder Canyon, and especially power reservoirs on the lower parts of the main tributaries, the silt percentages may be expected to decrease materially. The proposed Diamond Creek power dam, if constructed, would for many years stop a large part of the silt which would otherwise pass on into Boulder Canyon reservoir.

FLOOD CONTROL

NEED

On the lower river in California and Arizona and in the Imperial Valley in California and Mexico large areas of land have been reclaimed by irrigation. Most of the reclaimed lands in the Imperial Valley are below sea level, and the lands at Yuma and in the Palo Verde Valley are but little above the flood plain of Colorado River.

To protect these lands from floods extensive levee systems have been built and must be maintained. The value of the property that is menaced by the annual floods exceeds $100,000,000. Although millions of dollars have been spent in constructing the levees, these works alone, however well maintained, can not assure protection from the flood menace. There is grave danger that during periods of high run-off the levees will be breached and the entire flow of the Colorado will find its way into Imperial Valley and the Salton Sea. If these valuable properties on the lower river are to be protected, dangerous stages must be prevented by holding back a part of the flood-making waters. The need for flood control is therefore urgent.

HEADWATER RESERVOIR SITES

FLAMING GORGE RESERVOIR SITE

The Flaming Gorge reservoir site lies on Green River in Utah and Wyoming. (See Pl. I.) The dam site is in Horseshoe Canyon, 4 miles south of the Utah-Wyoming line. A dam here that would raise the water 200 feet would form a reservoir capable of storing 3,000,000 acre-feet of water. The Flaming Gorge is a valuable reservoir site; its chief value, however, would come from its operation in the interest of power development. Its use would not reduce materially the floods on the lower Colorado.

JUNIPER RESERVOIR SITE

The Juniper reservoir site is on Yampa River in Moffat County, Colo., the dam site being near the head of Juniper Canyon, about 6 miles above Maybell. (See Pl. I.) The capacity of a reservoir formed by a 150-foot dam at this site would be 827,000 acre-feet. By operating the upper 80 feet of this reservoir site in the interest of irrigation and power development, the flow of Yampa River would be under control. Such operation would affect the flow of the lower Colorado but would not materially reduce the floods of the lower river.

OURAY RESERVOIR SITE

The Ouray reservoir site is on Green River in northeastern Utah. (See Pl. I.) The basin above the dam site is formed by the widening of the canyon of Green River in the vicinity of the junction of Duchesne and White rivers with the Green. The capacity of a reservoir formed by a dam 170 feet high at this site would be 8,000,000 acre-feet.

By utilizing the Ouray reservoir site, the flow of Green River may be regulated as desired for irrigation and the development of power. Such regulation would also be beneficial to irrigation and the development of power on the lower Colorado River. The stored water thus released might eventually pass through power houses with an aggregate head of more than 3,400 feet, and the flood flow of the lower river would be materially reduced. If the flow of Green River were regulated, less storage capacity would be required at all hydraulic structures built on the lower river, whether operated in the interest of flood control, irrigation, or power development. This statement shows the value of upstream storage.

DEWEY RESERVOIR SITE

The Dewey reservoir site is on Colorado River in eastern Utah, below Westwater station on the Denver & Rio Grande Western Railroad. The dam site is 3 miles below the mouth of Dolores River, where the elevation of the water surface at low water is 4,087 feet above sea level. (See Pls. I and II.)

Data presented by the Bureau of Reclamation[6] indicate that a storage capacity of 4,000,000 to 4,500,000 acre-feet would be required to equalize the flow of Colorado River at this point; but the capacity of the site without interference with the present location of the Denver & Rio Grande Western Railroad is only 2,270,000 acre-feet. To obtain this capacity, it would be necessary to build a dam to raise the water 215 feet. If a capacity of 1,500,000 acre-feet were reserved for regulation of the flow about 90,000 horsepower could be developed. Operating the site in this way would have a beneficial effect on the flow of the lower Colorado. In fact, if this site were developed and operated in conjunction with the Ouray site, on Green River, the flood flow of the lower Colorado would be greatly reduced and the normal low-water flow would be increased.

BLUFF RESERVOIR SITE

The Bluff reservoir site is on San Juan River in southeastern Utah. (See Pls. I and II.) This site was investigated in 1914 by the Bureau of Reclamation, which found that a dam that would raise the water 214 feet would create a storage capacity of 1,600,000 acre-feet, and that a dam 264 feet high would give a capacity of 2,600,000 acre-feet.

San Juan River is subject to sudden and violent floods. The flood of October, 1911, was estimated at 150,000 second-feet.[7] If desired, a flood-detention dam could be built at the Bluff site. Such a dam with a storage capacity of 600,000 acre-feet would probably prevent the San Juan floods from reaching Colorado River. If only the peak floods were stored and all flows of 25,000 second-feet or less were

[6] Problems of Imperial Valley and vicinity: 67th Cong., 2d sess., S. Doc. 142, p. 181, 1922.

[7] U. S. Geol. Survey Water-Supply Paper 395, p. 213, 1916.

MAP OF COLORADO RIVER DRAINAGE BASIN
SHOWING LOCATION OF RESERVOIR SITES

allowed to pass the dam, the amount of silt that would be deposited in the reservoir would be small. If this reservoir site were operated in conjunction with the Ouray site on the Green and the Dewey site on the Colorado, the floods of the lower Colorado above the Gila could be controlled. However, the utilization of a flood-control reservoir site on the main stream below the mouth of San Juan River would probably afford a better solution of the flood problem.

The water surface of San Juan River at the Bluff dam site is 4,198 feet above sea level. The Glen Canyon flood-control reservoir site (see below) may be developed to an elevation of 3,513 feet without interfering with the development of the Dark Canyon dam site in Cataract Canyon. There are sites in the canyon of San Juan River below the Bluff dam site where dams may be built for the development of power. On the assumption that 175 feet of head may be used for the development of power at the Bluff site, about 800 feet of head may be developed above the flowage line of the Glen Canyon reservoir. Even with the ultimate irrigation development in the basin, it may still be possible to develop 150,000 horsepower on lower San Juan River.

RESERVOIR SITES ON MAIN STREAM BELOW CATARACT CANYON

GLEN CANYON RESERVOIR SITE

Glen Canyon covers the 186-mile section of Colorado River between Cataract Canyon, Utah, and Lees Ferry, Ariz. (See Pl. II, in pocket.) In 1921, in cooperation with the Southern California Edison Co., the Geological Survey made a topographic survey of the Glen Canyon reservoir site, carrying observations to an elevation of 3,900 feet above sea level. These surveys disclosed the fact that a dam of moderate height constructed 4 miles above Lees Ferry would create a storage reservoir with a capacity sufficient to regulate the flow of Colorado River.

In addition to the site 4 miles above Lees Ferry, which has been designated Glen Canyon dam site No. 1, there are seven alternative dam sites in this canyon and one at the head of Marble Gorge.[8] Glen Canyon dam site No. 1 is regarded by the writer as the best location for a dam to utilize the Glen Canyon storage basin and will be described first. The alternative sites will then be described in the order of their value. Topographic maps of the alternative sites are on file in the office of the Geological Survey at Washington.

[8] On February 4, 1925, the United States Geographic Board decided "that that portion of the Grand Canyon between the mouth of Paria River and the mouth of Little Colorado River heretofore known as Marble Canyon should hereafter be called Marble Gorge." That there is no marble in Marble Gorge was known to Maj. J. W. Powell when he named this stretch of canyon in 1869, for in his diary, on August 8, 1869 (Exploration of the Colorado River of the West and its tributaries, p. 75, 1875), he says, "The limestone of this canyon is often polished and makes a beautiful marble."

GLEN CANYON DAM SITE NO. 1

The position of the Glen Canyon reservoir site in the Colorado River basin is shown in Plate II (in pocket). The dam site here designated Glen Canyon dam site No. 1 is near the lower end of Glen Canyon, 4 miles above Lees Ferry, Ariz. The writer first examined this site in August, 1915, and at that time recommended that a thorough investigation should be made to determine its feasibility for flood control.

At this locality the canyon of Colorado River is carved in Jurassic sandstone. The walls rise about 1,000 feet above the river, and a drill hole put down at the dam site by the Southern California Edison Co. shows that the sandstone extends 200 feet or more below the water surface. So far as the dam itself is concerned, therefore, the construction problem has to deal only with this massive sandstone.

According to Bryan,[9]

The rocks of the dam site are essentially uniform in character from the water level to the top of the cliffs. The advantages and disadvantages are thus equal for any height of dam which may be constructed. The crushing strength of the rock is low, but the fact that it stands in great walls in a state of nature indicates that its crushing strength is ample for a high structure.

The following statements regarding the geologic features of the Glen Canyon dam site No. 1 are taken from an unpublished report of a board of engineers of the Bureau of Reclamation, dated December 20, 1922. The excerpts that relate to geology may properly be credited to F. L. Ransome, then of the Geological Survey, a member of the board:

The Jurassic sandstone * * * is a fine-grained, very uniform quartzose sandstone which appears to owe its reddish tint to the superficial redness of certain individual grains. The grains are imperfectly cemented, and the whole resembles in hardness the type of soft brick known to the trade as salmon brick. It crumbles under shock, such as that of ordinary blasting. * * * Notwithstanding its softness the rock stands remarkably well in the canyon walls, forming large smooth cliffs which rise for 1,000 feet or more above the river and which in places are within 5° of being vertical. A conspicuous feature of these walls is the presence of a series of nearly vertical fractures or joints which strike approximately east and west. These joints are not everywhere present but occur in groups, comprising many joints from a few inches to a few feet apart. At such places the sandstone is divided into great vertical, closely fitting slices. The joints themselves are very close and appear to be as a rule cemented by films of calcite. Under the action of weather, however, the joints form zones of relative weakness, and where they occur there is a tendency for the rocks to fall off in blocks and for the canyon walls to lose some of their sheer smoothness. One such zone of jointing crosses obliquely the line along which drilling is now in progress and constitutes a possible weakness in the abutments. Another section of the canyon, a few hundred yards downstream from the present drill line, offers better abutments with apparently no greater distance between them, but the top

[9] Bryan, Kirk, Discussion on rock-fill dam, Lees Ferry, Ariz.: Am. Soc. Civil Eng. Trans., vol. 86, p. 228, 1923.

of the Chinle (the red sandstone and shale) is probably a few feet nearer the bottom of the river than it is farther north. The upper beds of the Chinle, however, to a thickness of 200 feet or more, would probably be safe material upon which to base a dam. * * *

The Jurassic sandstone is unsuitable for use as concrete constituent. In large masses, however, it successfully resists the weight of the towering canyon walls and shows no signs of failure at the base of the cliffs where these come down to the water's edge. Under the atmospheric conditions prevailing at the canyon, moreover, the sandstone in spite of its softness withstands the action of the weather remarkably well. Some of the smooth walls must have stood without appreciable change for centuries.

In considering possible building materials attention should be given to the possibility of using the Shinarump conglomerate near Lees Ferry as a source of sand and gravel. The nearest rock suitable for crushing and use in concrete is probably the cherty Kaibab limestone, which is exposed over a large area a mile or two west of Lees Ferry and forms the walls of Marble Canyon. Considerable gravel, of recent geologic age, occurs at the mouth of the Paria, just below Lees Ferry, but it is doubtful whether the quantity would be sufficient for the construction of a dam of the size proposed.

The following information regarding the Glen Canyon dam site No. 1[10] was obtained by personal correspondence with the Southern California Edison Co., Los Angeles, Calif.:

Southern California Edison Co. conducted between November, 1922, and January, 1923, some core-drill explorations in order to determine the depth from the surface of the water to bedrock in the dam site. * * * Four vertical holes were drilled, the first of which is in solid rock for the entire distance. The second (in the approximate middle of the river channel) showed a depth of 66 feet to bedrock, the third (near the right-hand edge of the river channel) a depth of 80 feet to bedrock, and the fourth (midway between No. 1 and No. 2) a depth of 26 feet to bedrock. There were also drilled two other holes—No. 5 horizontally and No. 6 at an angle of approximately 40° with the horizontal—and in location No. 5 and No. 6 correspond very closely with No. 1 (Pl. V). For the purpose of securing some index as to the compressive strength of the rock, samples were taken from the cores in hole No. 1. These samples were cut to give a length equal to approximately twice the diameter, and they were tested for compression in the testing laboratory of the Smith-Emery Co., testing engineers at Los Angeles. * * * Three such cylinders taken from the core at the approximate depth of 88 feet showed an average compressive strength of 2,220 pounds per square inch; three other specimens taken from the core at an approximate depth of 210 feet showed an average compressive strength of 12,900 pounds per square inch, while three other specimens taken from the core at the approximate depth of 210 feet showed compressive strength of 10,480 pounds per square inch. * * * Among these last three specimens there was a wide variation in individual performance.

In July, 1924, tests were made to determine the strength of the dry rock as compared with that of a rock sample saturated with water. The samples tested were parts of the cores from drill holes No. 1 and No. 5. Mr. Dennis says:

[10] Memorandum regarding foundation for dam at Lees Ferry (Glen Canyon), by H. W. Dennis, chief construction engineer, Southern California Edison Co., Dec. 19, 1924.

Hole No. 1, as above mentioned, was a vertical hole, and the bedding planes are at right angles to the axis of the core. Hole No. 5, as above mentioned, is a horizontal hole, and the bedding planes are parallel to the axis of the core. * * * There is a diminution in strength of the wet specimen as compared with the dry specimen. * * * However, the lowest crushing strength noted, except for the horizontal hole, is 1,315 pounds per square inch, which is very much in excess of any unit stress which would be permitted in concrete of which the dam itself would be made.

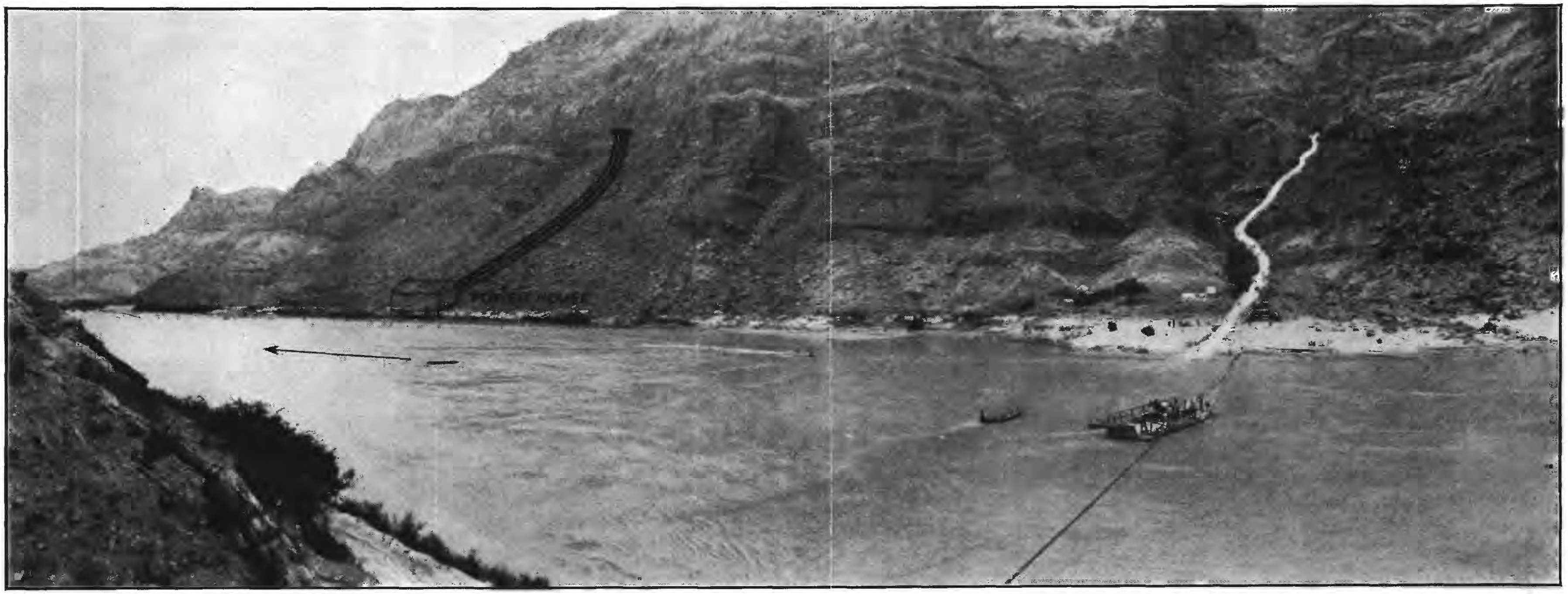
It is my opinion that the characteristics of the sandstone at the Lees Ferry dam site are such as will assure the stability and safety of any reservoir dam that may be justified financially at this site. The precedent of design of any such structure would dictate the excavation of a trench for the full length of contact between the dam and the foundation rock not only for the purpose of insuring the stability of the structure against sliding but to cause the removal of surface rock which may have partially weathered. Sound engineering practice also shows that great forces in compression may be safely brought upon materials that seem to have low cohesive strength provided material is confined and can not dissipate or spread under the effect of such pressure. The sides and bottom of such a trench into which this dam would be built would cause the satisfaction of these conditions of restraining the material against which the pressure would be carried, and the natural conditions at Lees Ferry are such as to easily permit an adequate spillway so that any surplus water may be discharged at a point remote from the toe of the dam and thereby eliminate the erosive action due to scour. The side walls of Glen Canyon and of many side canyons entering Glen Canyon stand nearly sheer for several hundred feet in this Jurassic sandstone formation and have so stood for many thousands of years, and there are many examples of tremendous pressure brought against this rock without failure. * * *

The tests herein mentioned have been made upon small specimens of core taken out by a diamond drill. These specimens are approximately 1.1 inches in diameter, and the test specimens have had a length equal to approximately twice that diameter. Failure has been typical of the tests of any concrete column—namely, by a bulging and by lateral displacement—and it is felt that these tests may be used as indices only and that the actual compressive value of the material in large block would be very much greater than the compressive strength as indicated by these specimens.

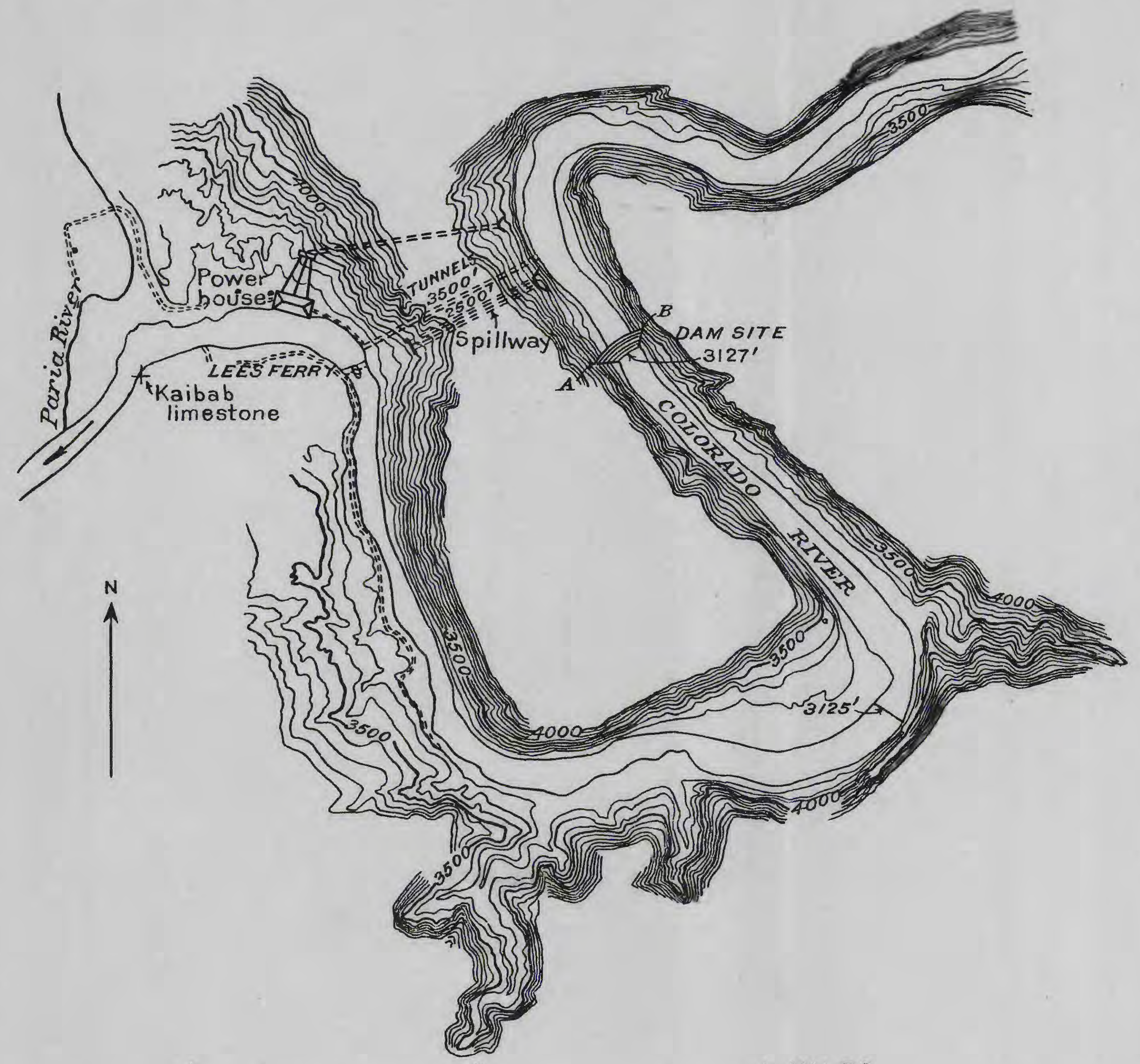
In consideration of the homogeneous and uniform nature of the rock, the results of the tests made upon the cores, and the conditions of restraint brought upon the foundation at the bottom of a trench, I have no hesitation in recommending the site of the Lees Ferry dam for a flood-control reservoir dam of such height as may be financially justified in the complete comprehensive development of the Colorado River.

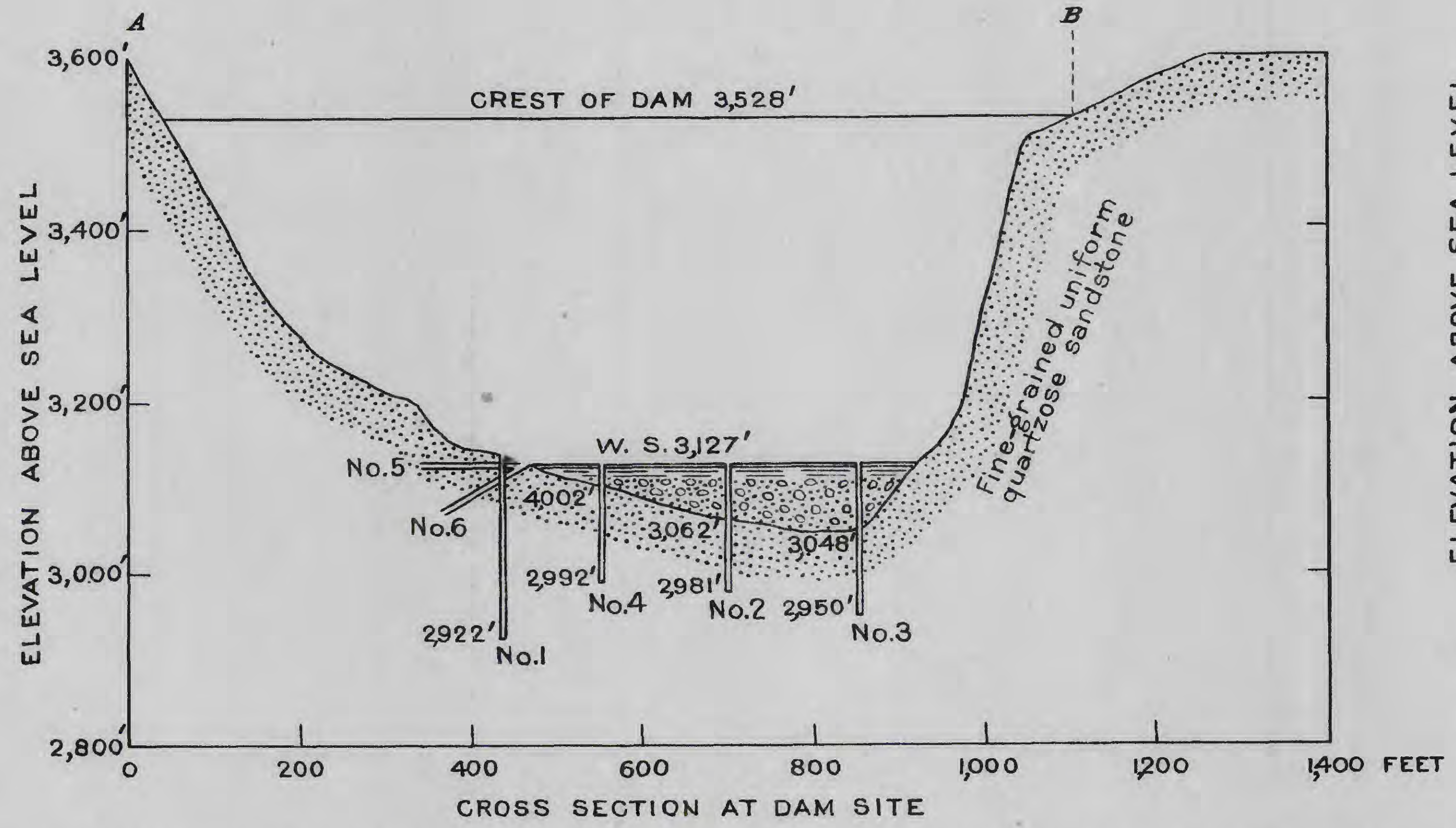
The fact that the sandstone at the dam site is not suitable for the concrete aggregate would not add to the cost of the dam, because adequate space for storage of building material is not available at the site. To complete the under-water work between successive flood periods it would be necessary to pour from 5,000 to 10,000 cubic yards of concrete a day, and therefore large supplies of sand, gravel, and crushed rock must be stored ready for use. The quarries and storage bins would be most conveniently located on the spacious flat

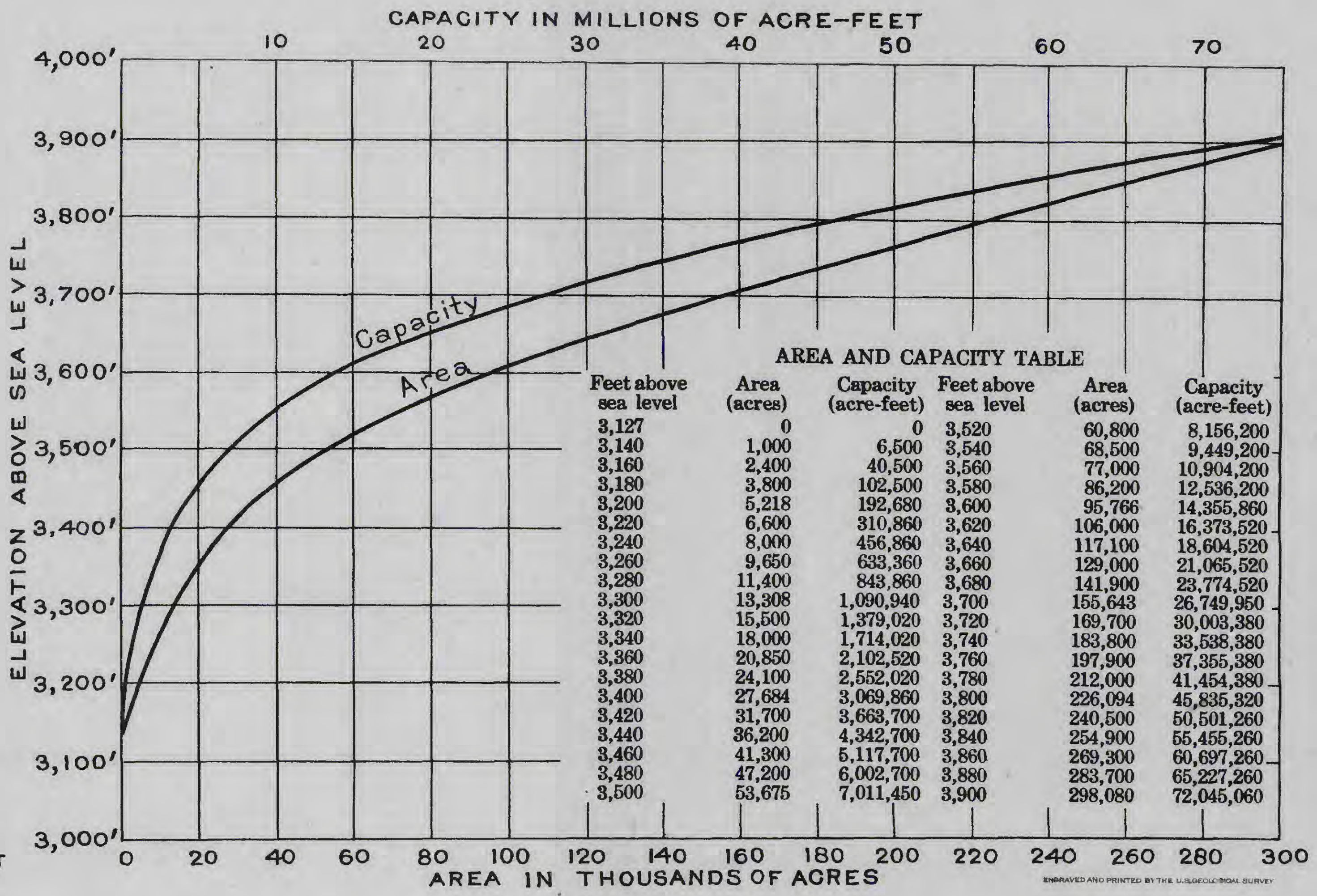
A. GLEN CANYON DAM SITE, 4 MILES ABOVE LEES FERRY



B. COLORADO RIVER AT LEES FERRY, SHOWING SPILLWAY AND POWER-HOUSE SITE OF THE GLEN CANYON FLOOD-CONTROL AND POWER SITE







AREA AND CAPACITY TABLE

Feet above sea level	Area (acres)	Capacity (acre-feet)	Feet above sea level	Area (acres)	Capacity (acre-feet)
3,127	0	0	3,520	60,800	8,156,200
3,140	1,000	6,500	3,540	68,500	9,449,200
3,160	2,400	40,500	3,560	77,000	10,904,200
3,180	3,800	102,500	3,580	86,200	12,536,200
3,200	5,218	192,680	3,600	95,766	14,355,860
3,220	6,600	310,860	3,620	106,000	16,373,520
3,240	8,000	456,860	3,640	117,100	18,604,520
3,260	9,650	633,360	3,660	129,000	21,065,520
3,280	11,400	843,860	3,680	141,900	23,774,520
3,300	13,308	1,090,940	3,700	155,643	26,749,950
3,320	15,500	1,379,020	3,720	169,700	30,003,380
3,340	18,000	1,714,020	3,740	183,800	33,538,380
3,360	20,850	2,102,520	3,760	197,900	37,355,380
3,380	24,100	2,552,020	3,780	212,000	41,454,380
3,400	27,684	3,069,860	3,800	226,094	45,835,320
3,420	31,700	3,663,700	3,820	240,500	50,501,260
3,440	36,200	4,342,700	3,840	254,900	55,455,260
3,460	41,300	5,117,700	3,860	269,300	60,697,260
3,480	47,200	6,002,700	3,880	283,700	65,227,260
3,500	53,675	7,011,450	3,900	298,080	72,045,060

ENGRAVED AND PRINTED BY THE U.S. GEOLOGICAL SURVEY

MAP, CROSS SECTION, AND AREA AND CAPACITY CURVES FOR GLEN CANYON FLOOD-CONTROL AND POWER SITE NO. 1

ground near the mouth of Paria River, a short distance below Lees Ferry, where there is an ample supply of the necessary material for concrete.

An upstream view of Glen Canyon dam site No. 1 is shown in Plate IV, *A*, and a cross section of the dam site, showing the results of diamond-drill boring, in Plate V. The exploration is incomplete, but the four holes drilled indicate that the greatest depth to bedrock is about 80 feet.

Lees Ferry is accessible from the north and south by automobile. A railroad from the south to the dam site would be about 135 miles long, and its construction would not be difficult. It seems probable, however, that the Union Pacific System (Los Angeles & Salt Lake Railroad) may be extended to the north rim of Grand Canyon. When this road is constructed, a branch about 50 miles long would reach the Glen Canyon dam site No. 1.

The map in Plate V shows the circuitous course of Colorado River in the vicinity of Lees Ferry. Tunnels to provide a permanent spillway may be constructed through the narrow neck of the loop. The spillway would thus discharge back into the river at a point 4 miles below the dam. On the lower side of the loop the canyon walls break away, leaving plenty of room for the construction of a power house and outbuildings. (See Pl. IV, *B*.) The physical conditions at the site are favorable not only for the construction of a high dam but for the development of power. However, on account of the distance to market, it is not likely that power will be developed at this site for some time to come.

In order to determine the probable flow of Colorado River at Lees Ferry, a study was made of records showing the measured flow of the upper Colorado and its tributaries since 1895. From these records the annual discharge at Lees Ferry was computed for the period 1895 to 1922. By comparison with the record showing the inflow of Great Salt Lake, the estimate of annual discharge of Colorado River at Lees Ferry has been extended to cover the period 1851 to 1922. (See Appendix A, p.121.) According to tradition the maximum flood at Lees Ferry in recent times occurred in 1884. (See p.14.) This flood probably reached a peak of 250,000 second-feet. The records indicate that the years of maximum run-off were 1868 and 1884, in which the total annual run-off was about 25,000,000 and 24,000,000 acre-feet, respectively.

By means of mass diagrams it can be shown that with a storage capacity of 8,000,000 acre-feet provided in Glen Canyon, the maximum flood at Yuma, floods in Gila River excepted, may be reduced to 50,000 second-feet or less and the flood menace effectively removed. A capacity of about 8,000,000 acre-feet can be obtained at the Glen Canyon reservoir site without interfering with the Dark Canyon dam site, in Cataract Canyon.

Paria, Little Colorado, Kanab, Virgin, and Williams rivers join the Colorado below Lees Ferry. The Paria, Kanab, Virgin, and Williams are unimportant tributaries which seldom, if ever, discharge a peak flood of 10,000 second-feet. The greatest flood of record on the Little Colorado occurred in September, 1923, when the peak discharge was about 100,000 second-feet and the total volume 370,000 acre-feet. It is apparent that the normal forebay capacity of one or more power dams in the Grand Canyon would have easily taken care of this flood from the Little Colorado. Even without any dams on the river, this flood was practically consumed by channel storage before it reached Yuma, where the peak discharge was only 56,000 second-feet.

The Dark Canyon dam site is in Cataract Canyon 186 miles above Lees Ferry, where the water surface is 3,528 feet above sea level. It has been assumed that the Glen Canyon reservoir site could be utilized to an elevation of 3,513 feet without interfering with the development of the Dark Canyon dam site. To utilize the 186-mile section of Glen Canyon in this way would require the construction of a dam near Lees Ferry to raise the water 386 feet, giving a storage capacity of about 8,000,000 acre-feet. In the following pages the alternative dam sites in Glen Canyon are described. It is believed by the writer that the 186-mile section of Glen Canyon can best be utilized by constructing a dam at the site 4 miles above Lees Ferry. Not only is this site more accessible, but materials for building the dam, except cement, are conveniently at hand.

The water level of Colorado River at Glen Canyon dam site No. 1 is 3,127 feet above sea level. If the flow of the river is regulated by storage in Glen Canyon the water thus released from the reservoir would not only be available for irrigation on the lower river but could be used for the development of power in the Grand Canyon. The continuous power capacity of all power sites in the Grand Canyon and on the lower river would be more than doubled by storage at Glen Canyon, and in addition every hydraulic structure subsequently built on the river below Glen Canyon could be constructed at a greatly reduced cost, as it would not be necessary to take care of long-continued flows of flood water during construction, and the spillway and storage capacity required at such works could be reduced to a minimum. It is estimated that building the Glen Canyon dam first would result in a saving of millions of dollars on dams subsequently built on the river below this point.

RAINBOW NATURAL BRIDGE

The Rainbow Bridge, a graceful natural arch of sandstone high enough to span the dome of the Capitol at Washington, surpasses in size and symmetry any other known natural bridge. It is situated in the Rainbow Bridge National Monument, a part of the former Piute Indian Reservation in San Juan County, southern Utah, more than 150 miles from a railroad, and can be reached only by traversing in boats the long canyons of Colorado and San Juan rivers or by traveling with pack train the few and little used trails.

This bridge is one of the scenic wonders of the world.[11] It attains a height of 309 feet above the creek, or 235 feet above the top of the inner canyon, and has a span of 278 feet (Pl. VI). If the Glen Canyon reservoir site were utilized to an elevation of 3,513 feet above sea level it would not in any way interfere with the Rainbow Natural Bridge. The backwater would extend up Bridge Canyon[12] only to a point 1¼ miles below the bridge. In fact, if the Glen Canyon dam were constructed to raise the water to the abutment of the Rainbow Bridge, the storage capacity would be about 32,000,000 acre-feet—four times the capacity proposed. The Glen Canyon reservoir would provide an easy means of access from the highway at Lees Ferry by motor boat to the bridge and the other scenic wonders of this almost unknown region. It is estimated that after the completion of automobile highways leading to the reservoir the number of tourists to this region would exceed 200,000 annually.

GLEN CANYON DAM SITE NO. 2

Site No. 2 is 9½ miles by river above Lees Ferry and 5½ miles above Glen Canyon dam site No. 1. The canyon walls at the site are composed of massive red sandstone. The depth to bedrock in the river channel is unknown but has been estimated at 80 feet. On account of the circuitous course of the river in this vicinity the site has some rather favorable features. A suggested plan of development is shown in Plate VII. A dam could be built for flood control only with spillway tunnels 1,150 feet in length, passing through the canyon walls. At some future time a power plant could be built on the left bank below the dam, the water to be carried to the power house by means of tunnels 750 feet long. The storage capacity of the site for given height of dam is practically the same as that of site No. 1. The less favorable features of the site are its inaccessibility and distance from the limestone that would probably be used in constructing the dam. The limestone may be obtained at the

[11] Miser, H. D., Trimble, K. W., and Paige, Sidney, The Rainbow Bridge, Utah: Geog. Rev., vol. 13, pp. 518-531, 1923.

[12] Not to be confused with Bridge Canyon on Colorado River in Arizona, 235 miles below Lees Ferry.

mouth of Paria River, which is about 11 miles downstream from the dam site.

SENTINEL ROCK DAM SITES NOS. 1 AND 2

The topographic map of the Glen Canyon reservoir site discloses the fact that if a dam were built on Colorado River between the mouths of Warm and Waweap creeks to raise the water to the 3,600-foot contour an open spillway could be provided in a low saddle between these creeks 2½ miles from the river. Two possible dam sites in this stretch and the spillway site were examined September 13 and 14, 1922. The saddle is underlain by a sandstone formation covered with a few feet of soil, and the conditions appeared favorable for the construction of an open spillway 3,000 to 4,000 feet in length. A detailed survey was made of Sentinel Rock dam site No. 1, which is 23½ miles above Lees Ferry, 4 miles below the mouth of Warm Creek, and 7 miles above the mouth of Waweap Creek. The water surface at this site is 3,152 feet above sea level, and a dam to raise the water to the 3,600-foot contour would have a length of 1,300 feet. The canyon walls are composed of massive red sandstone. Material for the construction of the dam may be obtained from the Kaibab limestone at the mouth of Paria River, about 25 miles below the dam site. This dam site is somewhat less accessible than the site near Lees Ferry. A railroad built to it would probably pass over the plateau region south of the river, and the construction camp for the dam would necessarily be located on the plateau 700 or 800 feet above the river.

A cross section of the canyon was taken at Sentinel Rock dam site No. 2, which is 18½ miles above Lees Ferry and 2 miles above the mouth of Waweap Creek. The water surface at this site is 3,147 feet above sea level, and a dam to raise the water to the 3,600-foot level would have a length of about 1,200 feet. Other conditions at this site are the same as those at Sentinel Rock dam site No. 1.

A dam at either of these sites high enough to raise the water to the 3,600-foot level would give a storage capacity of about 13,000,000 acre-feet. The flowage line of the Glen Canyon reservoir, however, can not be higher than 3,513 feet above sea level without interfering with the Dark Canyon dam site, in Cataract Canyon. Although the favorable conditions for a spillway between Warm and Waweap creeks constitute an attractive feature of the Sentinel Rock dam sites this spillway site would have small value if the flowage line of the Glen Canyon reservoir were limited to an elevation of 3,513 feet, as it would be necessary to excavate a channel across the saddle 9,700 feet long, with a maximum cut of 100 feet.

OAK CREEK DAM SITE

The Oak Creek dam site is in Glen Canyon 71 miles above Lees Ferry, a quarter of a mile below the mouth of Oak Creek, and 7 miles below the mouth of San Juan River. The water surface at this site is 3,341 feet above sea level. A detailed survey was made of this site September 11, 1922. It was found that a dam to raise the water to an elevation of 3,513 feet above sea level would have a length of 1,300 feet. The canyon walls are composed of massive red sandstone. The depth to bedrock in the river channel is probably not great. A side canyon on the left bank affords an excellent opportunity for a permanent spillway for a dam of the height mentioned. The conditions for a dam of this height are favorable, except that the site is not easily accessible and materials for construction of the dam are not near at hand.

SAN JUAN DAM SITE

The San Juan dam site is on Colorado River 78 miles above Lees Ferry and half a mile below the mouth of San Juan River, where the water surface of the river is 3,258 feet above sea level. This site was examined September 9 and 10, 1922. A detailed topographic survey of a narrow strip covering the center line of the proposed dam showed that a dam to raise the water to 3,513 feet above sea level would have a length of 1,700 feet. It is likely that bedrock is near the surface in the river channel at this point. The conditions for taking care of water during construction and the facilities for a permanent spillway are good. Owing to its great length the volume of the dam would be relatively large. The site is inaccessible at present except by boat.

ESCALANTE DAM SITE

The topographic features of the canyon 7 miles above the mouth of Escalante River appeared favorable for the construction of a dam, but a study of the site showed that at this point the river is cutting through shale, which appears in the canyon walls to a height of 50 feet above the river. This rock is unfavorable for the construction of a dam, and a detailed survey of the site was therefore deemed unnecessary.

BEDROCK DAM SITE

The bedrock dam site is on Colorado River 6 miles below Hall's Crossing and 1 mile below Lake Canyon, where the water surface is 3,325 feet above sea level. The bedrock, which extends across the river, is a very hard laminated red sandstone. The rock in the abutment walls was found to be satisfactory, with the exception of a few layers of soft sandstone. If a concrete dam were constructed at this point it would be necessary to excavate a considerable distance into these soft layers in order to prevent leakage around the end of the dam. A dam at this site to store 6,000,000 acre-feet would raise the water 372 feet. The volume of the dam would be 3,500,000 cubic yards. As bedrock is at the surface in the river channel the construction of the dam would be comparatively simple. However, a dam at this site would either interfere with the development of power in Cataract Canyon or afford inadequate storage capacity. Furthermore, the volume of the dam and the inaccessibility of the site make it less attractive than other sites lower on the river.

MARBLE GORGE DAM SITE

A dam built near the head of Marble Gorge, 4 miles below Paria River, would provide slightly greater storage capacity than a dam of the same height built at Glen Canyon dam site No. 1. Unfortunately the construction of a high dam at this site is not feasible, owing to the presence of soft shale in the bed of the river. The physical characteristics of the site are discussed under the heading "Marble Gorge bridge site" (pp. 52–53).

BOULDER CANYON RESERVOIR SITE

After leaving the Grand Canyon Colorado River forms the boundary between Nevada and Arizona for a distance of 150 miles. Here the river flows through small valleys separated by short stretches of canyon. At 11 miles below the mouth of Virgin River the Colorado has cut through the Black Mountains, forming what is known as Boulder Canyon. About 18 miles below the head of Boulder Canyon the river enters Black Canyon, which is separated from Boulder Canyon by a small valley about 5 miles long. Surveys made by the engineers of the Bureau of Reclamation show that great storage capacity can be obtained by building a high dam in either Boulder Canyon or Black Canyon.

BOULDER CANYON DAM SITE

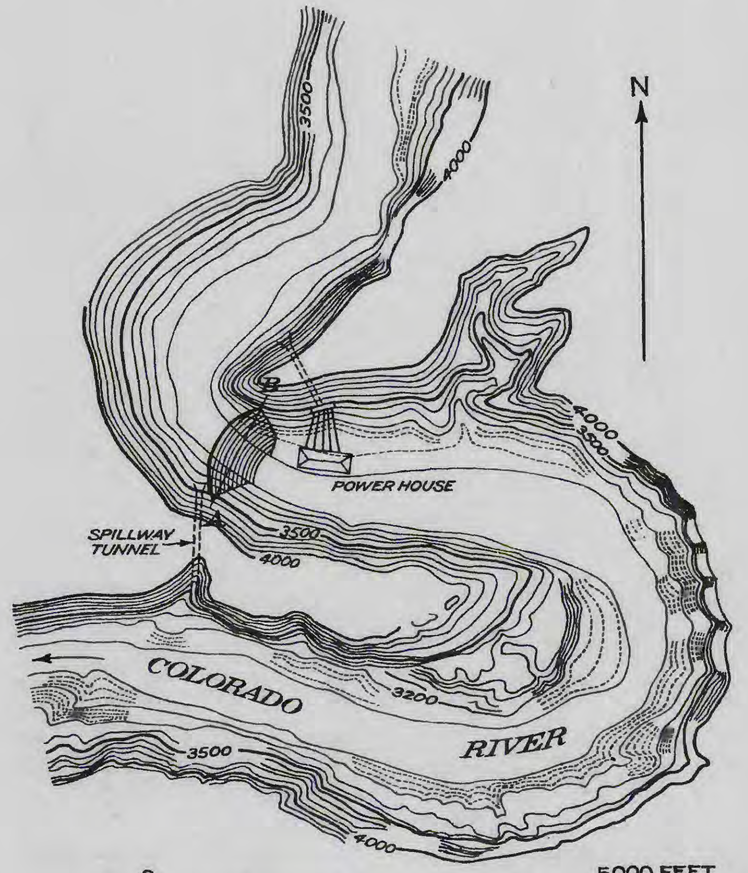
A map and cross section of the Boulder Canyon dam site are shown in Plate VIII. This site has been described by the former Director of the Bureau of Reclamation.[13] It was proposed to build a dam in Boulder Canyon to serve three purposes—flood control, regulation of the flow for irrigation, and the development of power.

The rock in the canyon walls is a fine-grained granite of good quality, although it is considerably jointed. The walls rise precipitously from the river to heights of 1,200 to 1,500 feet and continue upward on a gentler slope to the peaks of the mountain range (Pl. IX, *A*). The foundation was thoroughly investigated by means of diamond-drill borings, and the greatest depth to bedrock was found

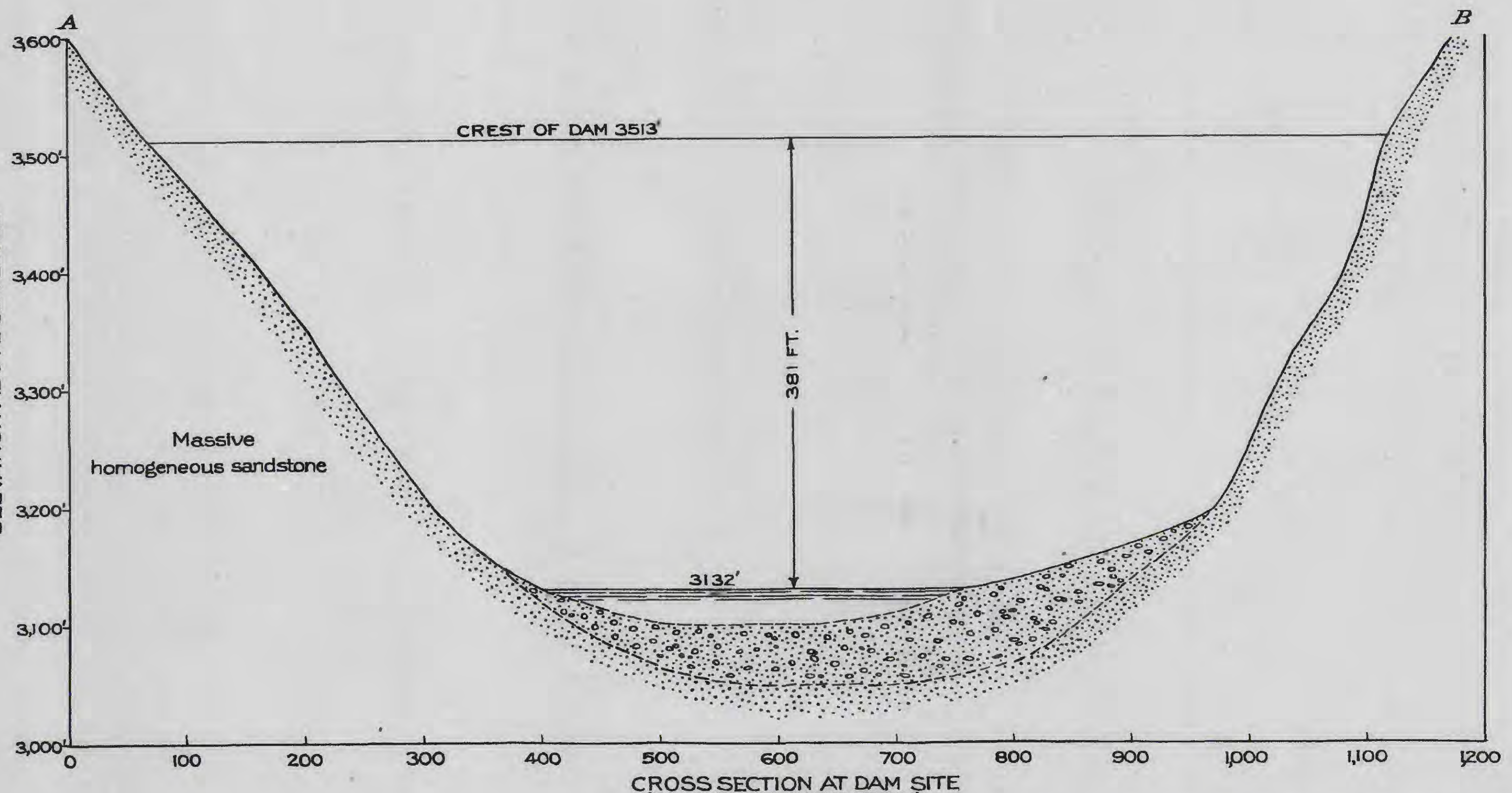
[13] Problems of Imperial Valley and vicinity: 67th Cong., 2d sess., S. Doc. 142, 1922.

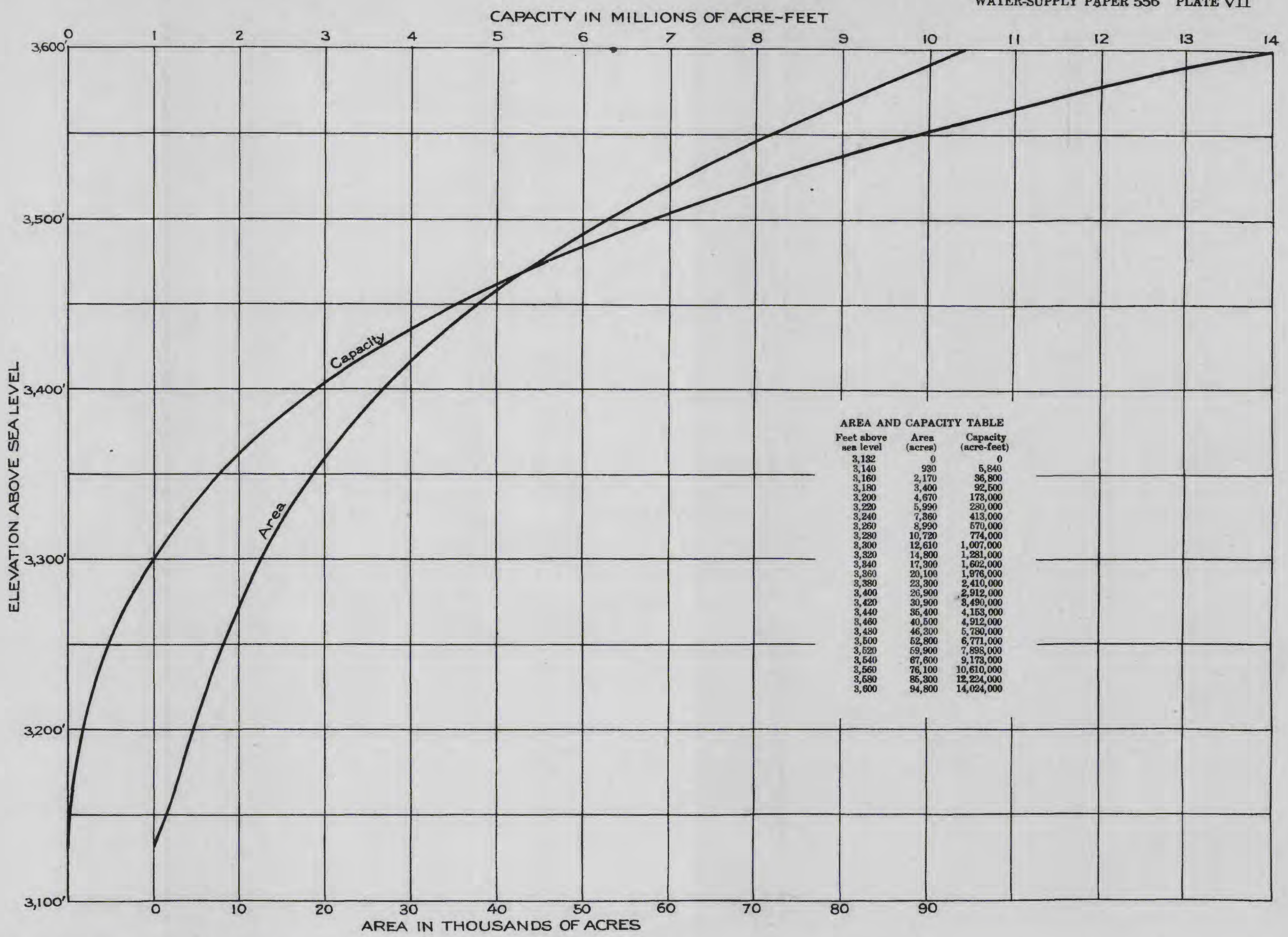
RAINBOW NATURAL BRIDGE, SOUTHEASTERN UTAH

The bridge spans a narrow inner canyon in which runs Bridge Creek, a branch of Aztec Creek, which joins Colorado River 6.5 miles below the mouth of San Juan River



Contour interval 100 feet
Dotted contours 20 feet
Surveyed August 12, 1921

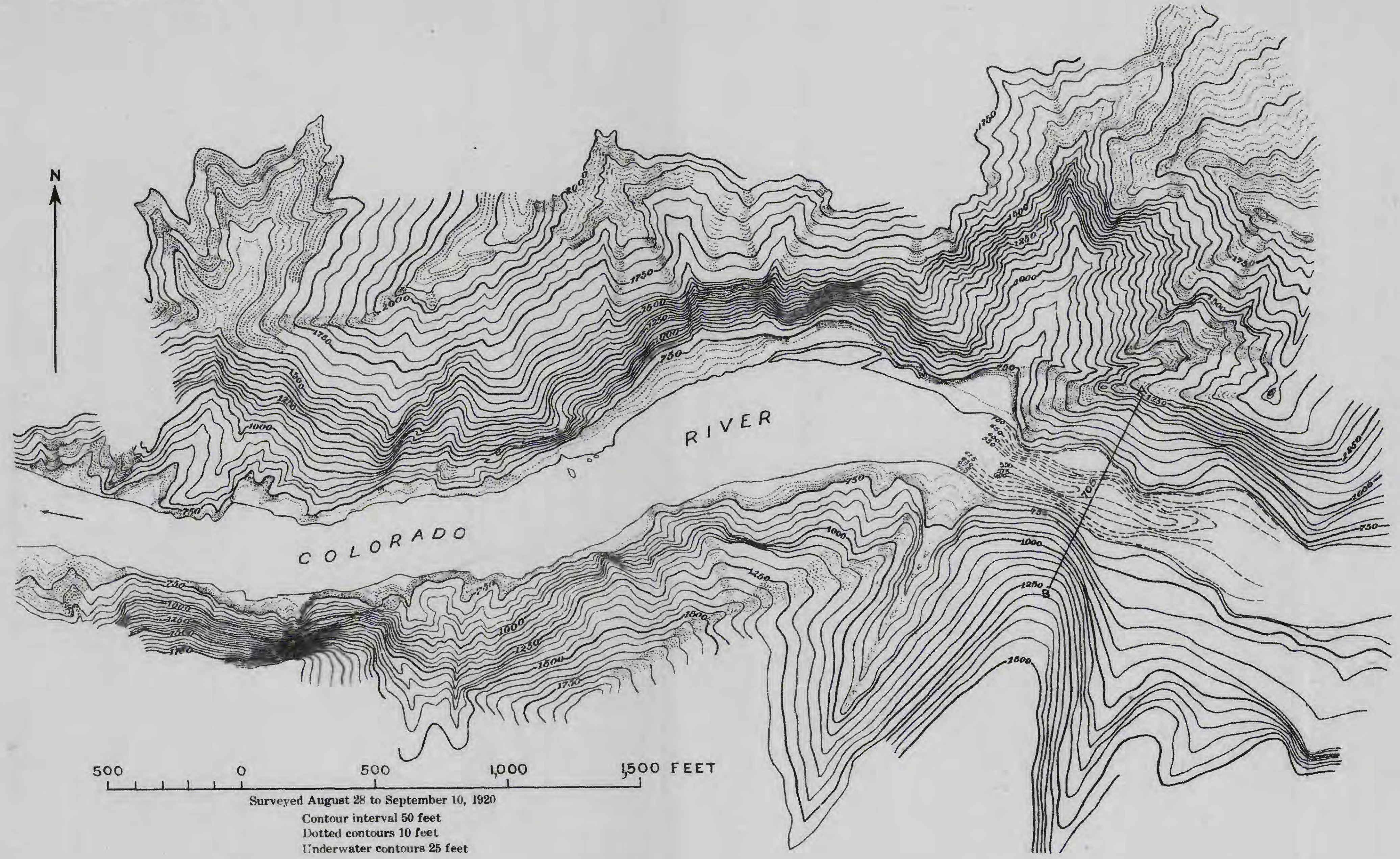


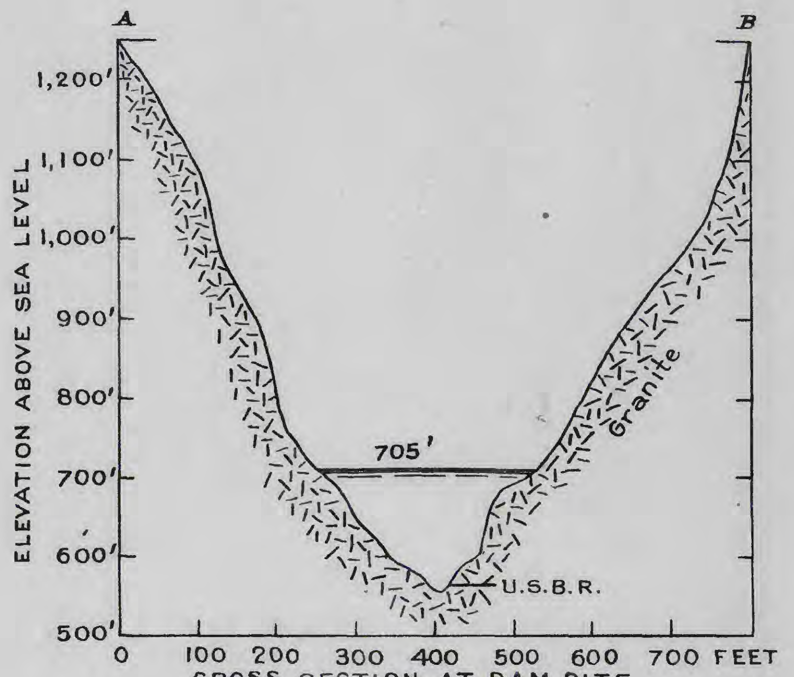


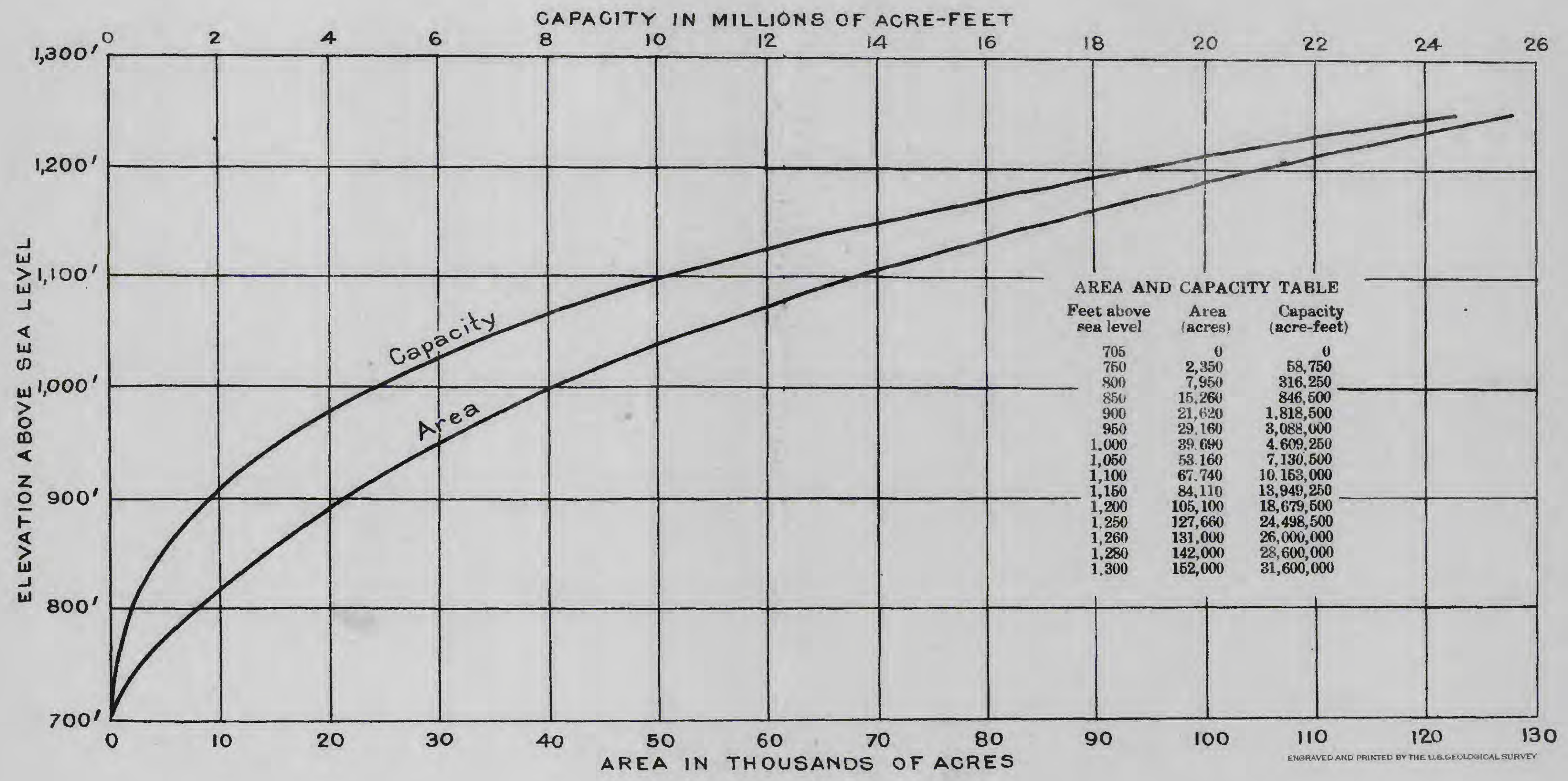
AREA AND CAPACITY TABLE

Feet above sea level	Area (acres)	Capacity (acre-feet)
3,132	0	0
3,140	930	5,840
3,160	2,170	36,800
3,180	3,400	92,500
3,200	4,670	173,000
3,220	5,990	280,000
3,240	7,360	413,000
3,260	8,990	570,000
3,280	10,720	774,000
3,300	12,610	1,007,000
3,320	14,800	1,281,000
3,340	17,300	1,602,000
3,360	20,100	1,976,000
3,380	23,300	2,410,000
3,400	26,900	2,912,000
3,420	30,900	3,490,000
3,440	35,400	4,153,000
3,460	40,500	4,912,000
3,480	46,300	5,780,000
3,500	52,800	6,771,000
3,520	59,900	7,898,000
3,540	67,600	9,173,000
3,560	76,100	10,610,000
3,580	85,300	12,224,000
3,600	94,800	14,024,000

MAP, CROSS SECTION, AND AREA AND CAPACITY CURVES FOR GLEN CANYON FLOOD-CONTROL AND POWER SITE NO. 2







AREA AND CAPACITY TABLE

Feet above sea level	Area (acres)	Capacity (acre-feet)
705	0	0
750	2,350	58,750
800	7,950	316,250
850	15,260	846,500
900	21,620	1,818,500
950	29,160	3,088,000
1,000	39,690	4,609,250
1,050	53,160	7,130,500
1,100	67,740	10,153,000
1,150	84,110	13,949,250
1,200	105,100	18,679,500
1,250	127,660	24,498,500
1,260	131,000	26,000,000
1,280	142,000	28,600,000
1,300	152,000	31,600,000

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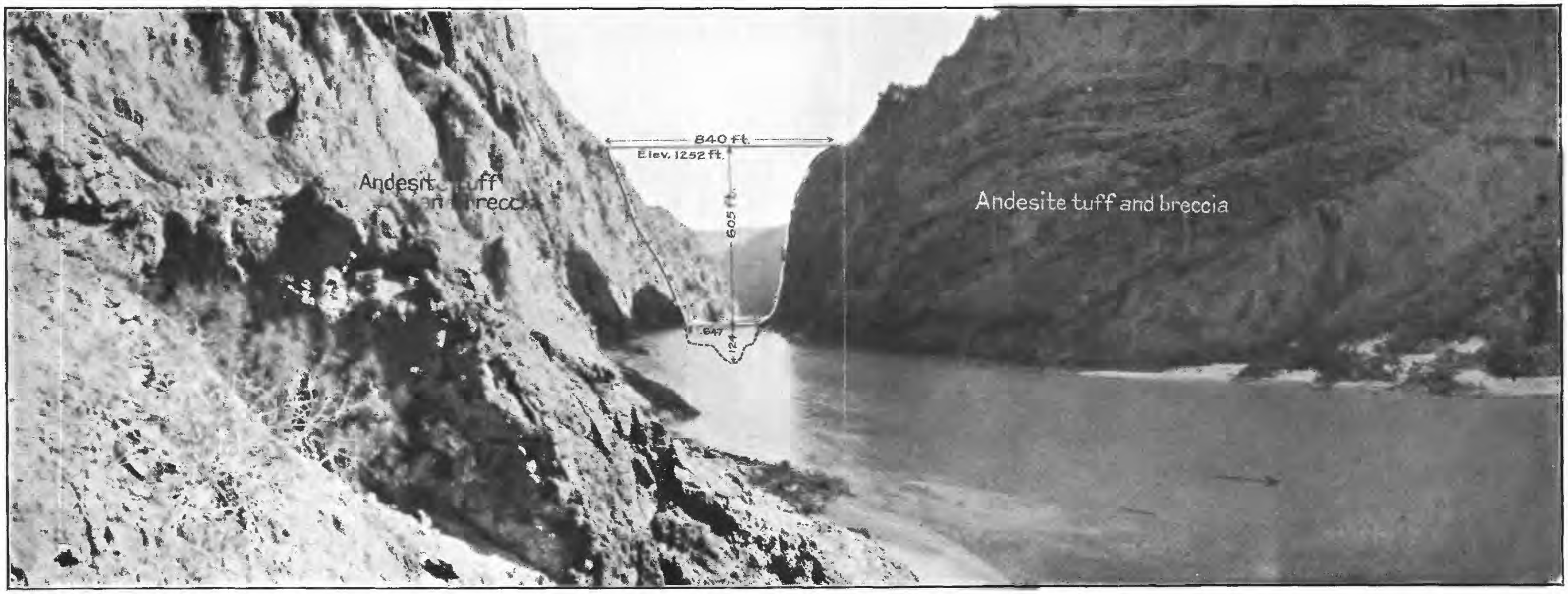
MAP, CROSS SECTION, AND AREA AND CAPACITY CURVES FOR BOULDER CANYON FLOOD-CONTROL AND POWER SITE

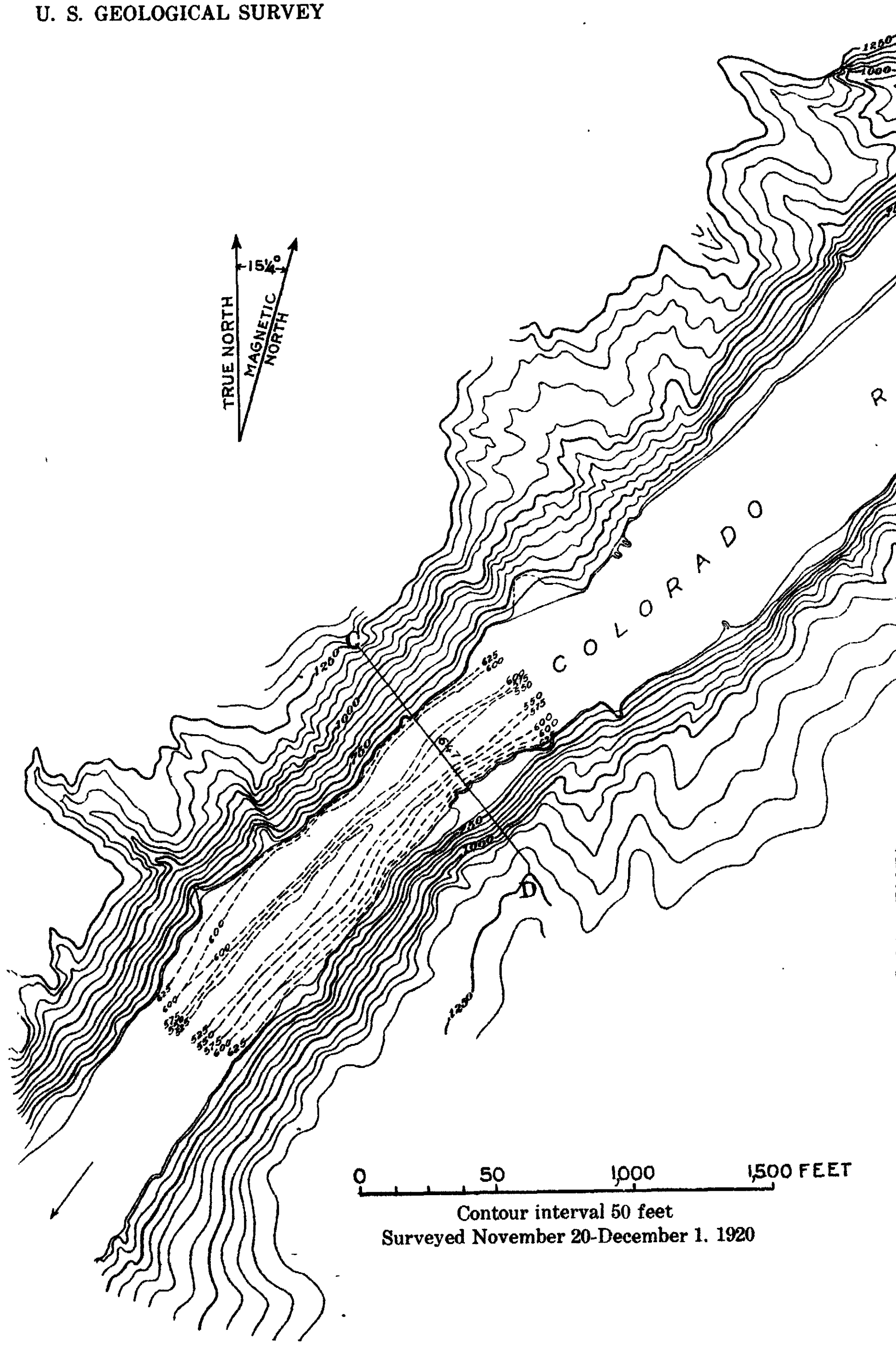
A. BOULDER CANYON DAM SITE, SHOWING BARGES USED IN DIAMOND-DRILL WORK

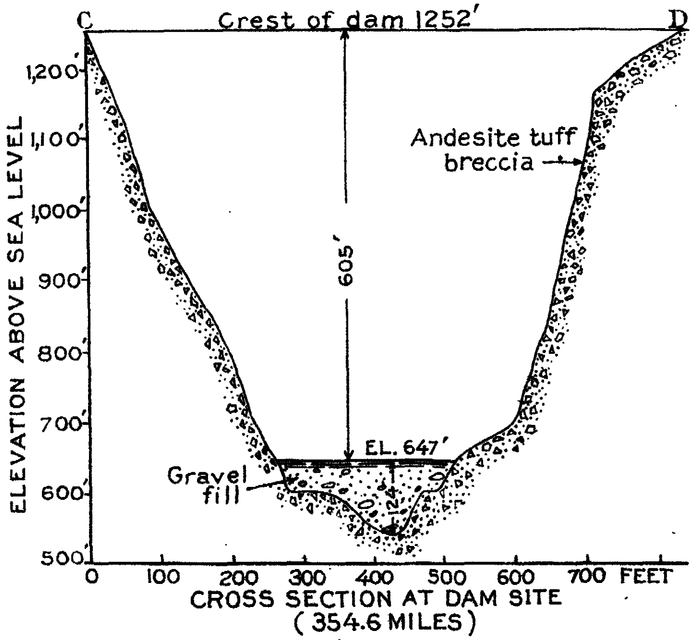
Geology by F. L. Ransome

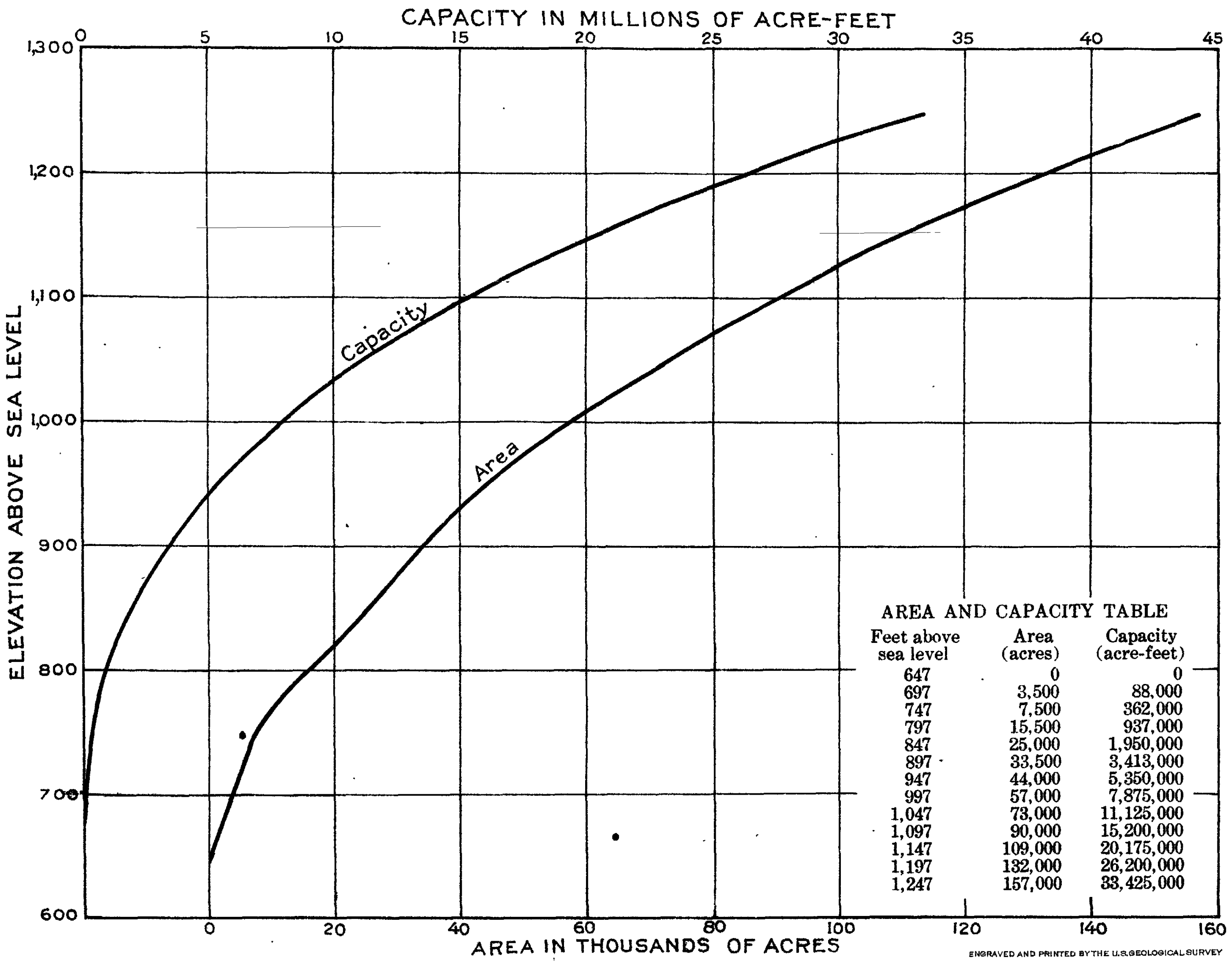


B. UPPER BLACK CANYON DAM SITE

Geology by F. L. Ransome







AREA AND CAPACITY TABLE

Feet above sea level	Area (acres)	Capacity (acre-feet)
647	0	0
697	3,500	88,000
747	7,500	362,000
797	15,500	937,000
847	25,000	1,950,000
897	33,500	3,413,000
947	44,000	5,350,000
997	57,000	7,875,000
1,047	73,000	11,125,000
1,097	90,000	15,200,000
1,147	109,000	20,175,000
1,197	132,000	26,200,000
1,247	157,000	33,425,000

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MAP, CROSS SECTION, AND AREA AND CAPACITY CURVES FOR BLACK CANYON FLOOD-CONTROL AND POWER SITE

to be 158 feet below the water surface. Sufficient drilling was done to furnish data for drawing under-water contours showing the position of the rock foundation at the site. (See Pl. VIII.) It was proposed to build a dam here to raise the water 600 feet and form a reservoir with a storage capacity of 31,400,000 acre-feet. The height of the dam above its foundation would be about 768 feet. The Bureau of Reclamation made exhaustive surveys of the Boulder Canyon reservoir site and of dam sites in Boulder and Black canyons. On account of the lesser depth to bedrock in Black Canyon and other features affecting the cost of construction, the plan to build a dam in Boulder Canyon has been abandoned by the Bureau of Reclamation in favor of a site in Black Canyon.

UPPER BLACK CANYON DAM SITE[14]

The upper Black Canyon dam site is about 18 miles below the dam site at the head of Boulder Canyon (Pl. II, in pocket). Although the distance between the walls in Black Canyon is somewhat greater than in Boulder Canyon, the depth to bedrock is less, being at most about 125 feet below the water surface. A dam in Black Canyon would give greater storage capacity than a dam in Boulder Canyon constructed to the same height above low water. A map of the upper Black Canyon dam site, a cross section at the dam site, and a diagram showing the area and capacity of the reservoir site are shown in Plate X. The upper Black Canyon site was thoroughly investigated by means of diamond-drill borings. The under-water contours (Pl. X) show the position of the rock floor of the canyon with relation to the water surface of the river.

The rock that forms the foundation and abutment walls at this site is of volcanic origin and has been classified by F. L. Ransome as andesite tuff-breccia. The rock is like concrete in that it is composed of rock fragments cemented together in a solid mass. The compressive strength of concrete is determined by testing a concrete core 6 inches or more in diameter. The compressive strength of the rock that is used as the aggregate may be forty times greater than the compressive strength of the concrete. The compressive strength of the volcanic breccia that forms the walls in Black Canyon should be determined by similar tests.

The plans of the Bureau of Reclamation as presented to the Committee on Irrigation and Reclamation of the House of Representatives,[15] in February, 1924, call for the construction of a dam in Black Canyon to raise the water 605 feet, which would create a storage

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[14] This site has been called the Black Canyon dam site, but to avoid confusion with the middle Black Canyon and lower Black Canyon sites, described elsewhere in this report, it is here called the upper Black Canyon site.

[15] 68th Cong., 1st sess., Hearings before Comm. Irrigation and Reclamation, House of Representatives, on H. R. 2903, by Mr. Swing, 1924.

capacity of 34,000,000 acre-feet. The height of the dam above bedrock would be 740 feet. A view of the dam site is shown in Plate IX, *B*. This dam is designed to serve four purposes—flood control, regulation of flow in the interest of irrigation, development of power, and storage of silt. For flood control only, F. E. Weymouth, formerly chief engineer of the Bureau of Reclamation, suggested a dam 523 feet in height above its foundation, which would raise the water to an elevation of 1,033 feet above sea level and create a storage capacity of 10,000,000 acre-feet. He has estimated the cost of such a dam at about $28,000,000. The Callville, Boulder Canyon, Virgin Canyon, Hualpai Rapids, Grand Wash Canyon, and Pierces Ferry dam sites would be submerged, and the backwater would interfere with the development of power at the Devils Slide site, which is 1,034 feet above sea level.

A dam at the upper Black Canyon site for flood control only would prevent dangerous floods, except those from Gila River.

MOHAVE CANYON RESERVOIR SITE

RESERVOIR BASIN

The Mohave Valley is a large basin extending from Bulls Head southward to The Needles. The center of the basin is occupied by a broad flood plain, which has an area of nearly 50,000 acres. Here the Colorado becomes a meandering stream, following a circuitous course 50 miles long in passing through the 35-mile stretch of Mohave Valley. Owing to its unstable banks and flat gradient, the course of the river is ever changing. At the lower end of the valley the low hills close in, and here the river occupies Mohave Canyon, a narrow channel 240 feet wide, flanked on both sides by walls of granitic rock. This narrow channel has a choking effect, for between high and low stages of flow the change in water level in Mohave Canyon is much greater than it is near the head of the valley, where the river channel is nearly 1 mile wide. Thus Mohave Valley, with its narrow outlet, acts as a natural detention basin storing the flood waters until the carrying capacity of the channel in Mohave Canyon becomes equal to the flood discharge entering the valley. During high stages of flow the bottom lands of the valley are submerged, giving the lower part of the valley the appearance of a large lake.

If a dam were built in Mohave Canyon, Cottonwood Valley, which lies just above Pyramid Canyon, would also be submerged. The lands in the lower Cottonwood Valley are now submerged during flood periods.

Within the flowage line of the proposed Mohave Canyon reservoir there is about 40,000 acres of land that is classed as irrigable. The greater part of this area is now subject to overflow during floods. This land lies in narrow strips along the river and can not be successfully reclaimed by irrigation unless an extensive levee system is constructed. Such a levee system would be required even if the floods were controlled by storage above. As the lands lie within the present flood plain of the river, a drainage system would also be required. It would be necessary to pump the drainage water back over the levee into the river. These features, combined with the diversion works and canal system, would make the reclamation of these lands by irrigation rather expensive.

Lieut. Joseph C. Ives,[16] of the Corps of Topographical Engineers, United States Army, who explored the Colorado River by steamboat in 1857, refers to Mohave Valley as follows:

> A system of irrigation and an improved method of agriculture would make the valley far more productive, but it is not certain that it would ever be a profitable place for white settlements. The shifting of the river bed, which to the Indians, who have a certain community of property, is a matter of little importance, would occasion serious embarrassment to settlers who had established permanent locations and improvements. The rapidity and extent of the changes in the position of the Colorado can scarcely be imagined by one who has not witnessed them. Having an opportunity to compare the conditions of things at present (1857) with what it was four years ago, I have been able to appreciate the transformations that are liable to occur and am satisfied that there are few places in the bottom lands that may not, during any season, be overrun.

Since 1910 about $500,000 has been spent, mostly by a private concern, on irrigation works in Mohave Valley. Diversion works, levees, and canals were built, and lands with water rights were sold at $60 an acre. The levee was destroyed by the river, and the diversion works were nearly covered by the deposition of silt. The project was soon abandoned, practically nothing having been accomplished in the way of reclaiming by irrigation the Mohave Valley lands. Lieutenant Ives correctly judged the conditions in this valley.

In view of these facts and the fact that there is more irrigable land below Parker in the United States than can be served with the available water supply, it seems reasonable to assume that the irrigable lands in Mohave Valley should not be a determining factor with reference to the feasibility of the Mohave Canyon reservoir site.

As has been explained, the Mohave Valley in its natural state acts as a detention basin when the river is in flood. Below the flowage line of the proposed reservoir there is 62,500 acres of land within 10 feet above the low-water level of the river, including the river bed. The natural loss of water in this area due to evaporation and transpiration from plant growth is about 360,000 acre-feet annually. If the basin were utilized as a reservoir for flood control, the loss of water due to evaporation would not exceed 375,000 acre-feet annually. The annual net loss to the river would therefore be about 15,000 acre-feet.

[16] Report upon the Colorado River of the West: 36th Cong., 1st sess., Ex. Doc., p. 73, 1861.

If the Mohave Canyon reservoir site were utilized, it would be necessary to relocate the town of Needles, the Mohave Indian School, and about 20 miles of the Atchison, Topeka & Santa Fe Railway. This work could be done at a reasonable cost.

MOHAVE CANYON DAM SITE

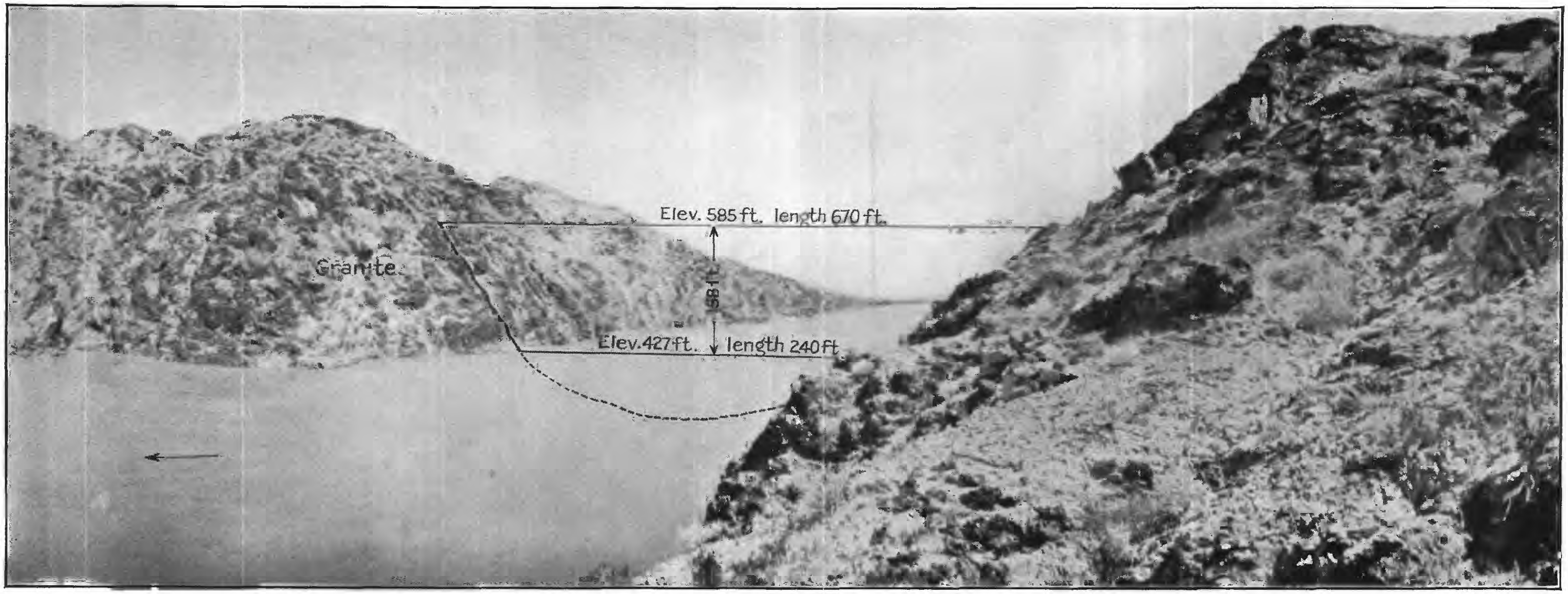
Location and geologic conditions.—The Mohave Canyon dam site is 2½ miles below Topock, Ariz. (See Pl. II, in pocket.) A detailed survey was made of the site in June, 1923, and a preliminary report in which attention was called to its possible value was prepared by the writer in July, 1923. Here the river has cut a narrow gorge through the granite, the distance between the canyon walls at the dam site being only 240 feet. Pictures of the dam site and part of the reservoir basin are shown in Plate XI.

The walls at the dam site consist of medium to coarse grained crystalline igneous rocks, which have been altered apparently by heated aqueous solutions. The rock is massive and hard, and although it is somewhat minutely fractured on long-exposed surfaces, there is no reason to doubt that in strength and in resistance to leakage it would be satisfactory for the foundation and abutments of a dam. The granite rocks extend from the river back several hundred feet to a saddle on the Arizona side. The rocks east of the saddle, though granitic, are softer, coarser grained, and more deeply disintegrated than the rocks nearer the river. All the evidence observed points to the conclusion that there is no likelihood of seepage of any importance through these rocks. A more detailed description of the rocks at the dam site is given in Appendix B, page 170.

In Plate XII will be found a topographic map and cross section of the dam site and curves showing the area and capacity of the reservoir. A dam to raise the water 155 feet would create a storage capacity of 10,000,000 acre-feet.

Plan of development.—A concrete dam of the overflow type is probably best adapted to fit the conditions at this site. The required height of dam will depend on the amount of storage capacity desired for flood control and on the decision whether or not power is to be developed at the dam. The development may be so planned that it can be operated in the interests of flood control and irrigation and also permit the development of sufficient power to pay for the cost of the dam. The writer believes that the saving of human life, the prevention of damage to property, and the regulation of the flow to meet the demand for water for irrigation are of sufficient importance to justify the construction of a strictly flood-control dam, which may at all times be operated in the interests of flood control and irrigation.

A dam in Mohave Canyon to raise the water 95 feet would create a storage capacity of 4,000,000 acre-feet, which would be sufficient to

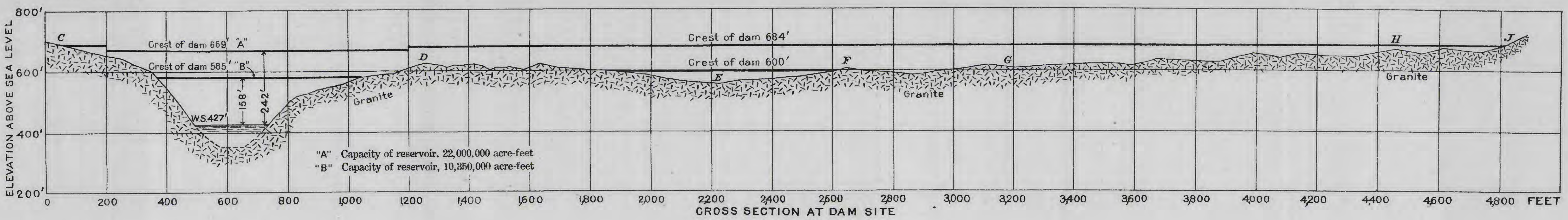


A. MOHAVE CANYON DAM SITE, NEAR TOPOCK, LOOKING UPSTREAM

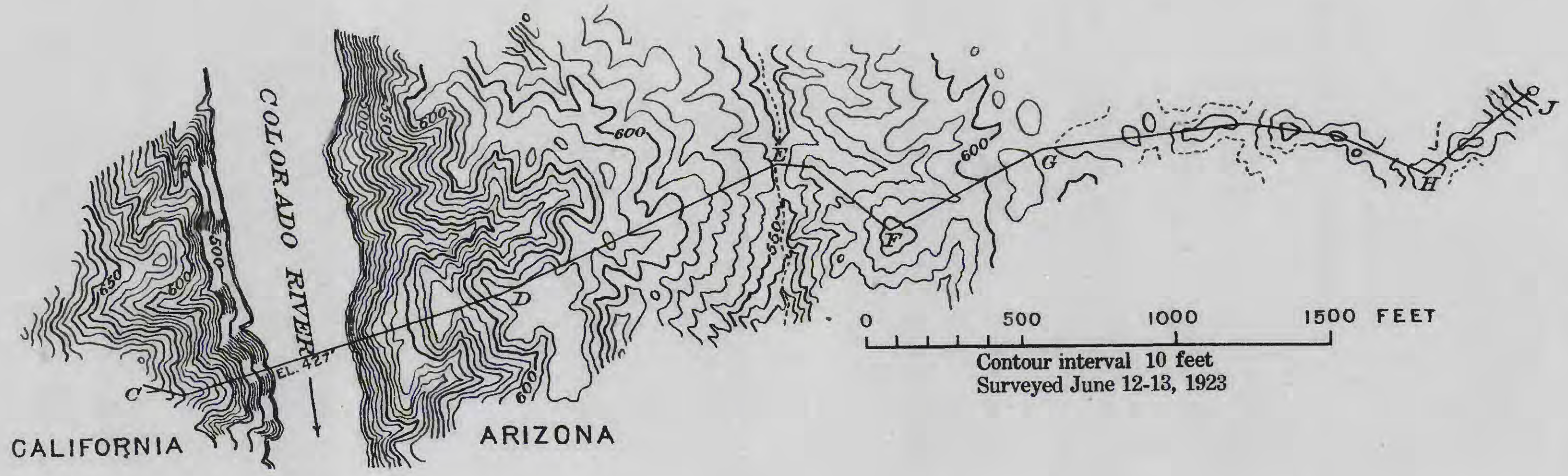
Geology by R. C. Moore

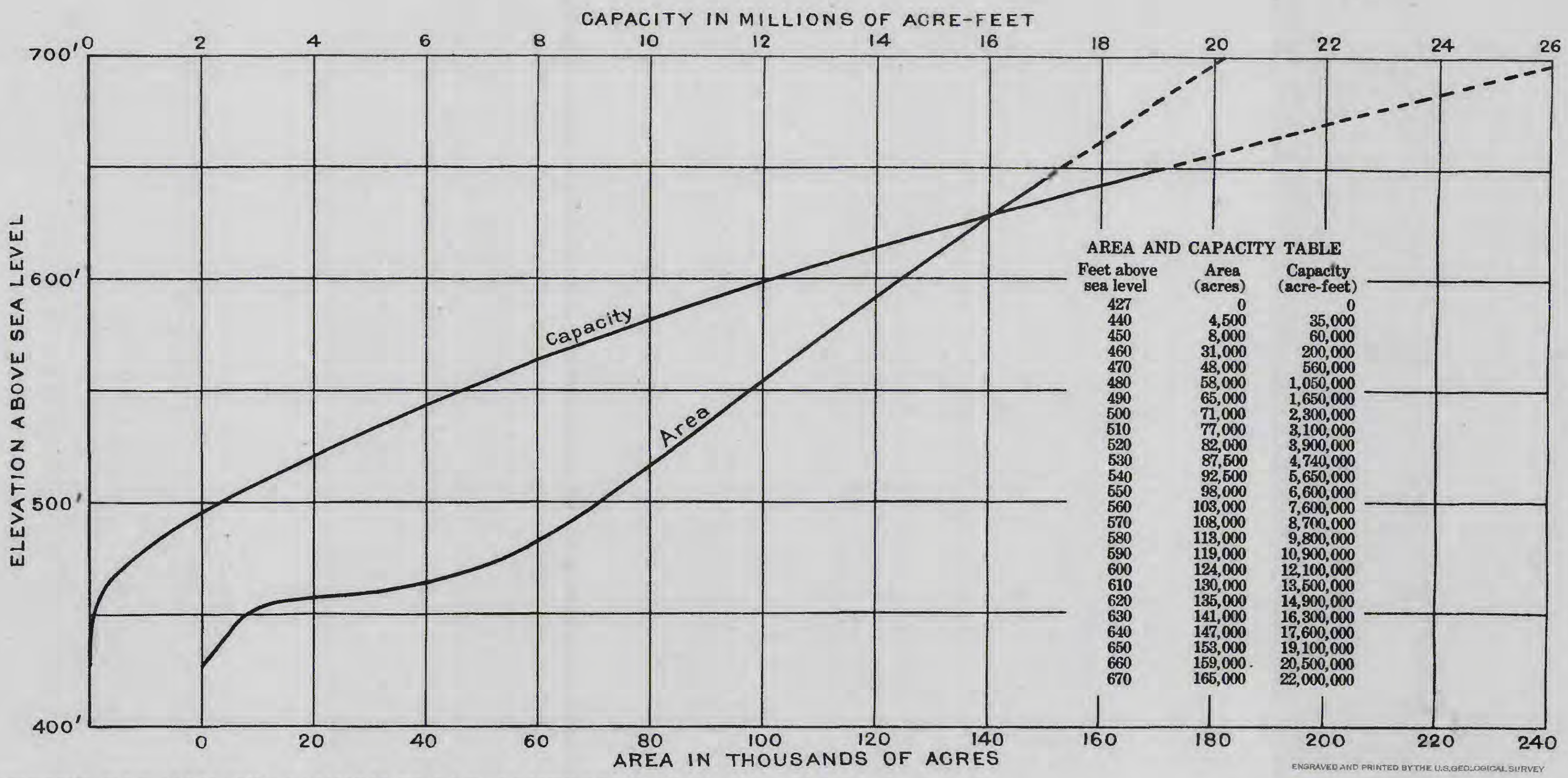
B. UPSTREAM VIEW OF COLORADO RIVER AT TOPOCK

Showing lower part of the basin that would be submerged if a dam were built in Mohave Canyon



CROSS SECTION AT DAM SITE





AREA AND CAPACITY TABLE

Feet above sea level	Area (acres)	Capacity (acre-feet)
427	0	0
440	4,500	35,000
450	8,000	60,000
460	31,000	200,000
470	48,000	560,000
480	58,000	1,050,000
490	65,000	1,650,000
500	71,000	2,300,000
510	77,000	3,100,000
520	82,000	3,900,000
530	87,500	4,740,000
540	92,500	5,650,000
550	98,000	6,600,000
560	103,000	7,600,000
570	108,000	8,700,000
580	113,000	9,800,000
590	119,000	10,900,000
600	124,000	12,100,000
610	130,000	13,500,000
620	135,000	14,900,000
630	141,000	16,300,000
640	147,000	17,600,000
650	153,000	19,100,000
660	159,000	20,500,000
670	165,000	22,000,000

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MAP, CROSS SECTION, AND AREA AND CAPACITY CURVES FOR MOHAVE CANYON FLOOD-CONTROL SITE

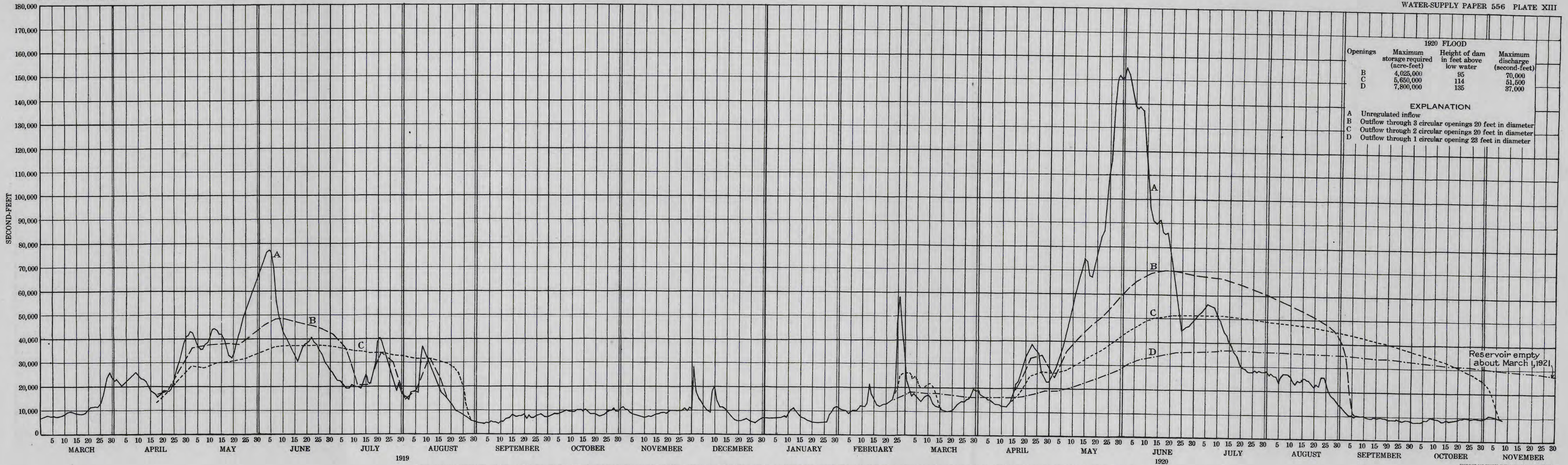

CHART SHOWING HOW THE FLOODS OF 1919 AND 1920 COULD HAVE BEEN CONTROLLED BY STORAGE AT MOHAVE CANYON RESERVOIR SITE

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reduce to 70,000 second-feet a flood like the one that occurred in 1920. This flood could have been reduced to 37,000 second-feet with a dam in Mohave Canyon constructed to a height of 135 feet above low water (Pl. XIII). It may be desirable to build the dam 23 feet higher still, or 158 feet above low-water level, to obtain a storage capacity of 10,350,000 acre-feet. The additional cost of the higher dam would be small in comparison with the total cost of the project, including the cost of the right of way.

Enlarged Mohave Canyon reservoir.—The Mohave Canyon reservoir could be developed to a capacity of 24,000,000 acre-feet by constructing a dam with spillway 242 feet above low water and with high-water line 15 feet above the spillway crest. Such a dam would have a total length of 4,760 feet, but its volume would be only 720,000 cubic yards, little more than half that of the Wilson dam on Tennessee River at Muscle Shoals, Ala. The cost of increasing the capacity from 10,000,000 to 24,000,000 acre-feet would not greatly exceed the cost of the additional concrete that would be required in the higher and longer dam. The enlarged reservoir could be operated with an ordinary maximum capacity of 10,000,000 acre-feet or less, thus avoiding interference with power development on the river above, the excess capacity over this ordinary maximum being reserved for use in time of an extraordinary flood due to natural causes or to the failure of dams upstream.

The comprehensive scheme of development suggested by the writer (p. 42) provides for 11 dams between the mouth of Green River and Mohave Canyon, and including a dam at the Dewey site the aggregate storage capacity would be 20,000,000 acre-feet, as shown in the following table:

Dam sites on Colorado River above Mohave Canyon that may be utilized for irrigation and power development

Site	Elevation above sea level [a]	Height of dam [b]	Area of water surface when reservoir is full	Storage capacity above dam
	Feet	*Feet*	*Acres*	*Acre-feet*
Dewey	4,087	215	11,800	2,270,000
Dark Canyon	3,528	512	39,100	3,850,000
Glen Canyon	3,127	380	58,300	7,760,000
Red Wall	2,886	222	2,050	160,000
Mineral Canyon	2,531	345	6,710	810,000
Ruby Canyon	2,235	286	2,050	244,000
Specter Chasm	2,002	223	1,770	169,000
Havasu	1,783	209	1,640	147,000
Bridge Canyon	1,207	566	12,400	2,280,000
Devils Slide	1,034	163	885	75,000
Hualpai Rapids	799	225	9,700	1,090,000
Lower Black Canyon	595	194	17,500	1,200,000
			163,905	20,055,000

[a] The figures in this column represent the elevation of the water surface at the dam site when the discharge of the river is 10,000 second-feet.
[b] The figures in this column indicate the height of the spillway above average low water.

Eventually this or some substantially equivalent scheme of development will be carried out. Should such a series of dams fail in quick succession, the enlarged Mohave Canyon reservoir, operated as suggested above, would control the resulting extraordinary flood of water without danger to the Mohave Canyon dam and thus prevent disaster on the lower river.

Although the maintenance of a great storage capacity unused through a period of years can not ordinarily be justified, the writer believes that here, as in the Miami Conservancy District, Ohio, the cost of developing the excess capacity of the reservoir will be so small in comparison with the great and ever increasing value of the property thus protected, that such maintenance may be warranted, and therefore that serious consideration should be given to the development and operation of the 24,000,000 acre-foot reservoir as suggested.

SUMMARY OF FLOOD CONTROL

GENERAL CONDITIONS

The flow of Colorado River at Yuma during floods has exceeded 200,000 second-feet. Properties on the lower river are menaced by these floods, and there is general agreement that they should be prevented by means of storage.

The Yuma Valley and the Imperial Valley in the United States and Mexico are menaced by floods from both the Colorado and its tributary the Gila. The floods of the Gila are commonly short and violent and usually occur in January, February, and March. The floods on Salt River, a tributary of the Gila, are now controlled by the Roosevelt dam. Congress has authorized the construction of a storage dam on Gila River at San Carlos, which will materially reduce the floods of the lower Gila. Storage dams are proposed on two other tributaries of Gila River, the Hassayampa and the Agua Fria. If these dams are built the waters of the Gila will be stored and released in the interest of irrigation and power development. Incidentally these storage works will solve the flood problem of the lower Gila.

The most dangerous floods in Colorado River occur during May, June, and July and are caused by melting snow in the upper part of the basin, in Utah, Wyoming, and Colorado. Reservoir sites in the upper basin are described above (pp. 17–19). The Flaming Gorge and Ouray sites are on Green River, the Dewey site is on the Colorado above the mouth of Green River, and the Bluff site is on San Juan River. A few years ago it was believed that the utilization of a combination of these reservoir sites in the upper basin offered the best solution of the problem of flood control on the lower river. However, at that time little was known of the storage sites on the main stream below San Juan River.

The operation of a combination of reservoirs in the upper basin in such a way as to control floods in the lower river might seriously affect the future irrigation and power development in the upper basin. As the floods of the lower river can be controlled by utilizing storage sites in the lower basin, it seems best that the reservoir sites in the upper basin should be reserved for use in furthering the interests of power development in that basin. Such developments in the upper basin would incidentally benefit the water users in the lower basin by creating a more uniform flow in the lower river.

Three reservoir sites below San Juan River suitable for flood control are known—namely, Glen Canyon, Boulder Canyon, and Mohave Canyon. The physical conditions at these sites are described on the preceding pages. In determining the relative value of the three sites the following fundamental features should receive serious consideration:

1. The time required to construct the project.
2. The effectiveness of the completed project in eliminating the flood menace.
3. The benefits other than flood control resulting from the construction of the project.
4. The adaptability of the project with relation to the full development of the water resources.
5. The cost of the project as compared with the benefits to be derived from it.

GLEN CANYON RESERVOIR SITE

At the Glen Canyon site bedrock lies 80 feet below the water surface. The conditions are favorable for taking care of the water during the construction period, and with bedrock so near the surface the time required to complete the under-water work would be reduced to a minimum. It is estimated that a dam which would provide about 8,000,000 acre-feet of storage capacity could be completed in six years.

Owing to its position on the river, a storage reservoir in Glen Canyon would afford slightly less effective flood control than a reservoir at either Boulder Canyon or Mohave Canyon. The incidental benefits that would result from the construction of a flood-control dam in Glen Canyon, however, are far greater than those at either of the other sites. There are 10 dam sites below Glen Canyon where a total head of 2,523 feet may be utilized for the development of power. At the present time, without storage, the total power capacity of these 10 sites is 1,758,000 horsepower. With storage in the Glen Canyon reservoir, the power capacity of these 10 sites would be increased to 4,345,000 horsepower. To obtain this amount of power, however, the reservoir would have to be operated primarily in the interest of power development; but the floods would incidentally be controlled. At some future time a reservoir below the Grand Canyon would be required to re-regulate the flow in such a way as to meet the demand for water for irrigation. It has been estimated that with ultimate development in the upper basin, 334,000 continuous horsepower may be developed at the Glen Canyon dam after reserving 4,000,000 acre-feet of storage capacity for regulation of the flow in the interest of power development.

The Glen Canyon dam would relieve the flood menace, provide water for future irrigation development, more than double the quantity of power that could be developed on the lower river, and greatly reduce the cost of all dams subsequently built on the river below Glen Canyon.

In view of the benefits of many kinds that may ensue from the completed project, the Glen Canyon dam would probably be the most valuable flood-control dam on the river. The writer believes that any comprehensive plan of development that provides for the full utilization of the water resources of the river must include the Glen Canyon reservoir site.

BOULDER CANYON RESERVOIR SITE

It has been suggested by the Bureau of Reclamation that the Boulder Canyon reservoir site may be utilized by building a dam in Black Canyon. According to this bureau, the purpose of such a project would be to provide either storage for flood control only or storage at one place to control floods, supply water for irrigation, and develop power. The dam that would serve for flood control only will be considered here. Such a dam would raise the water 388 feet and furnish a storage capacity of 10,000,000 acre-feet. It would be 523 feet in height above its foundation. The depth to bedrock is 44 feet greater here than at the Glen Canyon dam site, and the conditions for taking care of the water during the construction of the dam are less favorable. The time required for the construction of such a dam at Black Canyon, however, is estimated at six years, or the same as at the Glen Canyon site.

If 10,000,000 acre-feet of storage capacity at the Boulder Canyon reservoir site were available for flood control, the floods of the lower river could be eliminated, except those from Gila River. The stored water, however, would have small value for the development of power below the reservoir. The water surface at the Black Canyon dam site is 647 feet above sea level, and it is not likely that more than 200,000 horsepower will ever be developed on the river below this point. This quantity may be compared with the 4,345,000 horsepower which may be developed if storage is provided in Glen

Canyon. Although a dam at Black Canyon constructed for flood control only could be so operated as to regulate the flow in the interest of irrigation it would have small value for any other purpose.

If a dam were built at Black Canyon for flood control, it is not likely that a dam in Mohave Canyon would ever be built. It might be feasible to build a dam for the development of power at Bulls Head, where a head of about 100 feet could be utilized. A small amount of power could also be developed at the diversion dam proposed at Parker. If the plan to build a dam at Black Canyon for flood control only were carried out, it would prevent the development of 400,000 horsepower, for this amount of power could be developed in the Black Canyon section if storage for flood control and irrigation were provided at Mohave Canyon.

The Bureau of Reclamation estimates the cost of the Black Canyon flood-control dam at $28,000,000, which is probably less than the cost of a dam to provide the same amount of storage at Glen Canyon.

MOHAVE CANYON RESERVOIR SITE

A storage capacity of 10,000,000 acre-feet may be created at the Mohave Canyon reservoir site by building a dam to raise the water 155 feet. The depth to bedrock is unknown, but it seems reasonable to estimate the height of the dam above its foundation at 240 feet. This may be compared with 523 feet for a dam at Black Canyon to provide the same storage capacity. The Mohave Canyon dam site is easily accessible, being only 2½ miles from the railroad; the walls are low, and the conditions are favorable for carrying on the work of construction; and the volume of the dam would be relatively small. All these features lead the writer to believe that the dam could be built in three years. The work of relocating the railroad and the town of Needles could be carried on simultaneously with the construction of the dam and might easily be completed within the same time.

The Mohave Canyon reservoir site is low on the river, near the lands that are menaced by the floods, and would therefore be more effective in eliminating the flood menace than a flood-control dam at either Boulder Canyon or Glen Canyon.

The favorable features of this site may be summarized as follows:

1. It would provide more effective flood control than any other known reservoir site on the river.

2. The project may be constructed in less time and probably at less cost than any other project that would provide the same amount of storage capacity for flood control.

3. It is the only site where adequate storage capacity may be provided for flood control, and at the same time a maximum use of

the water for irrigation and for the development of power may be permitted.

4. It is the only site on the river where sufficient storage capacity may be provided to protect the interests on the lower river from floods due either to natural causes or to the failure of a series of dams constructed in and above the Grand Canyon, and at the same time permit maximum power development.

5. It is more accessible than any other known flood-control site on the river.

6. If deemed advisable, the site could be developed to serve four purposes—flood control, the storage of water for irrigation, the development of power, and the storage of silt.

7. The net additional loss of water due to evaporation would be materially less here than at any other known storage site on the river.

8. Materials suitable for the construction of the dam are available at the site.

9. For a given height of dam the storage capacity of the Mohave Canyon reservoir site is ten times greater than the storage capacity at either Boulder Canyon or Glen Canyon.

10. Under full irrigation development, no water should be permitted to pass the storage dam except as needed to meet the demand for water for irrigation. With a storage capacity of 22,000,000 acre-feet provided at Mohave Canyon, the excess flow during wet years can be stored and released to meet the demands for water during years of low run-off.

The unfavorable features of the Mohave Canyon site are these:

1. Stored water released at Mohave Canyon would have a minimum value for the development of power.

2. Storage at Mohave Canyon would not lessen the cost of dams subsequently built farther up the river.

CONCLUSIONS

If flood-control works are not built on the Colorado it is certain that before many years pass the river will experience a flood that will cause a property loss amounting to many millions of dollars. Such a flood may occur next year, or it may not occur for 10 years.

The benefits that would ensue through the construction of a flood-control dam in Glen Canyon, set forth in the preceding discussion, suggest that this site should be selected if it were known that the dam could be built in time to prevent the loss of property on the lower river. Six years may be required for the construction of a dam in Glen Canyon, whereas the time required to provide adequate storage for flood control at Mohave Canyon is estimated at three years. It is desirable to provide flood-control works as quickly as possible; therefore the Mohave Canyon site deserves first consideration and should be thoroughly investigated before a decision is reached.

WATER POWER

The present study of the water power that may be developed at sites on Colorado River below the mouth of Green River involves consideration of power capacities between elevations of 4,040 and 358 feet above sea level. In calculating the water-power value of the several sites, the problem of flood control and the use of water for irrigation have received first consideration. The power capacity is given for present conditions of stream flow and for future conditions when the flow will have been depleted by the development of irrigation.

METHOD OF ANALYSIS

UNITS OF DEVELOPMENT

A dam may be constructed in Cataract Canyon below the mouth of Green River to raise the water to an elevation of 4,040 feet above sea level without damage to the town of Green River or the railroad bridge at that point and without interfering with the development of the Dewey power site, on Colorado River below the mouth of Dolores River. The lowest power site on the Colorado considered in this report is 5 miles above Parker, Ariz., where the river surface at low water is 358 feet above sea level. The difference in elevation between the forebay of the proposed Cataract Canyon dam and the tail water at the proposed Parker dam is therefore 3,682 feet. All the potential power indicated by the total fall of 3,682 feet can not be made available. About 309 feet of the fall will probably be used at dams built for controlling floods and regulating the stream flow in the interest of irrigation and power development. At each power dam provision may be made for a draw-down in the forebay to take care of the daily fluctuation in load. Between power dams a certain amount of fall must be allowed to take care of the slope in reservoir surfaces. In dividing the river into units for storage and the development of power allowance has been made for these losses in head.

POWER COMPUTATIONS

The full static head at each power site may be obtained by noting the difference in elevation between the water in the forebay and the tail water at the outlet of the draft tubes. The power available for electrical transmission has been estimated as 70 per cent of the theoretical power, because of losses due to friction in diversion works, penstocks, water wheels, and draft tubes and losses in generators and transformers. The formula that has been used is

$$\text{Horsepower} = H \times Q \times 0.08$$

in which H is the average static head in feet, Q is the water supply in cubic feet per second, and 0.08 represents the horsepower at 70 per cent efficiency of 1 cubic foot of water per second discharging under a head of 1 foot.

WATER SUPPLY

A study has been made of the stream-flow records to determine the available water supply for present and future development on the lower river. The results of this study are given in detail in Appendix A. Only the conclusions relative to water supply will be given here.[17]

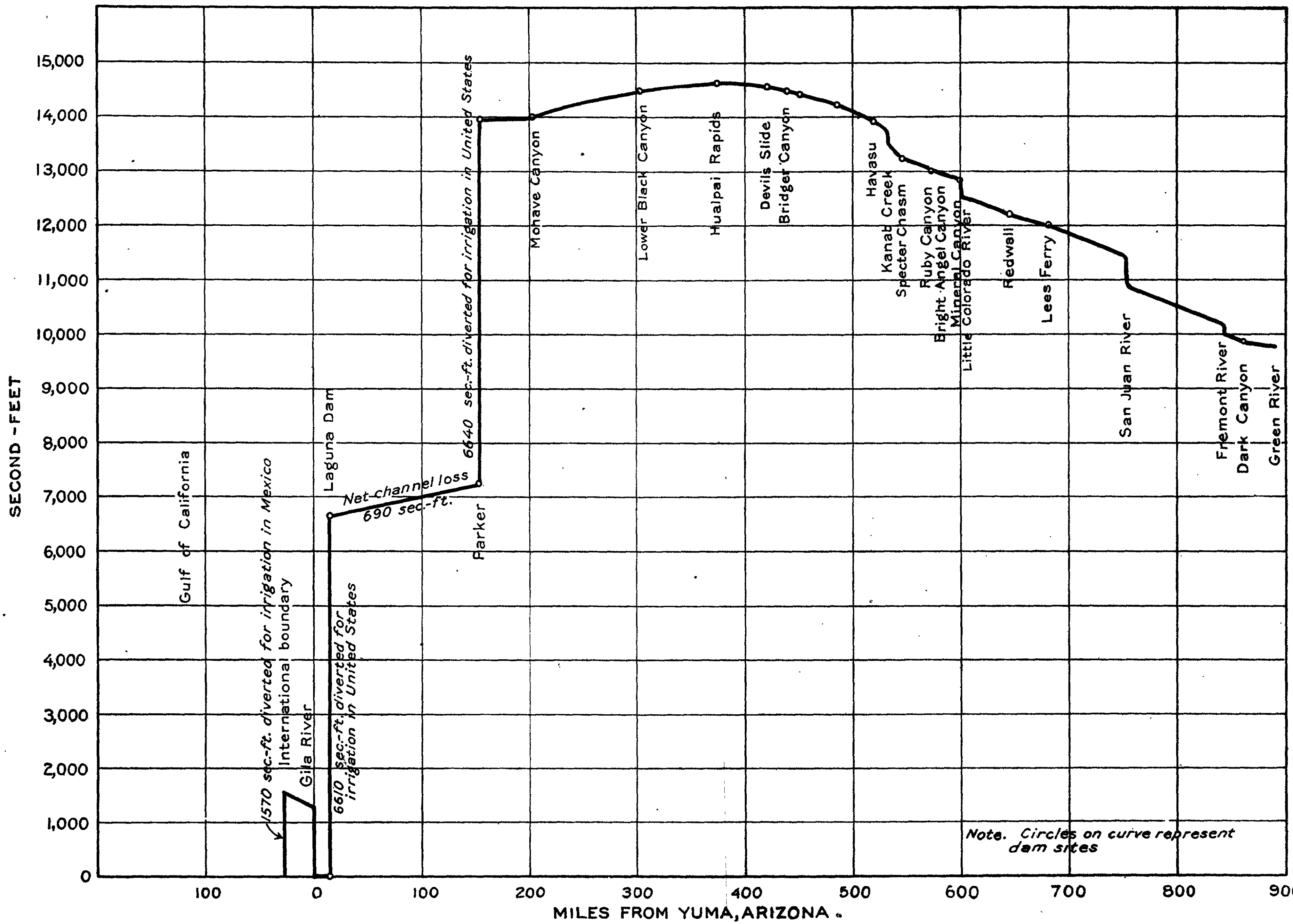
1. If there were no further depletion of the water supply in the upper basin, and if storage were provided at the site near Lees Ferry, it would be possible to maintain a uniform flow at Lees Ferry of about 19,300 second-feet. Inflow in the Grand Canyon would increase the flow available in this section of the river to a maximum of 22,600 second-feet at the lower Black Canyon dam site. Losses in the river channel below this dam site would reduce the amount of water available at Parker to about 22,100 second-feet.

The figures given in column 1, Table 9, Appendix A, represent the maximum available water supply, which could be utilized only for a short term of years. It is known that irrigation development in the upper basin will continue to increase, and therefore the maximum available water supply for the lower river will decrease correspondingly.

Under complete development in the basin the channel of Colorado River on the delta below the lowest canal heading in Mexico would become dry. Plate XIV shows graphically the average flow that may reasonably be expected at all points on Colorado River between the mouth of Green River and the Gulf of California after complete development of the water resources has been attained. This diagram shows that the average flow of the Colorado at the mouth of Green River will ultimately be about 9,750 second-feet, and at Lees Ferry 12,000 second-feet. Below Lees Ferry the average flow will increase, reaching a maximum of 14,730 second-feet at the lower end of the Grand Canyon, in the vicinity of Pierces Ferry. Below Pierces Ferry the average flow will be diminished by evaporation and other losses until at the Parker dam site it is reduced to 13,940 second-feet.

It is estimated that an average of 6,640 second-feet of water may be diverted at Parker for irrigation. The annual loss of water in the river channel between Parker and the Laguna dam, due to natural causes, is estimated at 1,000,000 acre-feet. The net loss of water

[17] As explained in footnote 1, p. 9, the computations made for conditions in 1922 apply equally well to 1925.



ESTIMATE OF WATER SUPPLY THAT MAY REMAIN AVAILABLE IN COLORADO RIVER BELOW THE MOUTH OF GREEN RIVER WITH COMPLETE DEVELOPMENT IN THE UPPER BASIN AND THE LOWER RIVER AS OUTLINED IN THIS REPORT

between Parker and the Laguna dam will be reduced to about 500,000 acre-feet annually, or 690 second-feet, by the return flow from the irrigated lands near the river below Parker. The average flow available at the Laguna dam is therefore estimated at 6,610 second-feet. At the Laguna dam the entire flow may be diverted for irrigation, leaving the channel of Colorado River dry between this dam and the mouth of Gila River.

The return flow that may be expected from irrigated lands in the lower basin of Gila River is estimated at 1,310 second-feet. This water, with some return flow from the Yuma project, may all be diverted for the irrigation of about 200,000 acres of land in Mexico, leaving the Colorado dry for the last 100 miles to its mouth.

2. Under present conditions of development in the upper basin, without storage, the flow available 50 per cent of the time would be about 9,540 second-feet at Lees Ferry, 10,900 second-feet at Bridge Canyon, and 11,100 second-feet at Black Canyon, Mohave Canyon, and Parker. (See column 2, Table 9, Appendix A.)

3. Under present conditions of development in the upper basin, without storage, the flow available 90 per cent of the time would be about 5,780 second-feet at Lees Ferry, 7,270 second-feet at Bridge Canyon, and 7,330 second-feet at Black Canyon, Mohave Canyon, and Parker. (See column 3, Table 9, Appendix A.)

4. The data relative to water supply given in the preceding conclusions would be applicable to any project constructed on the lower river before large projects for irrigation or storage are developed in the upper basin. A study to determine to what extent the water supply will be depleted by ultimate development in the upper basin should precede the construction of any large project on the lower river. Such a study has been made by the writer, with the data now available.

It seems reasonable to believe that when ultimate development is attained in the upper basin, and the river is developed in the canyon section and below as outlined in this report, the available water supply, including accretions from return flow, will be equivalent to a uniform flow of about 12,000 second-feet at Lees Ferry, 14,440 second-feet at Bridge Canyon, 14,600 second-feet at Greggs Ferry, 13,970 second-feet at Mohave Canyon, and 13,940 second-feet at Parker. (See column 4, Table 9, Appendix A.)

5. Under the conditions just outlined, the annual water supply of Colorado River available for irrigation below Parker will be about 9,593,000 acre-feet. (See Pl. II.) There is 2,304,000 acres of land below Parker, in and adjacent to the Colorado River basin in the United States, that is classed as irrigable. The annual water requirement for the irrigation of this land would be 9,909,000 acre-feet. The annual demand would exceed the water supply by only 316,000

acre-feet. These studies show that the entire flow of Colorado River can be used for irrigation in the United States. Only the return flow reaching Colorado River below the Laguna dam, estimated at 1,143,000 acre-feet annually, would pass into Mexico, an amount sufficient to irrigate about 200,000 acres.

6. The area of land in Mexico that is classed as irrigable from Colorado River is estimated roughly at 1,000,000 acres. The irrigation of this land would require about 3,357,000 acre-feet of water annually, in addition to the 1,143,000 acre-feet of return flow mentioned in the preceding paragraph.

The cities of southern California may find it advisable to divert 2,000 second-feet of water from Colorado River to augment their domestic water supply. This would be equivalent to an annual diversion of 1,448,000 acre-feet.

The total amount of water required annually to serve the irrigable lands in the United States and Mexico, referred to above, and to furnish a domestic water supply to the cities of southern California would be about 14,714,000 acre-feet. As the annual water supply will be only 9,593,000 acre-feet, it is obvious that plans for flood control, irrigation, and power development on Colorado River should be carefully studied so as to avoid all unnecessary waste of water. The irrigation of lands from which the waste water and return flow would become available for use lower on the stream would be desirable.

COMPREHENSIVE PLAN FOR DEVELOPMENT OF RIVER

DETAILS OF PLAN

Although this report deals primarily with the development of power below Green River, Utah, it is necessary in working out a plan of development to give due consideration to the possibilities for utilization of the water resources in the whole basin of Colorado River. If the plan presented here for the development of a part of the river is sound, it should form a part of a comprehensive plan for the entire basin. The main features of such a comprehensive plan may be summarized as follows:

1. Provision to take care of the urgent need for flood control.

2. Maximum practicable irrigation development on headwater tributaries, together with such diversions from the basin as can be justified, accompanied by water storage so far as needed for such purposes.

3. Maximum practicable power development in the upper basin, subject to irrigation development.

4. Power development in the canyon section below Green River, Utah, with storage reservoirs on this stretch of the river operated primarily in the interests of power develpoment.

5. Construction of a storage reservoir to be operated primarily in the interests of irrigation and flood control, the reservoir to be located as far downstream as practicable and to trespass on the canyon section only as far as may be found necessary.

6. Maximum practicable irrigation development below Parker.

The plan of development presented here will show with fair accuracy the power possibilities on Colorado River below an elevation of 4,050 feet above sea level, with adequate provision for flood control and maximum irrigation development. (See Pls. II and III, in pocket.) The plan is only a suggestion, and it is expected that a revision of the plan may be necessary when more data become available.

Between Green River, Utah, and Mineral Canyon, Ariz., at elevations of 4,050 and 2,531 feet above sea level respectively, there is but little choice with respect to sites to be included in the plan of development. There are three dam sites in Cataract Canyon, but the Dark Canyon site has been adopted in this report as the best for the development of power. In the 186 miles of Glen Canyon, between Dark Canyon and Lees Ferry, there are eight dam sites, of which seven have been classed as less favorable than Glen Canyon dam site No. 1, 4 miles above Lees Ferry. The unfavorable features of the alternative dam sites in Glen Canyon are their inaccessibility, wide sections, and lack of suitable building material. Owing to its position on the river, large storage capacity, and other favorable features, Glen Canyon with a dam near Lees Ferry has been selected as the site best adapted for the storage of water in the interest of power development in the Grand Canyon and below.

Owing to the presence of shale in the walls and river channel, there are no favorable dam sites in Marble Gorge until the Redwall limestone appears, 30 miles below the mouth of Paria River (Pl. XV). An excellent dam site was found in the Redwall formation at 2,886 feet above sea level. The Redwall dam site is presented as one unit of the comprehensive plan for power development.

As the Redwall rises above the river the underlying Bright Angel shale appears in the river channel and canyon walls. The next favorable dam site was found at Mineral Canyon, in Granite Gorge,[18] at

[18] There are three granite gorges in the Grand Canyon. On February 4, 1925, the Geographic Board named these gorges Granite Gorge, Middle Granite Gorge, and Lower Granite Gorge. The Granite Gorge, which is 41 miles long, begins below Hance Rapids at mile 77 below Paria River. The Middle Granite Gorge is 4 miles long and begins 8½ miles below the Granite Gorge. The Lower Granite Gorge is about 50 miles long and extends from mile 216 below Paria River to mile 266.

In Maj. J. W. Powell's diary, on August 14, 1869 (Exploration of the Colorado River of the West and its tributaries, p. 81, Smithsonian Institution, 1875), the name Granite Gorge as applying to the inner canyon below Hance Rapids is first mentioned. That there is very little granite in the so-called Granite Gorge was known to Major Powell, for in the publication cited he inserted a footnote explaining the use of the word granite as follows: "Geologists would call these rocks metamorphic crystalline schists, with dikes and beds of granite, but we will use the popular name for the whole series—granite."

2,531 feet above sea level. (See p. 56.) It is safe to assume that this site would form a unit of a plan for the development of power in the Grand Canyon.

The preceding suggestions call for the construction of four dams to utilize that part of Colorado River between elevations of 4,050 and 2,531 feet above sea level—a power dam in Cataract Canyon, a combination storage and power dam near Lees Ferry, a power dam in Marble Gorge 30 miles below Paria River, and a power dam at the mouth of Mineral Canyon. The physical conditions are such as to preclude any material change in this portion of the plan.

Below Mineral Canyon dam sites are numerous. Many plans may be suggested for the utilization of the water resources of this section of the river. For example, in the 79-mile section between Mineral Canyon and Havasu Creek 10 dam sites were surveyed and other reasonably favorable sites could be found. The fall in this stretch of the river is only 748 feet. In view of the physical conditions at the dam sites and their respective elevations above sea level, it seems probable that this section of the river may best be developed by utilizing three sites—Ruby Canyon, Specter Chasm, and Havasu. (See p. 60.) The development of power in this section of the Grand Canyon is a project for the distant future. Although a different plan of development may eventually be adopted, it will not change appreciably the figures given for the water-power value of this section of the river.

In the near future projects may be developed that will affect that part of Colorado River below Havasu Creek, which enters the river just below the west boundary of the Grand Canyon National Park. The plan of development for this stretch of the river therefore deserves serious consideration at this time. A careful examination was made of the 69-mile section of the river between Havasu and Diamond creeks. (See p. 86.) Here the rocks occurring in the walls and river channel are unfavorable for the construction of a dam except at one place where granite appears in the walls above the water surface. (See Pl. XV, in pocket.) A dam site was surveyed at this place (Prospect dam site), but it may not be feasible to build a dam here of sufficient height to back the water to Havasu Creek (p. 86). It may therefore be preferable to utilize the fall in the river below Havasu Creek by constructing a high dam at Diamond Creek or at some site below this point.

There are two good dam sites at Diamond Creek (pp. 88–91). The site above the mouth of the creek affords an excellent opportunity for the construction of a dam of moderate height for the development of power. However, to utilize fully the fall in the river below Havasu Creek it will be necessary to build a dam of sufficient height to raise the water to elevation 1,773 feet above sea level. Such a dam may be built either immediately below the mouth of Diamond Creek or at the Bridge Canyon site, 10 miles farther downstream.

It is the writer's opinion that it may be feasible to build a high dam at Bridge Canyon to form the point of diversion for a gravity system to furnish a domestic water supply for the cities of southern California. Such a dam would also make possible the full utilization of the fall in the river between Havasu Creek and Bridge Canyon. It is therefore suggested that the Bridge Canyon dam site should be reserved (p. 74). This site is presented here as a unit of a comprehensive plan for the full development of the river.

The plan here suggested for developing that section of the river between Bridge Canyon and Parker has taken account of the following facts:

1. As the water supply, with ultimate development in the upper basin, is inadequate to serve all the irrigable land below Parker, it follows that in order to permit maximum irrigation development all unnecessary losses of water due to evaporation from reservoirs should be prevented.

2. A reservoir on the river below the canyon section, near the lands to be benefited, would provide the most effective control of floods and the most efficient regulation of the flow in the interest of irrigation and would permit maximum development of power in the canyon section.

3. As there is more land below Parker than can be irrigated with the available water supply, it would not be good policy to abandon a favorable reservoir site in order to save a relatively small area of irrigable land in Mohave Valley.

Some 15 plans for developing the section of the river between Bridge Canyon and Parker were analyzed by the writer. The plans may be divided into two classes, including (*a*) those that call for the construction of a high dam to serve four purposes—that is, flood control, storage for irrigation, development of power, and storage of silt—and (*b*) the plan that calls for the construction of a dam at Mohave Canyon for flood control and irrigation storage, leaving the canyon section free for the development of power. The analysis of these plans showed that by providing flood control and storage for irrigation at Mohave Canyon and developing power in the canyon section, the floods can be most effectively controlled, more land can be irrigated, and a maximum amount of power can be developed. (See pp. 68–73.)

The plan that has been selected by the writer to form a part of the comprehensive plan of development presented in this report calls for the construction of power dams at the Bridge Canyon, Devils Slide, Hualpai Rapids, and lower Black Canyon dam sites, a storage dam at Mohave Canyon, and a combination diversion and power dam at the Parker dam site.

SUMMARY OF PLAN FOR POWER DEVELOPMENT

The plan for power development is shown in Plates II and III (in pocket). The power value of Colorado River between Green River, Utah, and Parker, Ariz., may be summarized as follows:

1. With the water supply as determined in 1922 and with storage at the site near Lees Ferry, the total continuous power available would be about 4,345,000 horsepower. If the plants operated under a load factor of 60 per cent, the total installed plant capacity would be 7,242,000 horsepower.

2. Without storage and with the water supply as determined in 1922, the total power available would be 1,758,000 horsepower 90 per cent of the time and 2,747,000 horsepower 50 per cent of the time.

3. With ultimate development in the upper basin, the total available continuous power would be about 3,419,000 horsepower. If the plants operated under a 60 per cent load factor, the total installed plant capacity would be 5,743,000 horsepower.

Water power on Colorado River between Green River, Utah, and Parker, Ariz.

Power site	Static head (feet)	Horsepower				
		With storage in Glen Canyon, water supply as in 1922, continuous power	Without storage, water supply as in 1922		With maximum use of water in upper basin	
			90 per cent of time	50 per cent of time	Continuous power	Installed capacity, 60 per cent load factor
Cataract Canyon	512		190,000	309,000	403,000	672,000
Glen Canyon	[a] 393	([b])	182,000	300,000	[a] 334,000	557,000
Marble Gorge	222	346,000	104,000	171,000	217,000	362,000
Mineral Canyon	345	566,000	177,000	282,000	353,000	588,000
Ruby Canyon	286	476,000	149,000	233,000	297,000	495,000
Specter Chasm	223	375,000	117,000	184,000	235,000	392,000
Havasu	209	363,000	116,000	179,000	232,000	387,000
Bridge Canyon	566	1,015,000	329,000	494,000	654,000	1,090,000
Devils Slide	163	294,000	95,600	143,000	190,000	317,000
Hualpai Rapids	225	407,000	132,000	200,000	263,000	438,000
Lower Black Canyon	194	351,000	114,000	172,000	225,000	375,000
Parker	90	152,000	52,800	80,000	16,000	[c] 70,000
	3,428	4,345,000	1,758,000	2,747,000	3,419,000	5,743,000

[a] Glen Canyon site used for storage of 4,000,000 acre-feet; average head available for power 348 feet.
[b] Glen Canyon site used for storage only.
[c] With water passing Parker diversion dam regulated for irrigation only, an installed capacity of 70,000 horsepower would utilize the high flow during summer.

POWER SITES

Most of Colorado River from its source in Colorado to the Mexican boundary and of Green River from its source in Wyoming to its junction with the Colorado has been surveyed by the topographic engineers of the Geological Survey and examined by hydraulic engineers and geologists. The hydraulic engineers selected and supervised the survey of all dam sites. The geologists examined the geologic setting at each dam site and ascertained the feasibility of the site as determined by the nature and structure of the rock formations.

Colorado River below Green River, Utah, is no longer a mystery. The recent surveys have made it possible to record for the first time the true course of the river, its fall, its rapids, the topography of its canyons, the geologic structure of the region through which it flows, and the location and physical characteristics of the possible dam sites and to formulate a plan for the utilization of its water resources.

Detailed information regarding each dam site will be found in the following pages, in which the sites are presented in downstream order. (See Pls. II and III, in pocket.)

CATARACT CANYON POWER SITE

DARK CANYON DAM SITE

Location.—As a result of detailed surveys and diamond-drill borings, the Bureau of Reclamation[19] in 1914 reported unfavorable foundation conditions for a dam immediately below the mouth of Green River. The writer having visited this region in 1914, was familiar with the conditions when in September, 1921, he assisted in the survey of Cataract Canyon. Although a careful examination was made, no dam sites were found near the head of this canyon. On account of wide sections and unfavorable rock structure, a feasible dam site was not found until 30 miles of the canyon below Green River had been surveyed. This site is 3 miles above Dark Canyon, near the lower end of Cataract Canyon, and 186 miles above Lees Ferry. (See Pl. II, in pocket.)

Physical characteristics.—At the Dark Canyon dam site the river surface at low water is 3,528 feet above sea level. The width of the canyon at the water surface is 260 feet, and a dam 532 feet in height above low water would have a length on top of 1,060 feet. (See Pl. XVI, *A*.) In Plate XVII will be found a cross section of the dam site, showing the rock structure, a map of the site, and the area and capacity curves of the reservoir.

Sidney Paige, geologist, of the Geological Survey, who accompanied the Cataract Canyon survey party, reports as follows on the geology at the Dark Canyon dam site:

> The rocks at the Dark Canyon dam site comprise limestone and sandstone. Some of the limestone is arenaceous, and some of the sandstone is calcareous. It is believed that these rocks are of quite sufficient strength to provide anchorage and foundation for a concrete dam. The presence of the limestone, which is compact and nowhere cavernous or porous, adds to the strength of the mass as a whole. Both side anchorage and foundations, however, should be carried to solid rock and preferably set in a notch in such rock to afford added assurance against seepage. The depth to bedrock does not exceed 40 feet, and it is believed to be less than this figure, perhaps 20 feet.

[19] Recl. Service Fifteenth Ann. Rept. p. 515, 1914.

Leakage through the rocks at the dam site or along bedding planes between limestone and sandstone should be negligible.

Plan of development.—The conditions are favorable for construction of a high concrete dam. The water surface under the railroad bridge at Green River, Utah, is 4,050 feet above sea level. In order that this bridge and the town of Green River may not be damaged, the elevation of the flowage line of the reservoir has been placed at 4,040 feet. It is proposed to place the power house in the canyon at the base of the dam and to take care of the surplus water by means of tunnels leading to a side canyon on the left bank through a narrow section of the canyon wall. The plan of development is clearly shown in Plate XVII. By this plan the water should never pass over the dam, and it is therefore suggested that a 20-foot freeboard should be provided. The crest of the dam would be 20 feet above the flowage line of the reservoir, or 4,060 feet above sea level. Such a dam would rise 532 feet above low-water level and would contain about 2,200,000 cubic yards of concrete. The effect of ice, débris, and silt on any hydraulic structure built in Cataract Canyon is referred to in the discussion beginning on page 12.

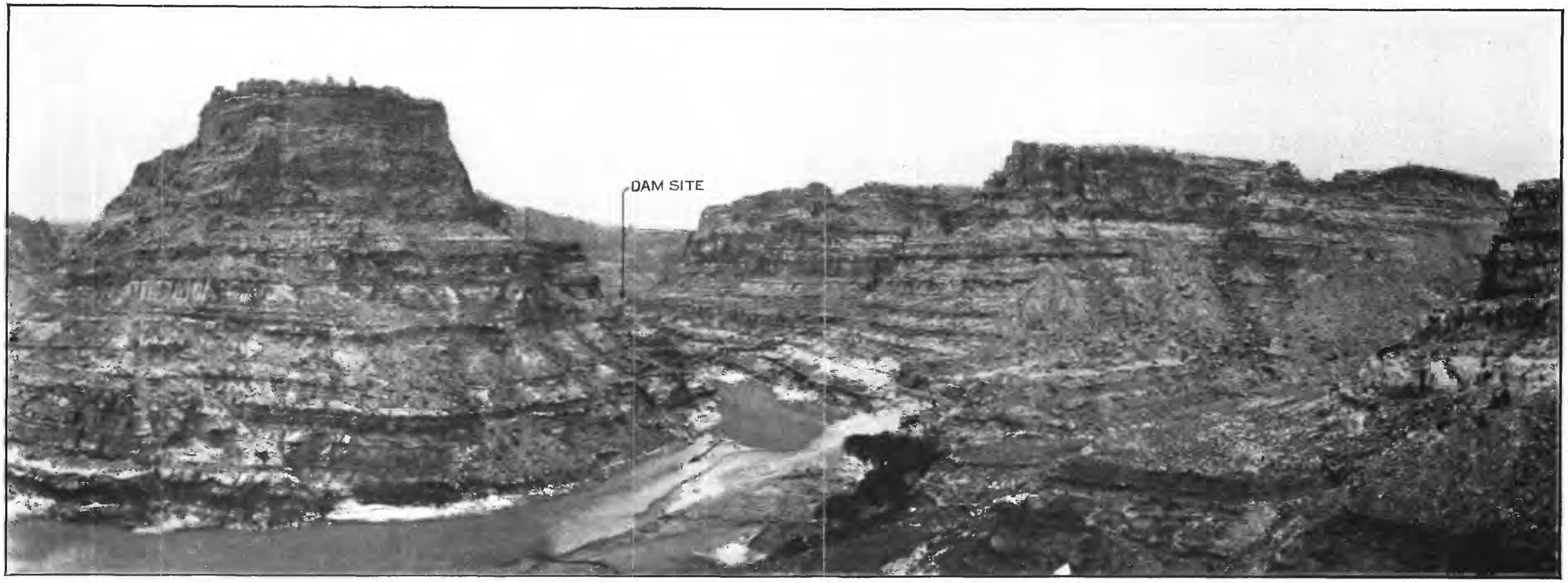
Water supply.—A full discussion of water supply is given in Appendix A, where Table 9 shows the water supply available at all power sites below Green River, Utah. It will be noted that with the water used as in 1922 and without storage the supply available at the Cataract Canyon power site would be 4,650 second-feet 90 per cent of the time and 7,540 second-feet 50 per cent of the time. With ultimate development in the upper basin, which obviously would require storage, a continuous flow of about 9,840 second-feet would be available in Cataract Canyon.

Power capacity.—The static head at the Cataract Canyon site would be 512 feet. The power capacity with this head and with the water supply given in the preceding paragraph would be as follows:

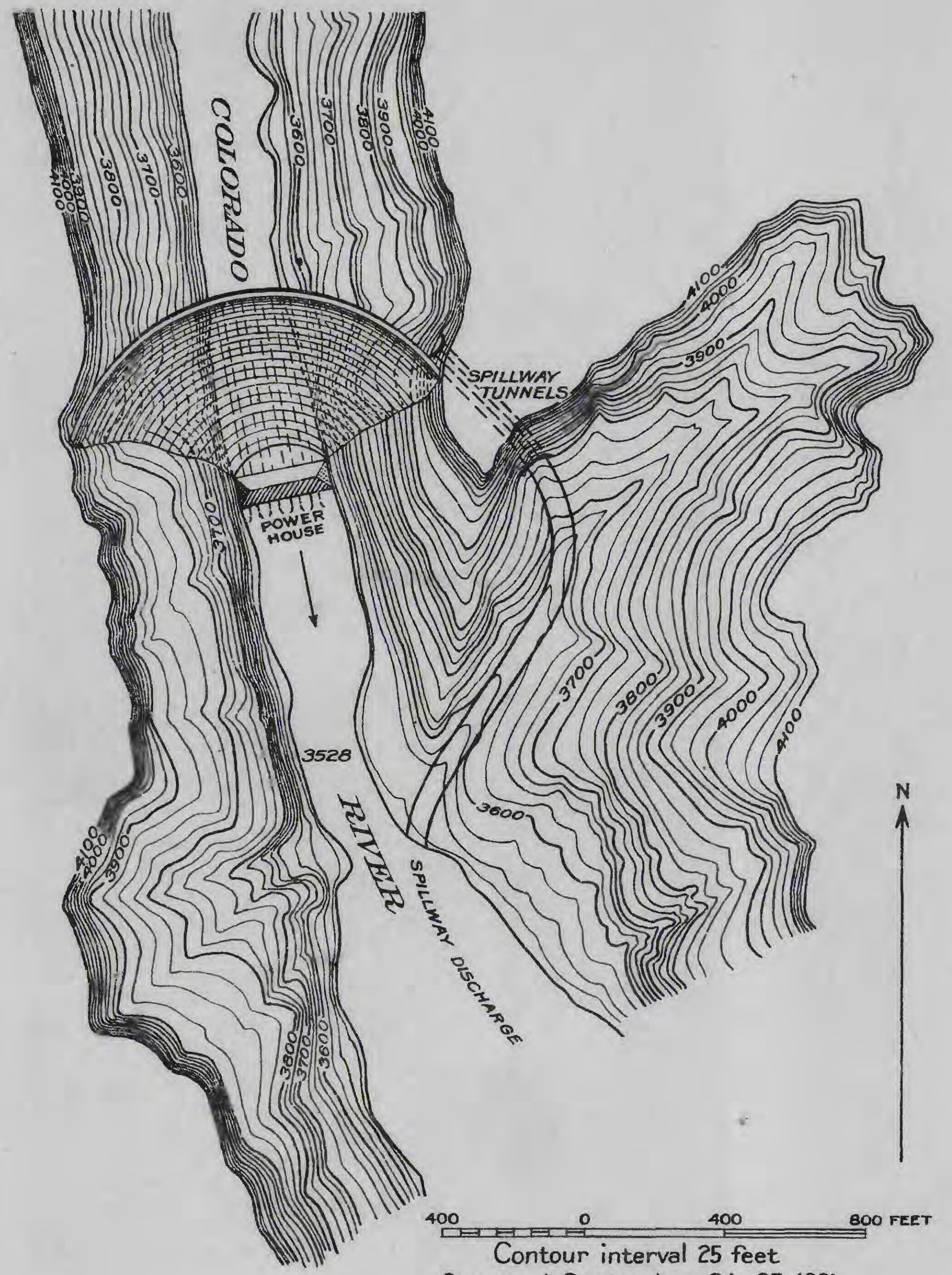
	Horsepower
Without storage and with the irrigation and power development in upper basin as in 1922:	
Capacity 50 per cent of time	309, 000
Capacity 90 per cent of time	190, 000
With storage and with ultimate irrigation and power development in upper basin:	
Continuous power available	403, 000
Installed capacity (load factor 60 per cent)	672, 000

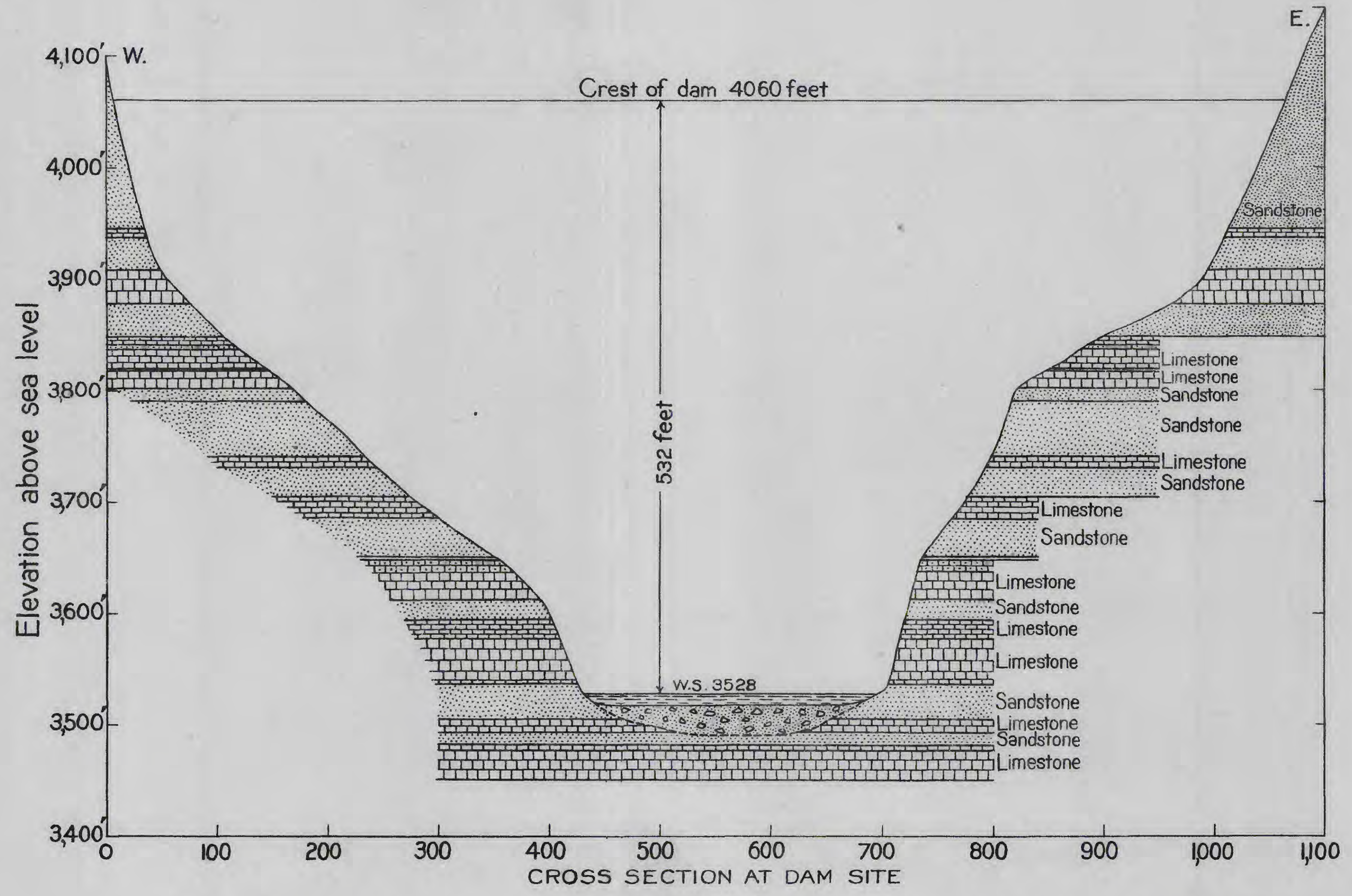
Right of way.—The flowage line of the proposed Cataract Canyon reservoir is shown in Plate XVIII. The flowage damage in Cataract Canyon and on Green River would be very small. On Colorado River the small settlement of Moab would be submerged, and it would be necessary to relocate the highway bridge at this point. The town of Moab could be moved to a higher and better location on Mill Creek.

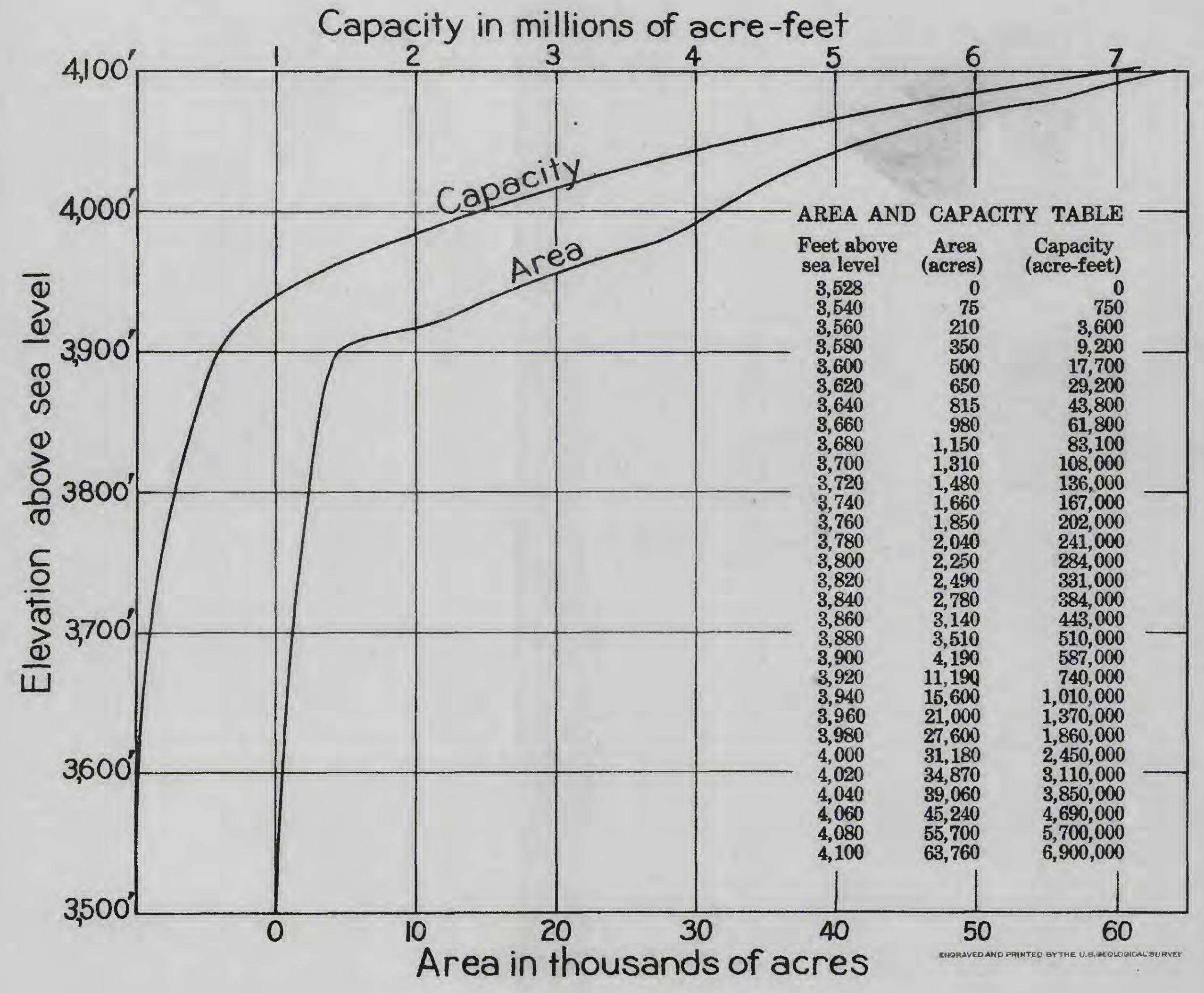
A. DARK CANYON DAM SITE, CATARACT CANYON



B. MILLE CRAG BEND DAM SITE, CATARACT CANYON







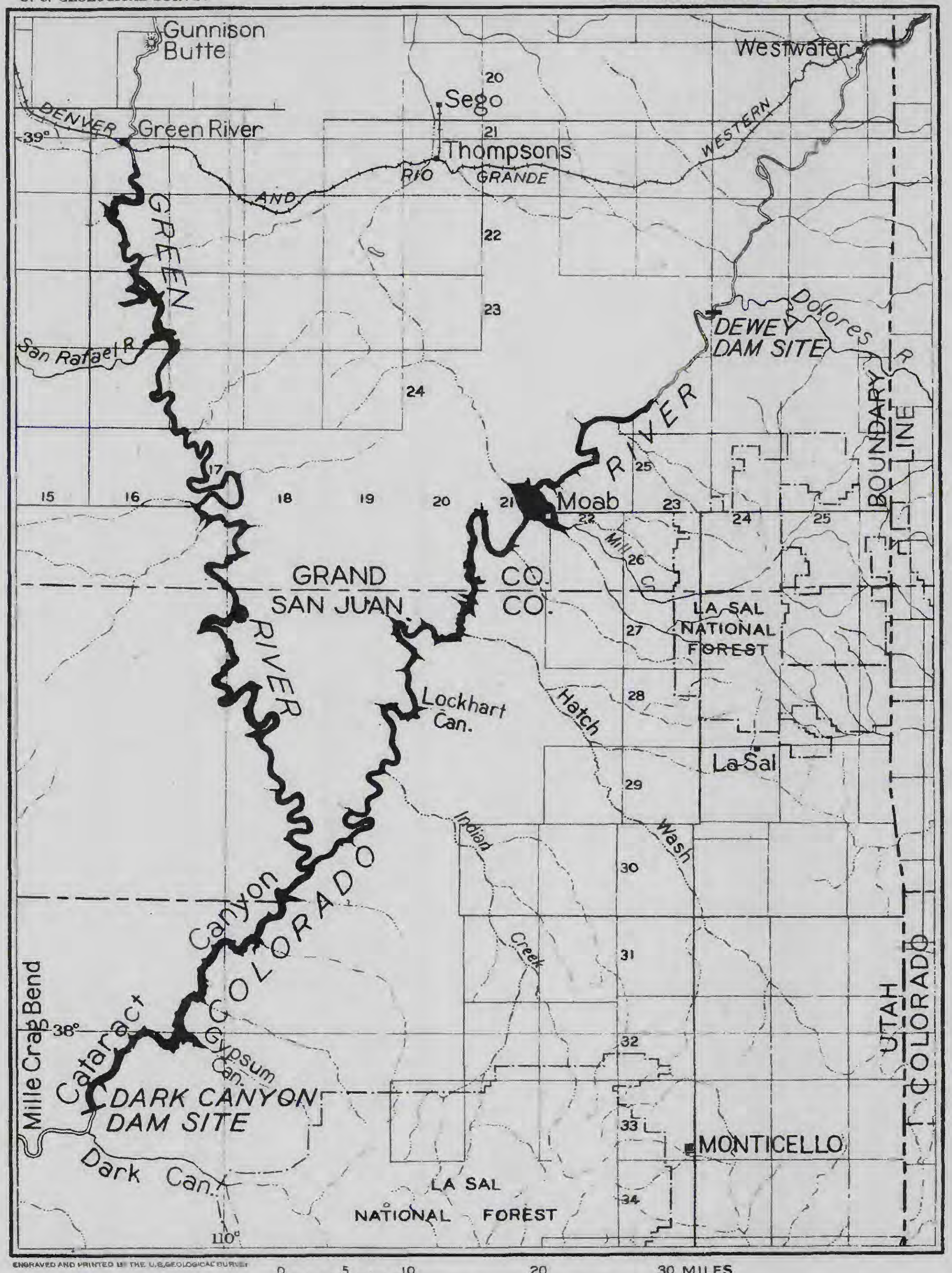
AREA AND CAPACITY TABLE

Feet above sea level	Area (acres)	Capacity (acre-feet)
3,528	0	0
3,540	75	750
3,560	210	3,600
3,580	350	9,200
3,600	500	17,700
3,620	650	29,200
3,640	815	43,800
3,660	980	61,800
3,680	1,150	83,100
3,700	1,310	108,000
3,720	1,480	136,000
3,740	1,660	167,000
3,760	1,850	202,000
3,780	2,040	241,000
3,800	2,250	284,000
3,820	2,490	331,000
3,840	2,780	384,000
3,860	3,140	443,000
3,880	3,510	510,000
3,900	4,190	587,000
3,920	11,190	740,000
3,940	15,600	1,010,000
3,960	21,000	1,370,000
3,980	27,600	1,860,000
4,000	31,180	2,450,000
4,020	34,870	3,110,000
4,040	39,060	3,850,000
4,060	45,240	4,690,000
4,080	55,700	5,700,000
4,100	63,760	6,900,000

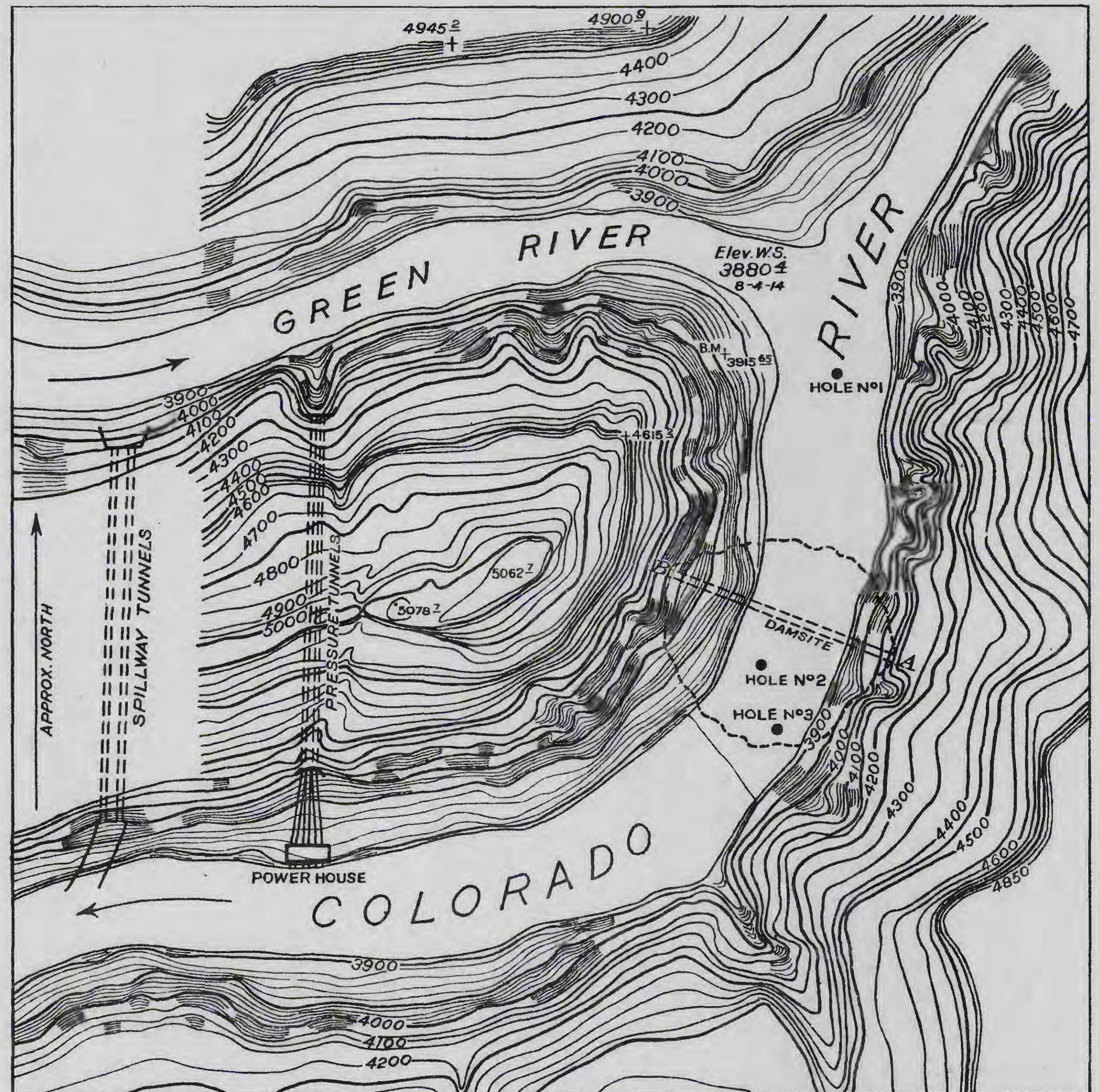
ENGRAVED AND PRINTED BY THE U.S. GEOLOGICAL SURVEY

MAP, CROSS SECTION, AND AREA AND CAPACITY CURVES FOR CATARACT CANYON POWER SITE

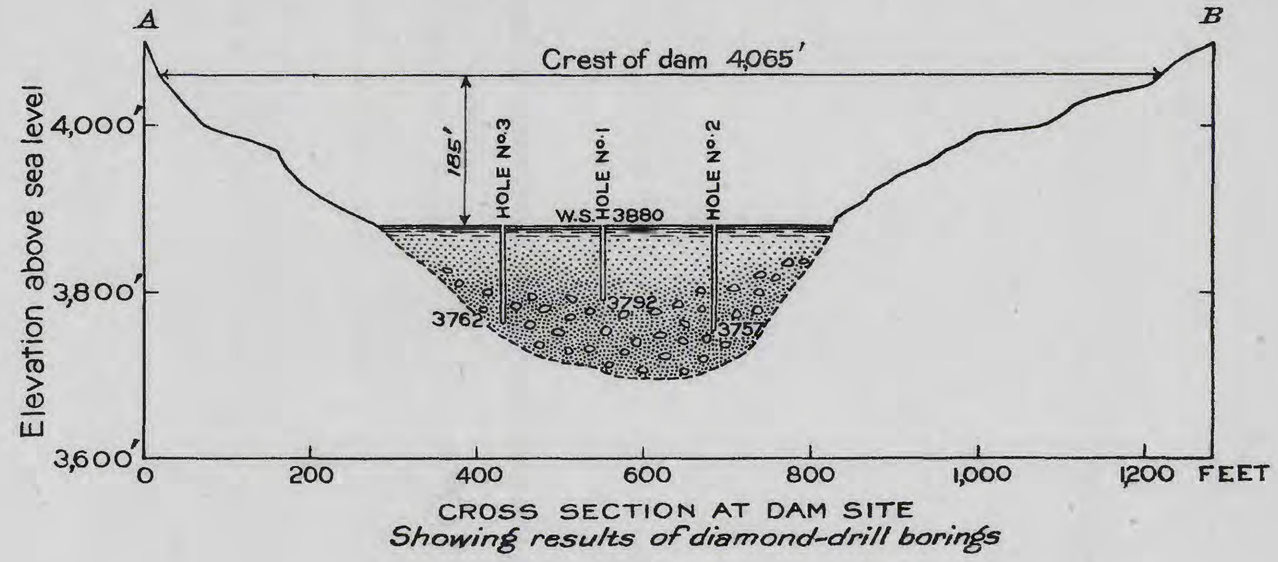
(DARK CANYON DAM SITE)



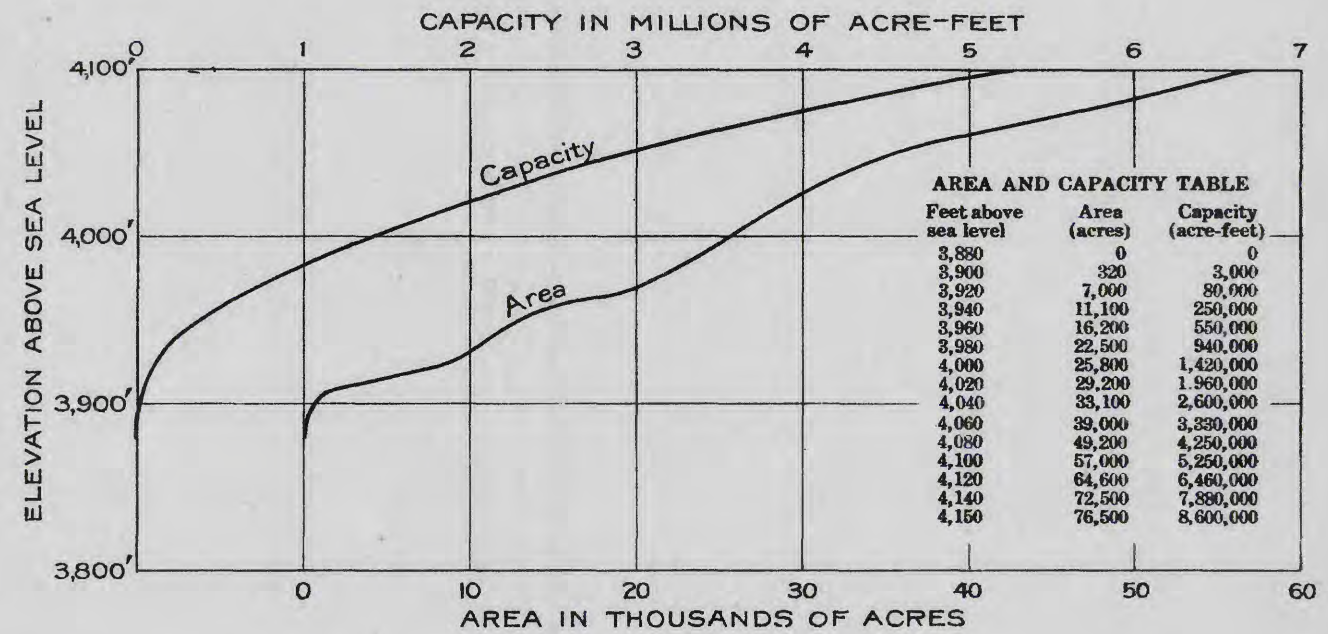
MAP OF RESERVOIR BASIN ABOVE DARK CANYON DAM SITE



Contour interval 10 feet
Surveyed by Bureau of Reclamation, August, 1914



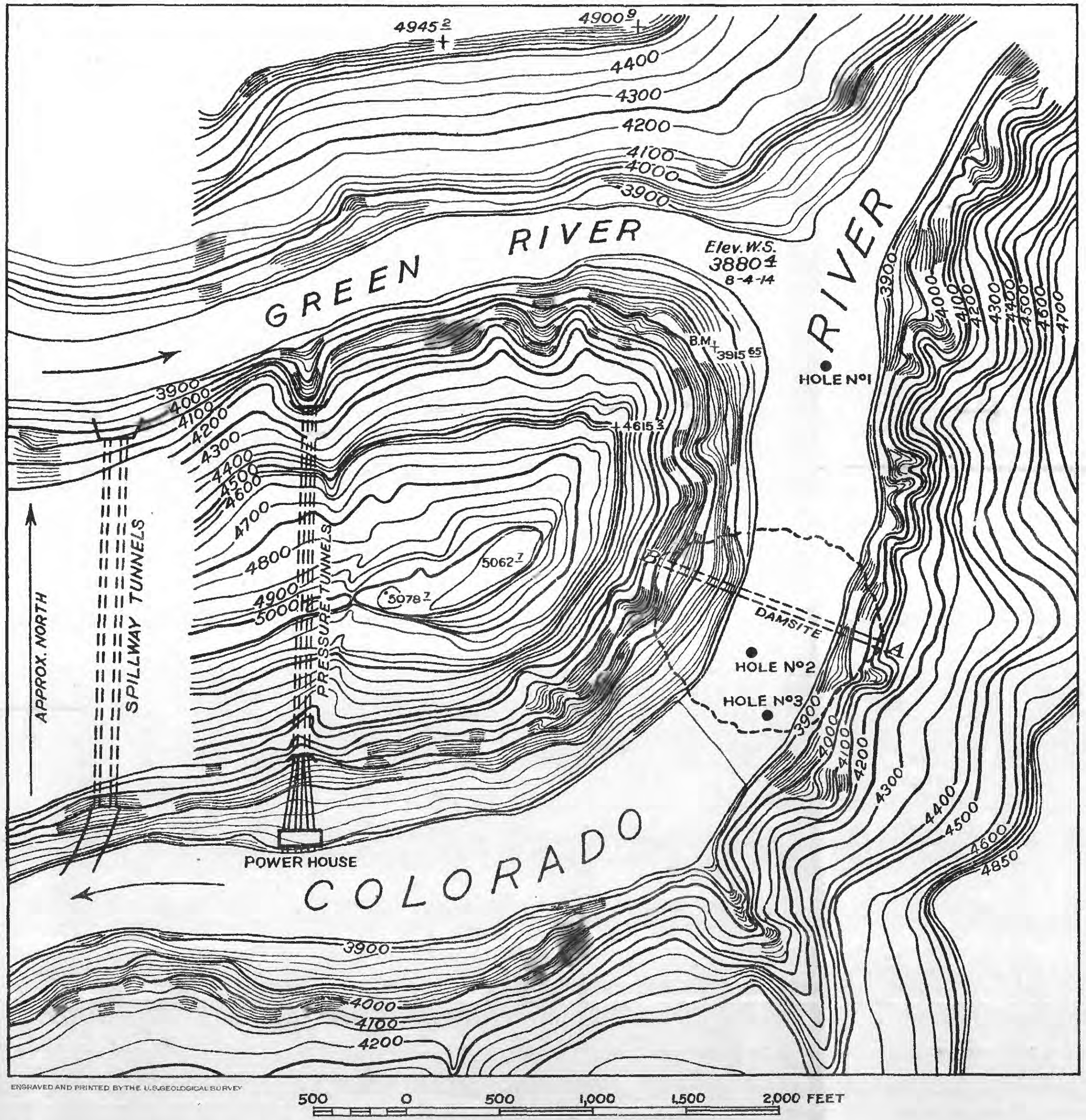
CROSS SECTION AT DAM SITE
Showing results of diamond-drill borings



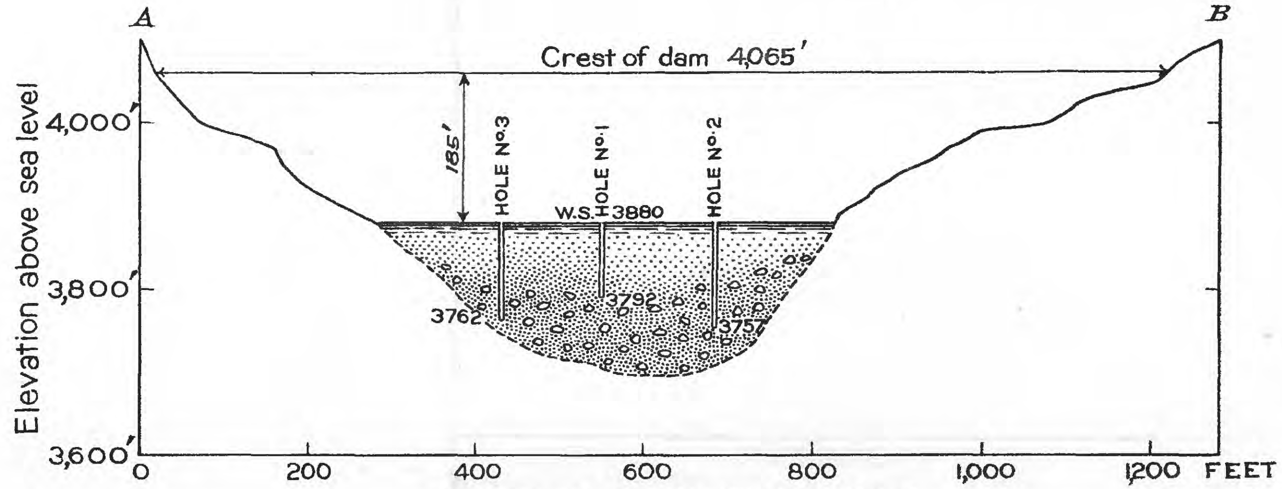
AREA AND CAPACITY TABLE

Feet above sea level	Area (acres)	Capacity (acre-feet)
3,880	0	0
3,900	320	3,000
3,920	7,000	80,000
3,940	11,100	250,000
3,960	16,200	550,000
3,980	22,500	940,000
4,000	25,800	1,420,000
4,020	29,200	1.960,000
4,040	33,100	2,600,000
4,060	39,000	3,330,000
4,080	49,200	4,250,000
4,100	57,000	5,250,000
4,120	64,600	6,460,000
4,140	72,500	7,880,000
4,150	76,500	8,600,000

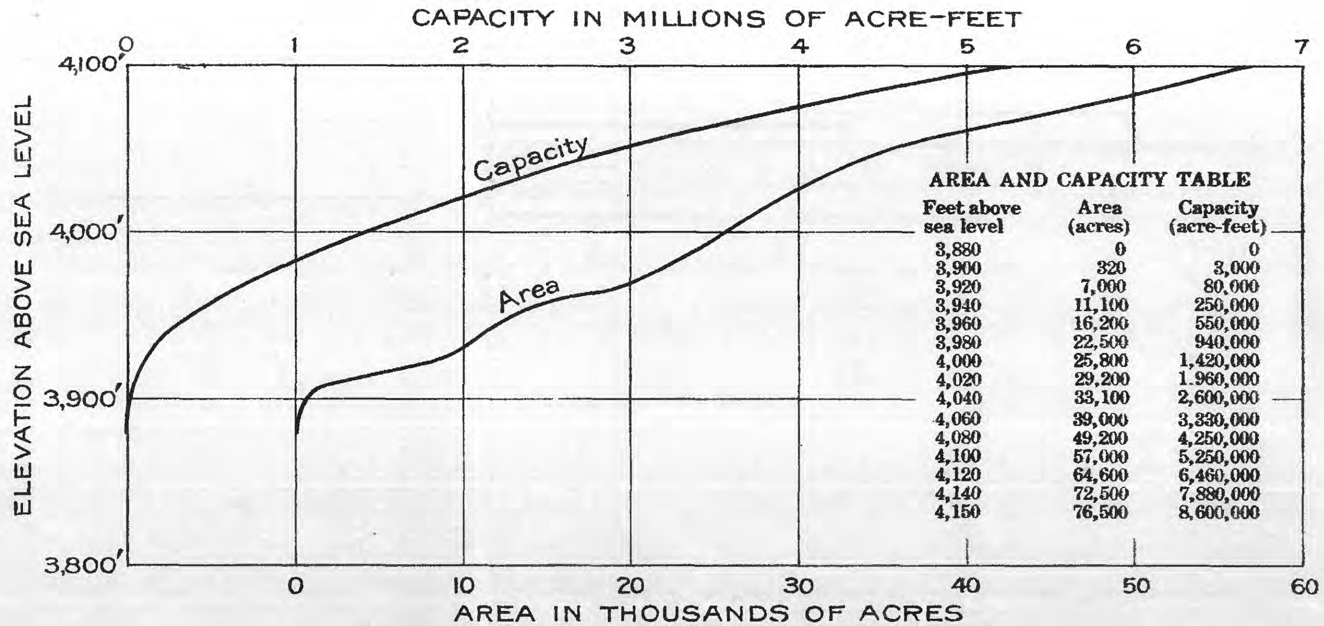
MAP, CROSS SECTION, AND AREA AND CAPACITY CURVES FOR CATARACT CANYON POWER SITE
(JUNCTION DAM SITE)



Contour interval 10 feet
Surveyed by Bureau of Reclamation, August, 1914



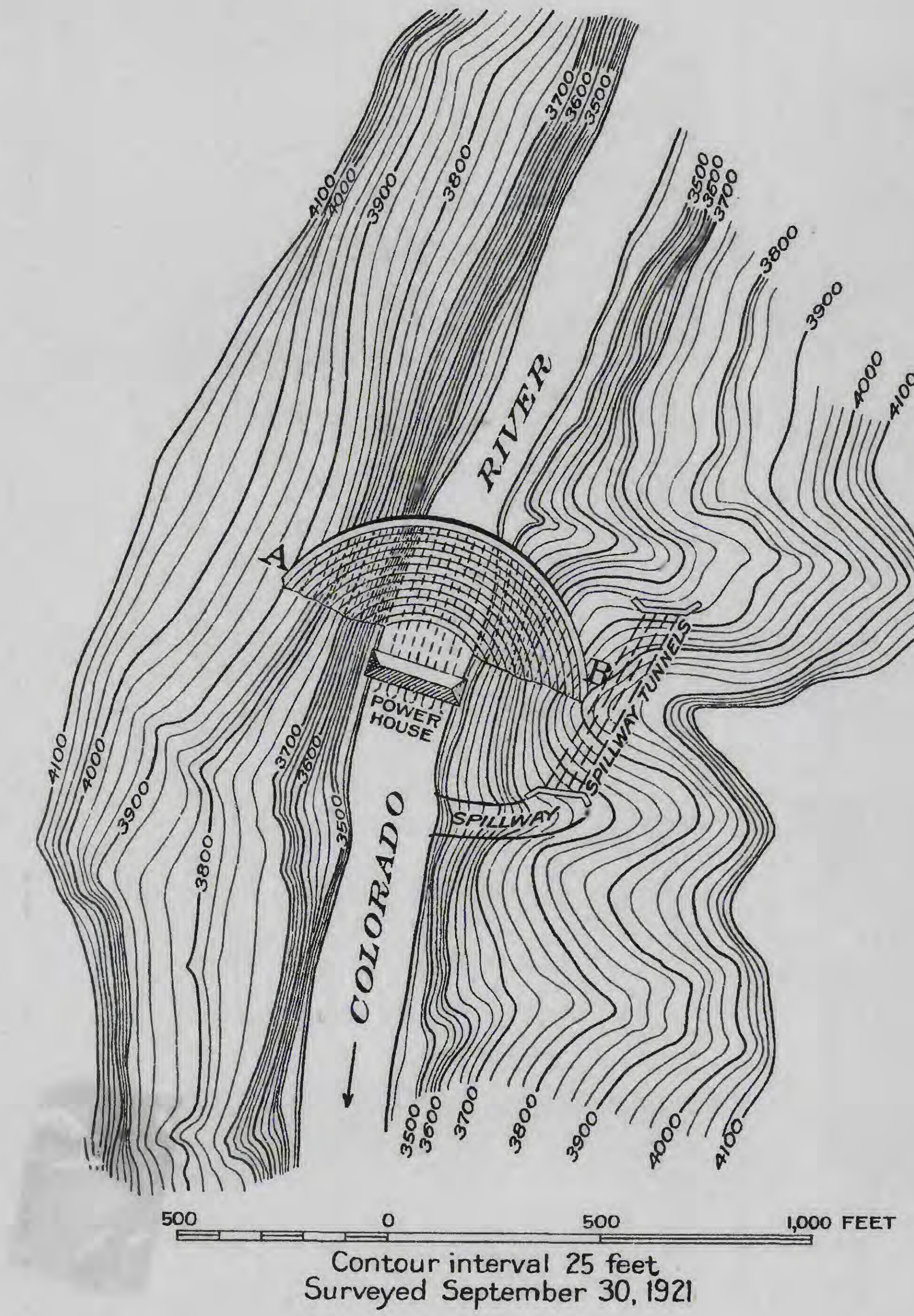
CROSS SECTION AT DAM SITE
Showing results of diamond-drill borings

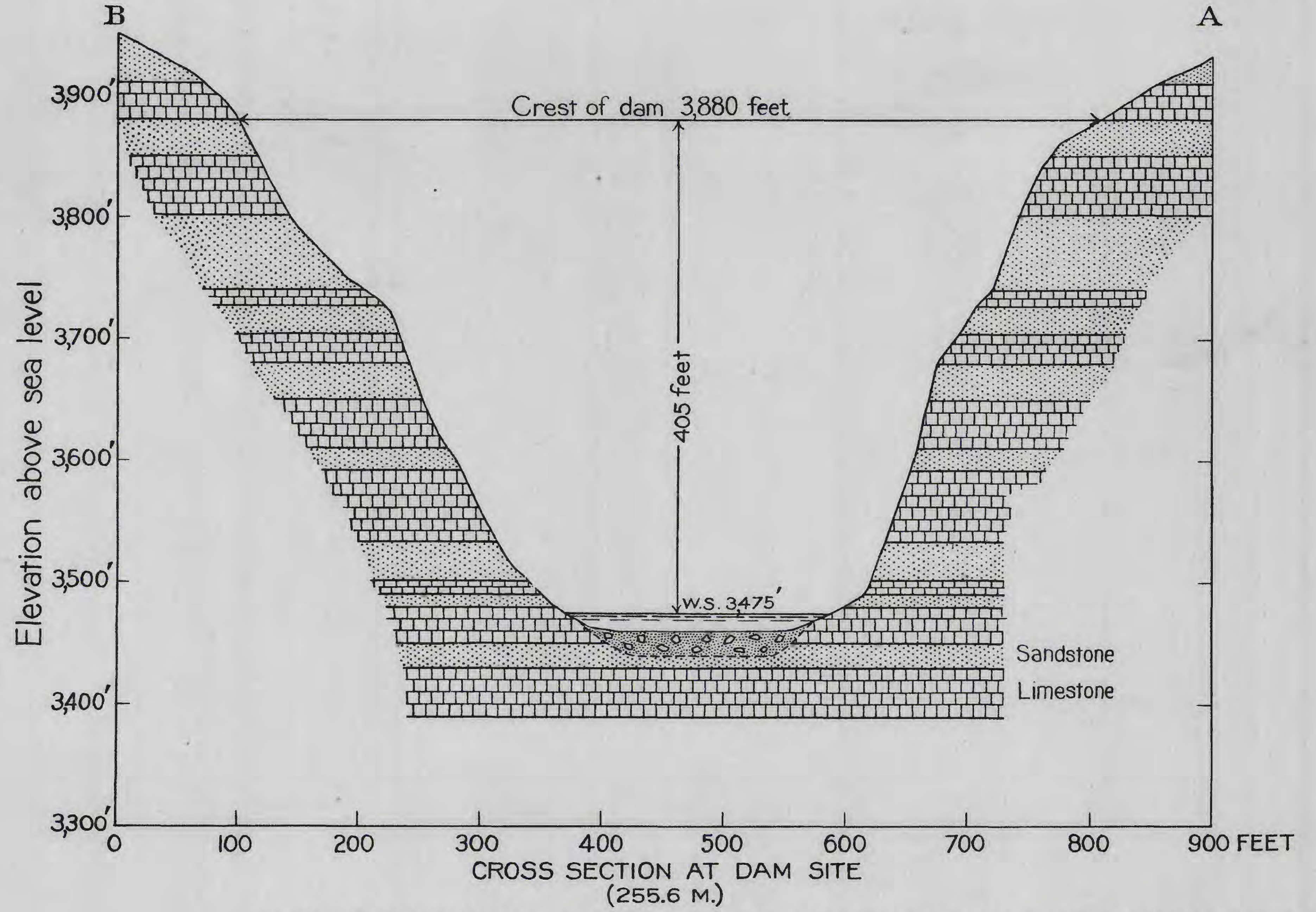


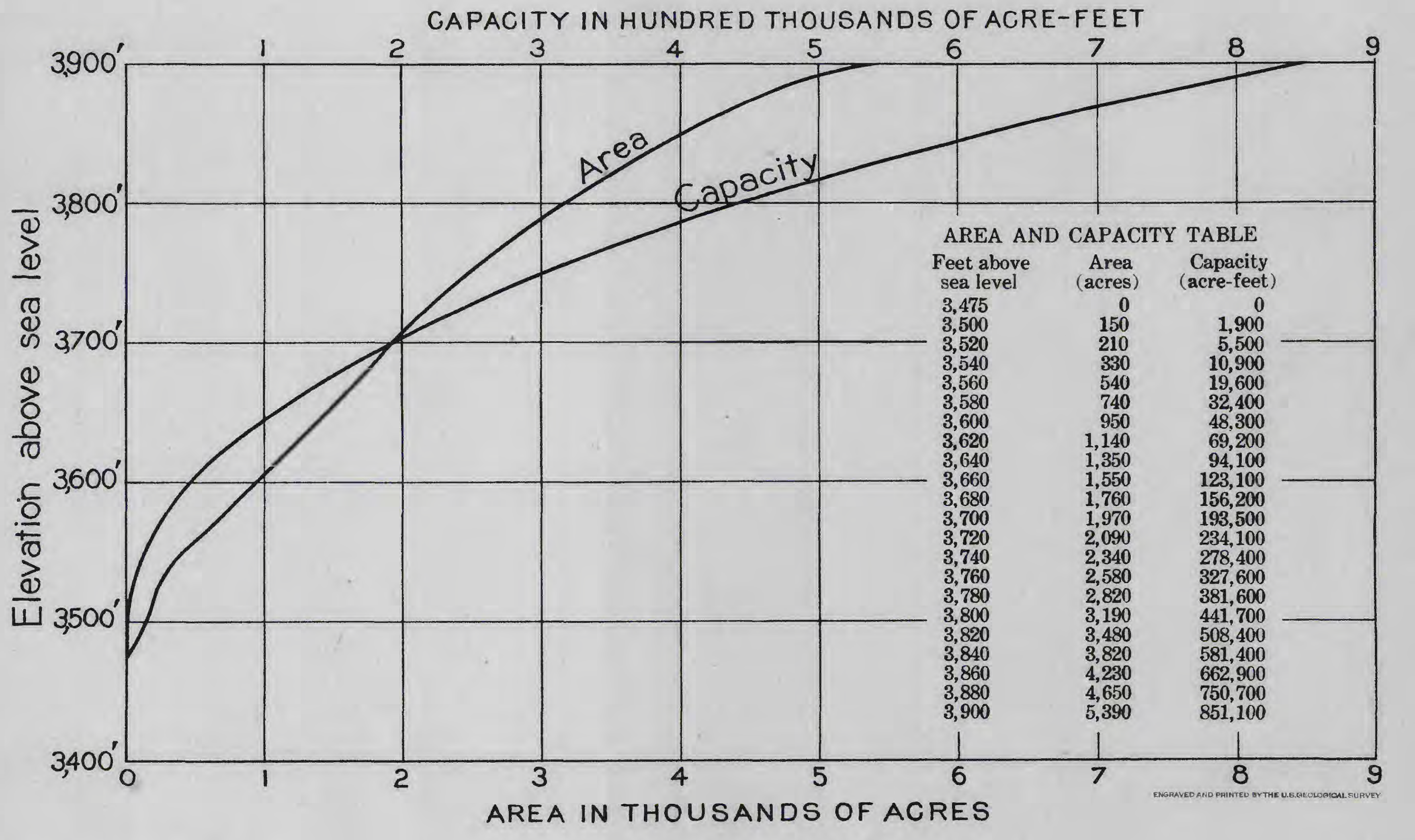
AREA AND CAPACITY TABLE

Feet above sea level	Area (acres)	Capacity (acre-feet)
3,880	0	0
3,900	320	3,000
3,920	7,000	80,000
3,940	11,100	250,000
3,960	16,200	550,000
3,980	22,500	940,000
4,000	25,800	1,420,000
4,020	29,200	1.960,000
4,040	33,100	2,600,000
4,060	39,000	3,330,000
4,080	49,200	4,250,000
4,100	57,000	5,250,000
4,120	64,600	6,460,000
4,140	72,500	7,880,000
4,150	76,500	8,600,000

MAP, CROSS SECTION, AND AREA AND CAPACITY CURVES FOR CATARACT CANYON POWER SITE
(JUNCTION DAM SITE)







AREA AND CAPACITY TABLE

Feet above sea level	Area (acres)	Capacity (acre-feet)
3,475	0	0
3,500	150	1,900
3,520	210	5,500
3,540	330	10,900
3,560	540	19,600
3,580	740	32,400
3,600	950	48,300
3,620	1,140	69,200
3,640	1,350	94,100
3,660	1,550	123,100
3,680	1,760	156,200
3,700	1,970	193,500
3,720	2,090	234,100
3,740	2,340	278,400
3,760	2,580	327,600
3,780	2,820	381,600
3,800	3,190	441,700
3,820	3,480	508,400
3,840	3,820	581,400
3,860	4,230	662,900
3,880	4,650	750,700
3,900	5,390	851,100

MAP, CROSS SECTION, AND AREA AND CAPACITY CURVES FOR CATARACT CANYON POWER SITE
(MILLE CRAG BEND DAM SITE)

Accessibility.—The Cataract Canyon power site is not readily accessible at this time. The development of the project is remote. When a railroad now proposed is built to the great agricultural region near Monticello, Utah, a 60-mile extension by way of Dark Canyon would reach the Cataract Canyon power site.

Value.—Although the development of the Cataract Canyon power site would tend to equalize the flow of the river in the interest of irrigation below, its chief value would come from the development of power. Its value as a flood-control site is small, owing to the fact that there are other sites lower on the river where the floods may be more effectively controlled at a much lower cost. However, at some future time the capacity of the Glen Canyon storage site may be seriously reduced by the deposition of silt. When this occurs it may be desirable to utilize the upper 100 feet of the Cataract Canyon power dam for river regulation. This would reduce the power capacity of the Cataract Canyon site and make available 3,200,000 acre-feet of storage capacity for flood control.

ALTERNATIVE PLANS OF DEVELOPMENT

Junction dam site.—The Junction dam site is about 1,500 feet below the mouth of Green River, at a point where low water in Colorado River stands 3,880 feet above sea level. Investigations made by the Bureau of Reclamation indicate that the conditions at this point are unfavorable for the construction of a concrete dam. The bureau's report on drill operations[20] is as follows:

> Diamond-drill work at Junction dam site was begun in August, 1914, the drill being hauled down from Green River, Utah, 25 miles to Wimmer's ranch, from which point it was taken down the river on scows. On August 29 the first hole had reached a depth of 90 feet, encountering nothing but river sand; there being no more drill rods on hand, hole No. 2 was started, and on September 16 a depth of 124.5 feet had been reached, 50 feet of which was river sand and the remainder sand and sandstone boulders. On September 30 hole No. 3, about 325 feet downstream, had reached a depth of 120 feet in boulders and sand, at which point a piece of casing broke off, lodging crosswise of the hole, and the drill was then moved to hole No. 4, approximately a quarter of a mile below the junction. On October 3 rock, probably a boulder, was encountered at 101.5 feet depth. By shooting it was penetrated 0.4 foot that day. On the following day the river suddenly rose nearly 8 feet, and the drift, notwithstanding the efforts of the men to hold the scows, snapped the cables and broke off the casing and rods in the hole. The drill was saved, and several days spent trying to recover the rods and casing, which proved impossible. Further drill work was then abandoned.

In Plate XIX will be found a map of the dam site, a cross section at the dam site, and area and capacity curves for the reservoir. The map also shows a plan of development, which calls for the construction of a rock-fill dam. A safe dam of this type could no doubt be built, as the spillway conditions are favorable. The crest of the dam would

[20] U. S. Recl. Service Fifteenth Ann. Rept., p. 515, 1916.

be 4,065 feet above sea level, or 25 feet above the flowage line of the reservoir.

The static head at the Junction site would be 160 feet. The power capacity with this head and with the water supply given on page 48 would be as follows:

	Horsepower
Without storage and with irrigation and power development in upper basin as in 1922:	
Capacity 50 per cent of time	96, 400
Capacity 90 per cent of time	59, 600
With storage and with ultimate irrigation and power development in upper basin:	
Continuous power available	126, 000
Installed capacity (load factor 60 per cent)	210, 000

Statements relative to flowage damage and accessibilty of the Dark Canyon dam site would apply also at the Junction dam site. A plan to utilize the Dark Canyon dam site in connection with the Junction dam site should be studied. However, it seems probable that the more practicable plan for utilizing the fall in the river between Green River, Utah, and lower Cataract Canyon is that calling for the construction of a relatively high dam at the Dark Canyon site.

Mille Crag Bend dam site.—The Mille Crag Bend dam site is near the lower end of Cataract Canyon, at the head of Mille Crag Bend, 7½ miles below the Dark Canyon dam site and 178½ miles above Lees Ferry. This site is very similar to the Dark Canyon dam site. (See Pl. XVI, *B*.) Plate XX shows the topography, cross section, and rock structure at the dam site and includes curves showing the area and capacity of the reservoir.

The river surface at low water at the Mille Crag Bend dam site is 3,475 feet above sea level. A dam built at this site to utilize the fall in the river from Green River, Utah, would rise about 630 feet above its foundation. A more practicable plan for utilizing the fall below Green River, Utah, would be to build this dam in connection with the dam at the Junction site, below the mouth of Green River. Under this plan the Mille Crag Bend dam would raise the water to an elevation of 3,870 feet, which would require a dam about 445 feet in height above its foundation.

The static head at the Mille Crag Bend site would be 395 feet. The power capacity with this head and with the water supply given on page 48 would be as follows:

	Horsepower
Without storage and with irrigation and power development in upper basin as in 1922:	
Capacity 50 per cent of time	238, 000
Capacity 90 per cent of time	147, 000
With storage and with ultimate irrigation and power development in upper basin:	
Continuous power available	311, 000
Installed capacity (load factor 60 per cent)	518, 000

The Mille Crag Bend site, if developed in combination with the Junction site, would produce 8 per cent more power than the Dark Canyon site, being lower on the river. However, a dam at the Mille Crag Bend site would seriously interfere with the development of the Glen Canyon storage reservoir site. It is desirable to reserve a storage capacity of about 8,000,000 acre-feet in Glen Canyon, and this capacity could be provided if the dam in Cataract Canyon were built at the Dark Canyon site. Development of the Mille Crag Bend site would limit the storage capacity of the Glen Canyon reservoir to about 5,000,000 acre-feet.

The utilization of the Dark Canyon dam site, in Cataract Canyon, would provide full development of the potential power between the dam site and Green River, Utah, and the plan confining the development to one site, where the required height of dam is not unreasonable, would be more practicable than the plan calling for the construction of a dam at Mille Crag Bend in combination with a dam at the Junction site.

GLEN CANYON POWER SITE

Owing to the position of Glen Canyon on the river and the relatively large storage capacity that may be obtained by building a dam at a site near Lees Ferry, the Glen Canyon section is chiefly valuable for providing storage. Detailed information regarding this site is therefore presented in connection with the discussion of the flood-control problem. (See p.19.)

It is impossible at this time to determine to what extent the flow of Colorado River at Lees Ferry will be equalized as a result of irrigation and power development in the upper basin. It seems reasonable, however, to assume that at some future time the effective storage capacity required at or near Lees Ferry to regulate the flow of the river in the interest of power development in the Grand Canyon and below will not exceed 4,000,000 acre-feet, a capacity that would be afforded in the Glen Canyon reservoir between elevations of 3,423 and 3,513 feet.

The results of rather meager observations in the upper basin indicate that perhaps half of the silt entering Glen Canyon is contributed by San Juan River. This stream enters the reservoir site downstream from the major part of the storage basin, at an elevation 256 feet below the maximum flow line and through a narrow box canyon that has little storage capacity. Owing to these conditions and to the flushing effect of occasional heavy flood flows, the delivery of silt from San Juan River will probably not result in any material encroachment on the effective storage capacity of 4,000,000 acre-feet in the upper 90 feet of the reservoir.

It has been assumed that at some future time it will be possible to develop power at the dam, reserving 4,000,000 acre-feet of storage capacity for river regulation. The plan for development of power is shown in Plate V.

Power capacity.—The static head at the Glen Canyon site would be 348 feet. The power capacity with this head and with the water supply available after ultimate development has been attained in the upper basin and with 4,000,000 acre-feet of storage capacity provided at this site would be as follows:

	Horsepower
Continuous power available	334,000
Installed capacity (load factor 60 per cent)	557,000

MARBLE GORGE POWER SITE

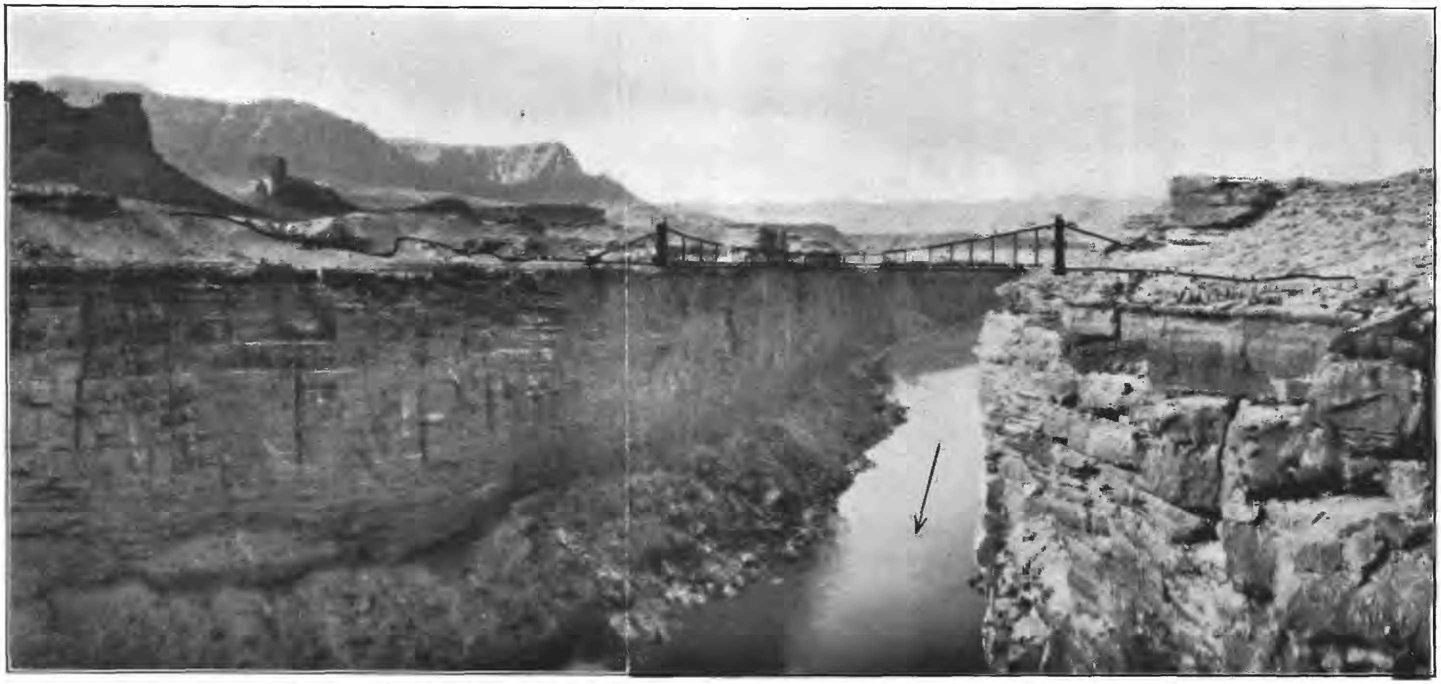
The name Marble Gorge is applied to the 60-mile section of the Grand Canyon between the mouths of Paria and Little Colorado rivers. The river falls from an elevation of 3,115 feet above sea level at Paria River to 2,715 feet at the Little Colorado, a drop of 400 feet. The height of the canyon walls above the river ranges from practically zero at the Paria to 3,400 feet at the Little Colorado. (See Pl. XXI, *A*.) Hotel El Tovar (Pl. XXI, *B*), on the south rim of the Grand Canyon, rests on the Kaibab limestone 6,900 feet above sea level, or 4,500 feet above the river, yet near Lees Ferry, at the head of Marble Gorge, 89 miles upstream, the river flows over the top of the Kaibab limestone at 3,115 feet above sea level. (See Pl. XV.)

Although the lower part of Marble Gorge is 3,400 feet deep, the walls are all in the sedimentary formation. The geologic structure in Marble Gorge is described in detail by R. C. Moore in Appendix B.

MARBLE GORGE BRIDGE SITE

The so-called bridge site is in Marble Gorge 4½ miles below Paria River. Here the depth of the canyon is 400 feet and the distance between the walls at the top is but little more than 600 feet. The site is easily accessible from both sides of the river and the conditions are favorable for the construction of a highway bridge at this point. (See Pl. XXII.)

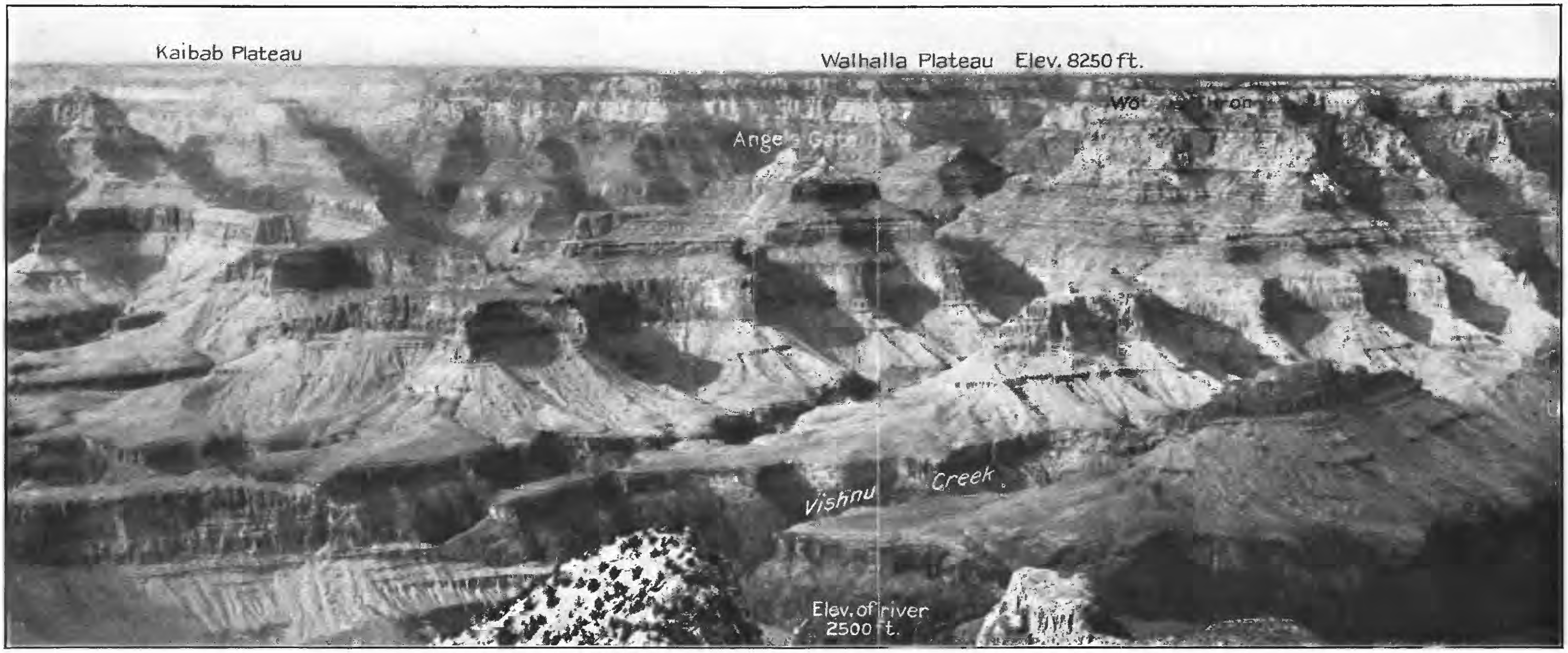
In July, 1923, the writer made a thorough study of this locality to determine its suitability as a site for a storage dam to utilize the Glen Canyon basin. For this purpose the water should be raised to an elevation of 3,513 feet above sea level. It was found that the walls at the bridge site are of sufficient height to permit the construction of such a dam. However, examination of the rock formations in the canyon with R. C. Moore, geologist, showed that the



MARBLE GORGE 5 MILES BELOW LEES FERRY, SHOWING BRIDGE SITE

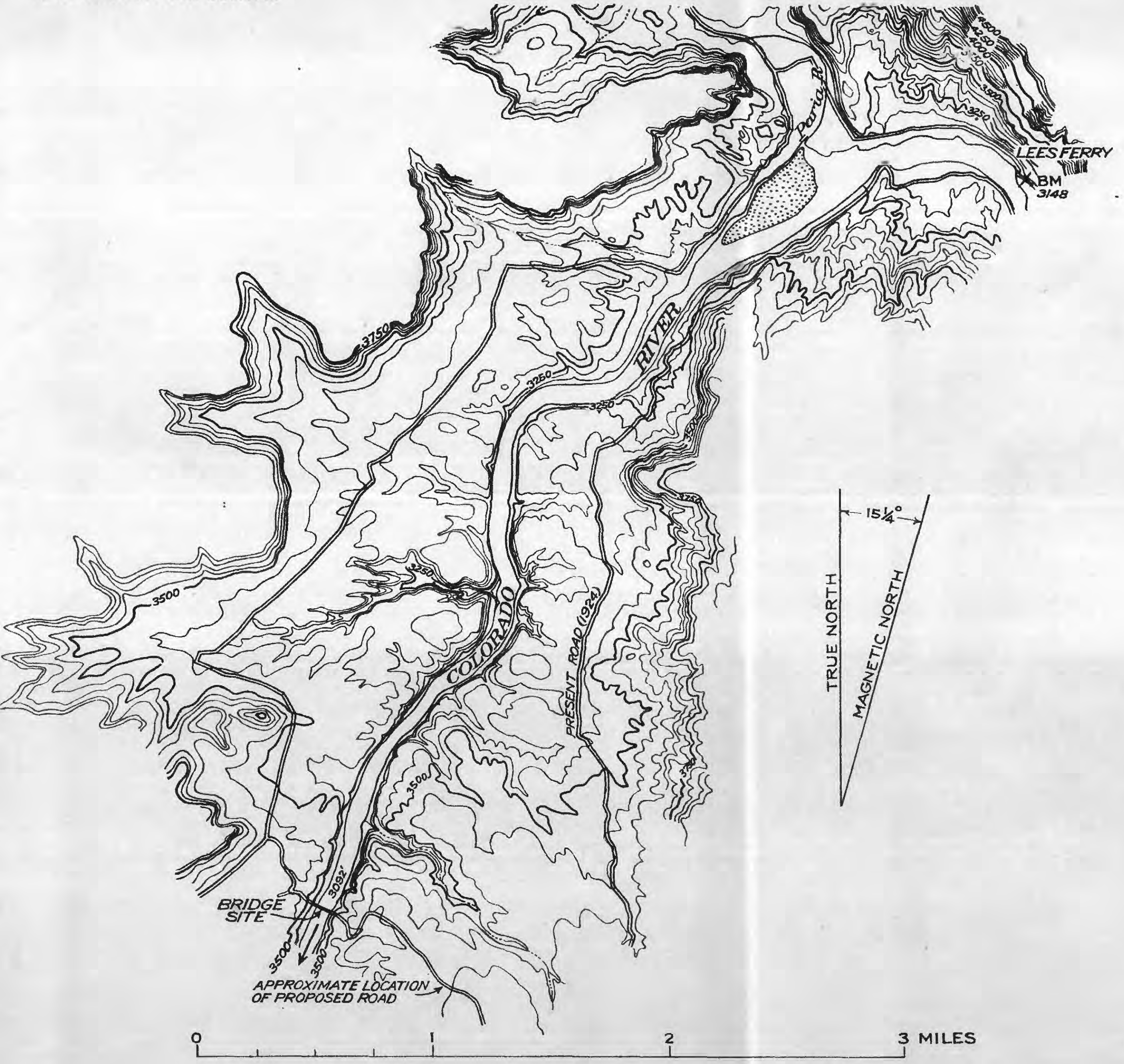
A. JUNCTION OF LITTLE COLORADO AND COLORADO RIVERS, SHOWING THE END OF MARBLE GORGE

Geology by R. C. Moore

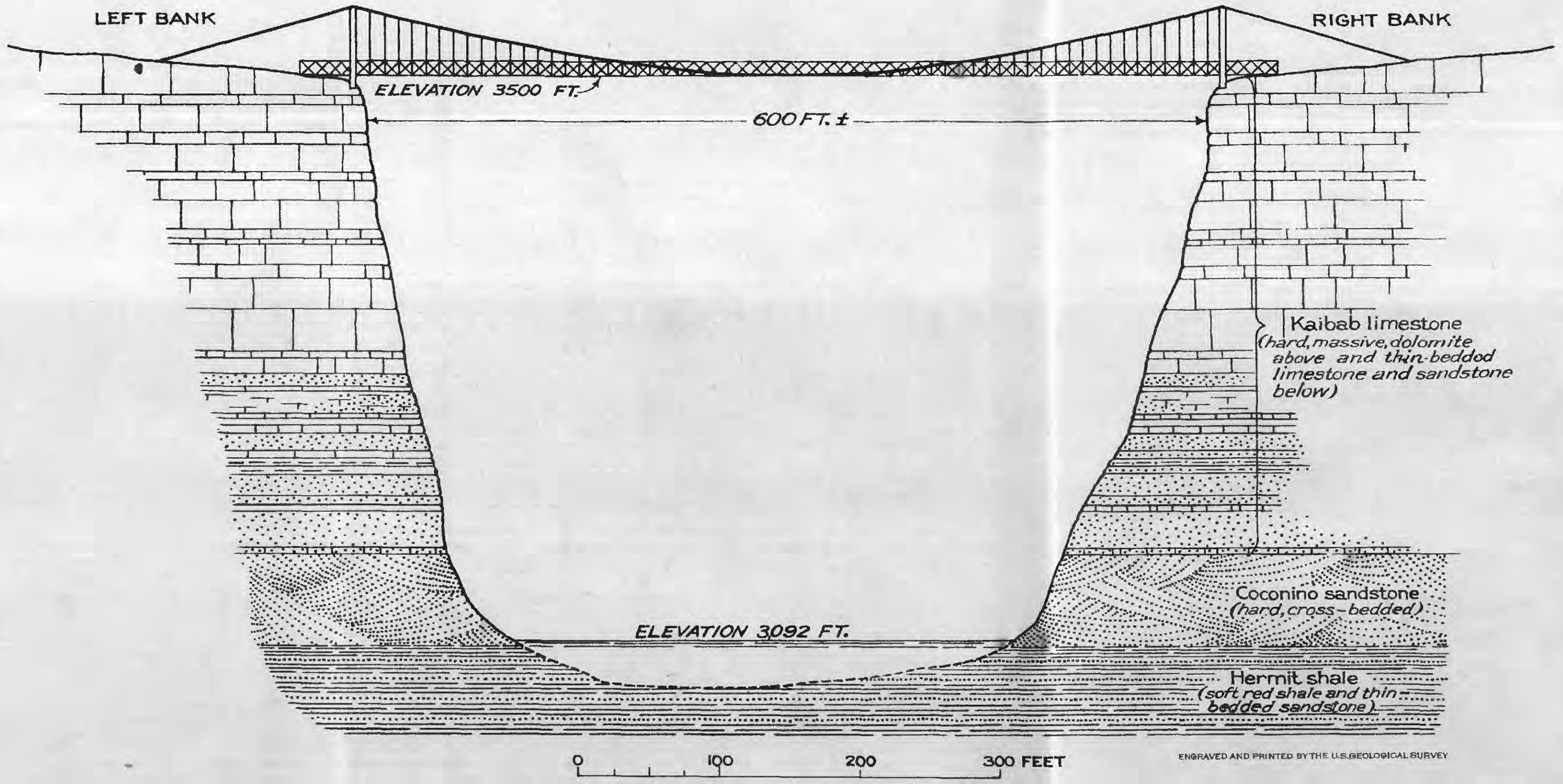


B. THE GRAND CANYON AS SEEN FROM THE SOUTH RIM AT GRANDVIEW POINT, 10 MILES EAST OF HOTEL EL TOVAR

The width of the canyon as measured between Grandview Point and Walhalla Plateau is 9 miles. The rim of Walhalla Plateau is 5,750 feet above the river, and its horizontal distance from the river is 5 miles. Photograph by N. W. Carkhuff



MAP OF BRIDGE SITE
Contour interval 20 feet
Surveyed in 1923



CROSS SECTION OF BRIDGE SITE

MAP AND CROSS SECTION OF MARBLE GORGE BRIDGE SITE

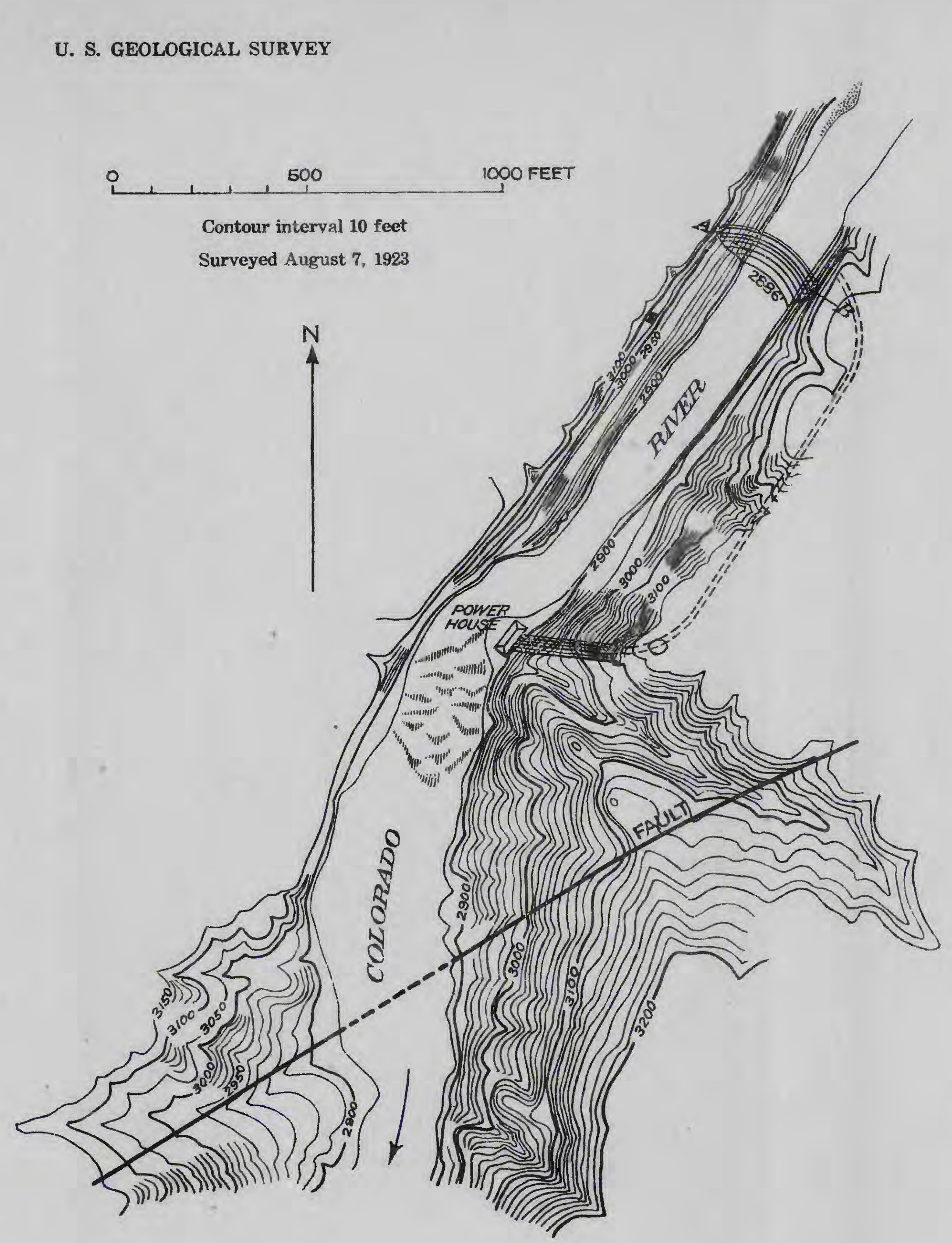
5 MILES BELOW LEES FERRY

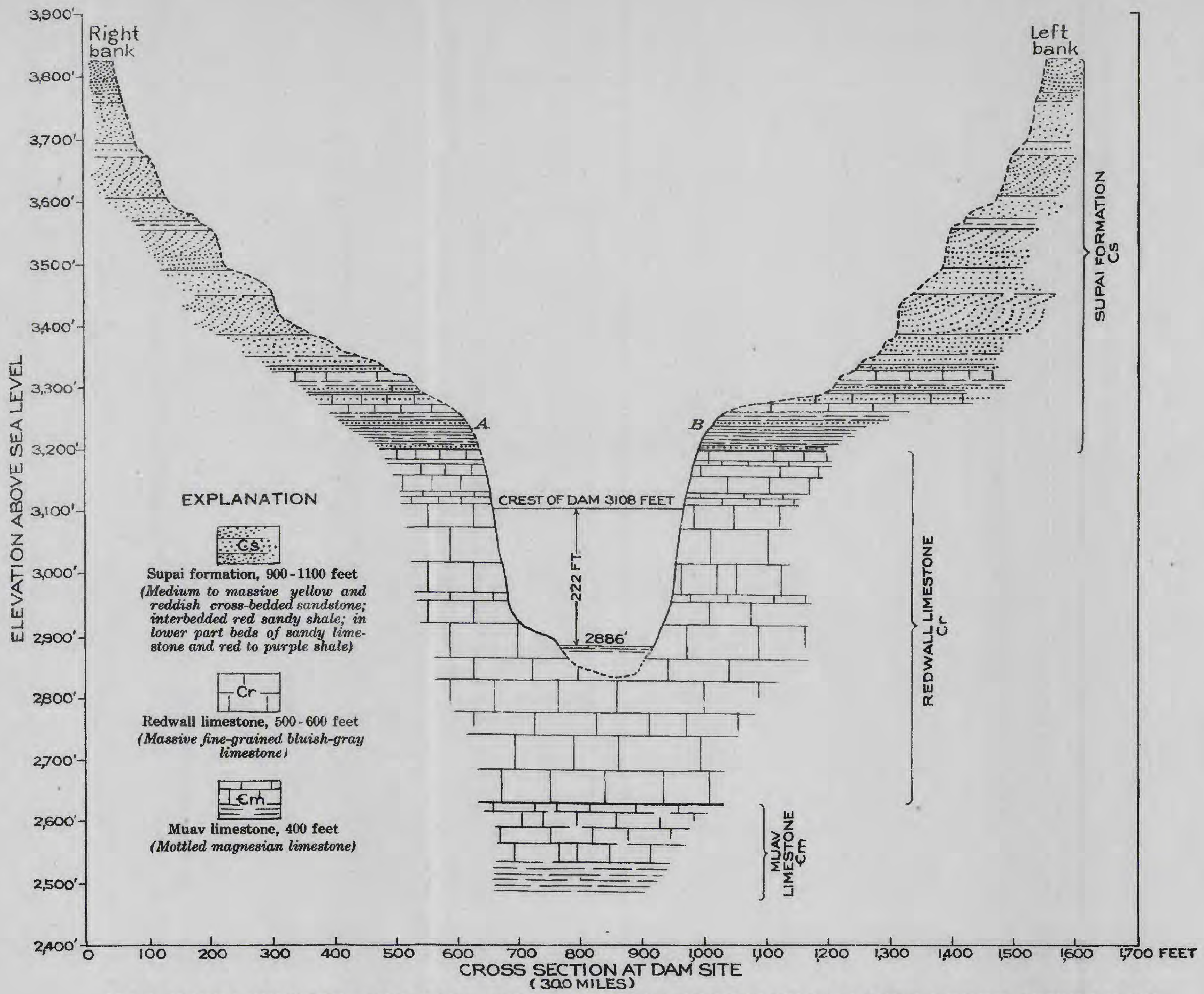
A. REDWALL DAM SITE, MARBLE GORGE 30 MILES BELOW PARIA RIVER

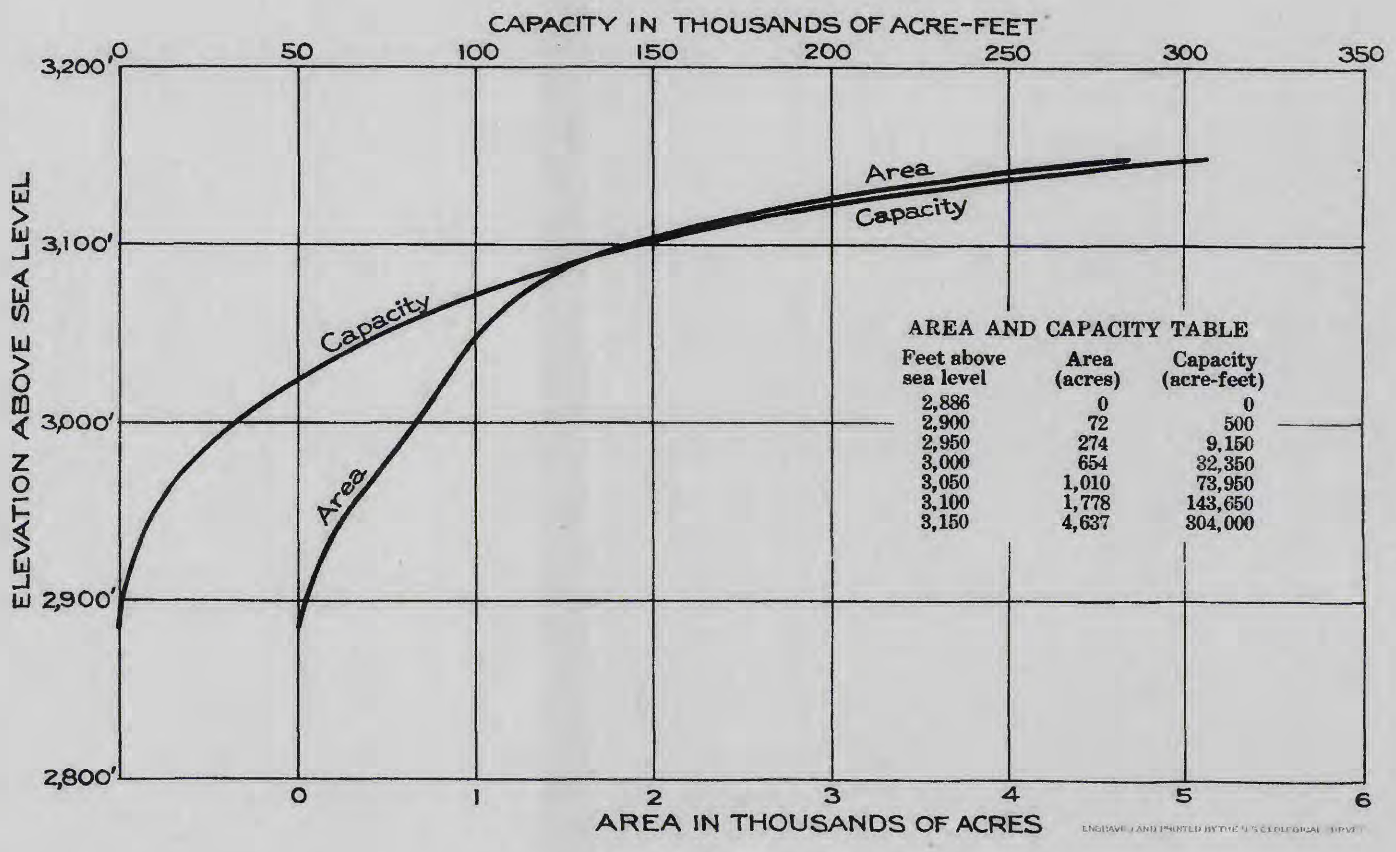
Geology by R. C. Moore

B. A CLOSE-UP VIEW OF THE REDWALL DAM SITE

Geology by R. C. Moore







AREA AND CAPACITY TABLE

Feet above sea level	Area (acres)	Capacity (acre-feet)
2,886	0	0
2,900	72	500
2,950	274	9,150
3,000	654	32,350
3,050	1,010	73,950
3,100	1,778	143,650
3,150	4,637	304,000

MAP, CROSS SECTION, AND AREA AND CAPACITY CURVES FOR MARBLE GORGE POWER SITE
(REDWALL DAM SITE)

canyon walls at the bridge site include practically all of the Kaibab limestone and Coconino sandstone. It follows, therefore, that the river has cut through these formations and that its bed is now in the soft Hermit shale, which underlies the Coconino sandstone. The Hermit shale consists of soft red shale and thin-bedded sandstone and is unsuitable for the foundation of a high dam. In Plate XXIII is a map of the site and a cross section showing the rock structure. Further information regarding the geology of this part of Marble Gorge will be found in Appendix B (p. 134). As shown by the topographic map of the bridge site, it would not be possible to build a dam farther upstream, because the walls are too low to support a dam of the required height. About 2 miles above the bridge site the foundation may be favorable, but the walls are low, and a dam of the maximum practicable height would create a storage capacity of less than 4,000,000 acre-feet and would not permit full utilization of the Glen Canyon reservoir site.

REDWALL DAM SITE

Location.—As the top of the Hermit shale is exposed in the river channel 4½ miles below Paria River, it was evident that no favorable dam site would be found in Marble Gorge until a point had been reached where the river had cut through the 500 feet of the Hermit shale and the 800 feet of the Supai formation and well into the Redwall limestone. Such a site was found 30 miles below Paria River and is here referred to as the Redwall dam site. (See Pls. II and XV, in pocket.)

Physical characteristics.—For several miles above and below the Redwall dam site the river flows between nearly vertical walls of Redwall limestone. At the site selected the water surface at the 10,000 second-foot stage is 2,886 feet above sea level,[21] and the width of the river at the dam site is 160 feet. Here the Redwall limestone rises to an elevation of 3,200 feet above sea level, which is nearly 100 feet higher than would be necessary to support a dam of sufficient height to back the water to the Lees Ferry site. Views of the dam site are shown in Plate XXIV.

The Redwall limestone is more than 500 feet thick, and as only 300 feet of the formation is exposed in the canyon walls, it follows that more than 200 feet of the same formation is in place below the water surface at the dam site. (See Pl. XXV.) The Redwall is a massive fine-grained bluish-gray limestone, very firm and practically free from bedding planes and solution channels. So far as the rock structure

[21] For that part of the river below Lees Ferry the figures given to indicate the elevation of the water surface at low water have been obtained by adjusting the recorded data so as to represent the elevation when the discharge of the river is 10,000 second-feet.

is concerned, the conditions at this site are ideal for the construction of a dam. Bedrock will probably be found at a depth between 40 and 60 feet below the water surface. More detailed information regarding the rock structure at this site is given in Appendix B (p. 136).

Plan of development.—The river surface at the Glen Canyon dam site is 3,127 feet above sea level. If that site should be used for the development of power, the power house would be placed at the lower end of the loop, 4 miles below the dam site, where the water surface is 3,118 feet above sea level. It has been assumed that the water level at the Redwall dam site may be raised to an elevation of 3,108 feet above sea level without interfering with power development at the Glen Canyon site.

The Redwall dam site is in a box canyon, where the walls rise from the river almost vertically for 300 feet. There is no natural spillway site near by, and the overflow type of dam is probably best adapted to fit the conditions at the site. The power house may be located at the mouth of a small side canyon on the left bank about 1,100 feet below the dam site. The suggested plan of development is clearly shown in Plate XXV. In this plan the tunnels leading to the power house would be about 1,100 feet long. Further study of the site on the ground may show that it would be feasible to build the dam farther downstream, shortening the length of the power tunnels to 400 feet. By fixing the crest elevation of the dam at 3,108 feet above sea level, the static head at the power plant would be 222 feet.

Material suitable for the construction of the dam, except cement, is available at this site. The Redwall limestone is satisfactory for use as the concrete aggregate, and sand in any quantity may be had by crushing the sandstone in the lower part of the Supai formation, which forms a slope above the Redwall cliff. Although pure limestone suitable for the manufacture of Portland cement is available, the other constituents of cement, such as shale of suitable quality, are not to be found in this locality.

Water supply.—A full discussion of the water supply is given in Appendix A, and the data relating to the Redwall dam site are given in Table 9 (p. 113). With the water used in the upper basin as in 1922 and without storage, the flow available at the Redwall dam site would be 5,880 second-feet 90 per cent of the time and 9,640 second-feet 50 per cent of the time. With ultimate development in the upper basin, a continuous flow of about 12,200 second-feet would be available at this site and in the lower part of Marble Gorge. With the water used as in 1922 and with storage in Glen Canyon, the available flow would be about 19,500 second-feet.

Power capacity.—The static head at the Marble Gorge power site would be 222 feet. The power capacity with this head and the water supply given in the preceding paragraph would be as follows:

	Horsepower
Without storage and with irrigation and power development in upper basin as in 1922:	
Capacity 50 per cent of time	171,000
Capacity 90 per cent of time	104,000
With storage in Glen Canyon and with irrigation and power development in upper basin as in 1922:	
Continuous power available	346,000
With storage and with ultimate irrigation and power development in upper basin:	
Continuous power available	217,000
Installed capacity (load factor 60 per cent)	362,000

Right of way.—There are no developments of any kind in Marble Gorge. The flowage damage would be negligible.

Accessibility.—At the present time the Redwall dam site is more than 100 miles from a railroad. It seems probable, however, that the Glen Canyon storage dam will be built before the development of the Redwall site is undertaken. Whether a railroad is built to Lees Ferry from the north or the south, a branch from such a railroad less than 25 miles long would connect with the Redwall dam site. The construction of such a railroad to the rim of Marble Gorge would not be expensive. To reach the dam site from the rim would require an inclined railroad or a road constructed on a grade of 5 or 6 per cent.

Adaptability of plan.—In discussing the flood-control problem the writer has called attention to the value of the Glen Canyon storage site. (See p. 35.) It is believed that the plan of development best adapted to conserve and utilize in the public interest the water resources of the lower Colorado will include the Glen Canyon storage project. It follows that no development in Marble Gorge should raise the water to an elevation sufficient to interfere with the development of the Glen Canyon site. Two alternative dam sites in the lower part of Marble Gorge are referred to below.

The writer believes that the most practical plan of development at any site in the Grand Canyon is that which calls for the construction of dams to raise the water between 200 and 300 feet, although owing to favorable conditions at certain sites it may be advisable to depart from this plan and recommend the construction of dams that would raise the water less than 200 feet or more than 300 feet. However, the Redwall site may be developed to furnish a static head for power of 222 feet without interfering with the Glen Canyon storage site. It is believed that this is the practical plan, and the Redwall site is therefore suggested as the first step for development of the potential power in the canyon below Lees Ferry.

ALTERNATIVE DAM SITES

In addition to the Redwall dam site, two other possible sites were selected in lower Marble Gorge. One of them is 1 mile above the Redwall site, where the water surface of the river is 2,894 feet above sea level. The conditions here are very similar to those at the Redwall site, except that there is no fault in the walls such as that below the Redwall site, and in consequence the upper site is not quite so accessible. However, this site should be examined further when the time arrives for the construction of a power dam in Marble Gorge. A view of the upper dam site is shown in Plate XXVI, *A*. In Plate XXVII will be found a map of the site, a cross section, and curves showing the area and capacity of the reservoir.

The other alternative dam site is at Vaseys Paradise, 2.2 miles below the Redwall site, where the water surface of the river is 2,868 feet above sea level. This site is in a box canyon, which is inaccessible except by boat (Pl. XXVI, *B*). The rock structure of the site is the same as that which has been described in connection with the Redwall dam site. There is no favorable place for a power house or a construction camp, and the site is mentioned here only as a possibility. A map and cross section of this dam site are given in Plate XXVIII.

MINERAL CANYON POWER SITE

General features.—Below Vaseys Paradise the river continues to flow between vertical cliffs of Redwall limestone. At mile 35.2 below Paria River the top of the Muav limestone appears in the river channel, the entire thickness of the Redwall formation being exposed in the canyon walls. At mile 46 the Muav limestone, here nearly 500 feet thick, is exposed above the river, and a short distance downstream the very dark green sandy shale and shaly sandstone of the upper part of the Bright Angel shale appear. As shown in the geologic section (Pl. XV, in pocket), at mile 24.2 the top of the Redwall limestone appears in the river channel at 2,944 feet above sea level, and at mile 46, where the water surface is 2,811 feet above sea level, the bottom of the Muav limestone is exposed. For the 22 miles between these points the river flows through the Redwall and Muav formations. Lying above the Redwall is the Supai formation, and below the Muav the Bright Angel shale appears. The rocks of both of these formations are too soft to serve as dam abutments and foundations, and it therefore follows that favorable dam sites in Marble Gorge are limited to that portion of the gorge between mile 24.2 and mile 46 below Paria River.

Having located a suitable dam site at mile 30 (Redwall site), where the water surface is 2,886 feet above sea level, the writer made a careful search for another site at or near an elevation of 2,636 feet above sea level. From mile 46 to mile 61.5 the Bright Angel shale is present in the river channel and canyon walls. At the mouth of the Little Colorado (mile 61.5) the top of the Tapeats sandstone appears above the river (Pl. XXI, *A*), and 3 miles farther downstream this formation rises in the walls to a height of 290 feet above the river. Although the topographic features of this Tapeats gorge are favorable, all hopes of finding a feasible dam site were abandoned when the geologist recognized the formation in the river channel as the soft shaly sandstone belonging to the Algonkian. The water surface here is 2,687 feet above sea level. Below the Tapeats gorge the lower part of the Grand Canyon is wide and open, as here the river has carved its way through the relatively weak Algonkian rocks

At 15 miles below Little Colorado River and half a mile above the Hance Rapids the Colorado flows through a narrow canyon where the walls rise several hundred feet above the river. The presence of shale in the lower part of the walls renders this site unfavorable for the construction of a dam. Here the river surface is 2,565 feet above sea level.

From Hance Rapids the beginning of Granite Gorge could be seen a short distance downstream. This being the first supply station, the Survey party remained here several days. A short trip downstream on foot disclosed a practicable dam site at the mouth of Mineral Canyon, 1 mile below Hance Rapids. Here the water surface is 2,531 feet above sea level. To back the water from this point to the Redwall dam site in Marble Gorge would require a dam of sufficient height to raise the water 345 feet.

The preceding description of the canyon between the Redwall and Mineral Canyon dam sites shows that no suitable dam sites exist between mile 46, where the river surface is 2,811 feet above sea level, and Mineral Canyon, where the elevation is 2,531 feet. These conditions require a departure from the preferred plan for building power dams to a height between 200 and 300 feet above the river level.

Location.—The Mineral Canyon dam site is in the Grand Canyon near the head of Granite Gorge, 77.8 miles below Paria River, 16.3 miles below Little Colorado River, and 1 mile below Hance Rapids. (See Pl. II, in pocket.)

Physical characteristics.—About a quarter of a mile below Hance Rapids the Archean rocks first appear in the river, and within a distance of less than 1 mile these hard crystalline rocks form the canyon walls to a height of 400 feet above the river.

The site selected for the dam is just below the mouth of Mineral Canyon. Here the rock walls consist of a complex of gneiss, schist, granite, and pegmatite. These are all hard crystalline rocks, which form a compact, solid mass that is entirely satisfactory for the foundation and abutment walls for a dam (Pl. XXIX, *A*). A more detailed description of the rocks is given in Appendix B (p. 142).

The topographic features of the site (Pl. XXX) are favorable for the construction of the dam, spillway, and power house. The depth to bedrock below the water surface is estimated at 40 to 50 feet.

Plan of development.—The river surface at the Redwall dam site, in Marble Gorge, is 2,886 feet above sea level when the discharge is 10,000 second-feet, and as it seems reasonable to assume, for the purpose of estimates, that a difference of 10 feet in elevation is sufficient to take care of the slope in the backwater from a dam built at the site next below, the normal elevation of the water surface of the reservoir at the proposed Mineral Canyon dam has been fixed at 2,876 feet above sea level. As the water surface of the river at the Mineral Canyon dam site is 2,531 feet above sea level, and the water may be raised to 2,876 feet, it follows that a static head of 345 feet may be utilized for the development of power.

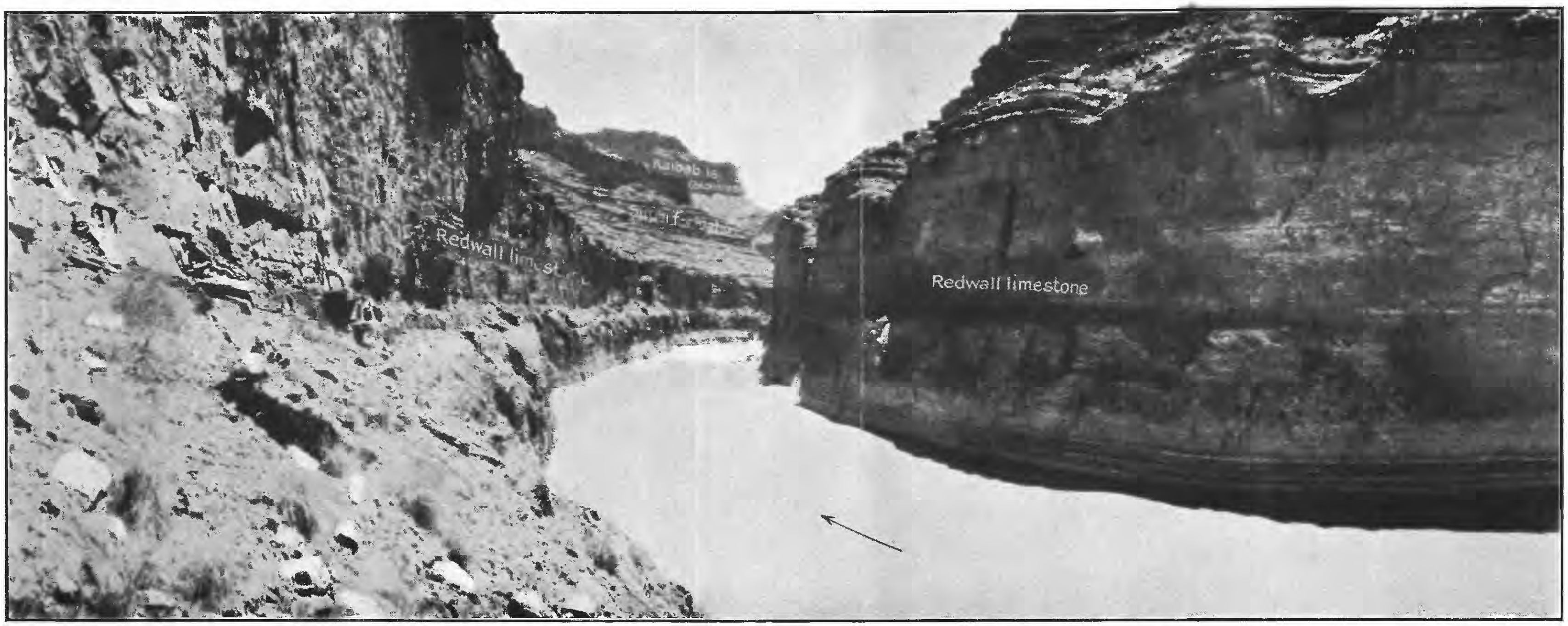
A concrete dam of the overflow type is suggested as best adapted to fit the conditions at this site. The crest elevation of the dam may be fixed at 2,876 feet above sea level. By providing discharge tunnels in the dam, the water level in the reservoir can be maintained at or near the crest. No water would pass over the dam except during periods of flood. It is thus clear that the works could be operated in such a manner as to avoid interference with the proposed development at the Redwall site.

A cross section and a map of the dam site are shown in Plate XXX. The writer believes that it would be more economical to place the power house on the left bank about 1,500 feet below the dam and utilize the side canyon as a site for diversion works.

Materials suitable for the construction of the dam, except cement, are available at the site. (See Appendix B, p. 142.)

Water supply.—With development in the upper basin as in 1922 and without storage, the water supply available at the Mineral Canyon dam site is 6,400 second-feet 90 per cent of the time, or 10,200 second-feet 50 per cent of the time. With storage provided in Glen Canyon and with the use of water as in 1922, a continuous flow of about 20,500 second-feet could be made available. With ultimate development in the upper basin, the continuous flow available would be reduced to about 12,800 second-feet. (See Appendix A, p. 113.)

Power capacity.—The static head at the Mineral Canyon site would be 345 feet. The power capacity with this head and the water supply given in the preceding paragraph would be as follows:

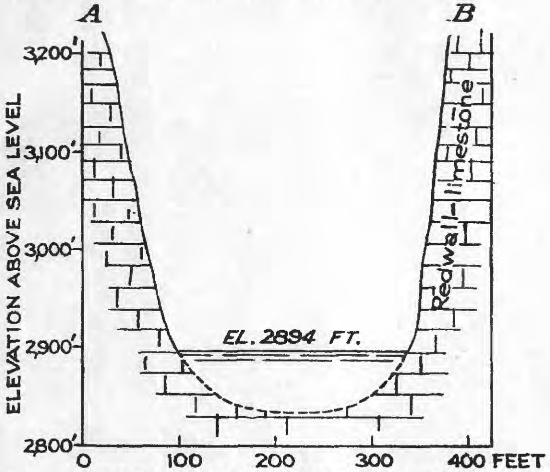


A. ALTERNATIVE DAM SITE IN MARBLE GORGE 29 MILES BELOW PARIA RIVER

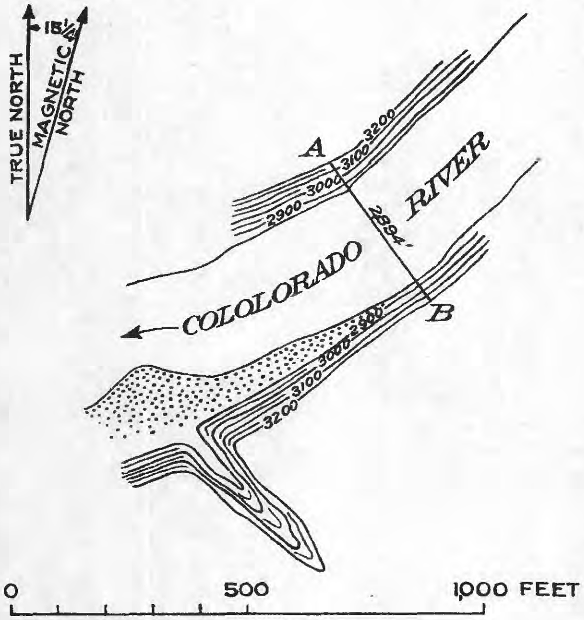
Geology by R. C. Moore

B. ALTERNATIVE DAM SITE IN MARBLE GORGE AT VASEYS PARADISE, 32.2 MILES BELOW PARIA RIVER

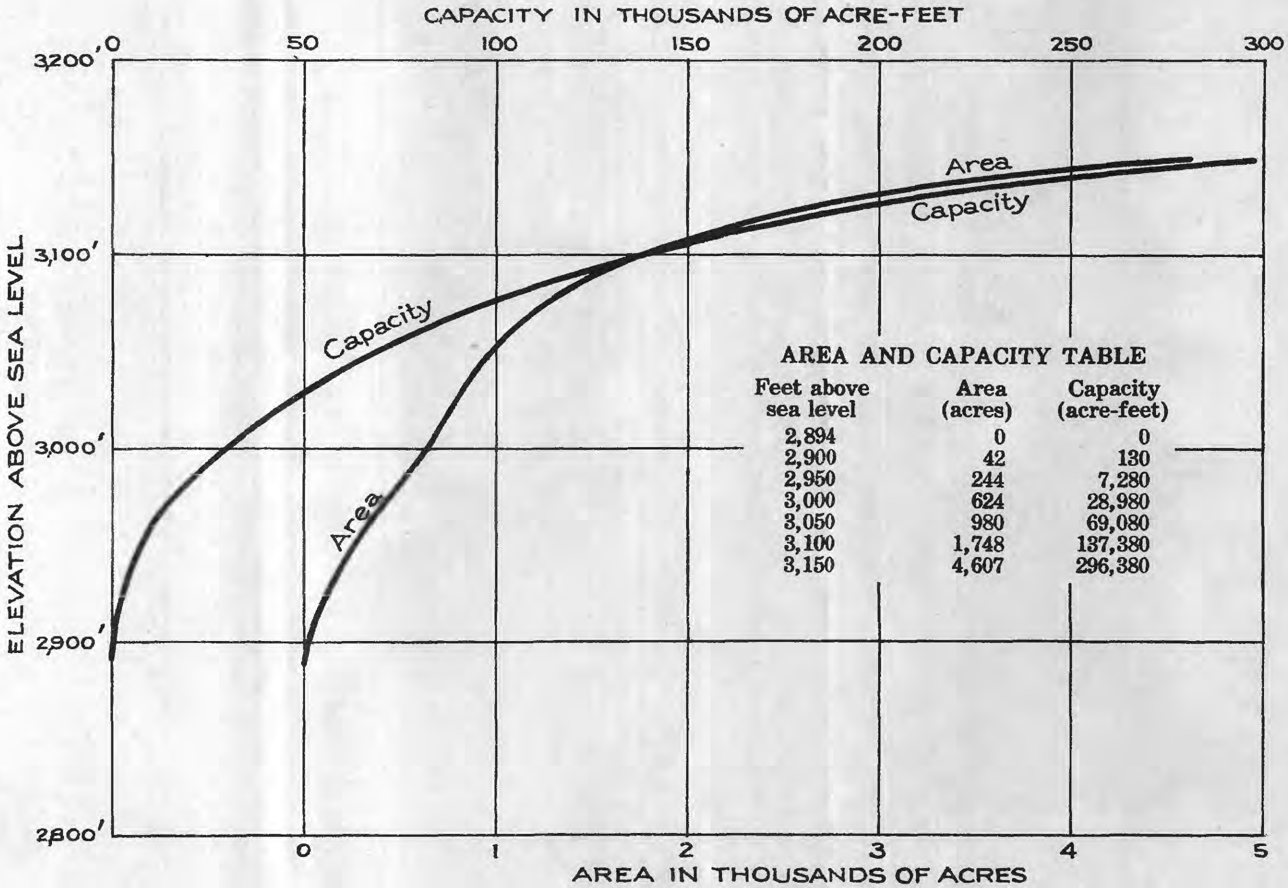
Geology by R. C. Moore



CROSS SECTION AT DAM SITE
(29.0 MILES)



Contour interval 50 feet
Surveyed August 7, 1923



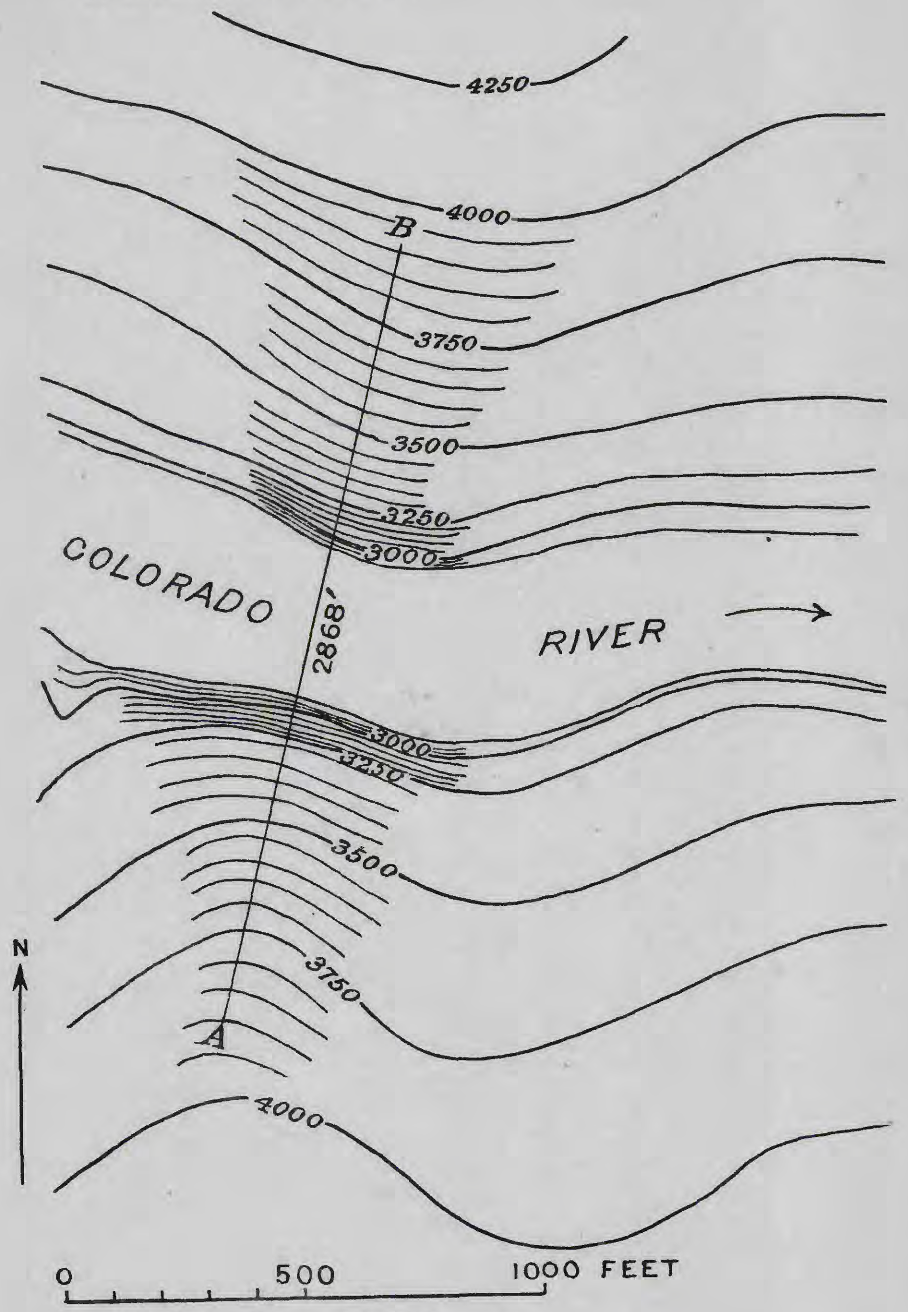
AREA AND CAPACITY TABLE

Feet above sea level	Area (acres)	Capacity (acre-feet)
2,894	0	0
2,900	42	130
2,950	244	7,280
3,000	624	28,980
3,050	980	69,080
3,100	1,748	137,380
3,150	4,607	296,380

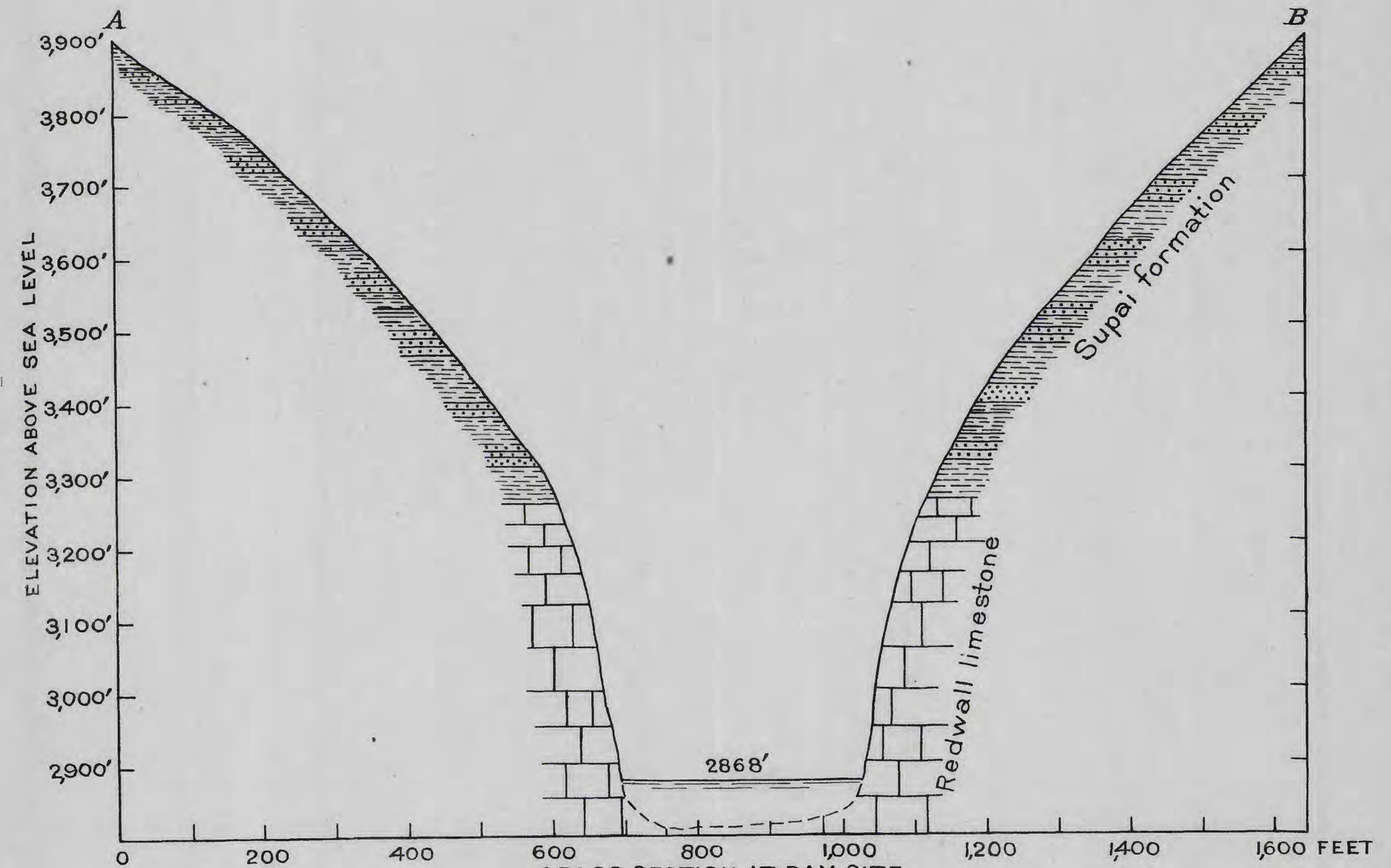
ENGRAVED AND PRINTED BY THE U.S. GEOLOGICAL SURVEY

MAP, CROSS SECTION, AND AREA AND CAPACITY CURVES FOR MARBLE GORGE POWER SITE

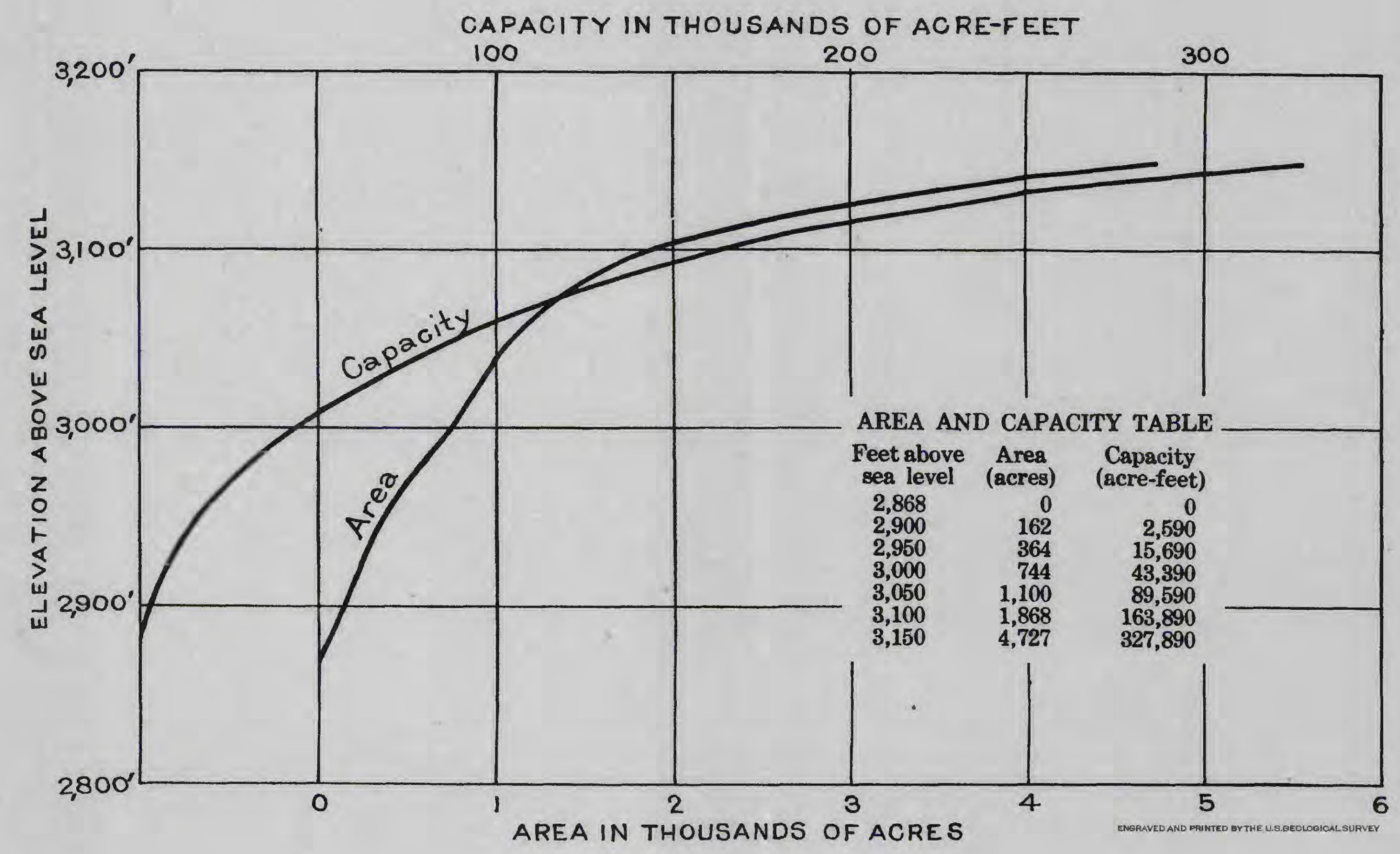
(ALTERNATIVE DAM SITE NO. 1)



Surveyed August 8, 1923
Contour interval 50 feet



CROSS SECTION AT DAM SITE
(32.2 MILES)



AREA AND CAPACITY TABLE

Feet above sea level	Area (acres)	Capacity (acre-feet)
2,868	0	0
2,900	162	2,590
2,950	364	15,690
3,000	744	43,390
3,050	1,100	89,590
3,100	1,868	163,890
3,150	4,727	327,890

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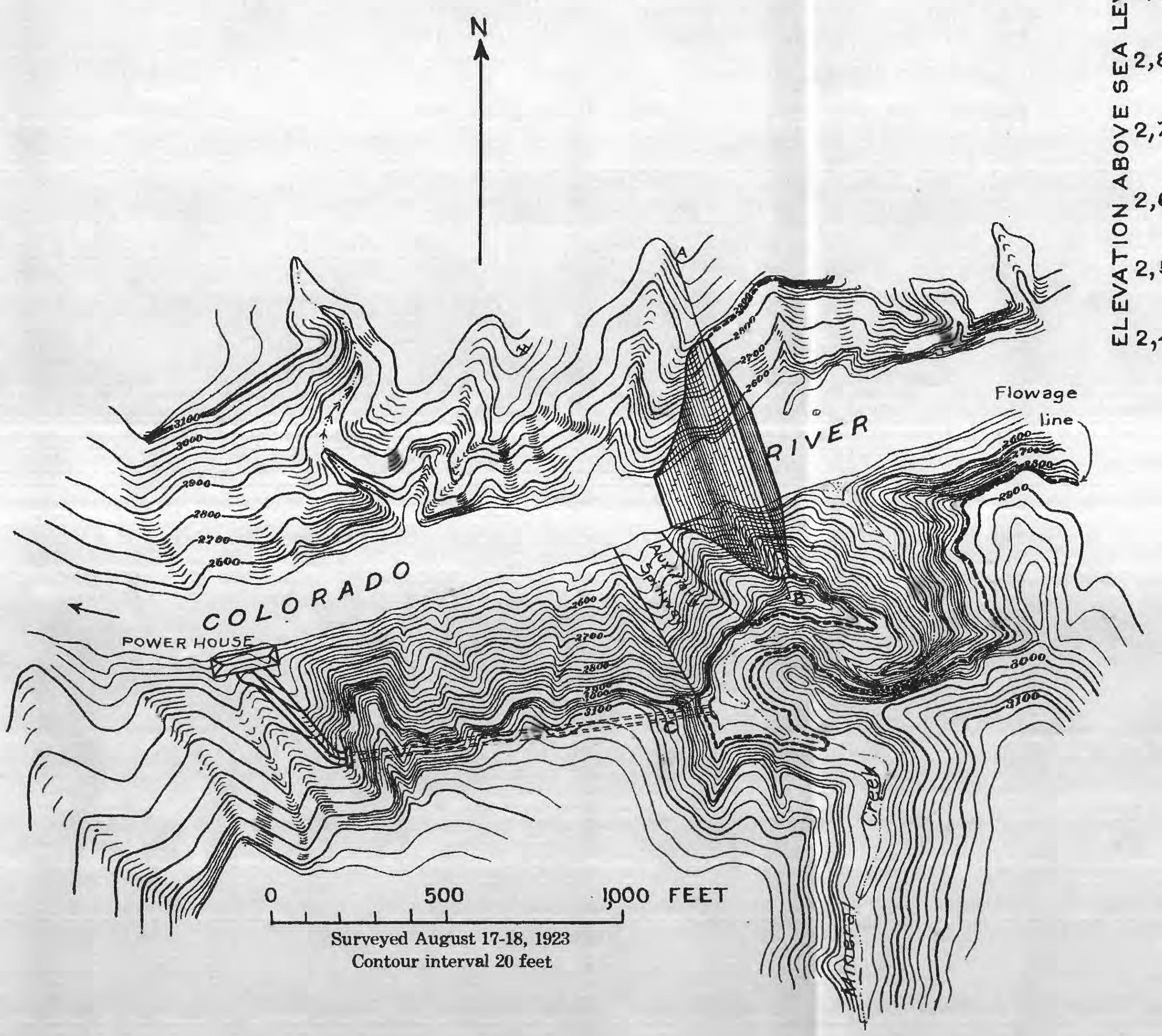
MAP, CROSS SECTION, AND AREA AND CAPACITY CURVES FOR MARBLE GORGE POWER SITE
(ALTERNATIVE DAM SITE NO. 2)

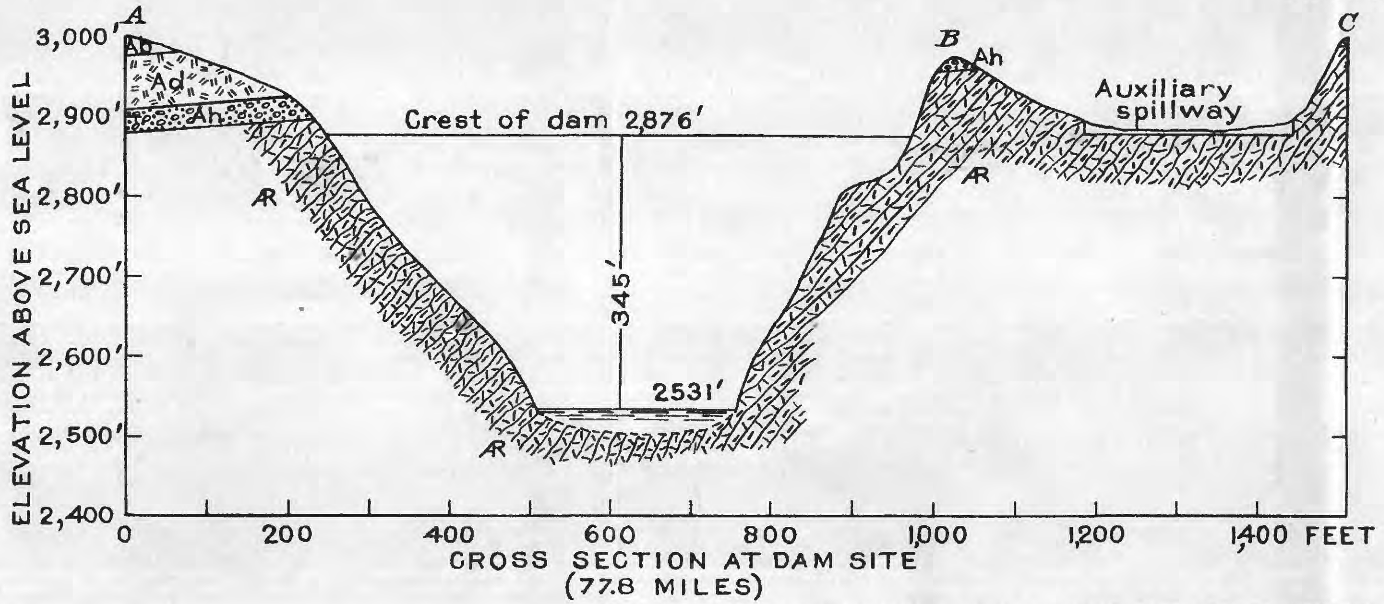
A. MINERAL CANYON DAM SITE, GRAND CANYON, 1 MILE BELOW HANCE RAPIDS

Geology by R. C. Moore

B. RUBY CANYON DAM SITE, GRAND CANYON, 16 MILES BELOW BRIGHT ANGEL CREEK

Geology by R. C. Moore





EXPLANATION

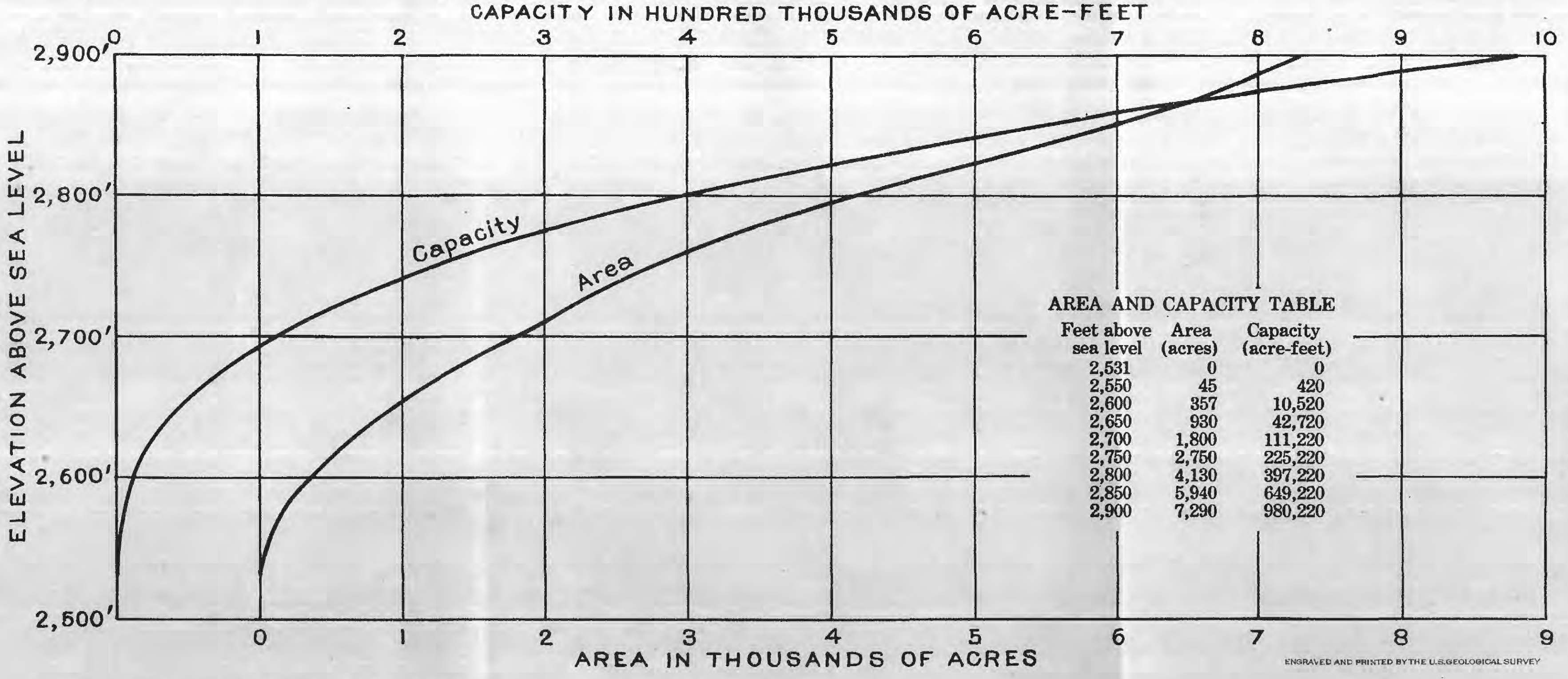
Ab — Bass limestone (*Light-gray fine-grained dense magnesian limestone, medium to massive beds; cliffs*)

Ah — Hotauta conglomerate (*Dark coarse conglomerate with well-rounded pebbles and cobbles*)

AR — Archean gneiss and schist (*Crystalline complex of gneiss, schist, granite, and pegmatite*)

IGNEOUS ROCKS

Ad — Diabase (Algonkian) (*Intrusive in Bass limestone*)



AREA AND CAPACITY TABLE

Feet above sea level	Area (acres)	Capacity (acre-feet)
2,531	0	0
2,550	45	420
2,600	357	10,520
2,650	930	42,720
2,700	1,800	111,220
2,750	2,750	225,220
2,800	4,130	397,220
2,850	5,940	649,220
2,900	7,290	980,220

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MAP, CROSS SECTION, AND AREA AND CAPACITY CURVES FOR MINERAL CANYON POWER SITE

	Horsepower
Without storage and with irrigation and power development in upper basin as in 1922:	
Capacity 50 per cent of time	282,000
Capacity 90 per cent of time	177,000
With storage in Glen Canyon and with irrigation and power development in upper basin as in 1922:	
Continuous power available	566,000
With storage and with ultimate irrigation and power development in upper basin:	
Continuous power available	353,000
Installed capacity (load factor 60 per cent)	588,000

Accessibility.—The Mineral Canyon power site is at the bottom of the Grand Canyon, 4,500 feet below the plateau on the south. The end of the railroad at Hotel El Tovar, on the south rim of the canyon, is about 30 miles from the dam site. Connection with the dam site could be provided by extending this railroad about 12 miles along the rim and building an inclined railroad into the canyon. At some future time a series of dams may be built in the Grand Canyon, the lower sites being developed first and each making the site next above accessible by means of the backwater.

Adaptability of plan.—The Mineral Canyon power site is 77.8 miles below Paria River, where the river surface is 2,531 feet above sea level. The tail water of the proposed power plant at Lees Ferry would be 3,118 feet above sea level. The writer believes that the fall of 587 feet in the section of the river between these points can best be utilized by developing two power sites—the Redwall site in Marble Gorge and the Mineral Canyon site lower down in the Grand Canyon. This belief is based on the theory that the most practical plan of development is that which calls for the construction of a series of dams of moderate height. To develop the fall in the river between Lees Ferry and Mineral Canyon in one unit would require a dam at Mineral Canyon about 600 feet high.

The data presented in the preceding pages show the physical conditions in the canyon from Green River, Utah, at 4,050 feet above sea level, to Mineral Canyon, at 2,531 feet above sea level. Every known dam site in this stretch is described. The value of Glen Canyon as a storage site to regulate the flow of the river in the interest of flood control, irrigation, and development of power is set forth. With Glen Canyon fixed as the proper location for a storage reservoir, the dam sites in Cataract Canyon and Marble Gorge and the Mineral Canyon site in the Granite Gorge may be developed primarily in the interests of power. The plan above presented provides for the full use of the fall in the river between Green River, Utah, and Mineral Canyon.

OTHER POWER SITES IN GRAND CANYON NATIONAL PARK

The east boundary of the Grand Canyon National Park crosses Colorado River at the mouth of Little Nankoweap Creek, 51.9 miles below Paria River and 9.5 miles above Little Colorado River. The west boundary of the park crosses the river about 1,000 feet above Havasu Creek. The river enters the park at an elevation of 2,795 feet above sea level and leaves it at 1,785 feet. Within the park the course of the river is 104.7 miles long, and the fall in this distance is 1,010 feet.

In the preceding pages a detailed description of the Mineral Canyon dam site is given. This site is in the upper part of the Grand Canyon National Park. There are no favorable dam sites within the park in the 26 miles above Mineral Canyon.

In the 79-mile section of the river between Mineral Canyon and Havasu Creek nine dam sites were surveyed, as follows:

Dam sites in the Grand Canyon between Mineral Canyon and Havasu Creek

Site	Distance below Paria River	Elevation of water surface above sea level	Rock at dam site
	Miles	*Feet*	
Clear Creek	84.4	2,452	Schist and granite.
Granite Wall	85.1	2,441	Granite.
Cremation	86.3	2,433	Do.
Pipe Creek	89.0	2,400	Granite, gneiss, and schist.
Ruby Canyon	103.9	2,235	Granite and schist.
Hakatai	110.7	2,157	Schist.
Big Bend	113.3	2,122	Granite gneiss.
Specter Chasm	130.0	2,002	Schist and gneiss.
Havasu	156.6	1,783	Muav limestone.

PLAN OF DEVELOPMENT

The gross head to be utilized between Mineral Canyon and Havasu Creek is 748 feet. Detailed information relating to each of the nine sites listed in the preceding table is presented below (pp. 61–68). A careful study of these data shows that in many respects the physical features of the dam sites are similar. For example, at each site the rock is satisfactory and the depth to bedrock is probably not great, and each site is inaccessible at the present time. The topographic features at some of the sites are more favorable for the location of power houses and auxiliary structures than at others. However, there would be relatively small differences in the cost of dams of given height constructed at the nine sites.

The development of power in this section of the Grand Canyon is a project for the distant future. The market will probably be found in southern California and southern Arizona, the transmission distance being from 200 to 350 miles. Power can not be transmitted such distances economically except in large blocks.

The writer believes that the gross head of 748 feet between Mineral Canyon and Havasu Creek can best be utilized by constructing power dams at the Ruby Canyon, Specter Chasm, and Havasu sites. With ultimate development in the upper basin the continuous power available at these three sites would be 297,000, 235,000, and 232,000 horsepower, respectively; and the installed capacity, with a 60 per cent load factor, would be 495,000, 392,000, and 387,000 horsepower.

The Clear Creek, Granite Wall, Cremation, and Pipe Creek dam sites were excluded on account of their position on the river. In order not to interfere with the development of the Mineral Canyon site, the elevation of the water surface above a power dam built below this site is limited to 2,521 feet above sea level. Therefore, a static head of only 69 feet could be developed at the Clear Creek dam site, 80 feet at the Granite Wall site, 88 feet at the Cremation site, and 121 feet at Pipe Creek. At the Ruby Canyon site, which is next below Pipe Creek, a static head of 286 feet could be developed. The next site in downstream order is the Hakatai, but utilization of this site to develop the head below Mineral Canyon would require a dam about 400 feet high. The construction of a dam of this unprecedented height may be avoided by selecting the Ruby Canyon site for development.

To avoid interfering with the development of the Ruby Canyon site, the next power dam below must have its flowage line fixed at an elevation not greater than 2,225 feet above sea level. At the Hakatai site, under this limitation, a static head of 68 feet could be utilized; at Big Bend, 103 feet; and at Specter Chasm, 223 feet. The next dam site below Specter Chasm is the Havasu, at an elevation 219 feet lower. If the Specter Chasm site were developed a static head of 209 feet could be utilized at Havasu. These two sites have therefore been selected to form units of the plan here presented for the development of power in the Grand Canyon.

The plan of development and the position of all alternative dam sites are shown on the profile of the river (Pl. III, in pocket) and on the map (Pl. II, in pocket). In the following pages will be found a detailed description of the nine dam sites between Mineral Canyon and Havasu Creek.

RUBY CANYON POWER SITE

Location.—The Ruby Canyon dam site is in the Grand Canyon half a mile above Ruby Canyon and 16 miles below Bright Angel Creek. (See Pl. II, in pocket.)

Physical characteristics.—At the dam site the river has carved a V-shaped canyon through the Archean granite and schist. The walls have a slope of about 45°, and a dam here would have a somewhat greater volume than a dam constructed where the walls are more nearly vertical. However, the gentle slope of the walls would make construction operations less difficult. The depth to bedrock below the water surface is estimated at 40 feet.

The granite and schist at the site are satisfactory for the construction of a high dam. A detailed description of these rocks is given in Appendix B (p. 147), where reference is also made to materials for construction. A view of the dam site is shown in Plate XXIX, *B*.

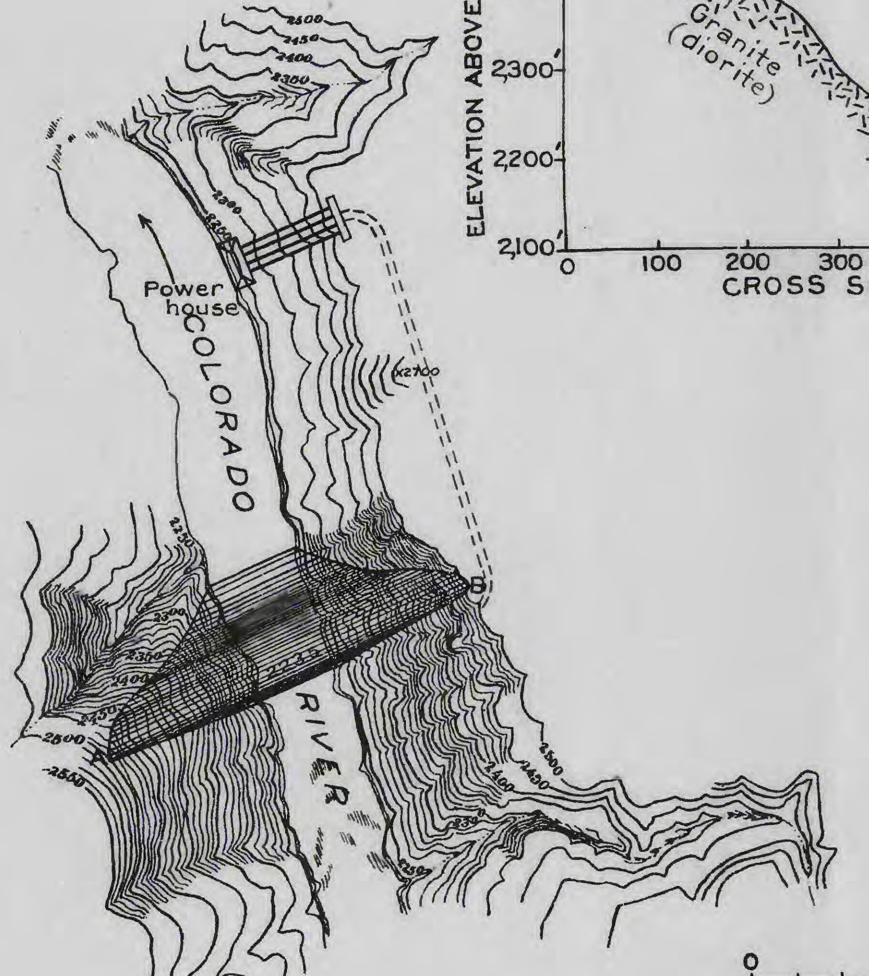
Plan of development.—A concrete dam of the overflow type is suggested as best adapted to fit the topographic conditions at this site, as there is no natural site for a spillway available. When the site was surveyed it was thought that it would be feasible to locate the power house in the side canyon on the right bank below the dam, with the power tunnel heading in the side canyon on the same side just above the dam. After a study of the map of the site it seems best to place the power house on the right bank about 800 feet below the dam and construct the tunnel heading at the dam near an elevation of 2,500 feet above sea level. The plan suggested is shown in Plate XXXI. The side canyons referred to are of value in that they afford access to the bottom of the main canyon during the construction period.

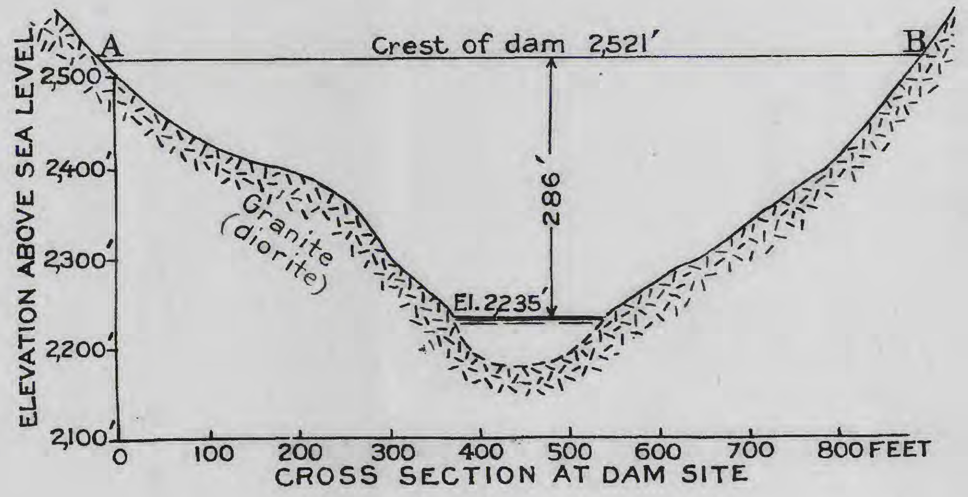
The water surface at the dam site is 2,235 feet above sea level. The water may be raised to an elevation of 2,521 feet without interfering with the proposed development at Mineral Canyon. A static head of 286 feet may therefore be utilized for the development of power.

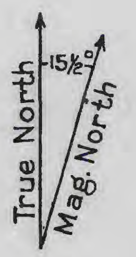
Water supply.—A discussion of water supply will be found in Appendix A (p. 113). With the water in the upper basin used as in 1922 the water supply available at Ruby Canyon dam site would be 6,500 second-feet 90 per cent of the time, or 10,200 second-feet 50 per cent of the time. With storage in Glen Canyon a continuous flow of 20,800 second-feet could be made available. When full development has been attained in the upper basin, the continous uniform flow available at Ruby Canyon will be reduced to about 13,000 second-feet.

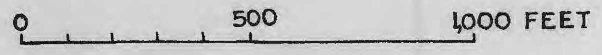
Power capacity.—The static head at the Ruby Canyon site would be 286 feet. The power capacity with this head and the water supply given in the preceding paragraph would be as follows:

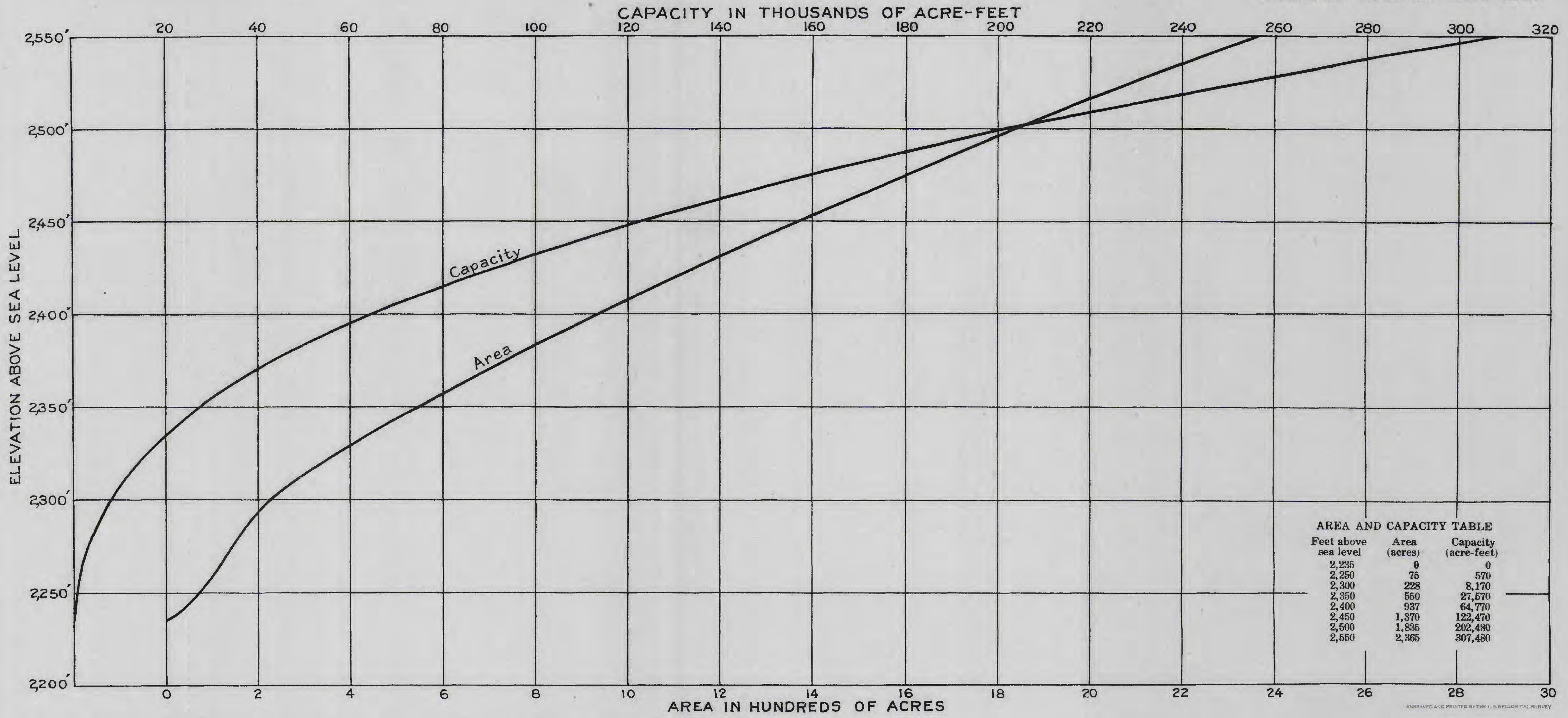
	Horsepower
Without storage and with irrigation and power development in upper basin as in 1922:	
Capacity 50 per cent of time	233, 000
Capacity 90 per cent of time	149, 000
With storage in Glen Canyon and with irrigation and power development in upper basin as in 1922:	
Continuous power available	476, 000
With storage and with ultimate irrigation and power development in upper basin:	
Continuous power available	297, 000
Installed capacity (load factor 60 per cent)	495, 000











AREA AND CAPACITY TABLE

Feet above sea level	Area (acres)	Capacity (acre-feet)
2,235	0	0
2,250	75	570
2,300	228	8,170
2,350	550	27,570
2,400	937	64,770
2,450	1,370	122,470
2,500	1,835	202,480
2,550	2,365	307,480

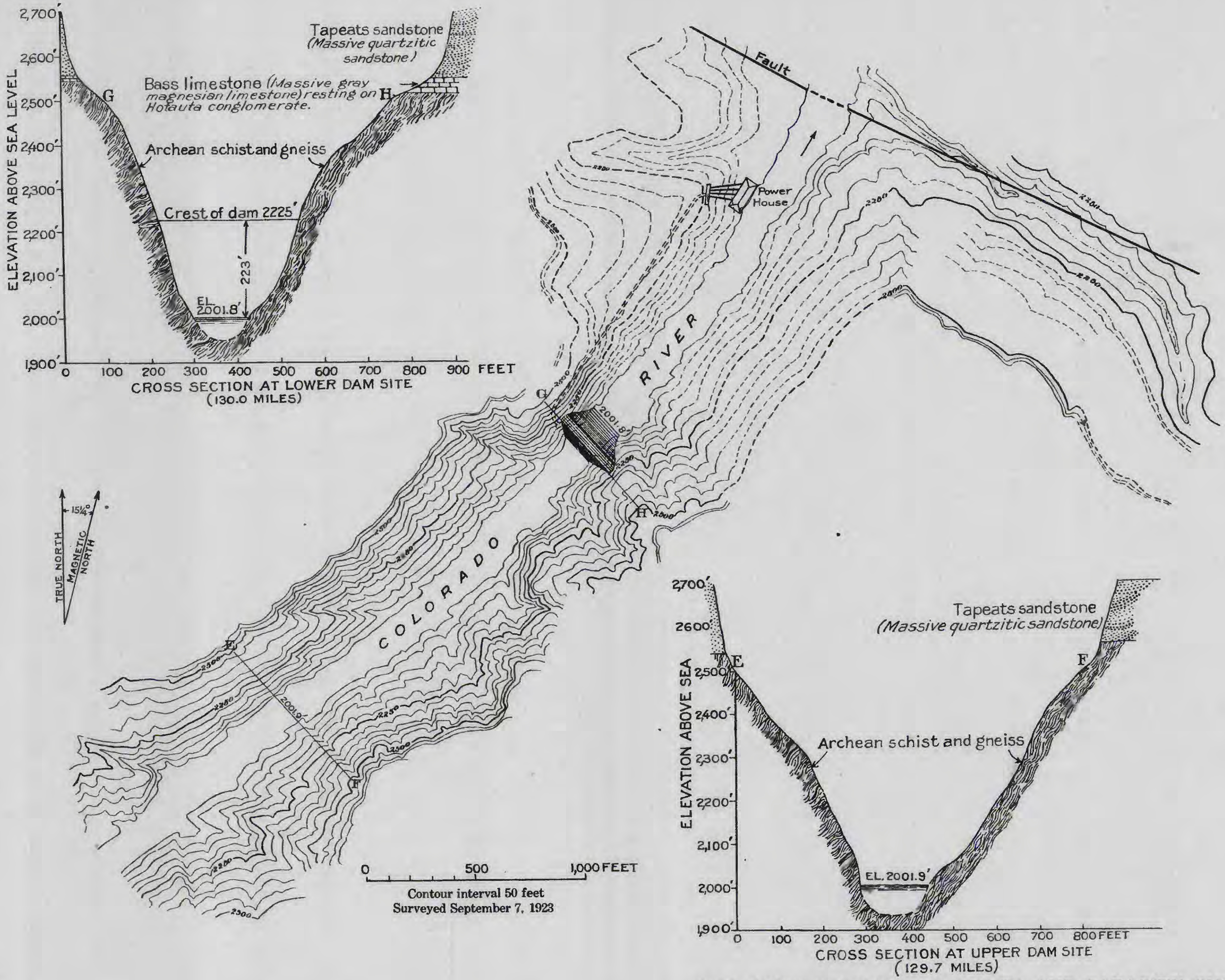
MAP, CROSS SECTION, AND AREA AND CAPACITY CURVES FOR RUBY CANYON POWER SITE

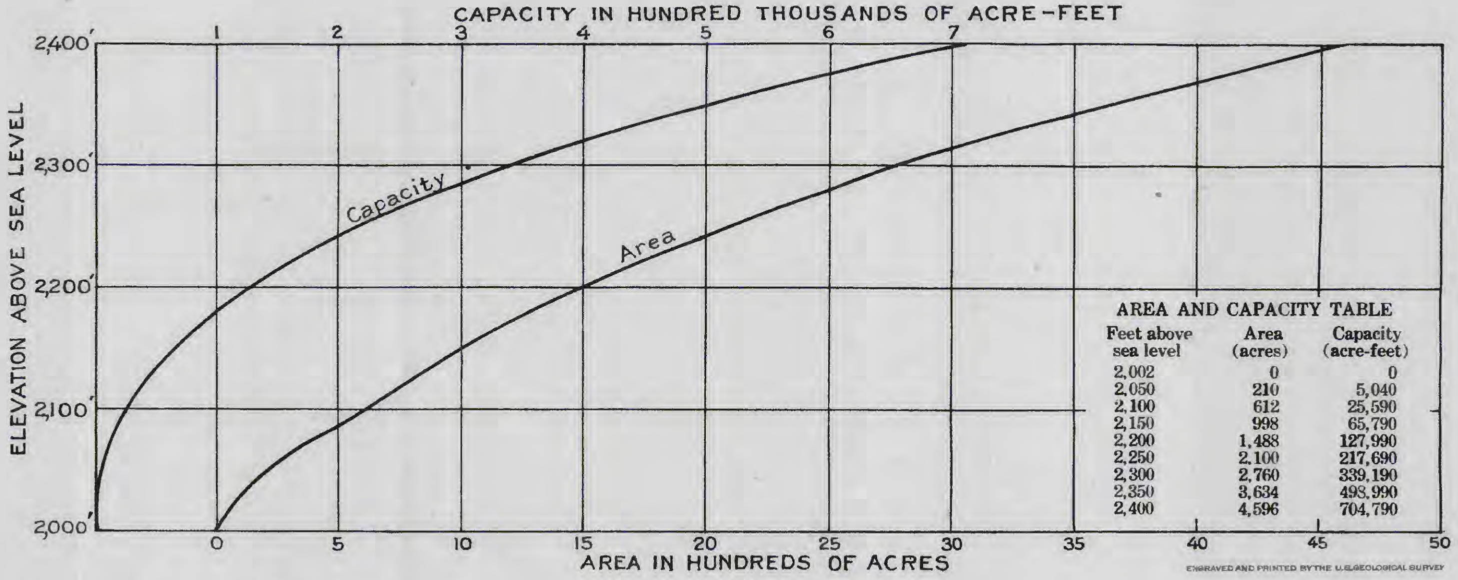
A. UPPER SITE

B. LOWER SITE

SPECTER CHASM DAM SITES, GRAND CANYON, 42 MILES BELOW BRIGHT ANGEL CREEK

Geology by R. C. Moore





AREA AND CAPACITY TABLE

Feet above sea level	Area (acres)	Capacity (acre-feet)
2,002	0	0
2,050	210	5,040
2,100	612	25,590
2,150	998	65,790
2,200	1,488	127,990
2,250	2,100	217,690
2,300	2,760	339,190
2,350	3,634	498,990
2,400	4,596	704,790

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MAP, CROSS SECTIONS, AND AREA AND CAPACITY CURVES FOR SPECTER CHASM POWER SITE

Right of way.—If the water were raised to an elevation of 2,521 feet above sea level, it would be necessary to relocate the Kaibab suspension bridge. If such a dam were built, however, a bridge would not be necessary, as a motor-driven ferry could easily take care of all traffic. The Phantom ranch, in the canyon of Bright Angel Creek, would be about 30 feet above the flowage line of the reservoir.

The backwater would extend up the river for 26 miles above the dam. The inner gorge of the Grand Canyon would thus become accessible to all who visit this region. Owing to the dangerous rapids a trip by boat through the Grand Canyon is a hazardous undertaking. Exclusive of the members of the Grand Canyon survey party of 1923, probably less than 5 men now living (1925) have seen the canyon throughout its length. If dams were built, motor-boat transportation could be provided, and the scenic wonders of the inner gorge of the Grand Canyon would thus become easily accessible.

In this report the writer is simply calling attention to the possibilities for power development in the Grand Canyon National Park and the effect of such development with respect to the accessibility of the canyon. He is not, however, advocating the construction of such dams.

If a dam were built at Ruby Canyon the amount of damage to property, except to the Kaibab bridge, would be small.

Accessibility.—This and all other dam sites in the Grand Canyon National Park are not easily accessible. Access to them could be provided in the manner indicated for the Mineral Canyon dam site (p. 59).

Adaptability of plan.—The plan for power development in the Grand Canyon National Park is discussed on page 60. As already stated, the transmission of power from the Grand Canyon to the nearest market, a distance of 200 to 350 miles, would not be practical except in blocks of 200,000 horsepower or more. The installed capacity at the Ruby Canyon site, with a 60 per cent load factor, would range from 248,000 to 495,000 horsepower, depending on the water supply.

SPECTER CHASM POWER SITE

Location.—The Specter Chasm dam sites are 42 miles below Bright Angel Creek and 13.5 miles above Kanab Creek. (See Pl. II, in pocket.)

Physical characteristics.—At the Specter Chasm sites the river has cut through massive Archean schist and gneiss. These hard crystalline rocks form almost vertical walls whose tops are 500 feet above the river. Two dam sites were surveyed; views of both sites are shown in Plate XXXII. The rock at both sites is satisfactory for the foundation and abutment walls of a dam of any height up to 550 feet.

The lower site, which is 1,800 feet below the upper site, offers the more favorable conditions. Here the canyon is very narrow, the distance between the walls at the water surface being only 150 feet. A dam to raise the water 223 feet would have a length on top of 315 feet. About 1,300 feet below the lower site the walls break away, leaving a comparatively open space on both sides of the river. Here the power house and other necessary buildings may be located. (See Pl. XXXIII.)

A discussion of the geologic setting at the dam site and the materials available for the construction of the dam will be found in Appendix B (p. 151).

Plan of development.—The water may be raised to an elevation of 2,225 feet above sea level at this site without interfering with the development of power at the Ruby Canyon site. As the water surface at the Specter Chasm site is 2,002 feet above sea level, a static head of 223 feet may be utilized for the development of power. No doubt a dam of the overflow type would best fit the conditions at this site. The crest elevation of the dam may be fixed at 2,225 feet above sea level, as the water could be held at or near this level by the proper operation of discharge tunnels constructed in the dam.

The power house may be placed in the open space on the left bank about 1,300 feet below the dam. The plan of development is shown in Plate XXXIII.

Although the writer believes that the more practicable plan for utilizing the 529-foot drop in the river between Mineral Canyon and Specter Chasm is that which calls for the construction of two dams of moderate height, it seems desirable to call attention to the fact that at Specter Chasm the conditions are favorable to the construction of a dam of sufficient height to back the water to Mineral Canyon. On account of the great length and small width of the pond that would be created, it would be desirable to allow 15 feet to take care of the backwater curve. The flowage line of the reservoir created by a high dam at Specter Chasm, therefore, would be fixed at 2,516 feet above sea level. Such a dam would create a static head of 514 feet. The length of the dam at the present water level would be 150 feet and its length on top would be only 660 feet. Under present conditions of development in the upper basin and with storage near Lees Ferry, 863,000 continuous horsepower could be developed. With a 60 per cent load factor, the required installed capacity would be 1,440,000 horsepower.

Water supply.—With the water in the upper basin used as in 1922 and without storage the water supply available at the Specter Chasm dam site would be 6,580 second-feet 90 per cent of the time, or 10,300 second-feet 50 per cent of the time. Under these conditions of development, and with storage provided in Glen Canyon, the continuous water supply would be 21,000 second-feet. With complete development in the upper basin, the water supply available at Specter Chasm will have been reduced to about 13,200 second-feet.

Power capacity.—The static head at the Specter Chasm site would be 223 feet. The power capacity with this head and the water supply given in the preceding paragraph would be as follows:

	Horsepower
Without storage and with irrigation and power development in upper basin as in 1922:	
Capacity 50 per cent of time	184, 000
Capacity 90 per cent of time	117, 000
With storage in Glen Canyon and with irrigation and power development in upper basin as in 1922:	
Continuous power available	375, 000
With storage and with ultimate irrigation and power development in upper basin:	
Continuous power available	235, 000
Installed capacity (load factor 60 per cent)	392, 000

Right of way.—The building of a dam at Specter Chasm to raise the water 223 feet would submerge a small area in the bottom of the Grand Canyon. The flowage damage would be negligible.

Accessibility.—The Specter Chasm dam site is in the bottom of the Grand Canyon, nearly a mile vertically below the canyon rim. To build a railroad to the site would be an expensive undertaking. Access could be provided in the manner indicated for the Mineral Canyon dam site (p. 59).

Adaptability of plan.—The writer believes that the building of a dam at the Specter Chasm site to utilize a head for power of 223 feet will become practicable when the demand for power justifies the development of the sites in the Grand Canyon National Park. As has been explained (p. 60), the utilization of the Specter Chasm site as here suggested, together with the sites at Ruby Canyon and Havasu, will provide full use of the fall in the river between Mineral Canyon and Havasu Creek, and the developments will be of a size that are economically feasible of construction.

HAVASU POWER SITE

Location.—The Havasu dam site is in the Grand Canyon 450 feet above the mouth of Havasu Creek and 600 feet below the west boundary of the Grand Canyon National Park. (See Pl. II, in pocket.)

Physical characteristics.—At the Havasu dam site the river has carved a narrow box canyon in the Muav limestone. (See Appendix B, p. 154.) The distance between the walls at the water surface is 150 feet, and a dam to raise the water 209 feet would be 330 feet long at the top. On the assumption that the depth to bedrock is 40 feet below the water surface, a dam of the overflow type would have a volume of 375,000 cubic yards.

The Muav limestone rises in the walls to a height of about 500 feet above the river and is estimated to extend 200 feet below the water surface. The limestone is fine grained, hard, and entirely free from solution channels. Next below the Muav is the Bright Angel shale, but this formation is believed to lie at a depth of 200 feet or more below the water surface at the dam site. In so far as the rock is concerned, it is believed that the conditions are favorable for the construction of a dam of the height proposed. In Plate XXXIV is a cross section at the dam site, which shows the rock structure. Further information regarding the geologic conditions at the site will be found in Appendix B (p. 154).

The Muav limestone when crushed will form excellent material for the concrete aggregate. Sand in any desired quantity may be obtained by crushing the sandstone in the lower part of the Supai formation, which caps the river cliffs.

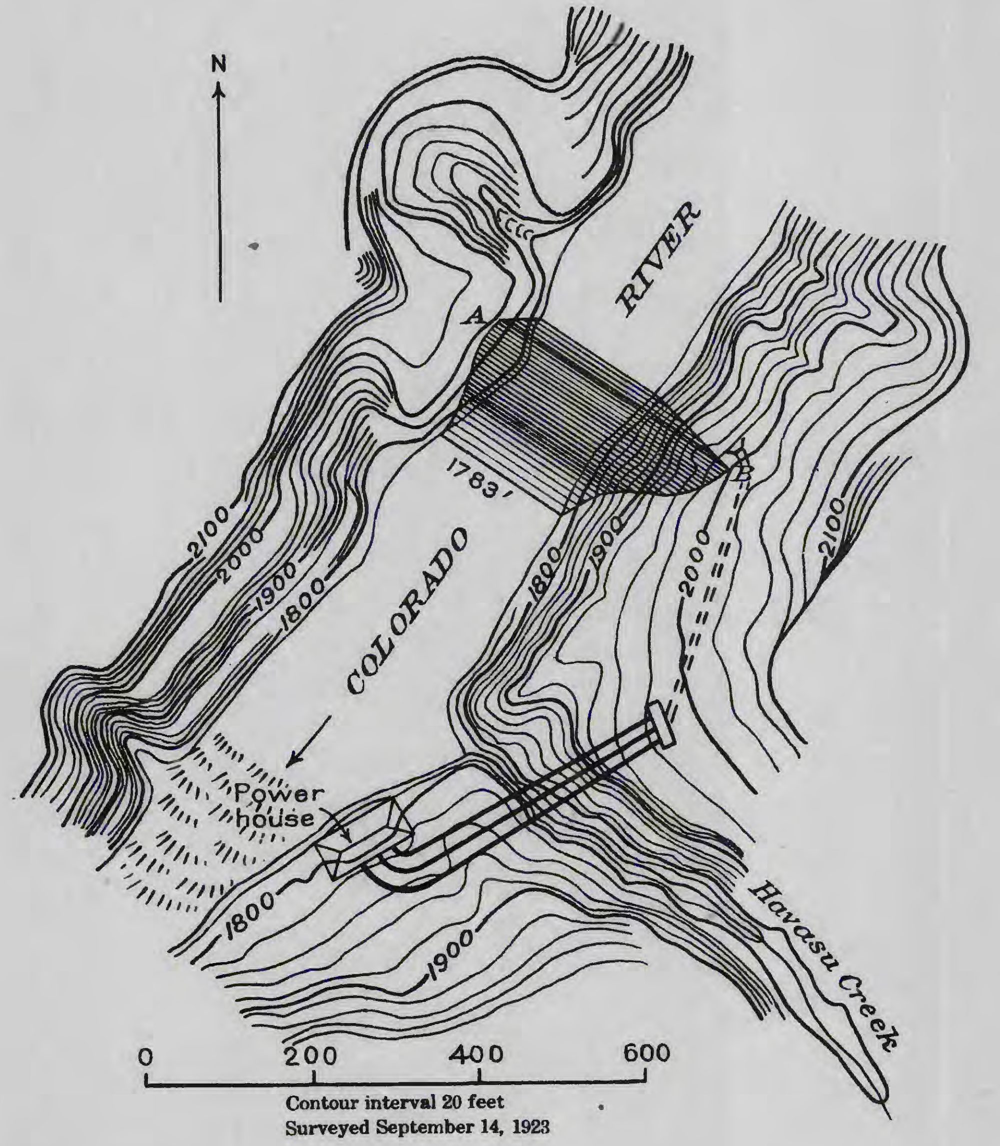
Plan of development.—Although the overflow type of dam is recommended, it would be advisable to avoid all overflow except at unusually high stages. The base of the dam would rest on the lower part of the Muav limestone, which is relatively weaker than the upper part of the same formation. It would therefore seem advisable to provide by-pass tunnels or discharge tunnels in the dam to take care of all surplus water except during floods.

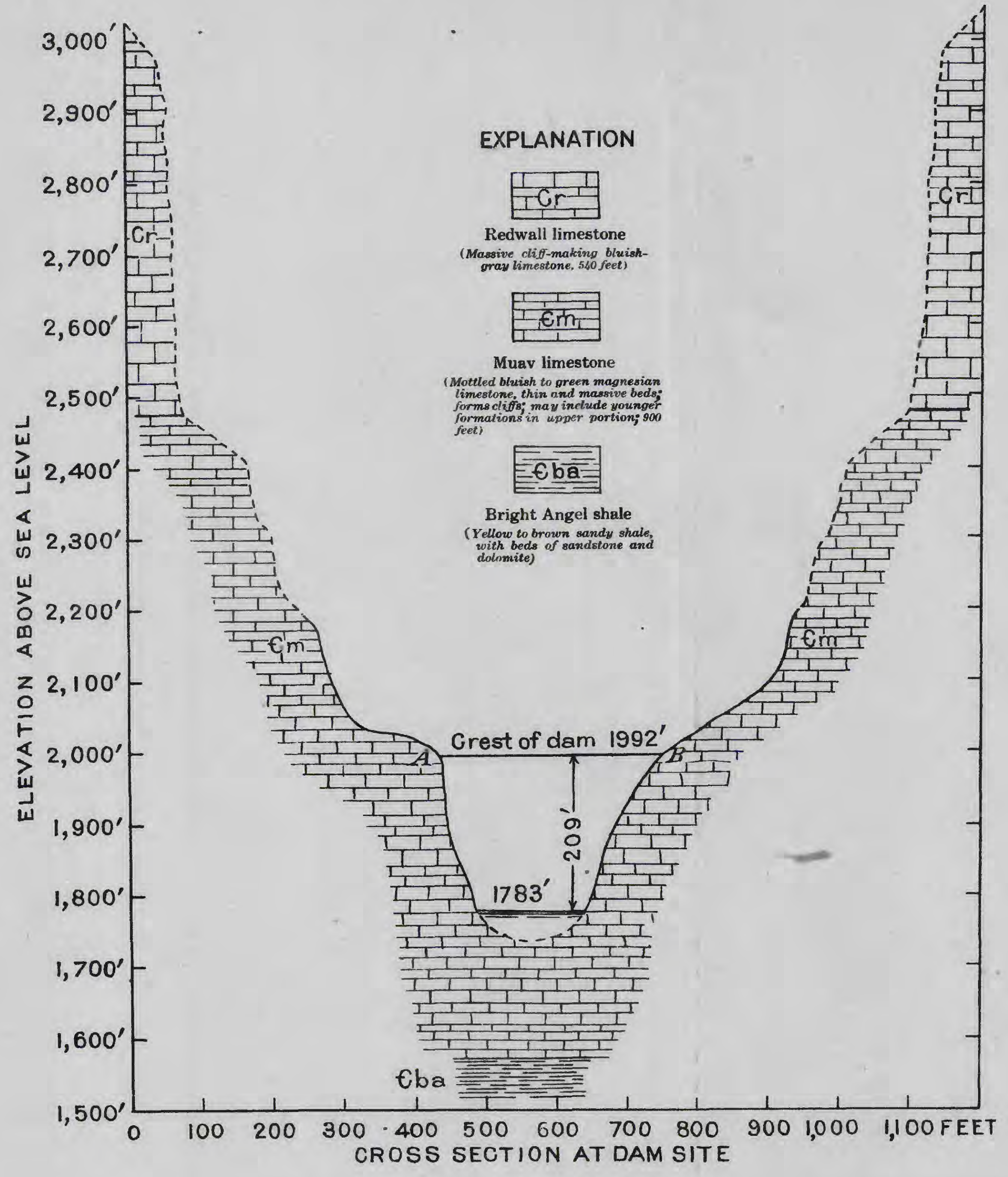
The power house may be built on the shelving limestone at the water's edge on the left bank, just below the mouth of Havasu Creek and 600 feet below the dam. The penstocks could pass over the inner gorge of Havasu Creek, as the gorge is only 6 feet wide at a point 40 feet above the water. An upstream view of the dam site is shown in Plate XXXV, *A.*

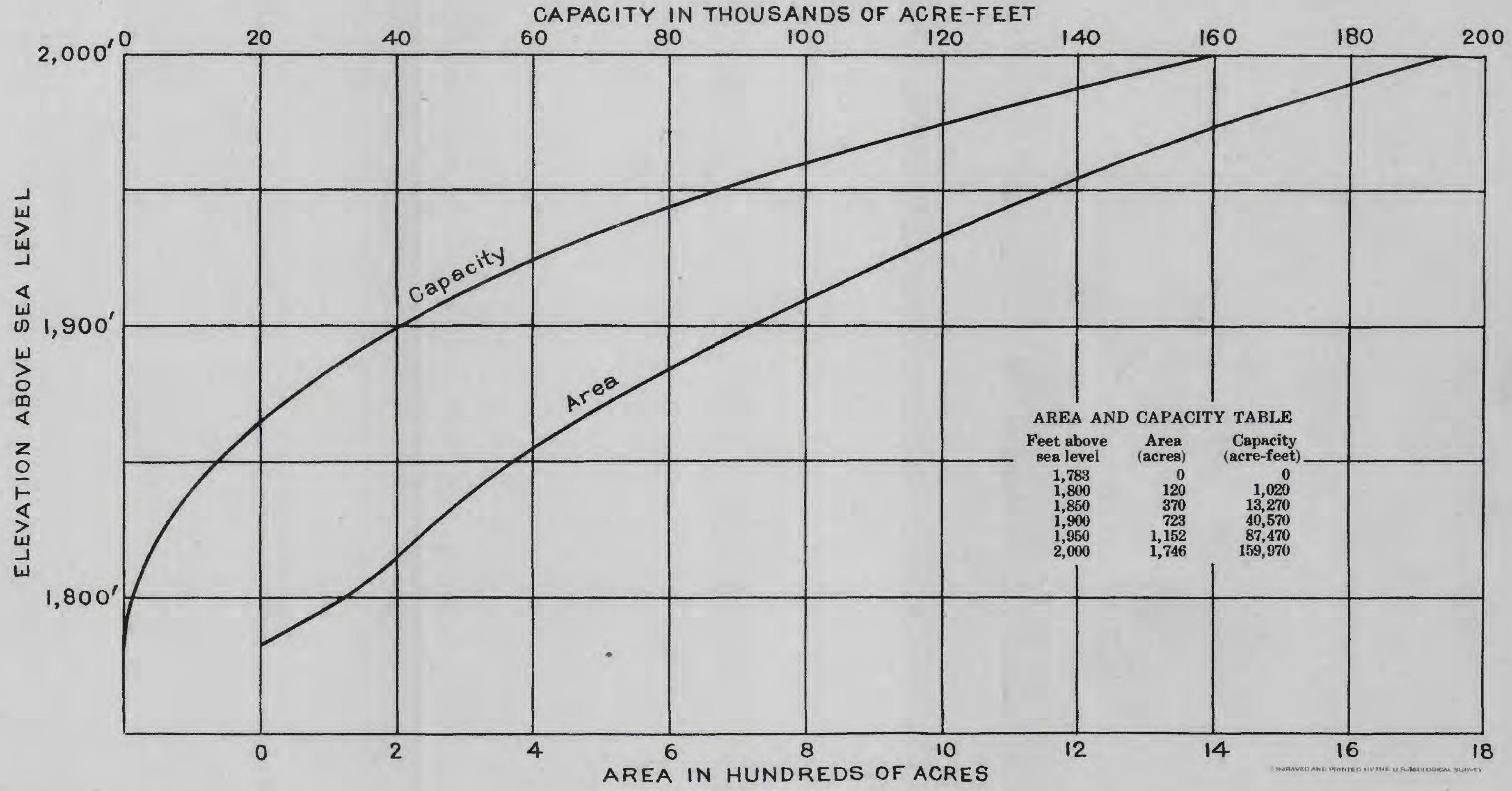
The dam may be built to raise the water to an elevation of 1,992 feet above sea level without interfering with the utilization of the Specter Chasm site. As the river surface at the dam site is 1,783 feet above sea level, a head of 209 feet may be used for the development of power. The plan of development is shown in Plate XXXIV.

Water supply.—With the water used as in 1922 and without storage the water supply available at the Havasu dam site would be 6,920 second-feet 90 per cent of the time, or 10,700 second-feet 50 per cent of the time. (See Appendix A, p. 113.) With the water used as in 1922 and with storage in Glen Canyon, the continuous flow available would be 21,700 second-feet. With ultimate development in the upper basin, the available water supply would be reduced to about 13,900 second-feet.

Power capacity.—The static head at the Havasu site would be 209 feet. The power capacity with this head and the water supply given in the preceding paragraph would be as follows:



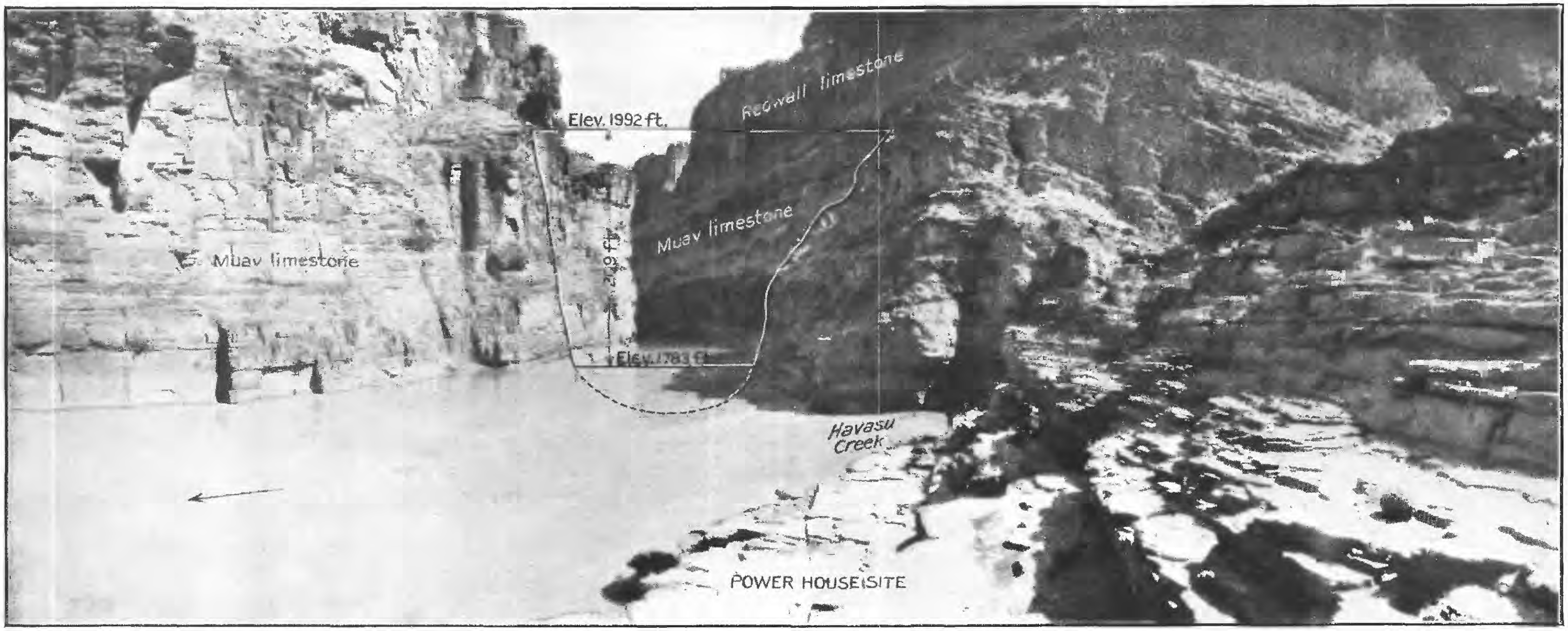




AREA AND CAPACITY TABLE

Feet above sea level	Area (acres)	Capacity (acre-feet)
1,783	0	0
1,800	120	1,020
1,850	370	13,270
1,900	723	40,570
1,950	1,152	87,470
2,000	1,746	159,970

MAP, CROSS SECTION, AND AREA AND CAPACITY CURVES FOR HAVASU POWER SITE

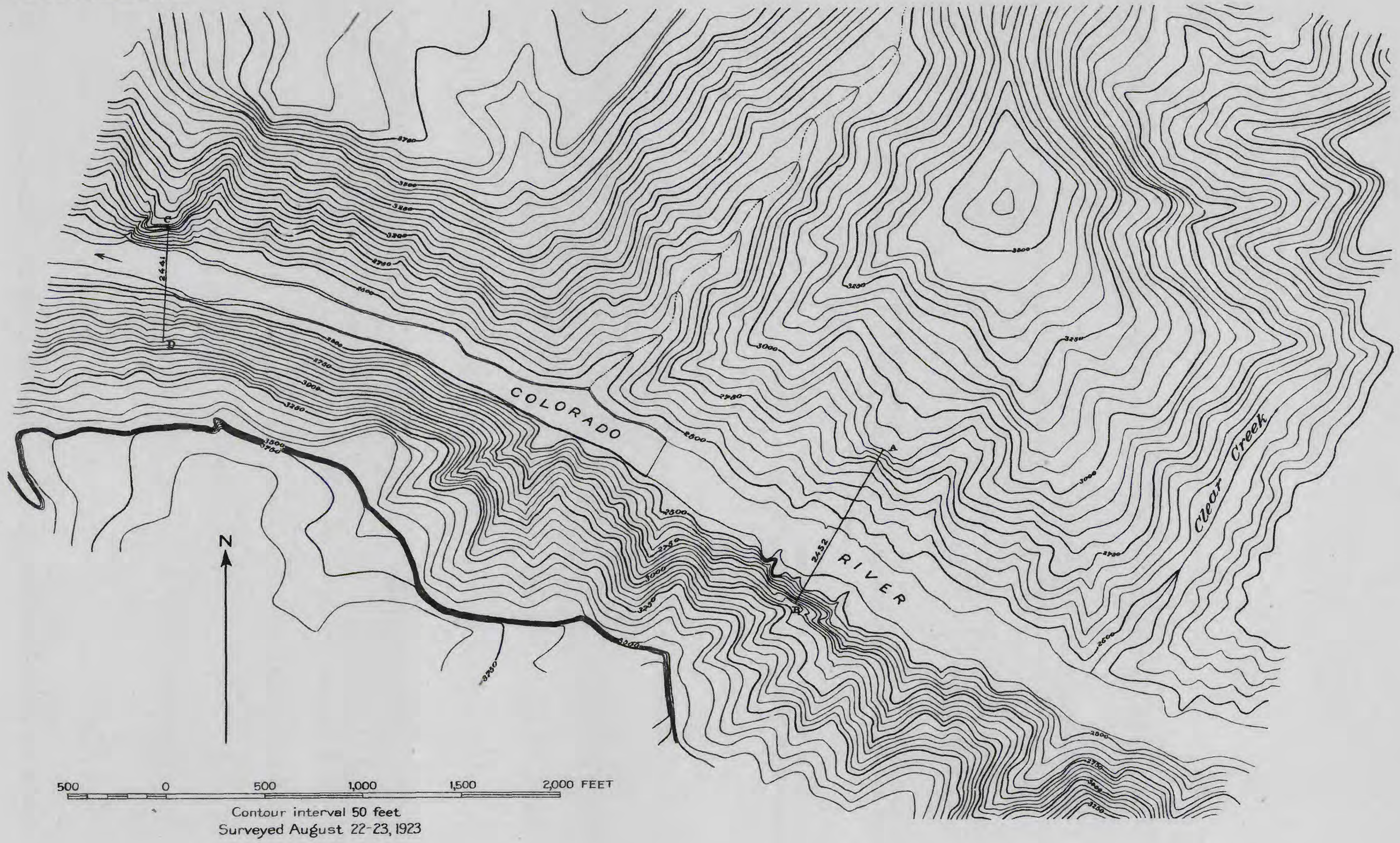


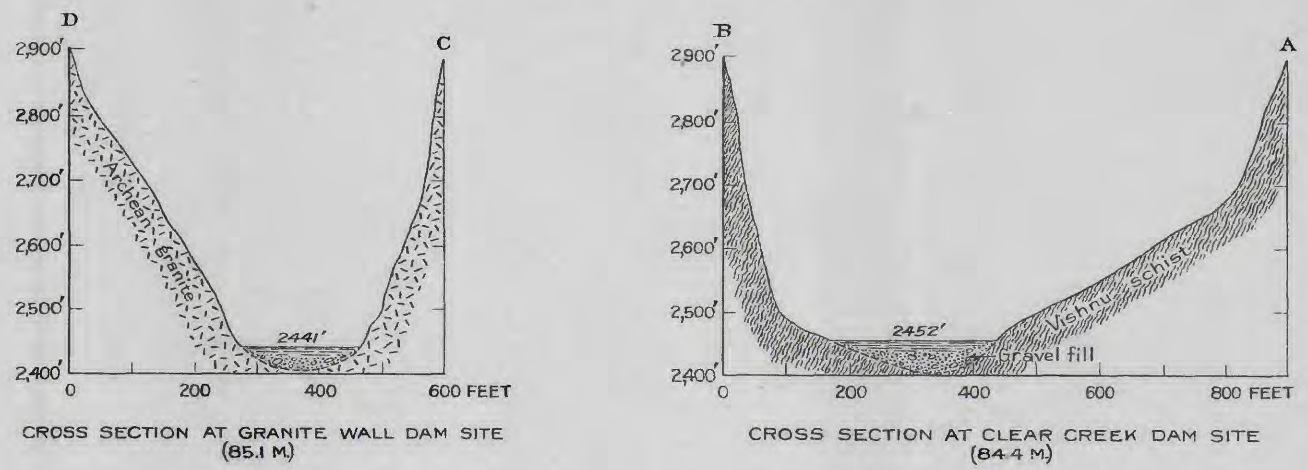
A. HAVASU DAM SITE, GRAND CANYON, 600 FEET BELOW WEST BOUNDARY OF GRAND CANYON NATIONAL PARK

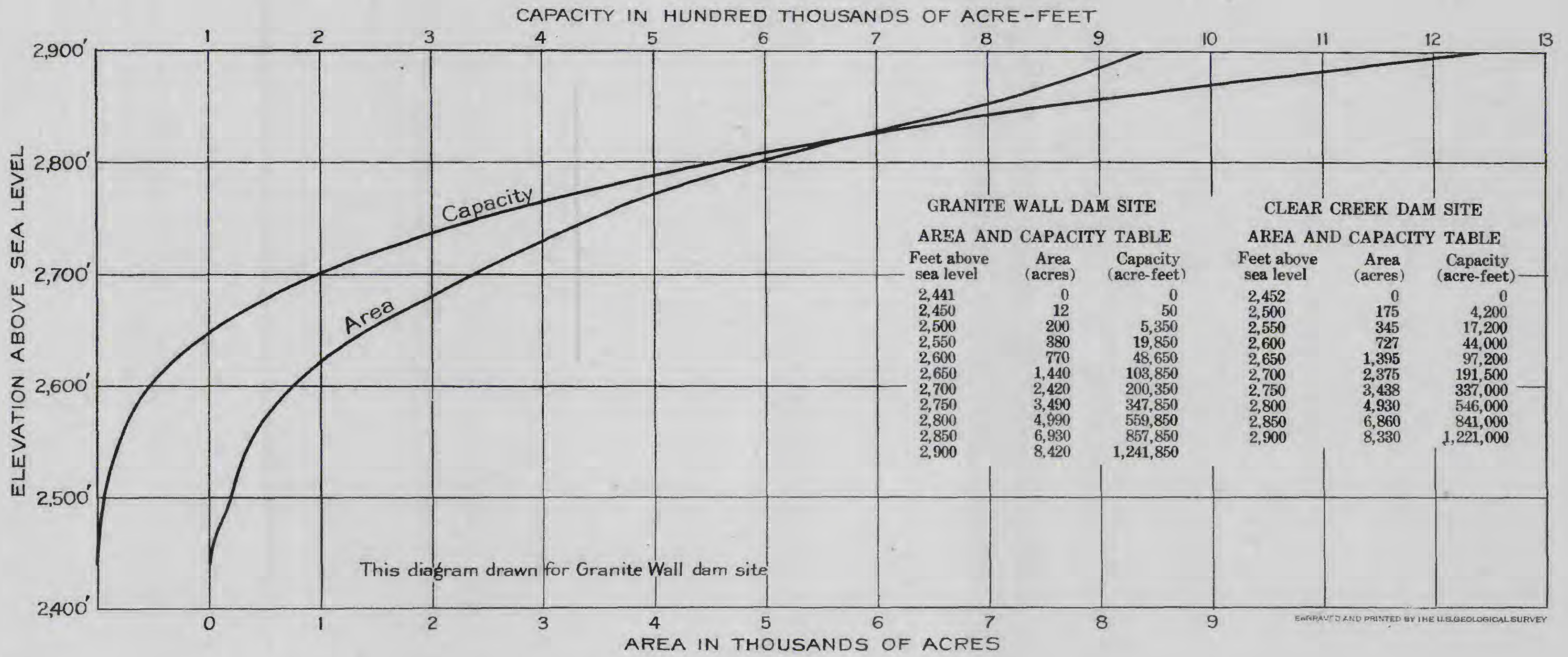
Geology by R. C. Moore

B. GRANITE WALL DAM SITE, GRAND CANYON, ABOUT 2 MILES ABOVE BRIGHT ANGEL CREEK

Geology by R. C. Moore







GRANITE WALL DAM SITE

AREA AND CAPACITY TABLE

Feet above sea level	Area (acres)	Capacity (acre-feet)
2,441	0	0
2,450	12	50
2,500	200	5,350
2,550	380	19,850
2,600	770	48,650
2,650	1,440	103,850
2,700	2,420	200,350
2,750	3,490	347,850
2,800	4,990	559,850
2,850	6,930	857,850
2,900	8,420	1,241,850

CLEAR CREEK DAM SITE

AREA AND CAPACITY TABLE

Feet above sea level	Area (acres)	Capacity (acre-feet)
2,452	0	0
2,500	175	4,200
2,550	345	17,200
2,600	727	44,000
2,650	1,395	97,200
2,700	2,375	191,500
2,750	3,438	337,000
2,800	4,930	546,000
2,850	6,860	841,000
2,900	8,330	1,221,000

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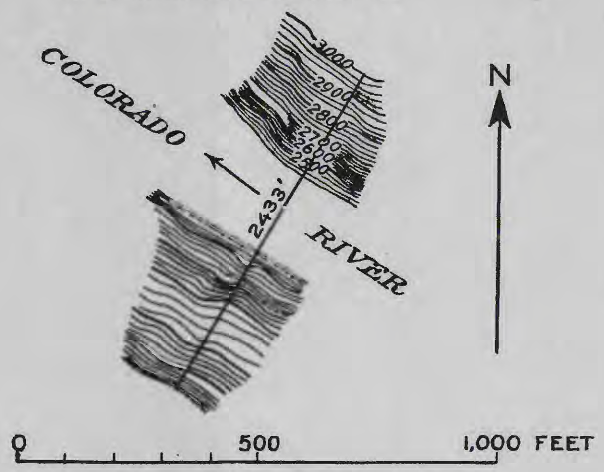
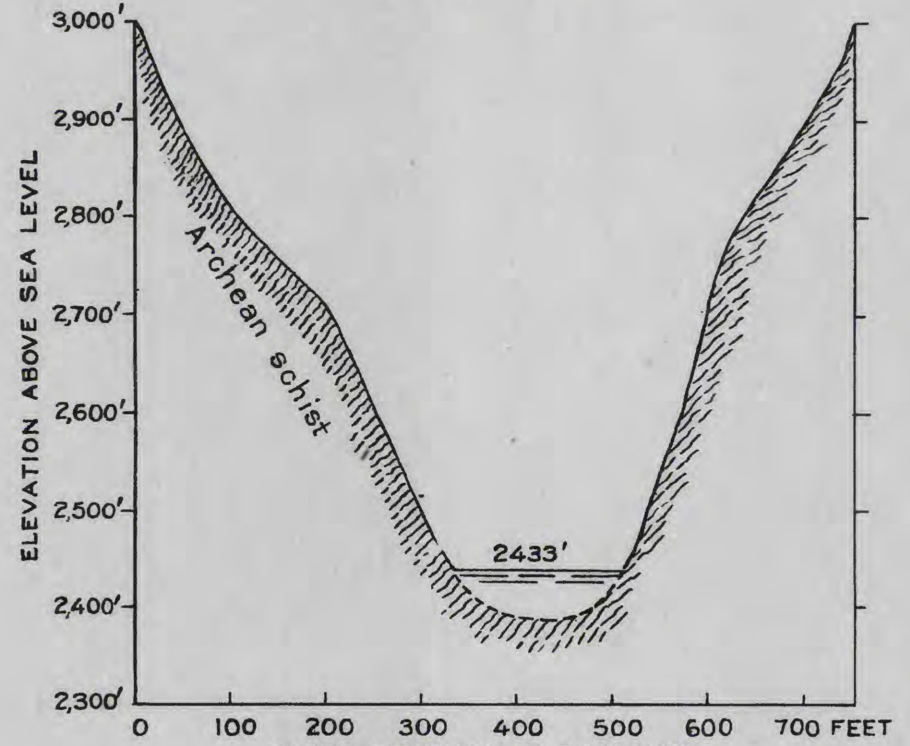
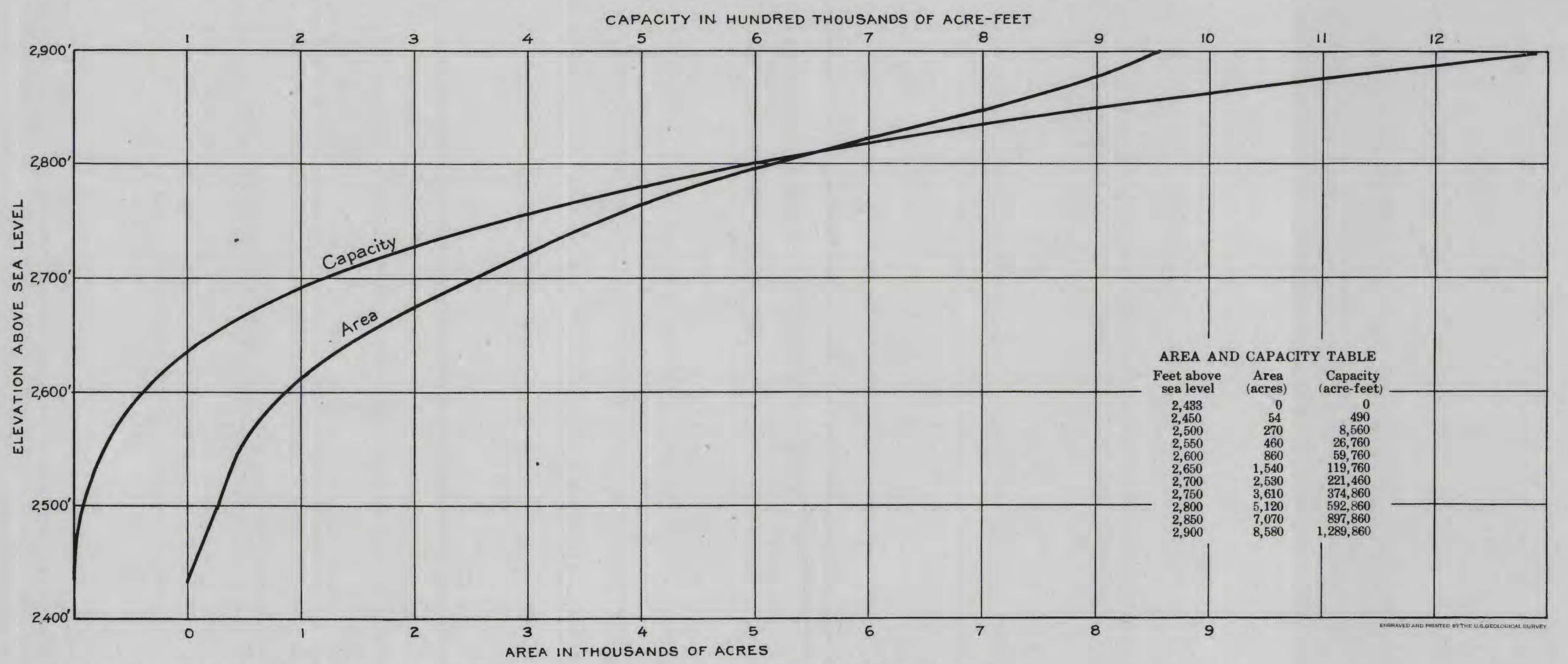
MAP, CROSS SECTIONS, AND AREA AND CAPACITY CURVES FOR GRANITE WALL AND CLEAR CREEK POWER SITES



Contour interval 20 feet
Surveyed August 23, 1923



CROSS SECTION AT DAM SITE
(86.3 MILES)



AREA AND CAPACITY TABLE

Feet above sea level	Area (acres)	Capacity (acre-feet)
2,433	0	0
2,450	54	490
2,500	270	8,560
2,550	460	26,760
2,600	860	59,760
2,650	1,540	119,760
2,700	2,530	221,460
2,750	3,610	374,860
2,800	5,120	592,860
2,850	7,070	897,860
2,900	8,580	1,289,860

MAP, CROSS SECTION, AND AREA AND CAPACITY CURVES FOR CREMATION POWER SITE

	Horsepower
Without storage and with irrigation and power development in upper basin as in 1922:	
Capacity 50 per cent of time	179,000
Capacity 90 per cent of time	116,000
With storage in Glen Canyon and with irrigation and power development in upper basin as in 1922:	
Continuous power available	363,000
With storage and with ultimate irrigation and power development in upper basin:	
Continuous power available	232,000
Installed capacity (load factor 60 per cent)	387,000

Right of way.—If a dam were built at the Havasu site to raise the water 209 feet, the backwater would extend up the river about 24 miles, forming a reservoir with a water-surface area of 1,630 acres. There would be no property damage.

Accessibility.—The Havasu dam site is in the bottom of the Grand Canyon, and the cost of building a railroad to the site would be great. The best means of making the site accessible is that indicated for the Mineral Canyon site (p. 59).

Adaptability of plan.—The plan for developing power in the Grand Canyon National Park is presented on page 60. The fall in the river between Mineral Canyon and Havasu Creek will be entirely utilized if the Havasu site forms the lowest unit in any plan for the development of power on this section of the river. There are no reasonably favorable dam sites in the Grand Canyon for a distance of 69 miles below Havasu Creek.

ALTERNATIVE DAM SITES IN GRAND CANYON NATIONAL PARK

Clear Creek and Granite Wall sites.—The Clear Creek dam site is about 1,600 feet below the mouth of Clear Creek and about 2 miles above Bright Angel Creek. The Granite Wall site is 3,200 feet below the Clear Creek site. At each site the rock formations and the topographic features are favorable for the construction of a high dam. (See Appendix B, pp. 144–145.) A map of the dam sites, cross sections, and area and capacity curves are given in Plate XXXVI. A downstream view of the Granite Wall dam site is presented in Plate XXXV, *B*.

Cremation site.—The Cremation dam site is 1.2 miles above Bright Angel Creek. Here, too, the conditions are favorable for the construction of a high dam, the granite walls rising more than 600 feet above the river. (See Appendix B, p. 145.) A cross section and map of the dam site, with curves showing the area and capacity of the reservoir, are shown in Plate XXXVII.

Pipe Creek site.—The Pipe Creek dam site is just below the mouth of Pipe Creek, 1.4 miles below Bright Angel Creek. The walls at the dam site are composed of Archean granite, gneiss, and schist. The conditions are favorable for the construction of a dam of any height up to 400 feet. (See Pl. XXXVIII and Appendix B, p. 146.) A downstream view of the dam site is presented in Plate XXXIX, *A*.

Hakatai site.—The Hakatai dam site is 800 feet above the mouth of Hakatai Creek (Pl. XXXIX, *B*) and 23 miles below Bright Angel Creek. The walls at this site are composed of the Archean Vishnu schist, and the conditions are favorable for the construction of a dam of any height up to about 225 feet. (See Pl. XL and Appendix B, p. 149.)

Big Bend site.—The Big Bend dam site is 26 miles below Bright Angel Creek. When this part of the canyon was being surveyed, the writer was aware of the fact that the course of the river continues south for a few miles and then turns west and north, forming a loop. The Big Bend dam site was therefore surveyed with the idea that a power-house site might be found on the lower side of the loop.

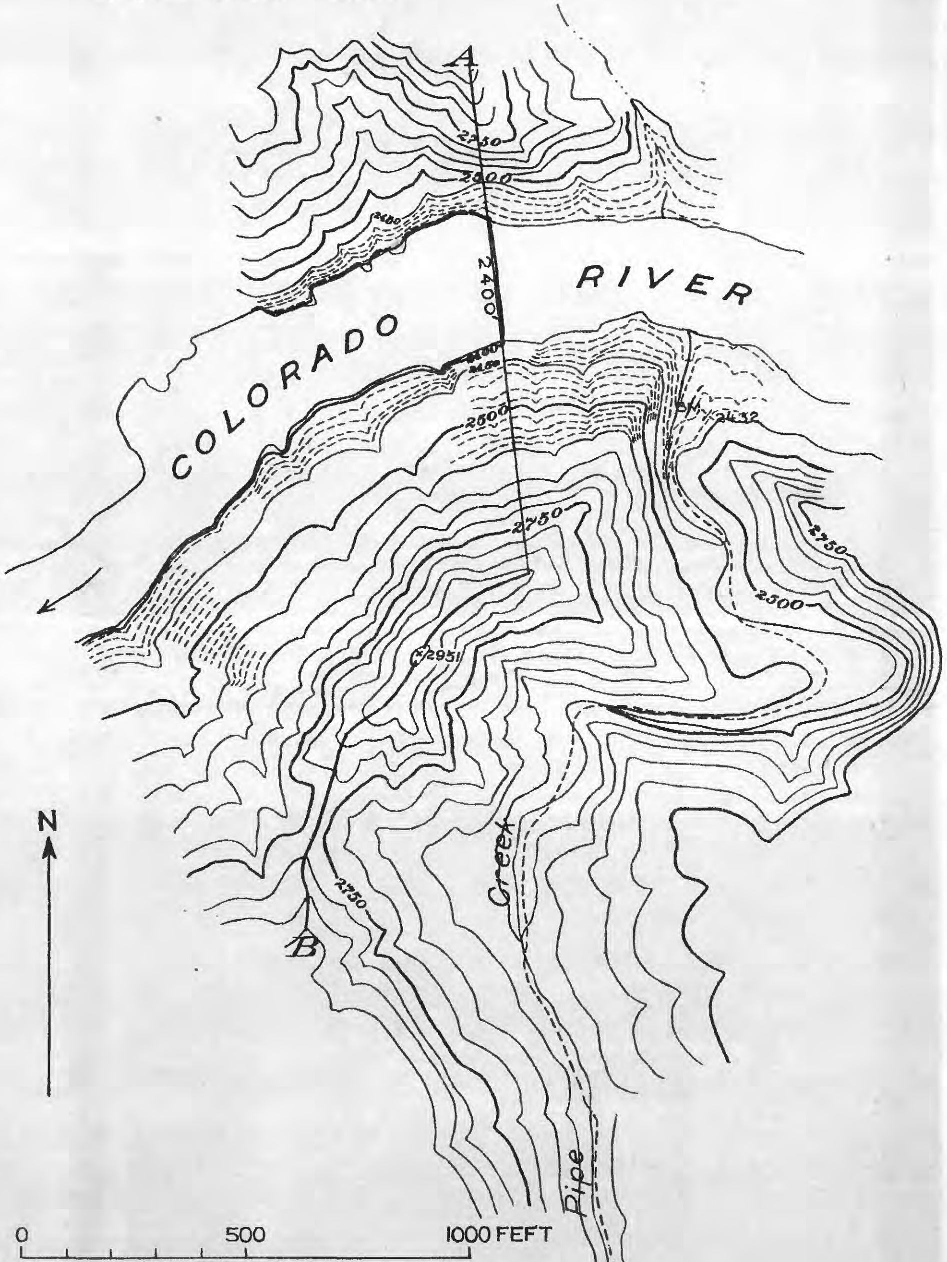
The distance through the neck of the loop, however, was found to be 10,000 feet, and a favorable site for a power house on the lower side of the loop does not exist. The dam site therefore has small value, for it is in a box canyon (Pl. XLI, *A*), which is inaccessible except by boat. Information regarding the dam site will be found in Plate XLII.

PLAN OF DEVELOPMENT BETWEEN WEST BOUNDARY OF GRAND CANYON NATIONAL PARK AND PARKER, ARIZ.

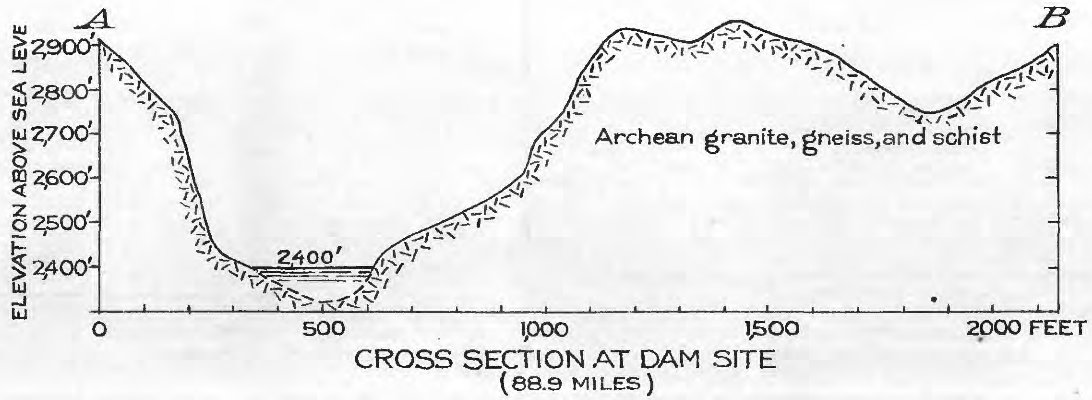
OUTLINE OF PLAN

There is general agreement to the effect that construction work should start at an early date for the purpose of providing flood-control works and water-power development on Colorado River. It seems probable that the first dam to be built on the river will be in the interest of flood control, with provision made for a small amount of storage to take care of present irrigation needs during occasional periods of low water. It is also probable that a dam for developing power will be built at an early date. These dams may be located below the west boundary of the Grand Canyon National Park.

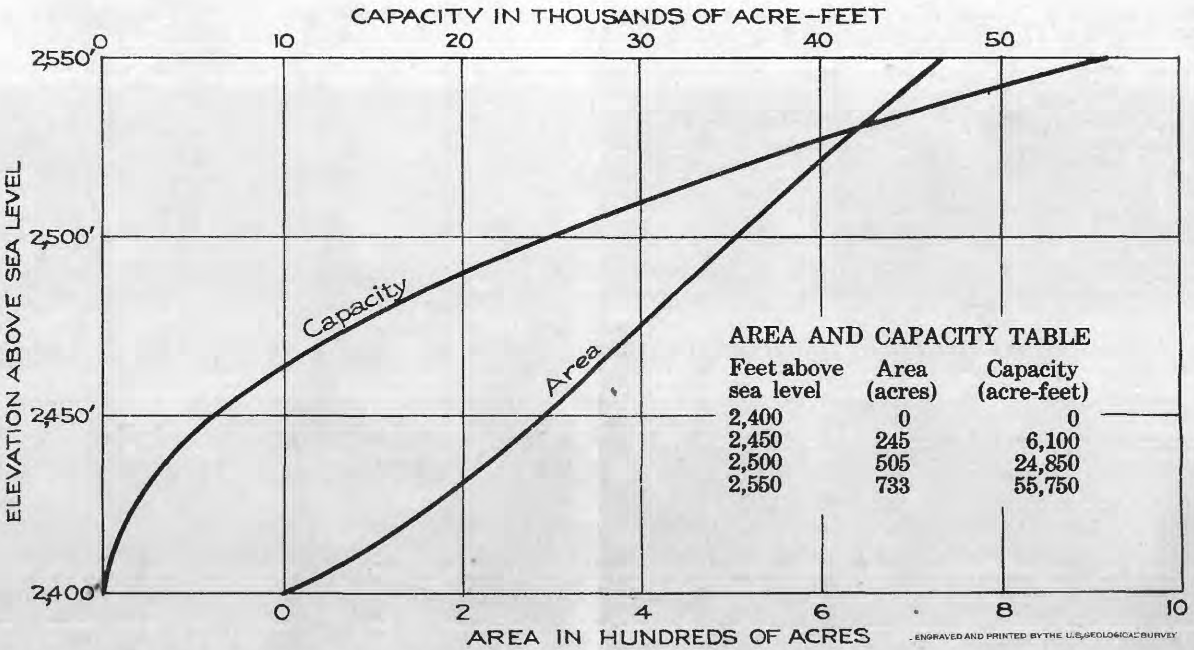
In the building of the cities of Washington, D. C., and Salt Lake City, Utah, a definite plan was followed. The soundness of this policy can not be successfully refuted. These cities, however, are exceptional. In other cities planning commissions are recommending that buildings be torn down or moved back so that streets may be widened, that new streets be opened, that parks be provided, and that business, industry, apartments, and residences be restricted to definite districts. To modernize in part the plan of these cities will



Contour interval 50 feet
Broken contours 10 feet
Surveyed August 28 1923



CROSS SECTION AT DAM SITE
(88.9 MILES)



AREA AND CAPACITY TABLE

Feet above sea level	Area (acres)	Capacity (acre-feet)
2,400	0	0
2,450	245	6,100
2,500	505	24,850
2,550	733	55,750

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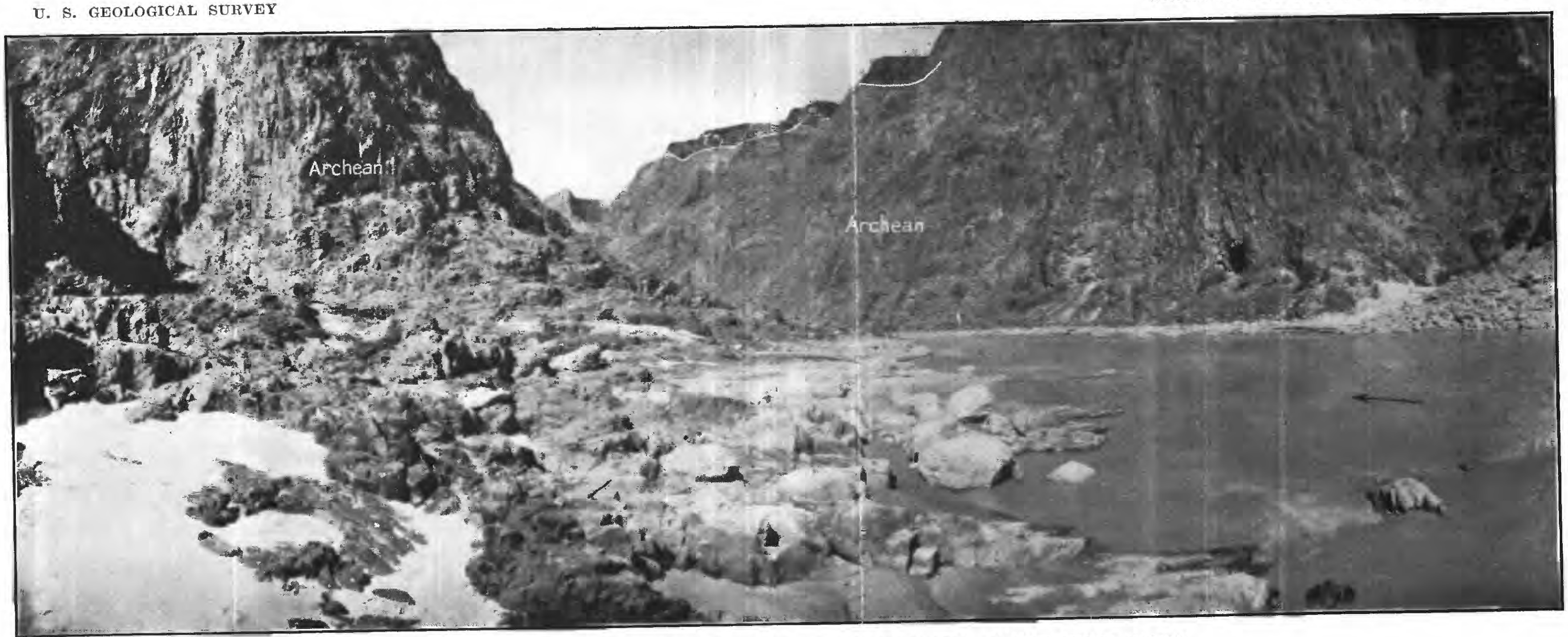
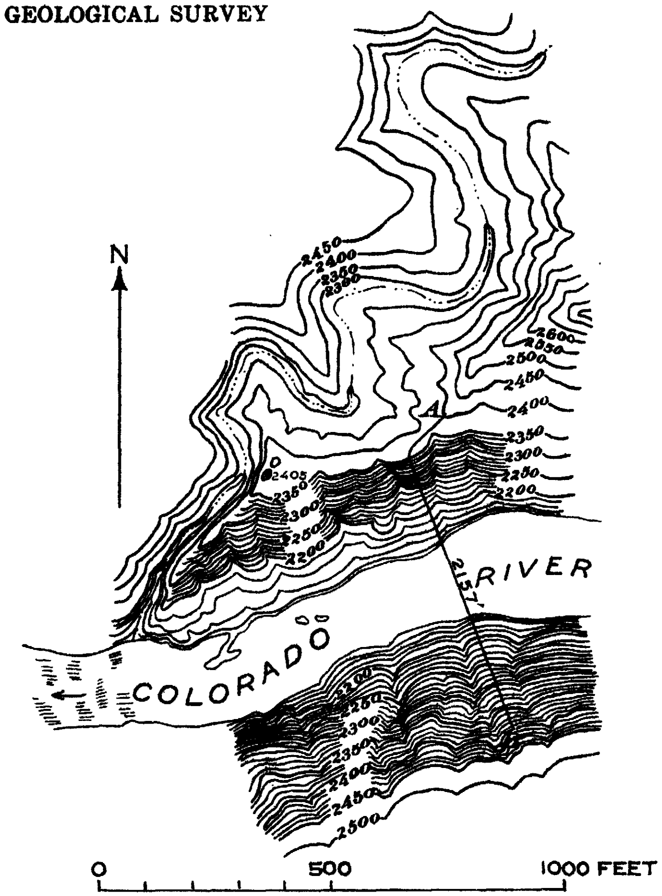
MAP, CROSS SECTION, AND AREA AND CAPACITY CURVES FOR PIPE CREEK POWER SITE



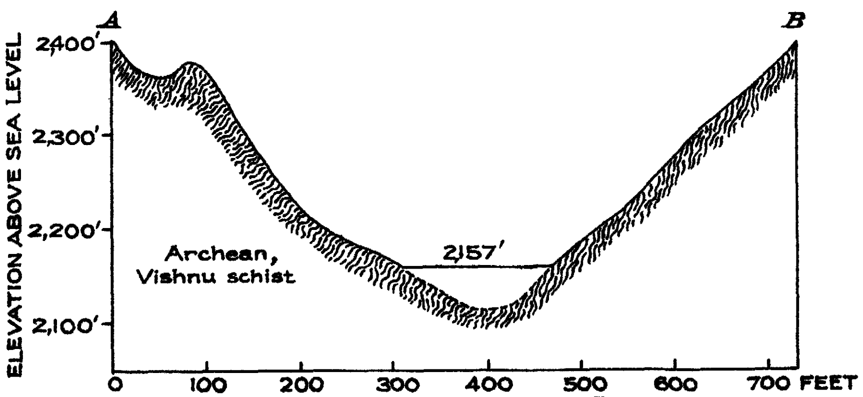
A. PIPE CREEK DAM SITE, GRAND CANYON, 1.4 MILES BELOW BRIGHT ANGEL CREEK
Geology by R. C. Moore

B. HAKATAI DAM SITE, GRAND CANYON, 23 MILES BELOW BRIGHT ANGEL CREEK
Geology by R. C. Moore

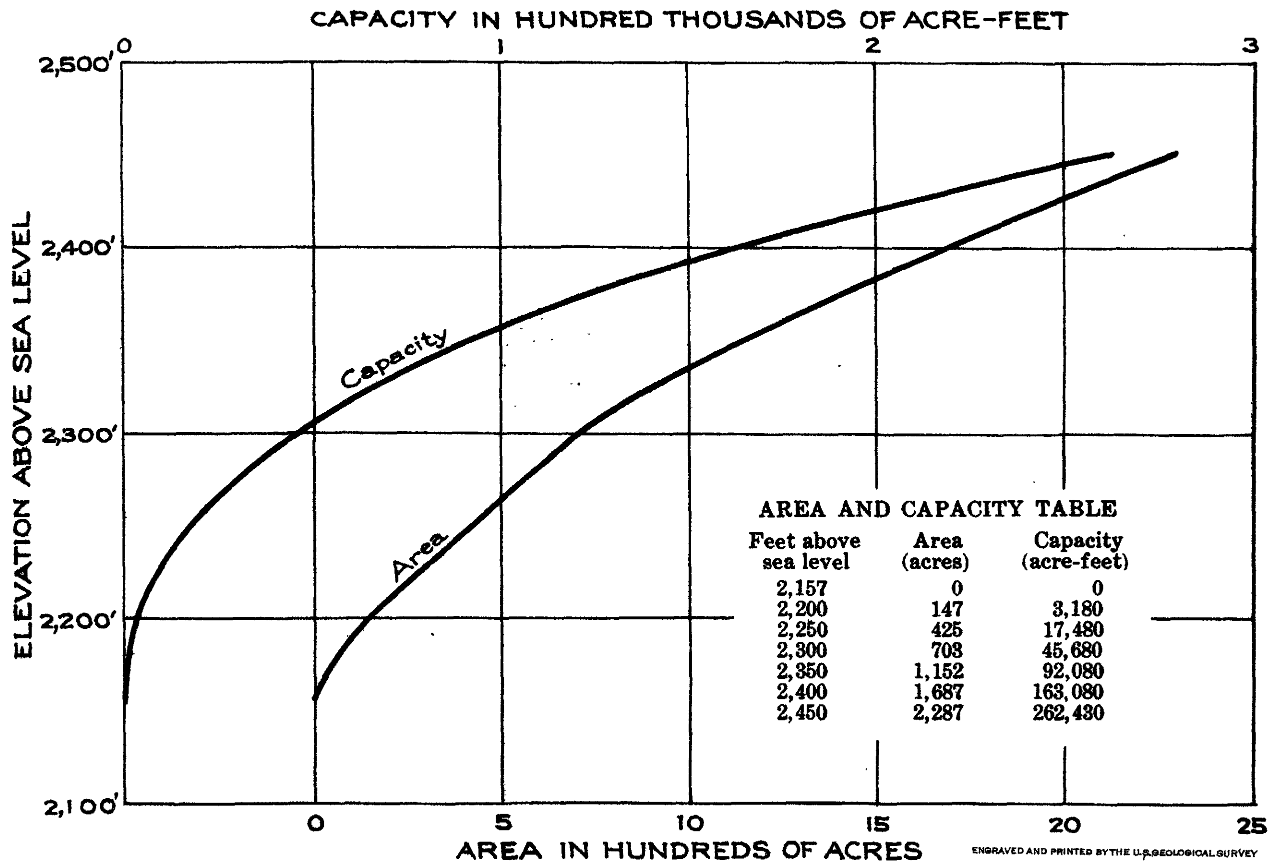


Contour interval 10 feet

Surveyed September 4, 1923



CROSS SECTION AT DAM SITE (110.7 MILES)



AREA AND CAPACITY TABLE

Feet above sea level	Area (acres)	Capacity (acre-feet)
2,157	0	0
2,200	147	3,180
2,250	425	17,480
2,300	703	45,680
2,350	1,152	92,080
2,400	1,687	163,080
2,450	2,287	262,430

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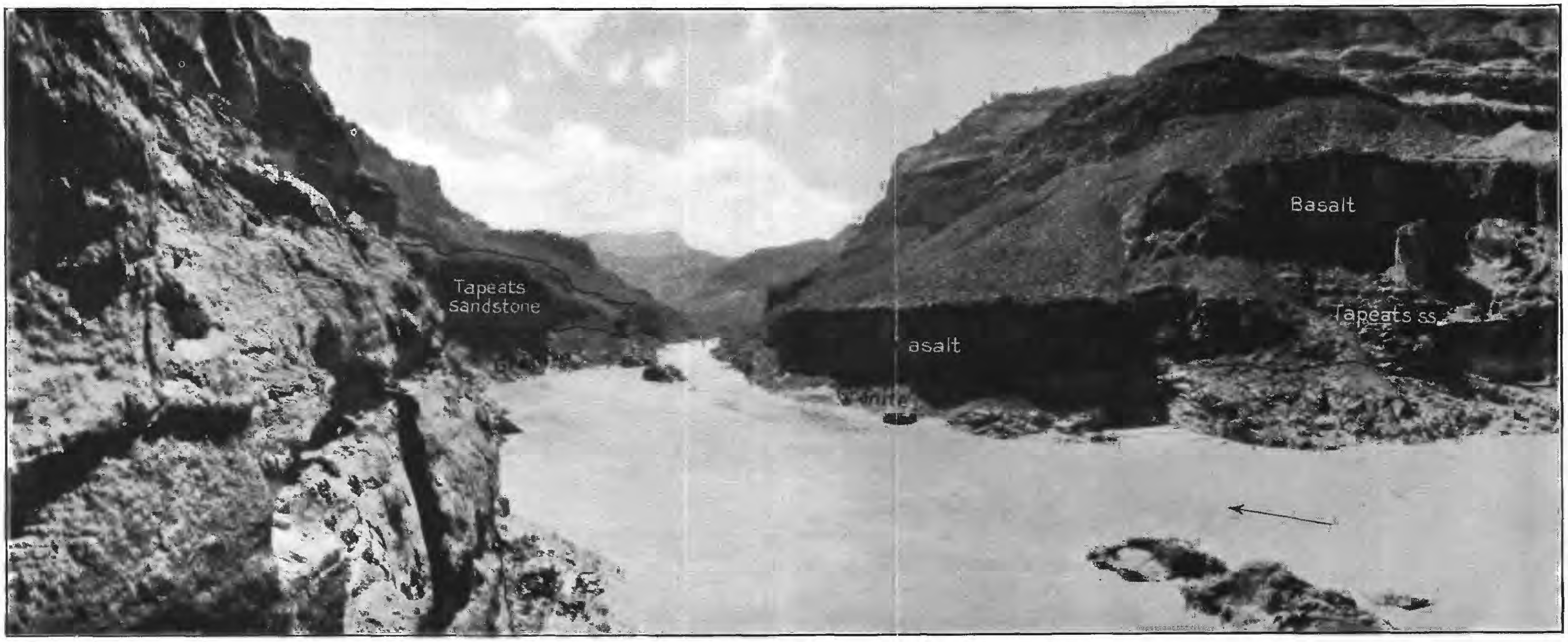
MAP, CROSS SECTION, AND AREA AND CAPACITY CURVES FOR HAKATAI POWER SITE

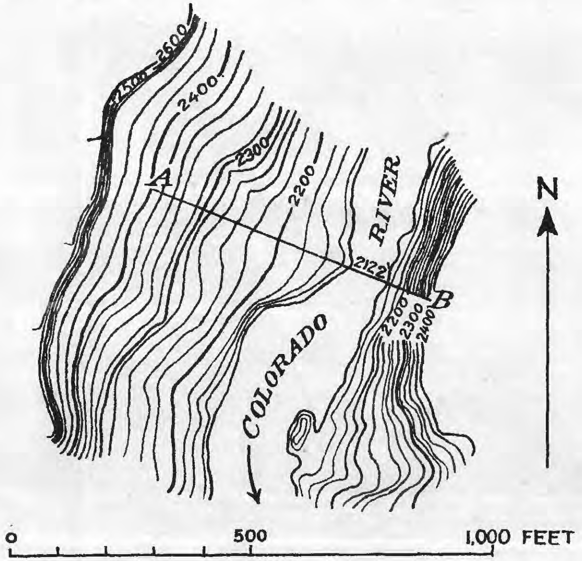
A. BIG BEND DAM SITE, GRAND CANYON, 26 MILES BELOW BRIGHT ANGEL CREEK

Geology by R. C. Moore

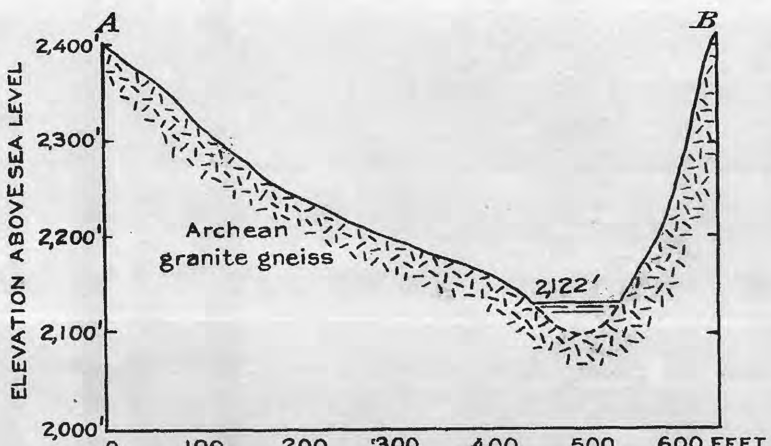


B. PROSPECT DAM SITE, GRAND CANYON, 33 MILES BELOW HAVASU CREEK

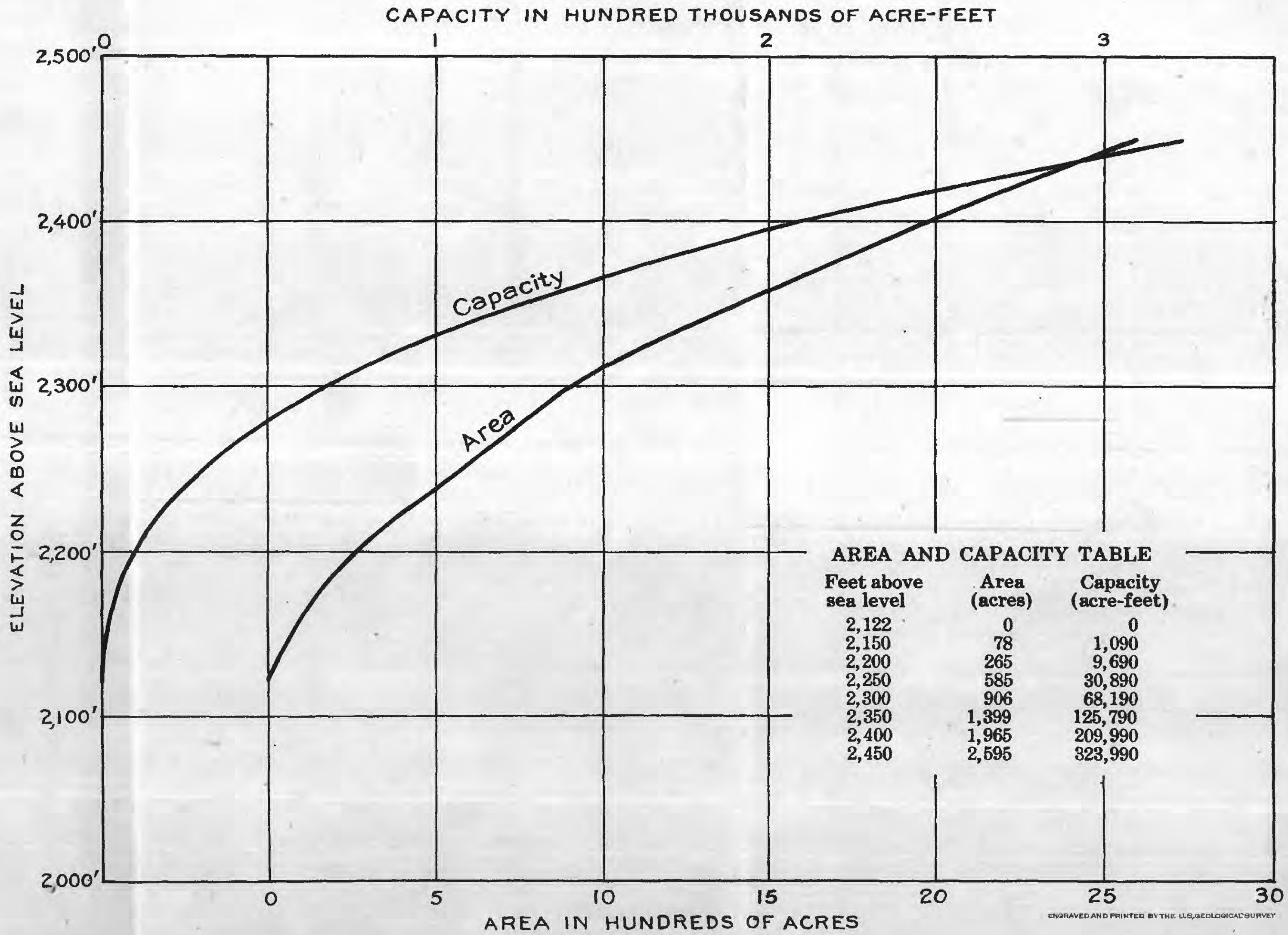
Showing granite outcrop in the river channel. Geology by R. C. Moore



Contour interval 20 feet
Surveyed September 6, 1923



CROSS SECTION AT DAM SITE
(113.3 MILES)



AREA AND CAPACITY TABLE

Feet above sea level	Area (acres)	Capacity (acre-feet)
2,122	0	0
2,150	78	1,090
2,200	265	9,690
2,250	585	30,890
2,300	906	68,190
2,350	1,399	125,790
2,400	1,965	209,990
2,450	2,595	323,990

MAP, CROSS SECTION, AND AREA AND CAPACITY CURVES FOR BIG BEND POWER SITE

cost millions of dollars. To make most of our larger cities really modern in plan would be infeasible on account of the cost.

In developing the water resources of our country the same haphazard policy has been followed. With respect to the development of our important rivers the writer does not know of an instance in which a comprehensive plan of development was prepared in advance of construction. Engineers have been sent into the field to locate the sites where water might be stored or power developed at a minimum cost. Almost without exception the projects for immediate development have been selected with little regard for future developments or the full utilization of the water resources of the region. Railroads have been built through valuable dam sites, and dams have been built that will forever prevent full utilization of the water resources except at prohibitive cost. Such mistakes should not be made on Colorado River.

Twenty-three dam sites on Colorado River between the west boundary of the Grand Canyon National Park and Parker, listed in the following table, have been surveyed, and at four of the sites the character of the foundation has been determined by diamond-drill borings:

Dam sites on Colorado River between the west boundary of the Grand Canyon National Park and Parker, Ariz.

Site	Distance below Paria River	Elevation above sea level [a]	Character of rock at site	Limit in height of dam [b]
	Miles	*Feet*		*Feet*
Havasu	156.6	1,783	Limestone	300
Prospect	190.1	1,579	Granite and sandstone	200
Diamond Creek (upper)	225.5	1,335	Granite	320
Diamond Creek (lower)	225.9	1,323	do	680
Travertine Canyon	228.6	1,294	Granite gneiss	950
Bridge Canyon	236.3	1,207	do	800
Spencer Canyon	246.2	1,105	Granite	650
Devils Slide	255.6	1,034	do	370
Flour Sack Rapids	266.0	960	Granite, sandstone, and shale	250
Pierces Ferry	277.3	905	Granite and sandstone	150
Grand Wash Canyon	284.2	867	Limestone	400
Hualpai Rapids	301.6	799	Granite	320
Virgin Canyon	304.7	790	Archean rock	400
Boulder Canyon	334.1	705	Granite	1,000
Callville	341.8	684	do	240
Upper Black Canyon	354.6	647	Breccia	950
Middle Black Canyon	364.9	622	do	500
Lower Black Canyon	373.9	595	do	450
Eldorado	377.1	590	do	100
Eagle Rock	397.0	553	Andesite and gravel	100
Bulls Head	421.9	505	Granite and gravel	100
Mohave Canyon	475.0	427	Granite	240
Parker	524.0	358	do	100

[a] The figures given in this column represent the elevation of the water surface at the dam site when the river is discharging 10,000 second-feet.

[b] The figures given in this column indicate the height of dam which may be built at the site as determined by the cross section, height of abutment walls, elevation of spillway saddle, and rock formations.

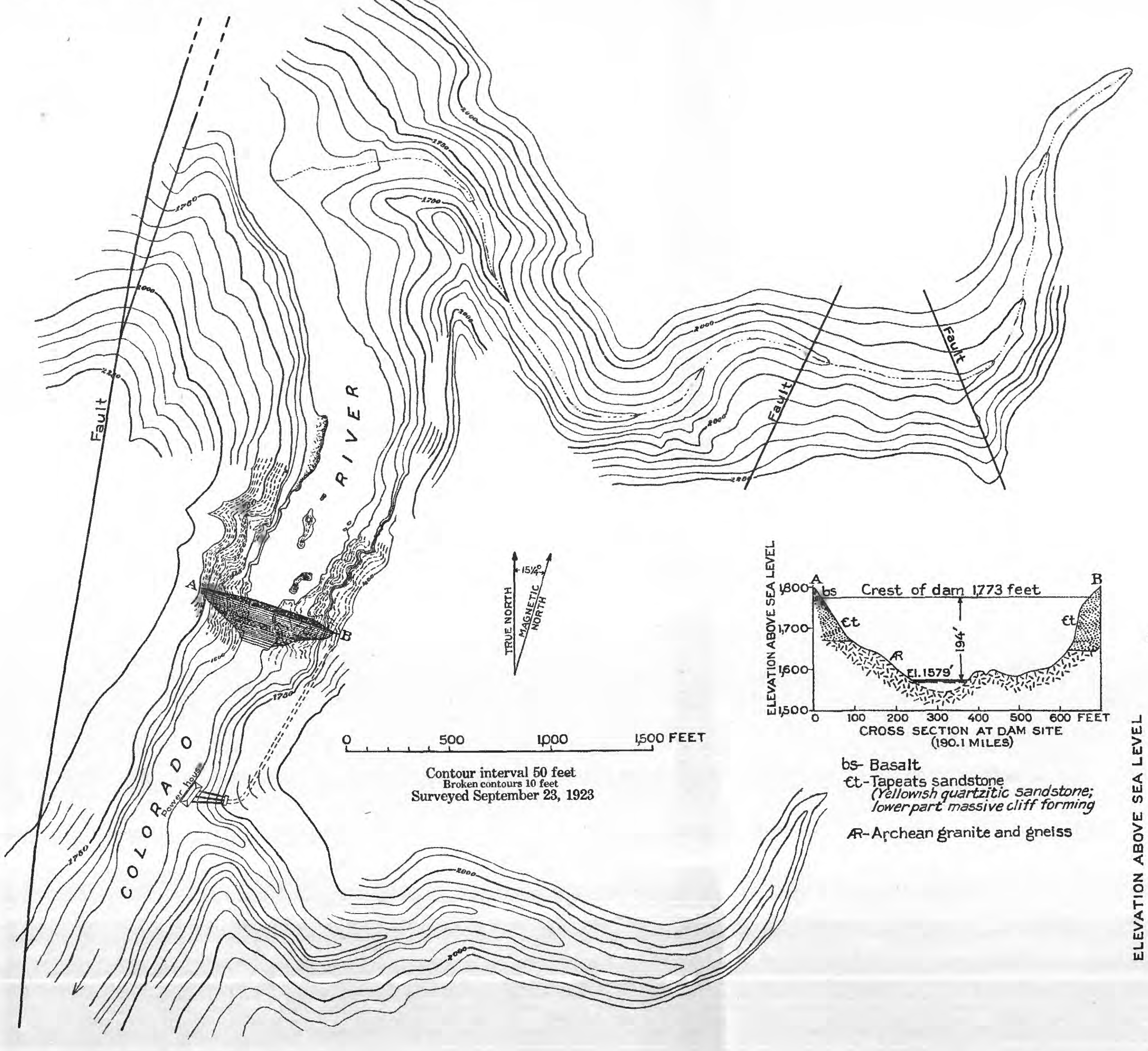
The rapid increase in population and the drought in 1924 have caused the people of the cities of southern California to realize that before many years pass they must procure an additional domestic water supply from Colorado River. The use of water for domestic purposes is rated as a higher use than irrigation or the development of power. Therefore, in preparing a plan for the development of lower Colorado River consideration should be given the fact that at some future time 1,000 to 2,000 second-feet of water may be diverted from the river to augment the domestic water supply of southern California.

Irrigation is rated as a higher use than the development of power, and the problem is further complicated by the fact that there are valuable properties on the lower river that are menaced by the summer floods. The floods should be prevented, and the use of water for domestic purposes, irrigation, and the development of power should be harmonized so far as practicable. It has been shown that with ultimate development in the upper basin the available water supply is not sufficient to furnish a domestic water supply to the cities of southern California and serve all the lands adjacent to the river in the United States that are classed as irrigable. Therefore the plan of development that will provide the greatest benefit to the community is that which will best conserve the water supply, adequately control floods, provide a domestic water supply, and permit maximum irrigation and power development.

In the 368-mile section of Colorado River between the west boundary of the Grand Canyon National Park and Parker, Ariz., the fall is 1,425 feet. Some of the 23 dam sites surveyed on this section of the river, as is shown below, are relatively poor and should be abandoned. Obviously the better dam sites should be utilized if their position on the river will permit a maximum utilization of the water resources.

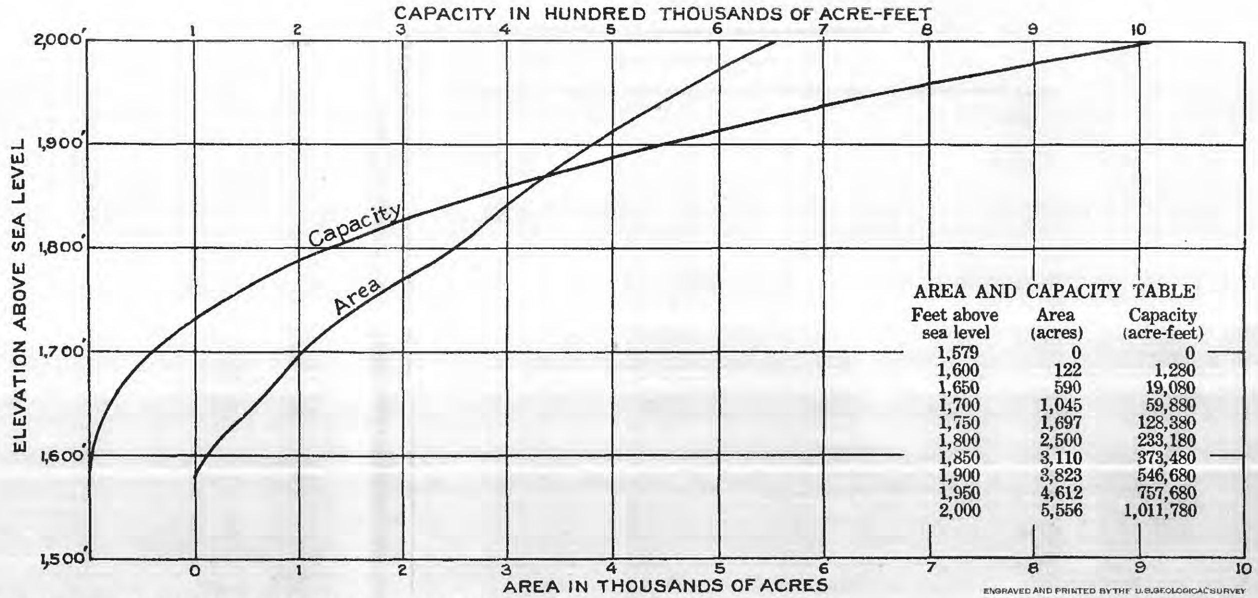
All the plans heretofore suggested for the development of this section of the river have been based on incomplete data as to dam sites. In September and October, 1924, the writer directed the survey of six dam sites below Diamond Creek that had not previously been considered. At least two of these sites are admirably adapted to form units of a comprehensive plan of development.

The numerous plans that have been suggested for the development of lower Colorado River may be divided into two classes. One class embraces those plans which are based on the theory that the best solution of the problems involved may be obtained by build-



Contour interval 50 feet
Broken contours 10 feet
Surveyed September 23, 1923

bs- Basalt
Ɛt-Tapeats sandstone
(Yellowish quartzitic sandstone; lowerpart massive cliff forming
Ʀ-Archean granite and gneiss



AREA AND CAPACITY TABLE

Feet above sea level	Area (acres)	Capacity (acre-feet)
1,579	0	0
1,600	122	1,280
1,650	590	19,080
1,700	1,045	59,880
1,750	1,697	128,380
1,800	2,500	233,180
1,850	3,110	373,480
1,900	3,823	546,680
1,950	4,612	757,680
2,000	5,556	1,011,780

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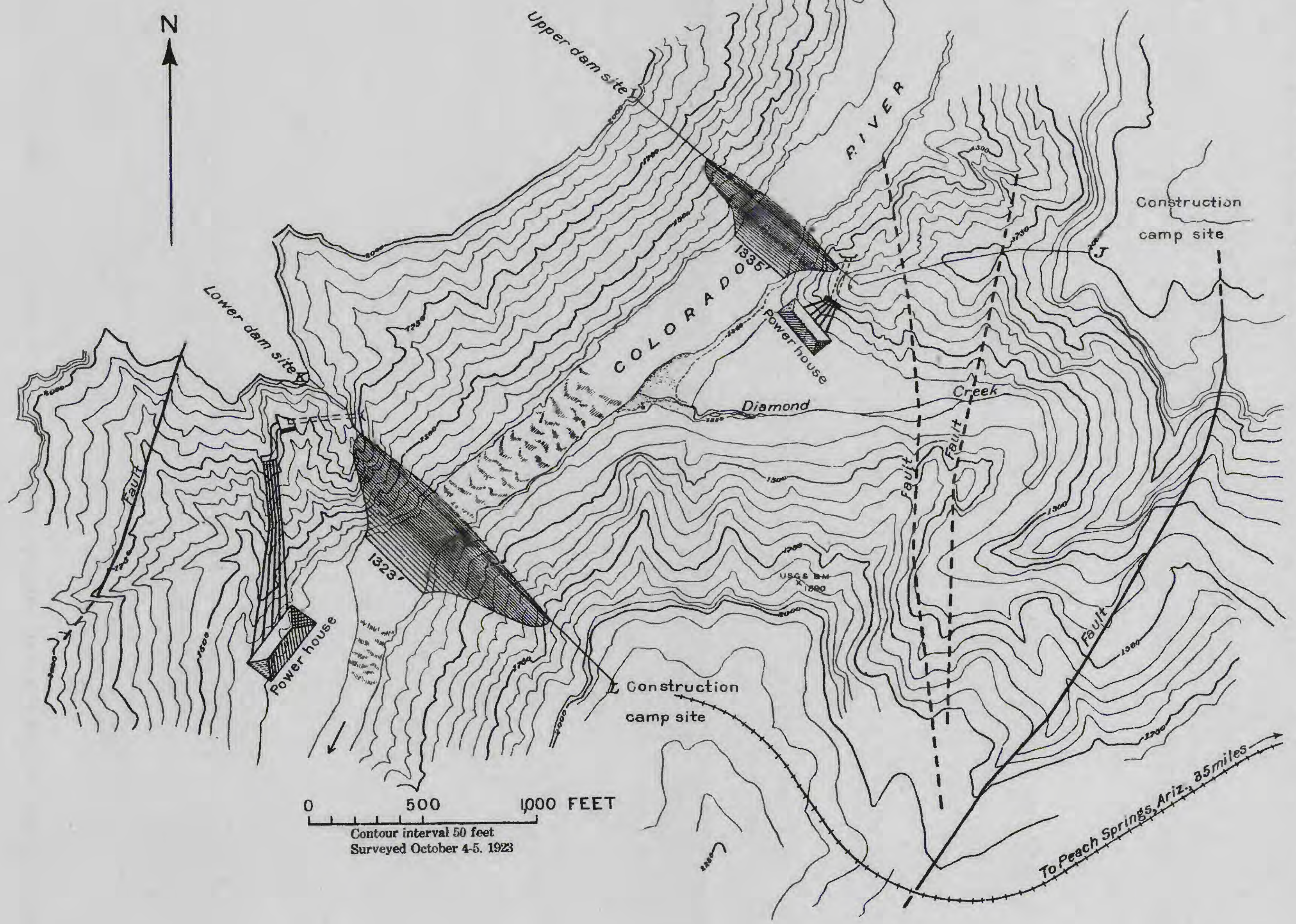
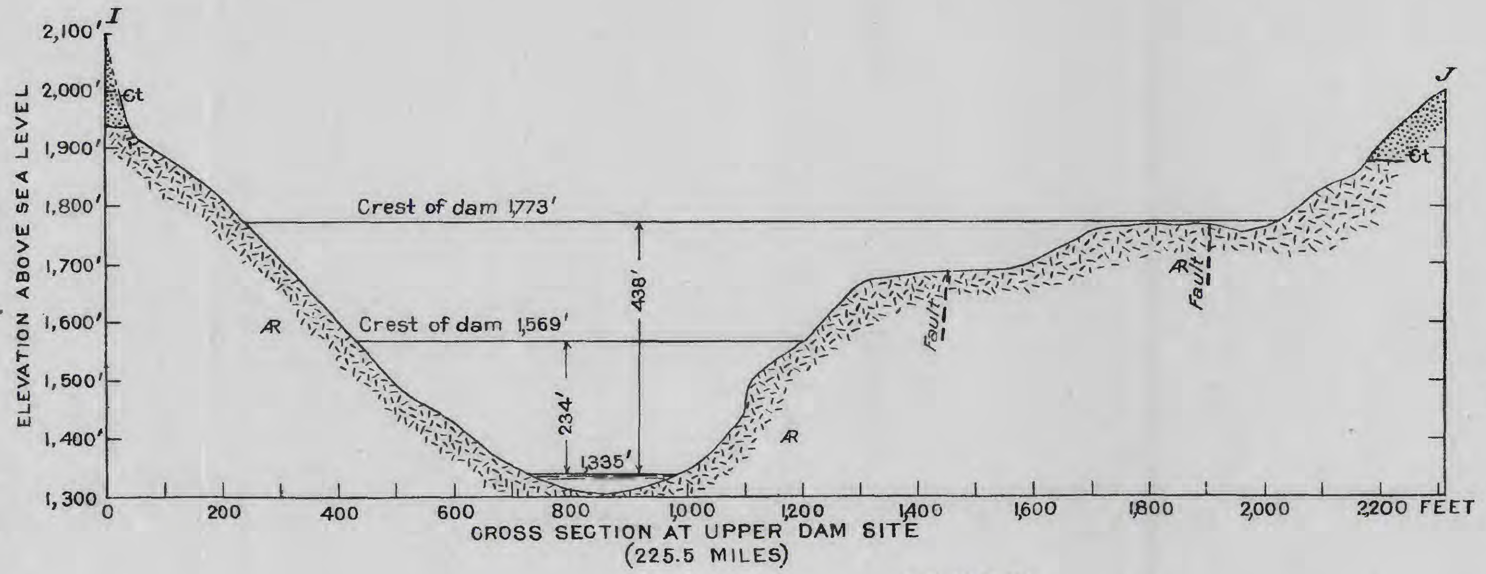
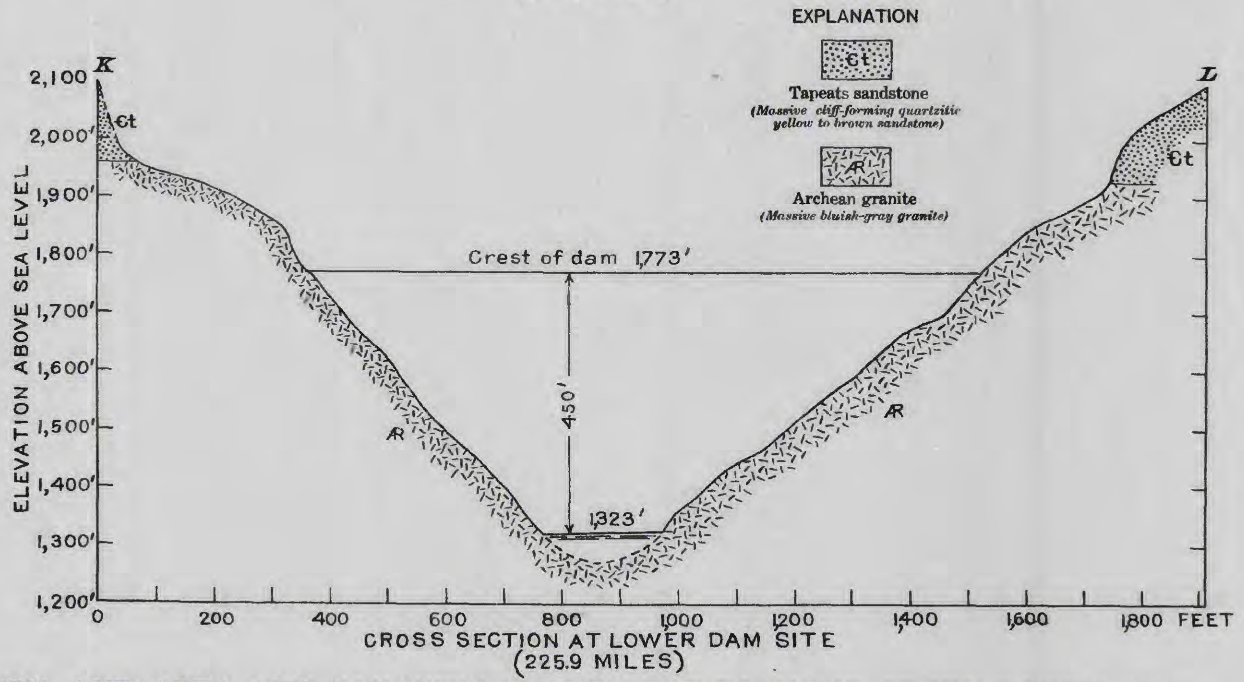
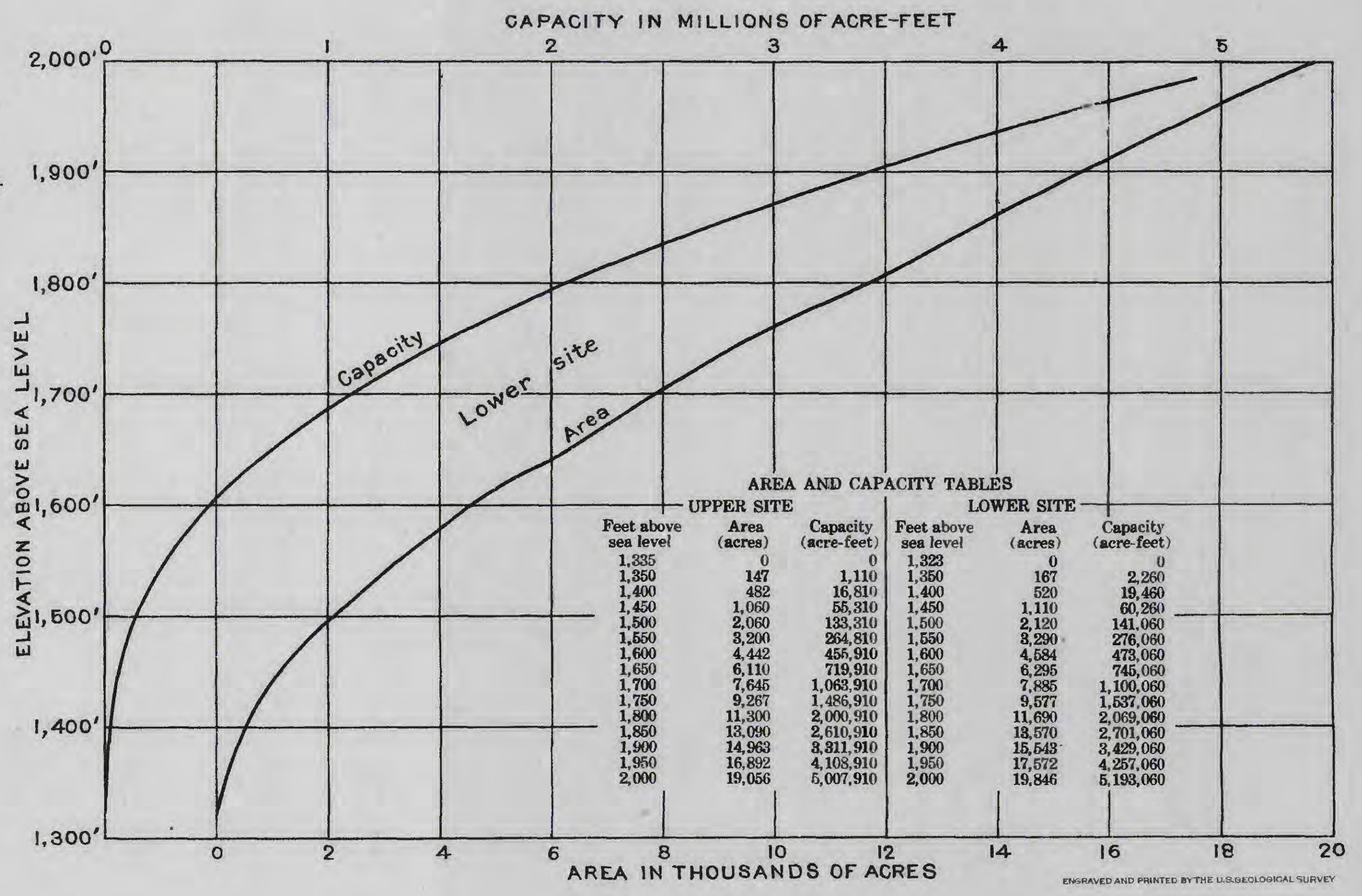
MAP, CROSS SECTION, AND AREA AND CAPACITY CURVES FOR PROSPECT POWER SITE









AREA AND CAPACITY TABLES

UPPER SITE			LOWER SITE		
Feet above sea level	Area (acres)	Capacity (acre-feet)	Feet above sea level	Area (acres)	Capacity (acre-feet)
1,335	0	0	1,323	0	0
1,350	147	1,110	1,350	167	2,260
1,400	482	16,810	1,400	520	19,460
1,450	1,060	55,310	1,450	1,110	60,260
1,500	2,060	133,310	1,500	2,120	141,060
1,550	3,200	264,810	1,550	3,290	276,060
1,600	4,442	455,910	1,600	4,584	473,060
1,650	6,110	719,910	1,650	6,295	745,060
1,700	7,645	1,063,910	1,700	7,885	1,100,060
1,750	9,267	1,486,910	1,750	9,577	1,537,060
1,800	11,300	2,000,910	1,800	11,690	2,069,060
1,850	13,090	2,610,910	1,850	13,570	2,701,060
1,900	14,963	3,311,910	1,900	15,543	3,429,060
1,950	16,892	4,108,910	1,950	17,572	4,257,060
2,000	19,056	5,007,910	2,000	19,846	5,193,060

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MAP, CROSS SECTION, AND AREA AND CAPACITY CURVES FOR DIAMOND CREEK POWER SITE

A. UPPER SITE

B. LOWER SITE

DAM SITES AT THE MOUTH OF DIAMOND CREEK, GRAND CANYON

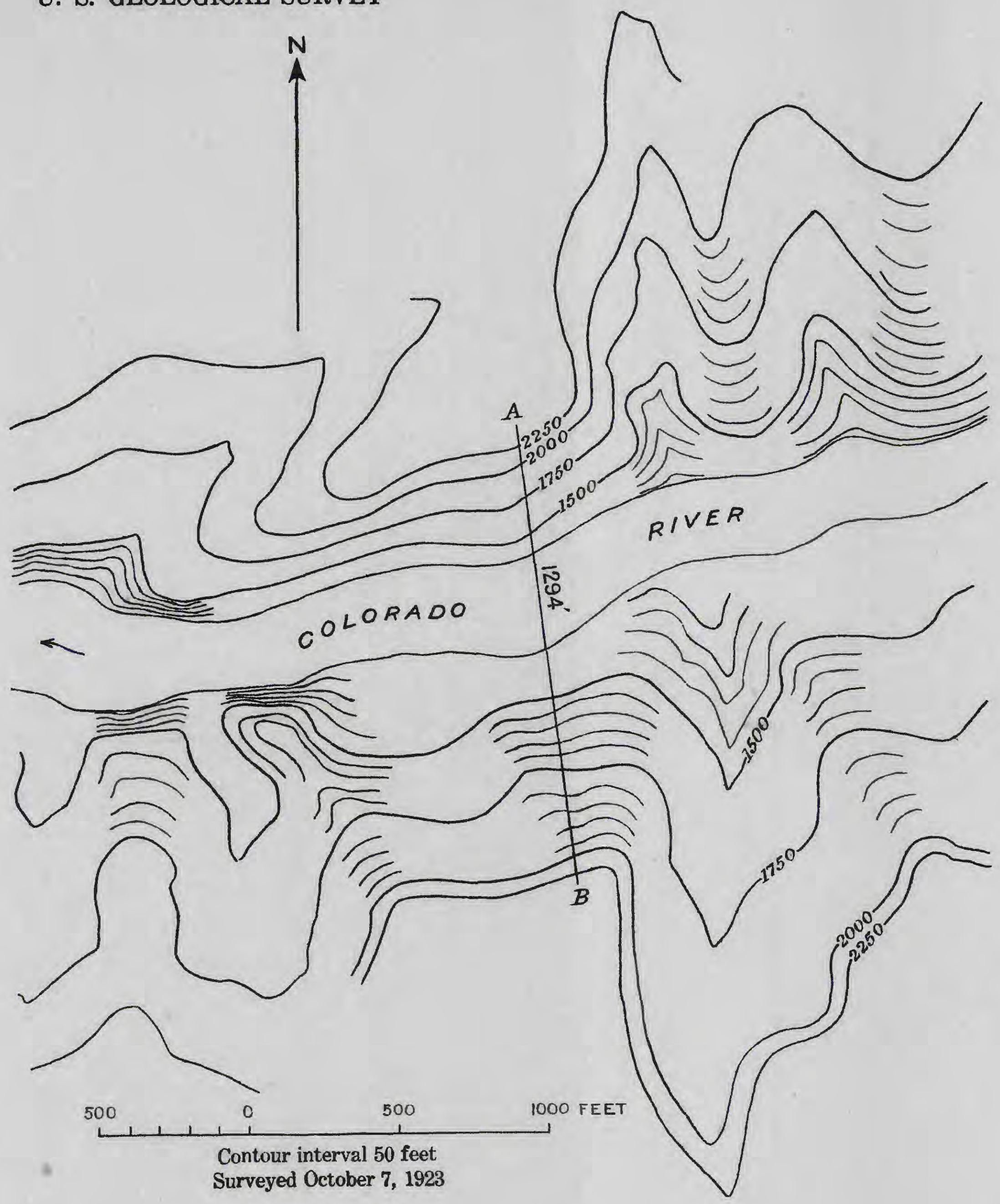
Geology by R. C. Moore

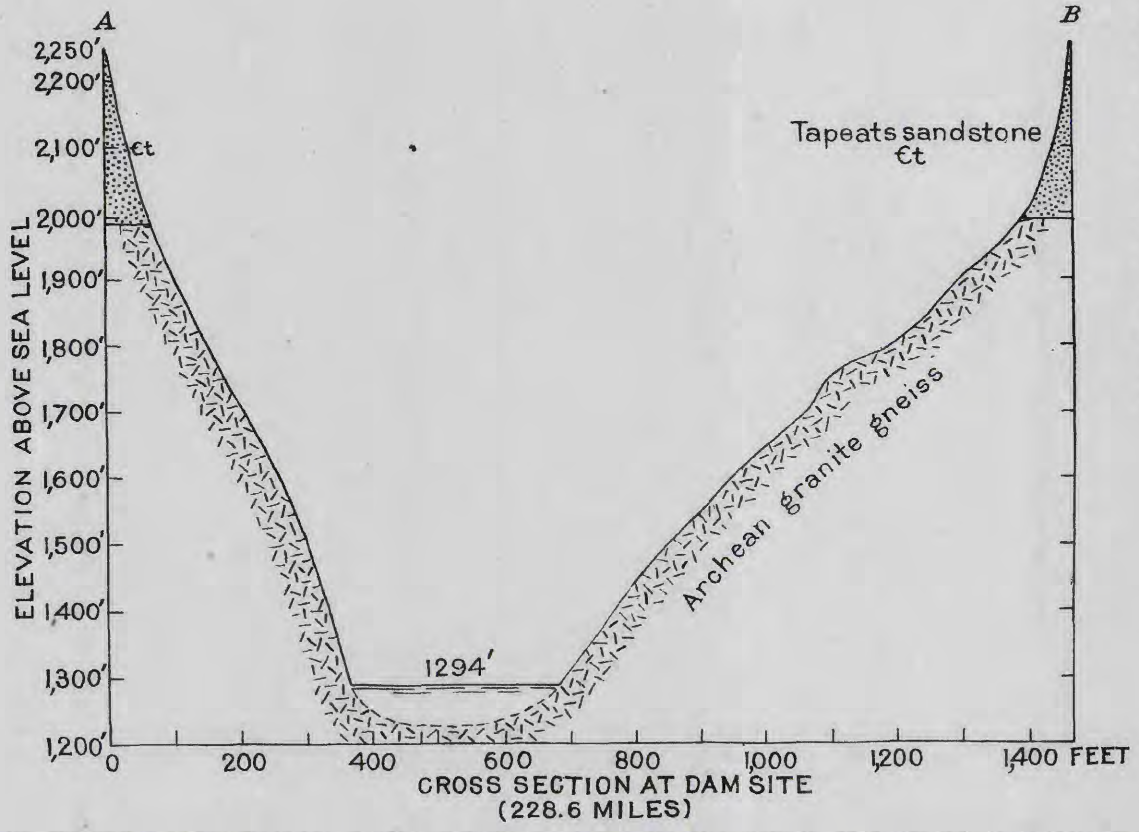
A. VIEW DOWN GRAND CANYON FROM POINT ON MESA 2,500 FEET ABOVE SEA LEVEL, ABOUT THREE-FOURTHS MILE BELOW THE MOUTH OF DIAMOND CREEK

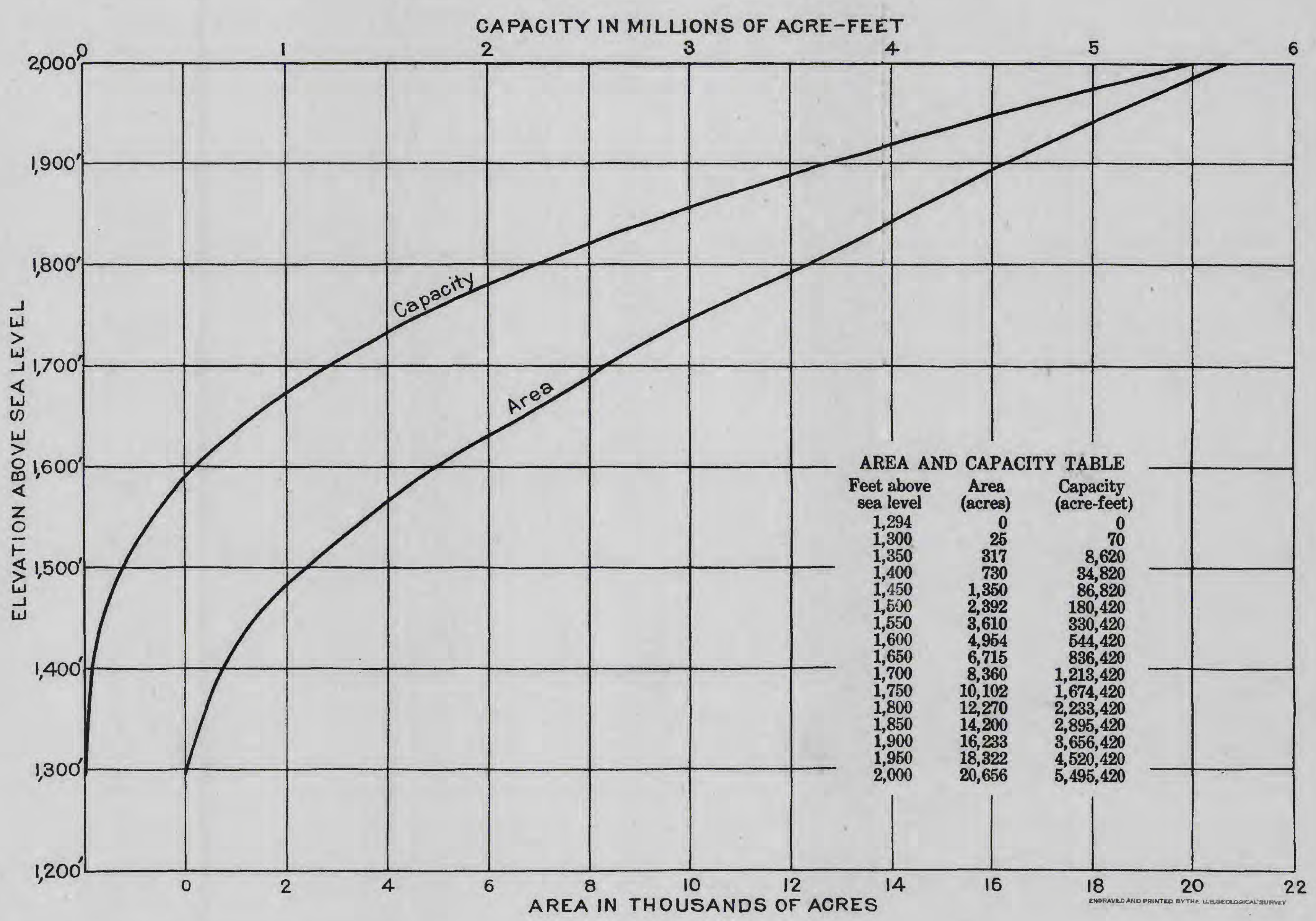
Geology by R. C. Moore

B. TRAVERTINE CANYON DAM SITE, GRAND CANYON, 3 MILES BELOW THE MOUTH OF DIAMOND CREEK

Geology by R. C. Moore







AREA AND CAPACITY TABLE

Feet above sea level	Area (acres)	Capacity (acre-feet)
1,294	0	0
1,300	25	70
1,350	317	8,620
1,400	730	34,820
1,450	1,350	86,820
1,500	2,392	180,420
1,550	3,610	330,420
1,600	4,954	544,420
1,650	6,715	836,420
1,700	8,360	1,213,420
1,750	10,102	1,674,420
1,800	12,270	2,233,420
1,850	14,200	2,895,420
1,900	16,233	3,656,420
1,950	18,322	4,520,420
2,000	20,656	5,495,420

MAP, CROSS SECTION, AND AREA AND CAPACITY CURVES FOR TRAVERTINE CANYON POWER SITE ing a high dam at or near Boulder Canyon to serve four purposes—flood control, storage for irrigation, storage of silt, and the development of power—a scheme of development which has never been tried. The other class embraces the plans which are based on the theory that major regulation of flow by storage can be developed by dams at or above Lees Ferry and that one dam should be built in Mohave Canyon to furnish preliminary and eventually supplemental storage for flood control and irrigation, the canyon section of the river being left free for power development, with the power dams incidentally providing for the storage of silt. One plan of the latter class is suggested by the writer. (See Pl. L.) Though a high dam is included in this plan for the purpose of showing the power value of the stretch of river between the Bridge Canyon site and the boundary of the Grand Canyon National Park, in the opinion of the writer dams of great height should not be built unless alternative plans for development of this stretch of river by lower dams are found infeasible or unless one such dam is decided upon as a point of diversion for a gravity water supply for irrigation in Arizona or for domestic use in the cities of southern California.

For the remaining stretch of the river here considered, between Bridge Canyon and Parker, all plans of the first class include a storage dam of unprecedented height, whereas the plans of the second class (see Pl. L) include only dams of moderate height, well within the limits set by modern engineering practice.

The plan suggested by the writer is based on the theory that a more efficient use of the available water supply may be had by separating the problem of flood control and storage for irrigation from the power problem. In his plan 10,200,000 acre-feet of storage capacity for flood control and irrigation is to be provided at Mohave Canyon. A diversion dam at Parker is recommended so that the waters of Colorado River may be used for the irrigation of lands situated in the United States. For the stretch above the Mohave Canyon reservoir the plan calls for the construction of dams that may be operated to obtain a maximum development of power. These dams step up the river to the west boundary of the Grand Canyon National Park, so as to permit full use of the fall in the river for power. Four power dams are suggested—at lower Black Canyon, Hualpai Rapids, Devils Slide, and Bridge Canyon. (See Pl. L.) An analysis of the suggested plan of development is given in the following table:

Analysis of plan for development of Colorado River between west boundary of Grand Canyon National Park and Parker, Ariz.

[Length of river involved, 368 miles; total fall, 1,425 feet]

Dam site	Elevation of dam site[a]	Height of dam[b]	Reservoir capacity available for flood control and irrigation	Loss of water due to evaporation[c]	Reduction in irrigable area due to evaporation[d]	Reduction in water supply due to evaporation[e]	Average flow available for power[f]	Average static head available for power	Power capacity at present[g]	With ultimate development: Reduction in water supply due to evaporation[e]	With ultimate development: Water supply available for power[h]	With ultimate development: Average static head available for power	With ultimate development: Power capacity[g]	With ultimate development: Area that may be irrigated[i]
	Feet	*Feet*	*Acre-feet*	*Acre-feet*	*Acres*	*Sec.-feet.*	*Sec.-feet.*	*Feet*	*Horsepower*	*Sec.-feet*	*Sec.-feet*	*Feet*	*Horsepower*	*Acres*
Bridge Canyon	1,207	566	0	44,000	9,780	61	22,340	566	1,012,000	61	14,400	566	654,000	
Devils Slide	1,034	163	0	1,670	370	2	22,440	163	293,000	2	14,540	163	190,000	
Hualpai Rapids	799	225	0	39,800	8,850	55	22,480	225	405,000	55	14,600	225	263,000	
Lower Black Canyon	595	194	0	65,200	14,500	90	22,390	194	347,000	90	14,480	194	225,000	
Mohave Canyon	427	158	10,200,000	15,000	3,330	21		0	0	[j] 269	13,720	107	117,000	
Parker	358	99	0	112,000	24,900	155		90	[k] 70,000	[l] 155	13,690	90	[k] 70,000	
		1,405	10,200,000	277,670	61,730	384		1,238	2,127,000			1,345	1,519,000	2,203,000

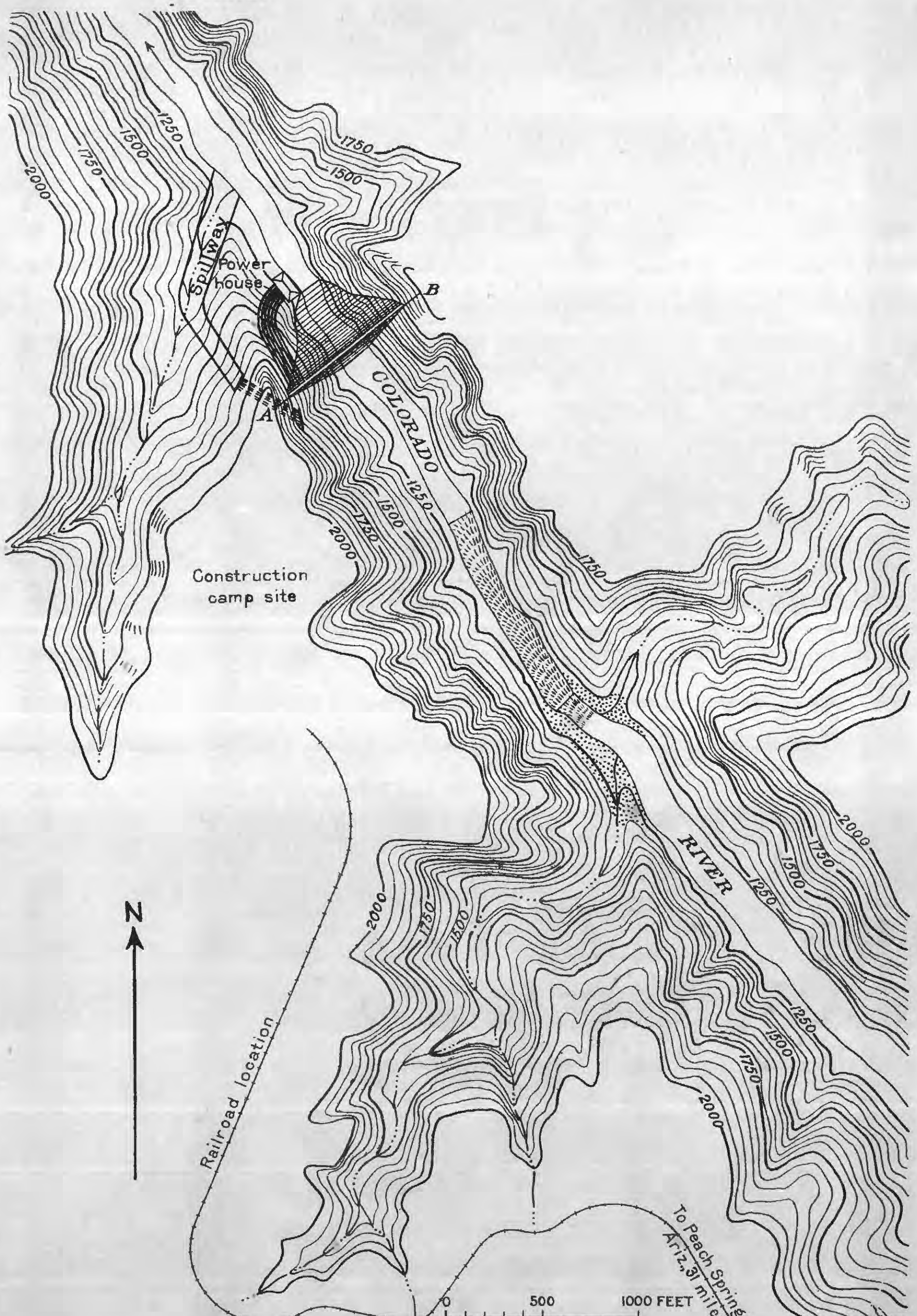
[a] Elevation above sea level of the water surface of the river at the dam site when the river discharge is 10,000 second-feet.
[b] Height the water is to be raised at the dam site.
[c] Evaporation loss from reservoir surface minus loss from present river channel.
[d] Based on the assumption that the average annual water requirements will be 4.5 acre-feet per acre, measured at the point of diversion.
[e] Rate of flow that is equivalent to the average rate of evaporation at the dam site.
[f] Water supply available after the normal supply has been reduced by an amount equal to the net loss of water due to evaporation.
[g] Continuous horsepower, except at Parker dam site.
[h] Water supply available after full development of the water resources above the dam site has been attained.
[i] Amount of land that could be irrigated with the remaining water supply with a head-gate duty of 4.5 acre-feet a year. However, a part of the water may be used for domestic purposes in the cities of southern California.
[j] At the Mohave Canyon site 4,000,000 acre-feet of storage capacity is to be reserved for flood control and irrigation storage. Using the Mohave Canyon site in this way would permit a loss of 269 second-feet of water through evaporation. Without power development, the net loss due to evaporation from the Mohave reservoir would be 21 second-feet, which would leave 13,940 second-feet available at Parker dam site.
[k] Water passing the Parker diversion dam is to be regulated only in the interest of irrigation. With an installed capacity of 70,000 horsepower, the high flow during the summer could be utilized for power.
[l] The calculated evaporation loss due to Parker diversion dam is 180 second-feet, and the average inflow from Williams River is estimated at 150 second-feet, leaving a net loss between Mohave Canyon and the Parker dam site of 30 second-feet.

A. VIEW DOWN GRAND CANYON FROM A POINT ON THE RIM, SHOWING BRIDGE CANYON DAM SITE, 10.5 MILES BELOW THE MOUTH OF DIAMOND CREEK

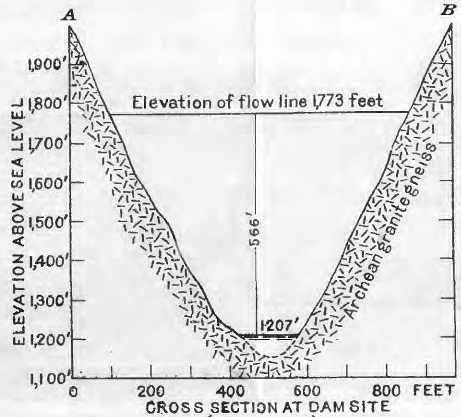
Geology by E. C. La Rue

B. A CLOSE-UP VIEW OF THE BRIDGE CANYON DAM SITE

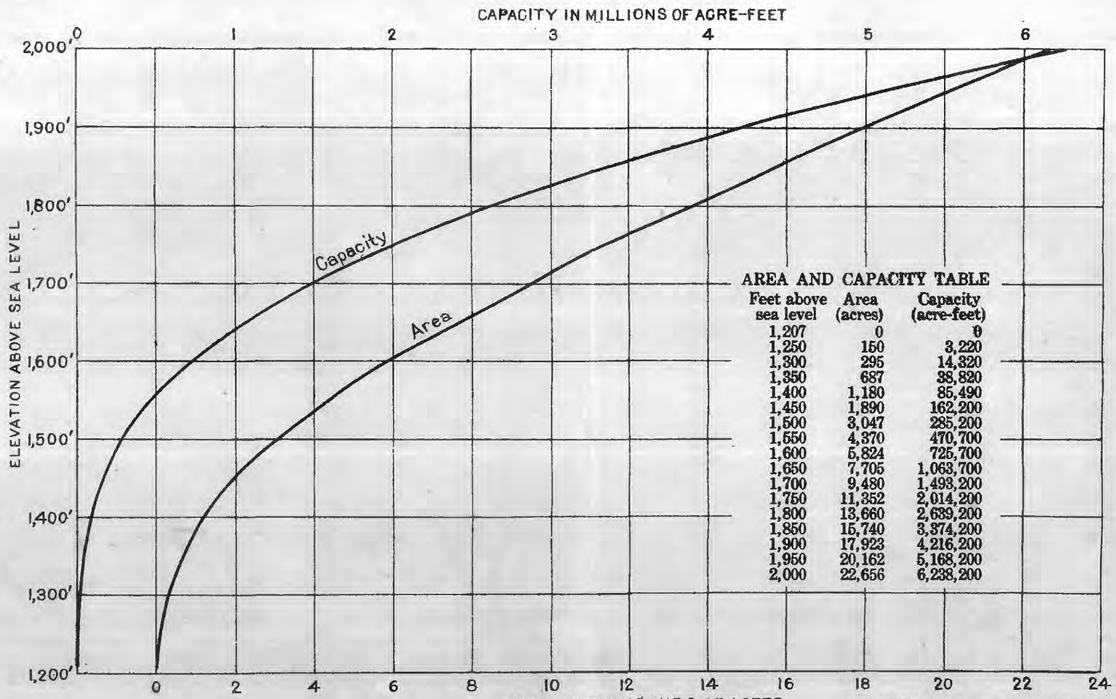
Geology by R. C. Moore



Contour interval 50 feet
Surveyed October 9, 1923



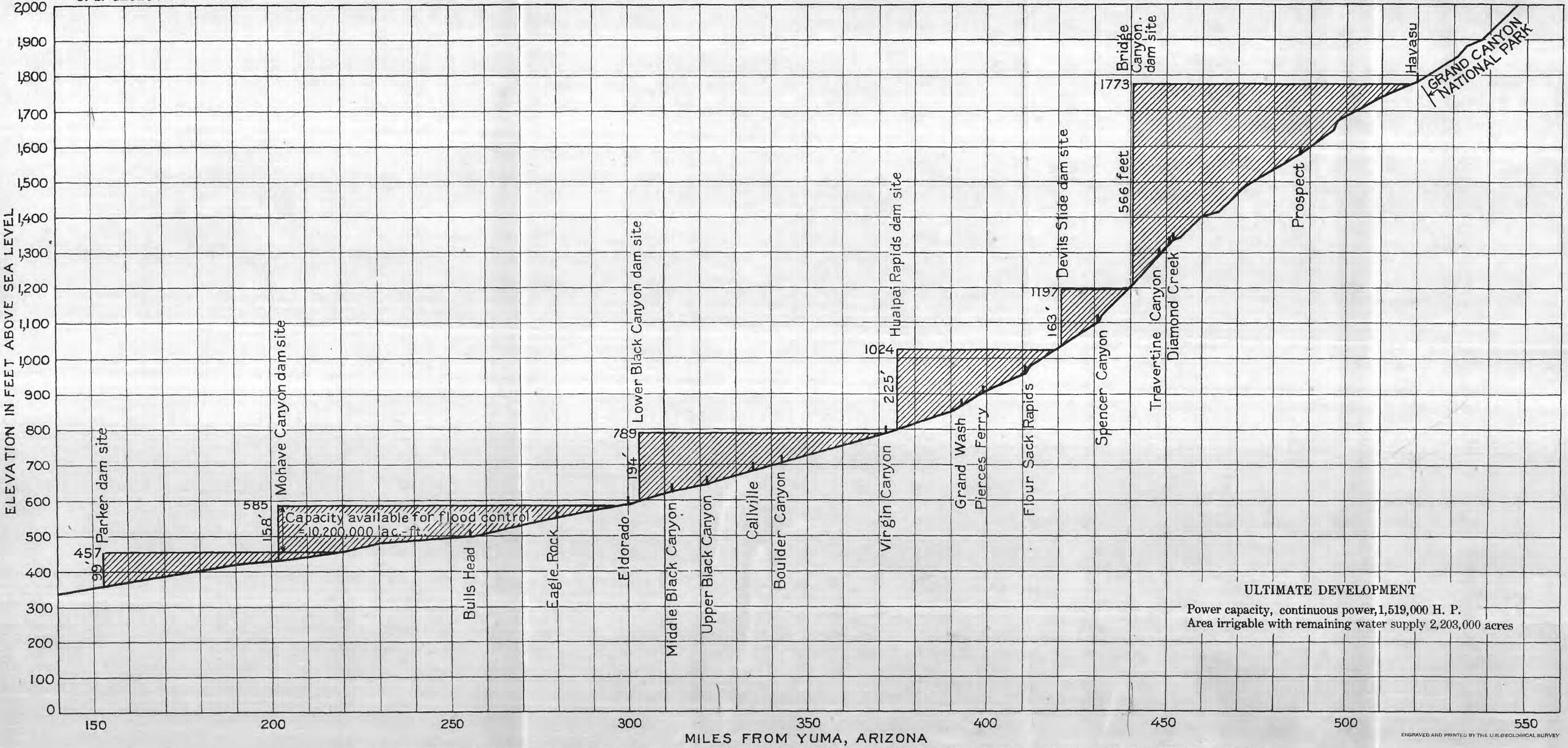
CROSS SECTION AT DAM SITE
(236.3 MILES)



AREA AND CAPACITY TABLE

Feet above sea level	Area (acres)	Capacity (acre-feet)
1,207	0	0
1,250	150	3,220
1,300	295	14,320
1,350	687	38,820
1,400	1,180	85,490
1,450	1,890	162,200
1,500	3,047	285,200
1,550	4,370	470,700
1,600	5,824	725,700
1,650	7,705	1,063,700
1,700	9,480	1,493,200
1,750	11,352	2,014,200
1,800	13,660	2,639,200
1,850	15,740	3,374,200
1,900	17,923	4,216,200
1,950	20,162	5,168,200
2,000	22,656	6,238,200

MAP, CROSS SECTION, AND AREA AND CAPACITY CURVES FOR BRIDGE CANYON POWER SITE



PLAN OF DEVELOPMENT OF COLORADO RIVER BETWEEN GRAND CANYON NATIONAL PARK AND PARKER, ARIZONA

Names below profile represent alternative dam sites

With the water supply now available and with development accomplished as suggested by the writer the loss of water due to evaporation would be reduced to a minimum, and a maximum amount of power could be developed. If the plan of development that calls for a high dam at or near Boulder Canyon were followed the additional loss of water due to evaporation from the water surface of the reservoirs would be about 800 second-feet, and the consequent loss of power would exceed 230,000 horsepower.

The loss of water at present is not a serious matter, for a great surplus passes into the Gulf of California each year. Before many years pass, however, the demand for water will be greater than the available supply. It would therefore be unwise to carry out a construction plan that would forever prevent the full use of the water resources of the river. The real test of the soundness of the several plans suggested lies in a comparison on the basis of ultimate development of the water resources of the region. A thorough analysis of the plans that call for a high dam at or near Boulder Canyon shows that with complete development in the upper basin and with the lower river developed as suggested by the writer, 103,000 acres more land could be irrigated and an additional 251,000 horsepower could be developed.

The Mohave Canyon storage reservoir, operated solely in the interest of flood control and irrigation, would provide the most satisfactory solution of this phase of the problem, as it would be 120 miles nearer the lands that would be benefited by such storage than the Boulder Canyon site.

It would be possible to provide 2,000,000 acre-feet of available storage capacity at the Parker dam site, but such a plan would seriously interfere with the full use of water for irrigation. Under such a plan it would be necessary to pump the water an additional 33 feet to reclaim by irrigation some 700,000 acres of land below Parker. With the Mohave Canyon reservoir in operation, it would not be necessary to provide available storage capacity at the Parker dam site.

The writer suggests that his plan should be given serious consideration for the following reasons:

1. It provides the most effective means of flood control and storage for irrigation.

2. It solves the problem of silt storage for several generations.

3. It provides a maximum use of water for both irrigation and power development.

4. It calls for a minimum departure from present engineering practice in the construction of dams.

SITES RECOMMENDED

BRIDGE CANYON POWER SITE

Location.—The Bridge Canyon dam site is about 236 miles below Lees Ferry and 10½ miles below Diamond Creek. (See Pls. II and III, in pocket.)

Physical characteristics.—The Archean crystalline rocks rise above the river at a point 10 miles above Diamond Creek and are continuously exposed in the canyon walls for a distance of about 50 miles. This section of the canyon is known as the Lower Granite Gorge. (See footnote, p. 43; also Pl. XV, in pocket.) Here, as in the Granite Gorge, the rocks are very hard and form walls that rise steeply from the river banks. The Bridge Canyon dam site is near the deepest part of the inner gorge where the crystalline rocks form the canyon walls to a height of nearly 800 feet above the river. The rock is a rather complex mass of granite gneiss with thin veins of pink granite and pegmatite. All these rocks are hard and closely joined together, forming one solid mass. The rock in the river channel and canyon walls is highly satisfactory for the foundation and abutments for a dam of any height up to 800 feet. (See Appendix B, p. 163.)

Abundant materials suitable for the construction of the dam are conveniently available at the site. Just above the site for the construction camp will be found the massive beds of dolomitic limestone in the upper part of the Bright Angel shale. This limestone when crushed will make excellent material for concrete aggregate. Bordering the camp site is the Tapeats sandstone, from which sand and gravel may be obtained (Pl. XLVIII, *A*). It would be necessary to transport the cement from some distant point, as all the materials necessary for the manufacture of cement are not to be found in the vicinity of the dam site.

The cross section of the canyon at the dam site is relatively narrow, the width of the river being only 160 feet. A dam to raise the water 566 feet would have a crest length of 740 feet. The narrow gorge at the dam site is clearly shown in Plate XLVIII, *B*.

Plan of development.—The plan of development is shown in Plates XLVIII and XLIX. The power house may be placed below the dam on the left bank. The surplus water may be taken care of by means of tunnels 400 feet long, leading to the side canyon on the left bank.

The rock in the side canyon is schist, which is much harder than concrete. It would therefore not be necessary to pave the side canyon with concrete in order to prevent erosion.

The flat bench in the Bright Angel shale on the left bank above the dam site would afford an excellent site for the construction camp and permanent living quarters. (See Pls. XLVIII, *A*, and XLIX.) The concrete mixers, storage bins, and other apparatus may also be placed on this bench in convenient position above the dam site. The position of the dolomitic limestone for the concrete aggregate and of the sandstone for the sand and gravel with respect to the camp site is shown in Plate XLVIII, *A*.

Although the conditions at Bridge Canyon are favorable for the construction of a dam of any height up to 800 feet above the river for the purpose of this report, in showing the possible water-power resources of Colorado River, a dam to raise the water 566 feet has been selected. Such a dam would back the water to the Havasu power site, at the west boundary of the Grand Canyon National Park.

Water supply.—Without storage and with the water in the upper basin used as in 1922, the water supply available at the Bridge Canyon dam site would be 10,900 second-feet 50 per cent of the time, or 7,270 second-feet 90 per cent of the time. Under the same conditions of use, but with storage in Glen Canyon, the water supply would be 22,400 second-feet. With ultimate development in the upper basin and in the canyon section above Bridge Canyon the supply would be reduced to about 14,440 second-feet. (See Appendix A, p. 113.)

Power capacity.—The static head at the Bridge Canyon site would be 566 feet. The power capacity with this head and the water supply given in the preceding paragraph would be as follows:

	Horsepower
Without storage and with irrigation and power development in upper basin as in 1922:	
Capacity 50 per cent of time	494,000
Capacity 90 per cent of time	329,000
With storage in Glen Canyon and with irrigation and power development in upper basin as in 1922:	
Continuous power available	1,015,000
With storage and with ultimate irrigation and power development in upper basin:	
Continuous power available	654,000
Installed capacity (load factor 60 per cent)	1,090,000

Right of way.—If a dam were built at the Bridge Canyon site to raise the water 566 feet, a lake would be formed having a length of 78 miles and a surface area of 8,500 acres. There are no important improvements in this part of the Grand Canyon. The flowage damage would therefore be negligible.

Accessibility.—In May, 1924, the writer made a reconnaissance investigation to determine the feasibility of building a railroad to the Bridge Canyon dam site. It was found that a railroad could be constructed from Peach Springs, Ariz., which is on the main line of the Atchison, Topeka & Santa Fe Railway, to the northeast corner of T. 26 N., R. 12 W. Gila and Salt River meridian, a distance of 18 miles, with a ruling grade of probably less than 1 per cent. This part of the railroad could be constructed at a minimum cost, as it would be located on a plateau or relatively smooth table-land. The construction of the remaining 13 miles to the dam site would be more difficult. A plane-table survey to determine the best location for this portion showed that by building a tunnel 1½ miles long the head of Bridge Canyon could be reached. The construction from the head of Bridge Canyon to the dam site would not be difficult. The ruling grade in the tunnel and down Bridge Canyon would be 5.8 per cent. The location of the proposed railroad from the mouth of Bridge Canyon to the construction-camp site is shown in Plate XLVIII, *A*. The total length of the construction railroad from Peach Springs to the Bridge Canyon dam site would be about 31 miles. The data available indicate that so far as the cost of constructing a railroad to the site is concerned the Bridge Canyon dam site is more accessible than the Diamond Creek sites described on pages 88–91.

Adaptability of plan.—The Bridge Canyon power site has been selected to form a unit of a comprehensive plan for the full development of the water resources of Colorado River. This selection is based on the following facts:

1. The narrow cross section and the rock formations at the dam site are favorable for the construction of a dam of any height up to 800 feet above the river.

2. There is a good site for a power house on the left bank below the dam site, and the spillway site is excellent. These favorable features, together with the presence of an ideal site for a construction camp, the ready accessibility of building material, and the relative ease with which the dam site could be connected with a main-line railroad, indicate that the project could be constructed at a reasonable cost.

3. Owing to its position on the river with respect to other dam sites, the utilization of the Bridge Canyon site will permit full development of the power resources of the river both above and below the site. With respect to the development of power at the Bridge Canyon site the facts are as follows: A head of 118 feet at the Bridge Canyon site may be utilized without interfering with the development of the upper dam site at Diamond Creek (p. 88); if the Prospect site (p. 86) is to be developed instead of a site at Diamond Creek, then the head available for power development at Bridge Canyon would be 362 feet; if the Havasu site (p. 65) is to be developed in connection with Bridge Canyon, the available head at the Bridge Canyon site would be 566 feet.

At some future time it may be necessary to divert 1,500 to 2,000 second-feet of water from Colorado River to augment the domestic water supply of the cities of southern California. If a gravity system is built, the point of diversion would probably be at Bridge Canyon dam site. The gravity system would require a diversion dam about 825 feet in height above its foundation, or to an elevation of 1,992 feet above sea level, and the construction of a 72-mile tunnel to carry the water to a point near Topock, Ariz., where it would be carried across Colorado River by means of inverted siphons operated under a maximum head of perhaps 1,300 feet. With the present use of water in the upper basin, with storage in Glen Canyon, and with 2,000 second-feet of water diverted at Bridge Canyon, there would remain available at the Bridge Canyon dam site a flow of 20,400 second-feet. Under a static head of 785 feet, the amount of power that could be developed at the diversion dam would be 1,280,000 horsepower. The installed capacity of the plant, at a 60 per cent load factor, would be 2,133,000 horsepower. With complete development in the upper basin and with 2,000 second-feet of water diverted at Bridge Canyon 781,000 continuous horsepower could be developed, and at a 60 per cent load factor the installed capacity of the plant would be 1,302,000 horsepower. The value of this power would more than offset the cost of the diversion dam. It therefore appears that the plan calling for the construction of a gravity system has merit. In view of these facts, it is suggested that, pending a decision as to the plan for furnishing the southern California cities with a domestic water supply, the Bridge Canyon power site should be reserved for development to an elevation of 1,992 feet above sea level. The diversion dam to this elevation would back the water to the Specter Chasm power site, in the Grand Canyon National Park, and would, of course, preclude the utilization of the Diamond Creek, Prospect, and Havasu sites.

DEVILS SLIDE POWER SITE

Location.—The Devils Slide dam site is in the lower part of the Grand Canyon, 255½ miles below Lees Ferry and 30 miles below the mouth of Diamond Creek. (See Pl. II, in pocket.)

Physical characteristics.—At the Devils Slide dam site the river has carved its channel in the hard granitic rock. The granite is capped by the Tapeats sandstone at 366 feet above the river. (See cross section of dam site, Pl. LI.)

The cross section is relatively narrow, the width of the river at the dam site being only 170 feet. The canyon of Salt Creek joins the Colorado 500 feet above the dam site. Spillway tunnels or an open spillway cut may be constructed from the canyon of Salt Creek to discharge into the river 800 feet below the proposed dam.

The dam site is in the Devils Slide Rapids. The rapids indicate that the river is shallow and that its channel is firm (Pl. LII, *A*). Coffer dams could be built at a minimum cost. The depth to bedrock in the river channel is estimated at 50 feet.

Materials necessary for the construction of the dam are available at the site. Sand and gravel may be obtained by crushing the Tapeats sandstone, and coarser aggregate for the concrete may be obtained by crushing the dolomitic limestone in the upper part of the Bright Angel shale. (See Appendix B, p. 166.)

Plan of development.—The plan suggested by the writer calls for the construction of a dam at the Devils Slide site to back the water to the Bridge Canyon site. Such a dam would raise the water 163 feet, or to an elevation of 1,197 feet above sea level. A dam of the nonoverflow type is probably the best adapted to the conditions, as adequate spillway capacity may be provided by constructing tunnels or an open cut through the narrow ridge between the canyon of Salt Creek and the main canyon of Colorado River. There is a good site for a construction camp. The power house may be built at the base of the dam, as the spillway tunnels would discharge into the river at a point 800 feet farther down. (See Pl. LI.)

The canyon above the Devils Slide dam site is very narrow, and its walls are steep. The lake above the dam would be confined between the walls of the Lower Granite Gorge. (See Pl. LII, *B.*) The area of water surface exposed to evaporation would be 880 acres, and the net additional loss of water thus entailed by the building of the dam would be about 2 second-feet.

Water supply.—With development in the upper basin as in 1922, the water supply available at the Devils Slide dam site would be 7,330 second-feet 90 per cent of the time, or 11,000 second-feet 50 per cent of the time. Under the same conditions of development but with storage in Glen Canyon, the available flow would be 22,500 second-feet. With full use of water in the upper basin and with power development in the canyon section as outlined in this report, the water supply available at the Devils Slide dam site would be reduced to 14,540 second-feet. A detailed analysis of the water-supply records may be found in Appendix A.

Power capacity.—The static head at the Devils Slide site would be 163 feet. The power capacity with this head and the water supply given in the preceding paragraph would be as follows:

	Horsepower
Without storage and with irrigation and power development in upper basin as in 1922:	
Capacity 50 per cent of time	143, 000
Capacity 90 per cent of time	95, 600
With storage in Glen Canyon and with irrigation and power development in upper basin as in 1922:	
Continuous power available	294, 000
With storage and with ultimate irrigation and power development in upper basin:	
Continuous power available	190, 000
Installed capacity (load factor 60 per cent)	317, 000

Right of way.—The dam proposed at the Devils Slide site would form a lake in the Lower Granite Gorge with a surface area of 880 acres. No improvements of any kind would be affected, and the flowage damage would therefore be negligible.

Accessibility.—A railroad could be built to the Devils Slide dam site from Antares station, on the main line of the Atchison, Topeka & Santa Fe Railway. Such a road would be 87 miles long and would follow the Hualpai Valley to Red Lake and thence go over a low divide to Grapevine Wash, down Grapevine Wash to Colorado River, and up the canyon of the river to the dam site. About 37 miles of the railroad would require heavy construction, but on the other 50 miles the construction would be unusually light.

It seems probable that the Devils Slide dam site will become accessible by means of the backwater from a dam built lower on the river, and in that event it would not be necessary to construct a railroad to the site.

Adaptability of plan.—The Devils Slide power site forms a unit of the comprehensive plan here suggested. (See Pl. L and discussion under heading "Outline of plan.")

HUALPAI RAPIDS POWER SITE

During September and October, 1924, the writer made a thorough investigation of the river from a point 13 miles above Pierces Ferry to Needles, Calif., in which six new dam sites were surveyed. The Hualpai Rapids dam site, one of the six, has many favorable features, and it is suggested as a unit of the comprehensive plan of development. The site had been examined by J. B. Lippincott, consulting engineer, Los Angeles, Calif., in October, 1902.

Location.—The Hualpai Rapids power site is at the head of Virgin Canyon, just below the mouth of Hualpai Wash, about 302 miles below Lees Ferry, 3½ miles below Greggs Ferry, and about 60 miles due north of Kingman, Ariz. (See Pl. II, in pocket.)

Physical characteristics.—After passing through the valley at Greggs Ferry the river enters Virgin Canyon, a narrow gorge about 4 miles long. At the upper end of this canyon the conditions are favorable for the construction of a dam. The topographic features of the dam site are shown in Plate LIII.

The width of the river at this site is 310 feet, and a dam to raise the water 225 feet would have a length on top of 910 feet. The hard Archean crystalline rocks form the abutment walls and foundation. The depth to bedrock in the river channel is estimated at 60 feet.

The canyon walls at the dam site are low and extend back on a gentle slope from the river. The whole site would be easily accessible during the construction period. (See Pl. LIV, *A*.) These favorable features may be compared with those existing at dam sites located in deep, narrow canyons, where the walls are precipitous and the sites are inaccessible except by boat.

At Hualpai Rapids there are two sites where the conditions are favorable for the location of a construction camp. One is on the flat mesa about 100 feet above the river on the north bank of Hualpai Wash. This site, however, might be submerged before the dam was completed. The camp site shown on the map in Plate LIII is on the low hills 2,000 feet from the dam site. Here permanent quarters could be built, for the site would not be submerged when the project is constructed and placed in operation.

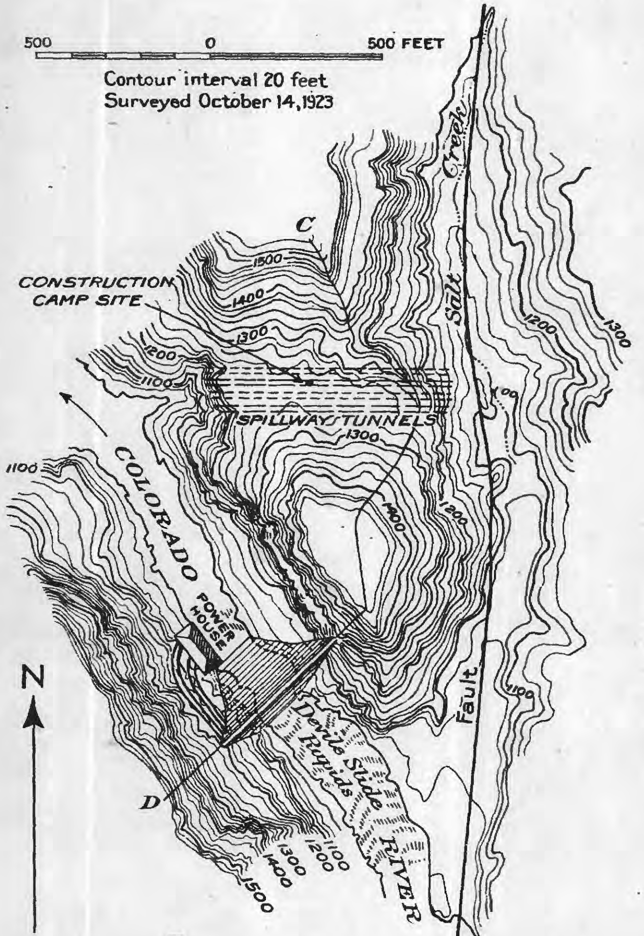
The dam site is about 300 feet above the lower end of Hualpai Rapids, which are about 1,400 feet long. It is therefore apparent that a firm foundation for cofferdams would be found at a moderate depth below the water surface. There is a boulder bar above the dam site which could be used as the base for the upper cofferdam. (See Pl. LIV, *B*.) Very little additional work would be necessary to divert the river into a flume or by-pass tunnels. In the opinion of the writer the cost of taking care of the water during construction would be less at the Hualpai Rapids site than at any other dam site on the lower river. Building materials are available at the site.

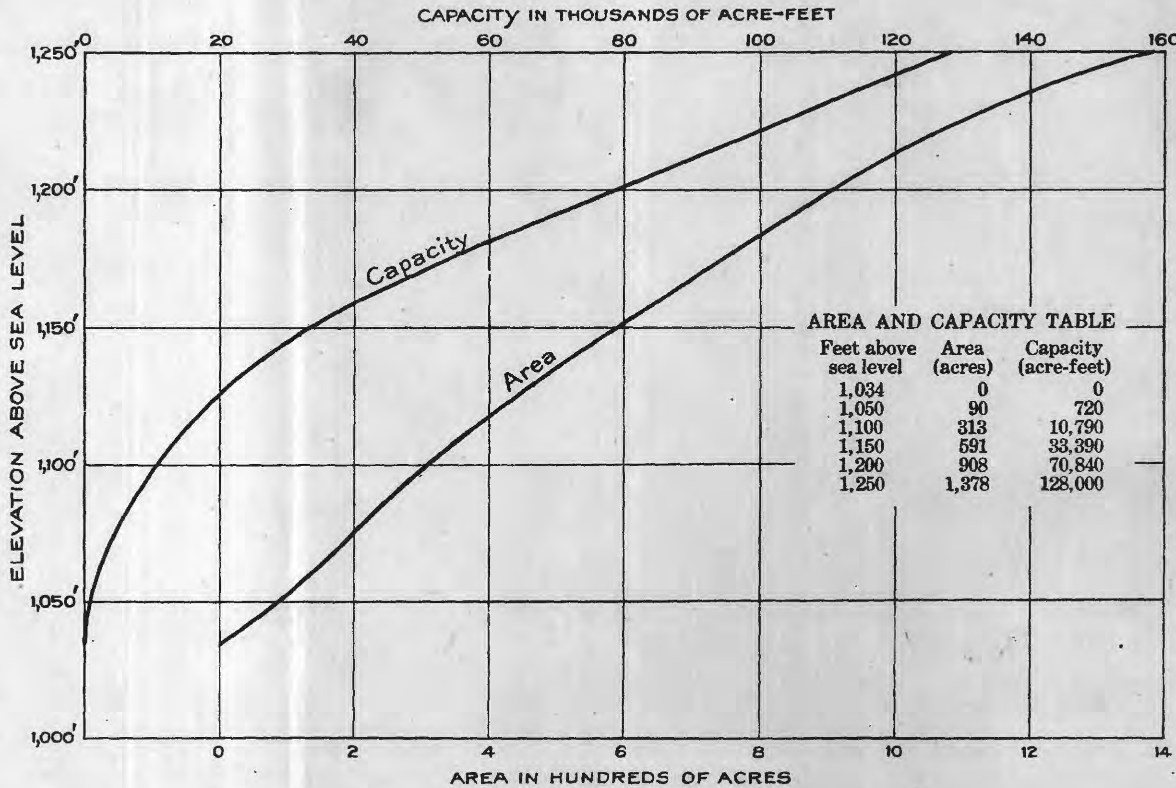
Plan of development.—At the Hualpai Rapids site a dam to raise the water 225 feet, or to an elevation of 1,024 feet above sea level, would not interfere with the development of power at Devils Slide, or the construction of a bridge across Colorado River at Pierces Ferry. A dam of the overflow type is suggested, although a spillway separate from the dam could be provided by utilizing the saddle 3,000 feet east of the dam site. (See Pl. LIII.) For the height of dam proposed, it would be necessary to excavate the saddle to a depth of 70 feet or more.

The power house may be placed on the left bank 400 feet below the dam. The combined length of power tunnels and penstocks would be about 1,000 feet. The suggested plan of development is shown in Plate LIII.

Water supply.—With the use of water in the upper basin as in 1922 and without storage, the water supply available at the Hualpai Rapids dam site would be 7,330 second-feet 90 per cent of the time, or 11,100 second-feet 50 per cent of the time. Under the same conditions of use but with storage in Glen Canyon, the available water supply would be 22,600 second-feet. With full use of water in the upper basin and with the canyon section of the river developed as outlined in this report, the water supply available at the Hualpai Rapids dam site would be reduced to 14,600 second-feet.

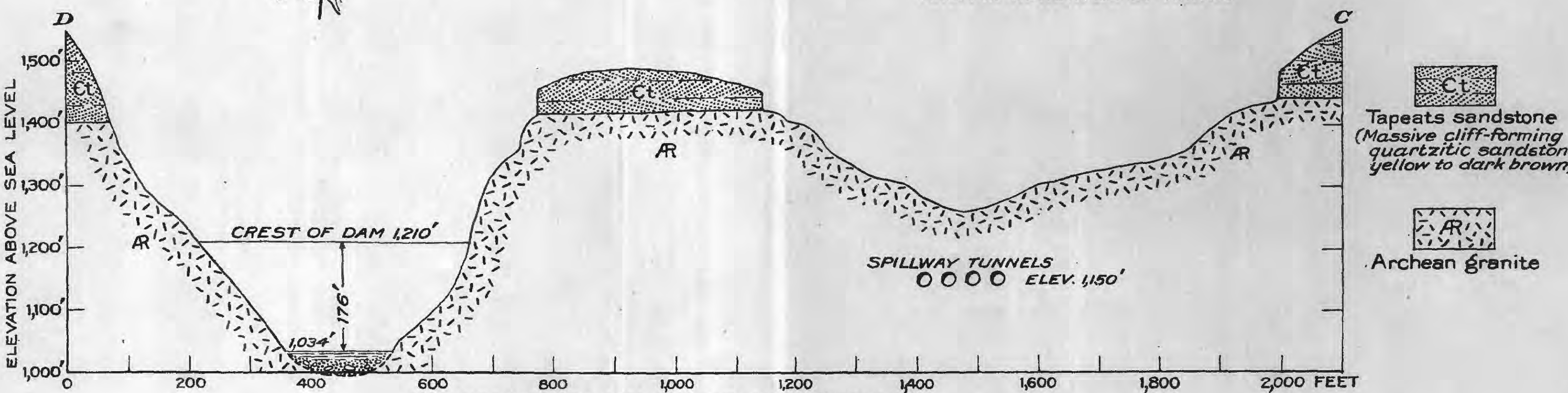
Power capacity.—The static head at the Hualpai Rapids site would be 225 feet. The power capacity with this head and the water supply given in the preceding paragraph would be as follows:





AREA AND CAPACITY TABLE

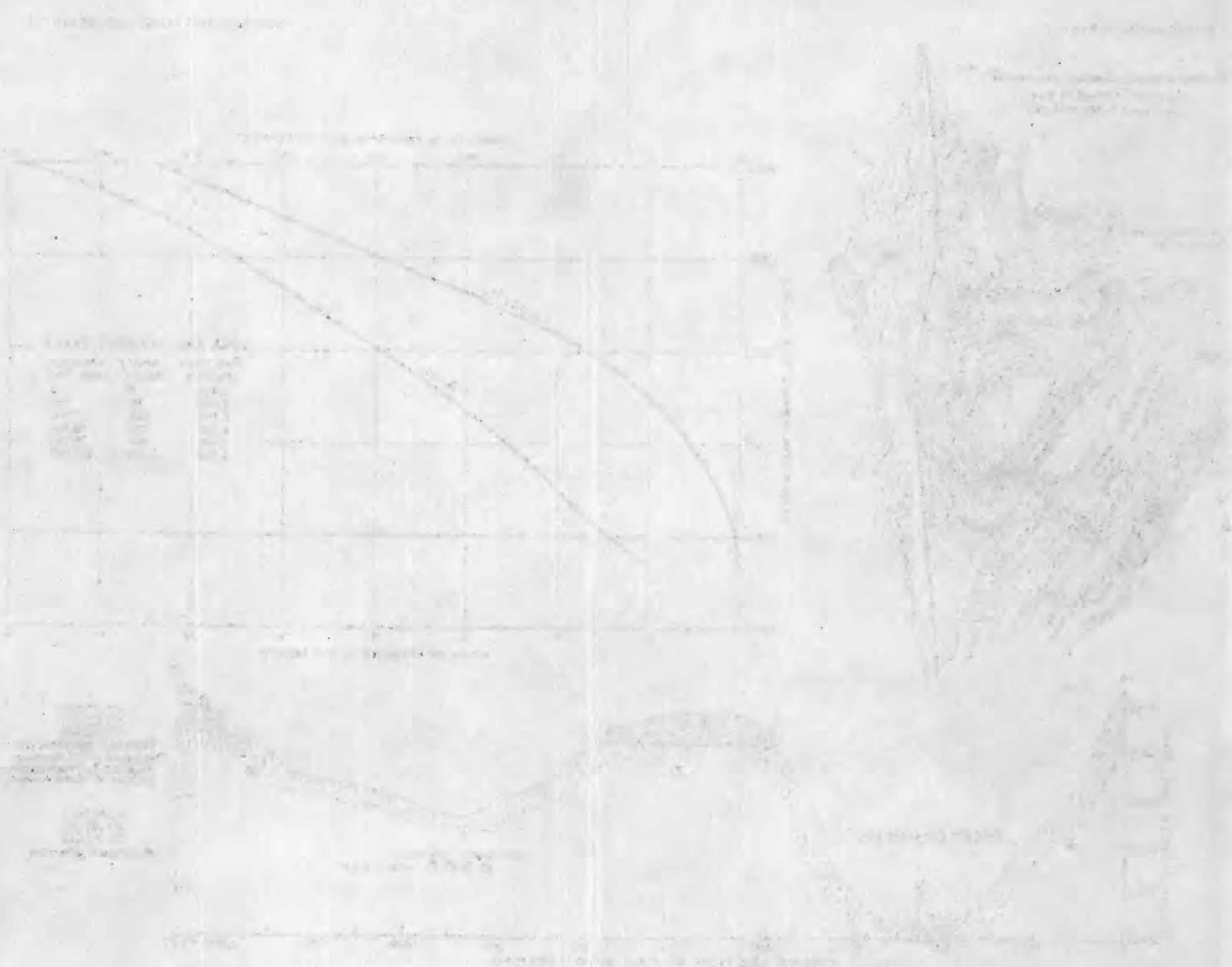
Feet above sea level	Area (acres)	Capacity (acre-feet)
1,034	0	0
1,050	90	720
1,100	313	10,790
1,150	591	33,390
1,200	908	70,840
1,250	1,378	128,000



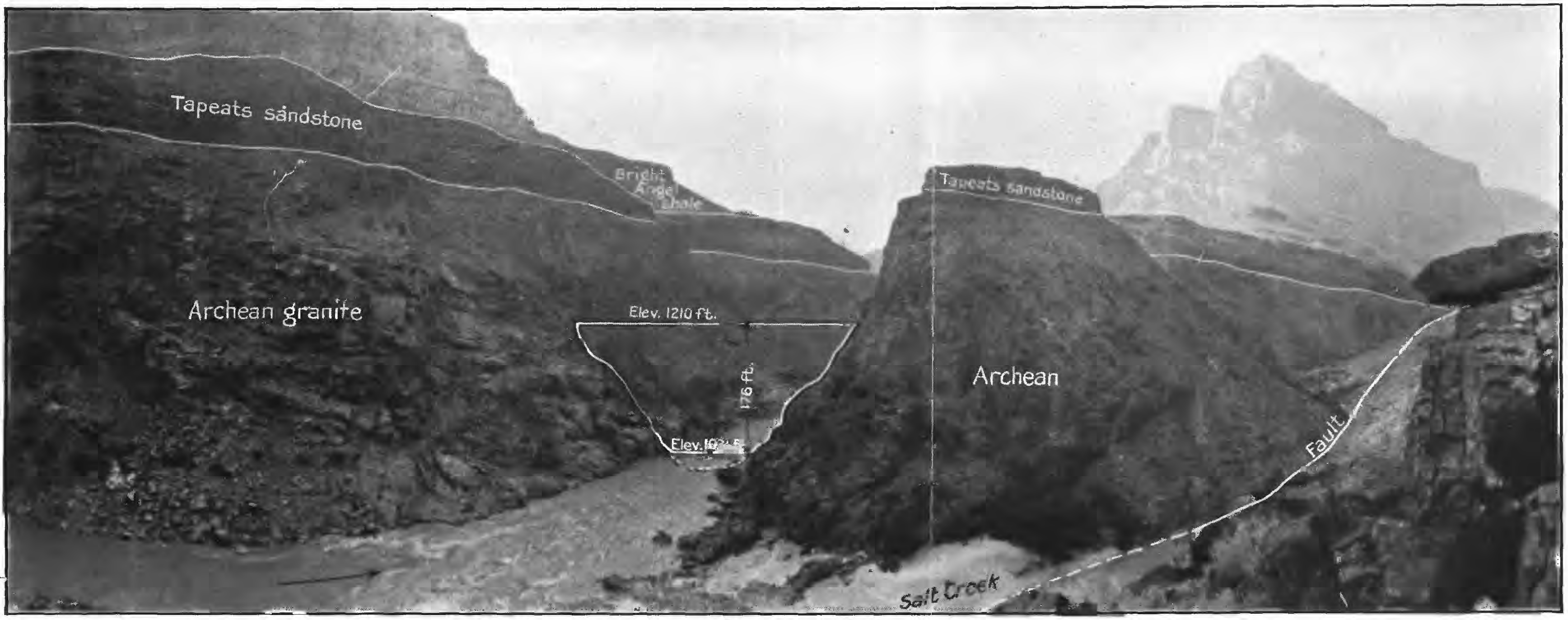
CROSS SECTION AT DAM SITE (255.6 M.)

MAP, CROSS SECTION, AND AREA AND CAPACITY CURVES FOR DEVILS SLIDE POWER SITE

ENGRAVED AND PRINTED BY THE U.S. GEOLOGICAL SURVEY



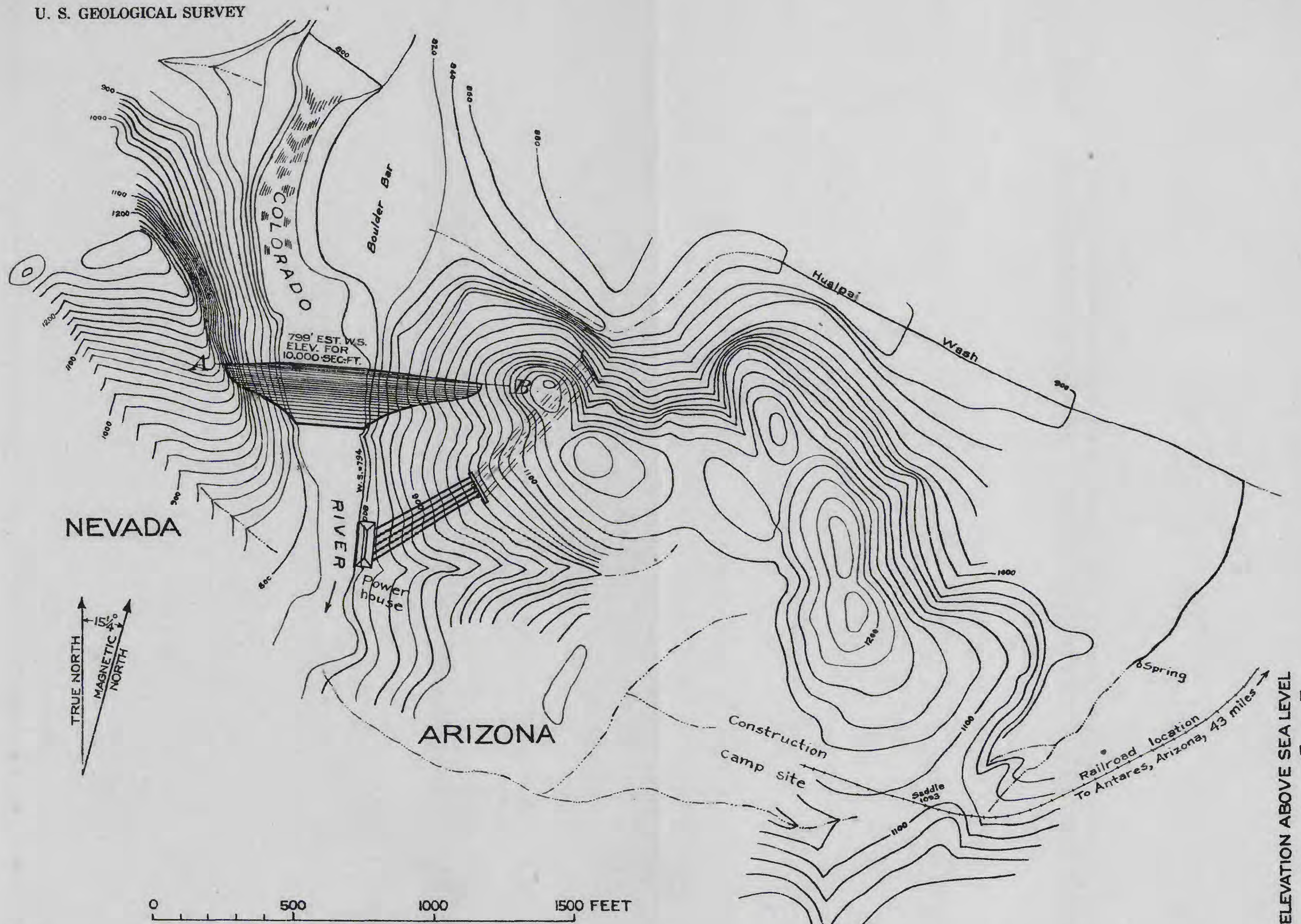
[illegible] CROSS SECTION, AND AREA-CAPACITY CURVES FOR [illegible] SITE

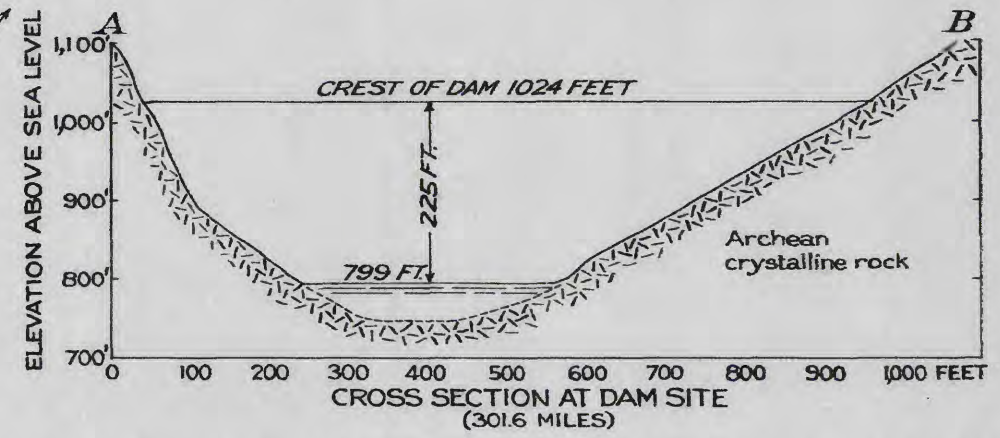


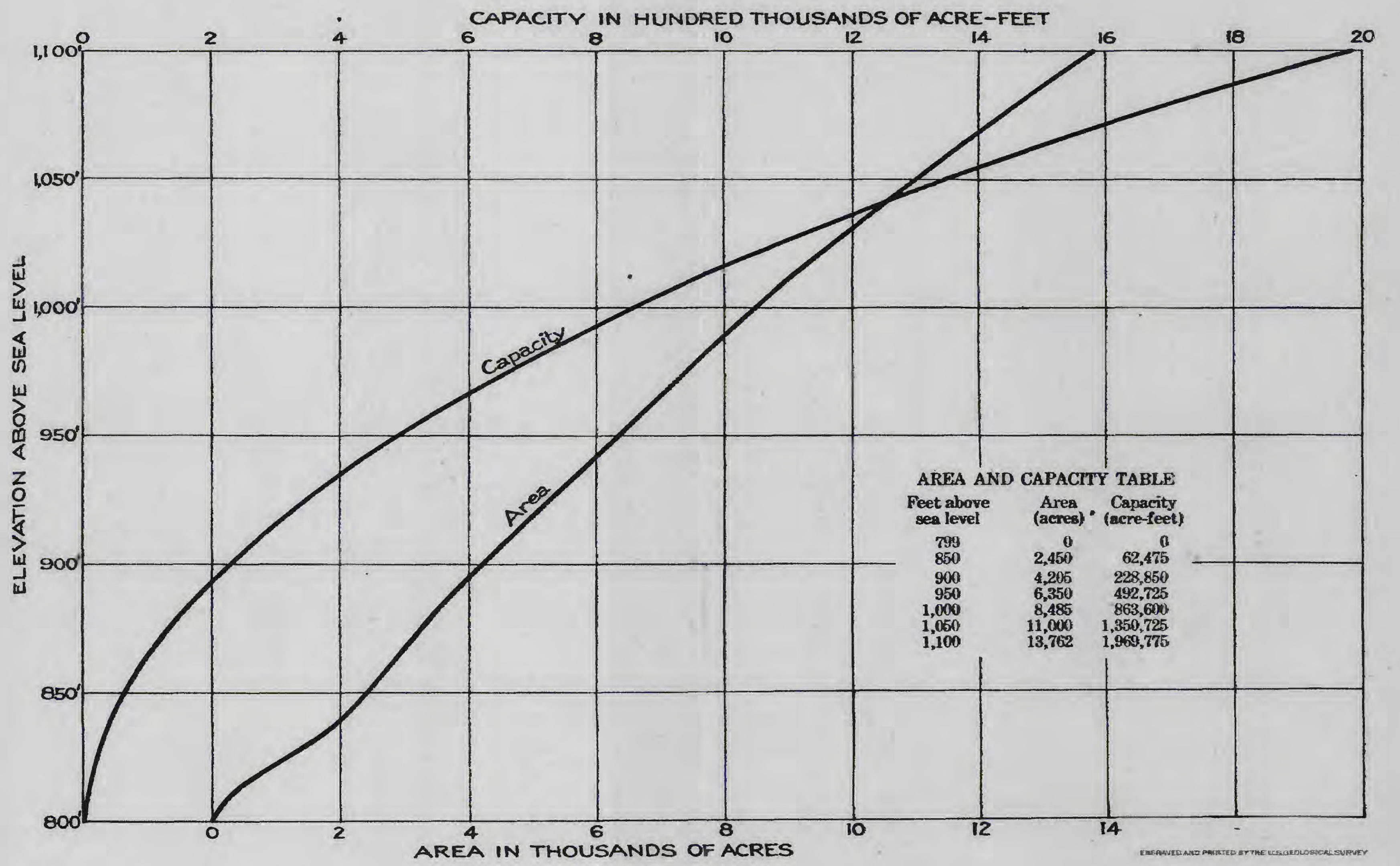
A. DEVILS SLIDE DAM SITE, GRAND CANYON, 30 MILES BELOW THE MOUTH OF DIAMOND CREEK

Geology by R. C. Moore

B. LOWER GRANITE GORGE, GRAND CANYON, 5 MILES ABOVE DEVILS SLIDE DAM SITE





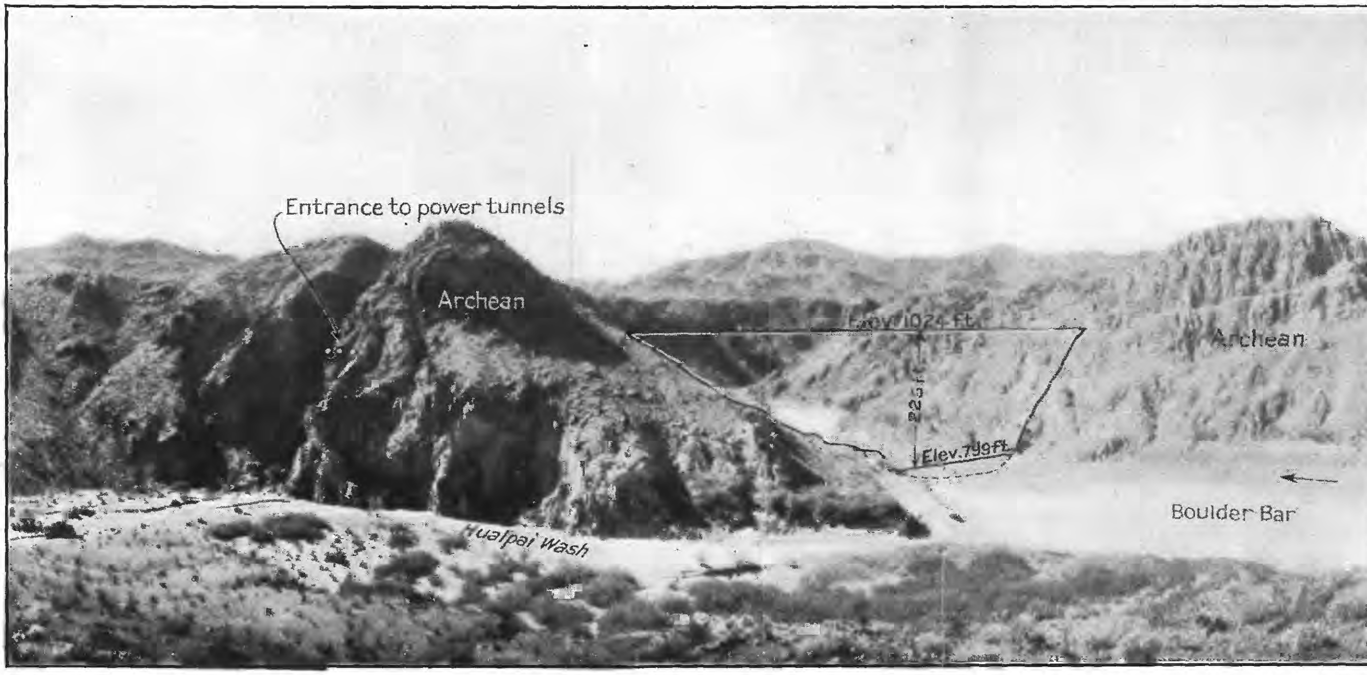


AREA AND CAPACITY TABLE

Feet above sea level	Area (acres)	Capacity (acre-feet)
799	0	0
850	2,450	62,475
900	4,205	228,850
950	6,350	492,725
1,000	8,485	863,600
1,050	11,000	1,350,725
1,100	13,762	1,969,775

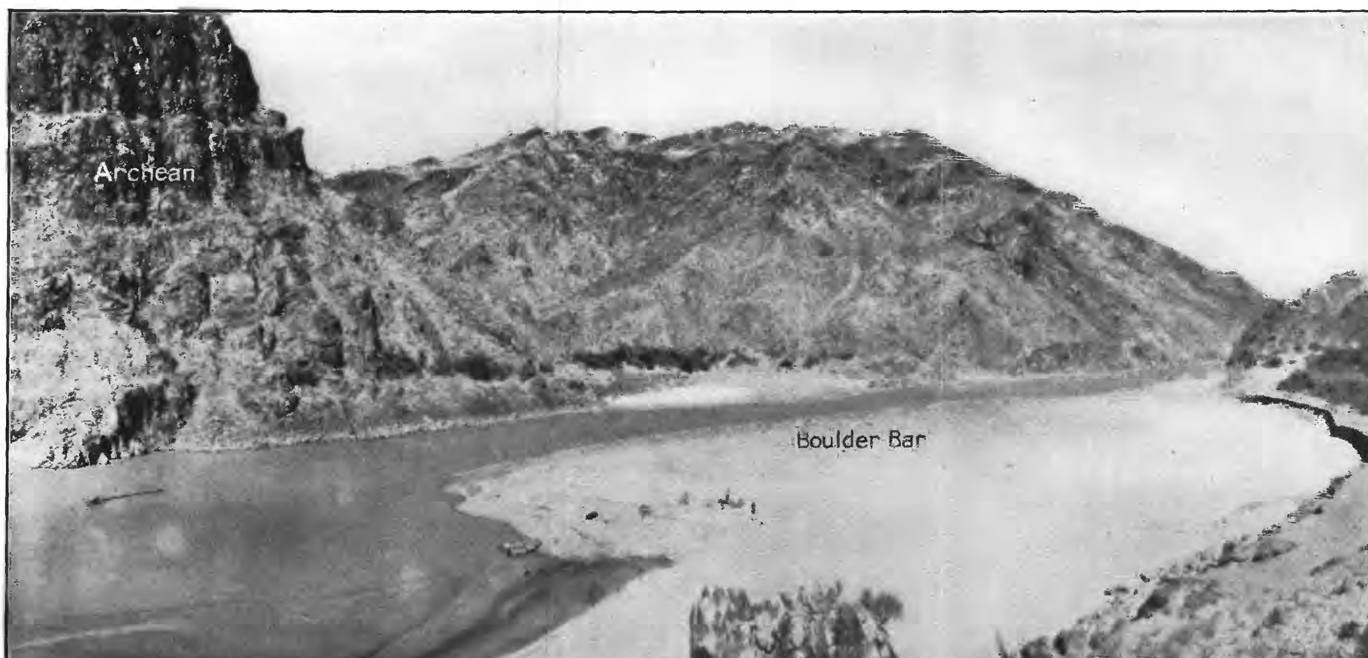
ENGRAVED AND PRINTED BY THE U.S. GEOLOGICAL SURVEY

MAP, CROSS SECTION, AND AREA AND CAPACITY CURVES FOR HUALPAI RAPIDS POWER SITE



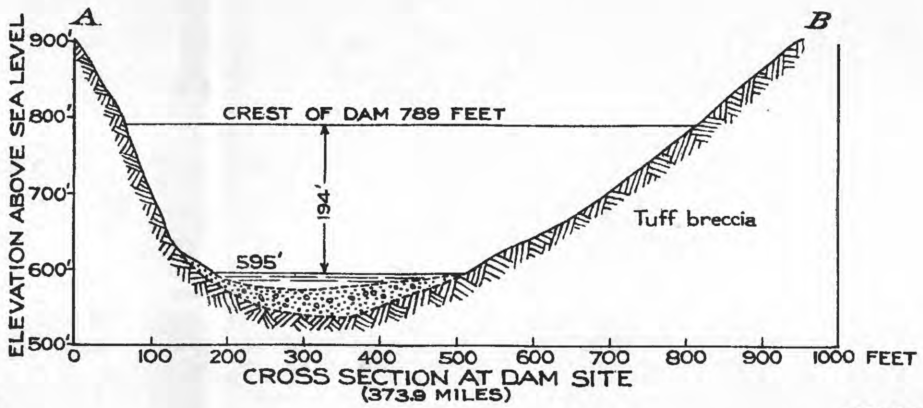
A. HUALPAI RAPIDS DAM SITE, 3 MILES BELOW GREGGS FERRY

Geology by E. C. La Rue

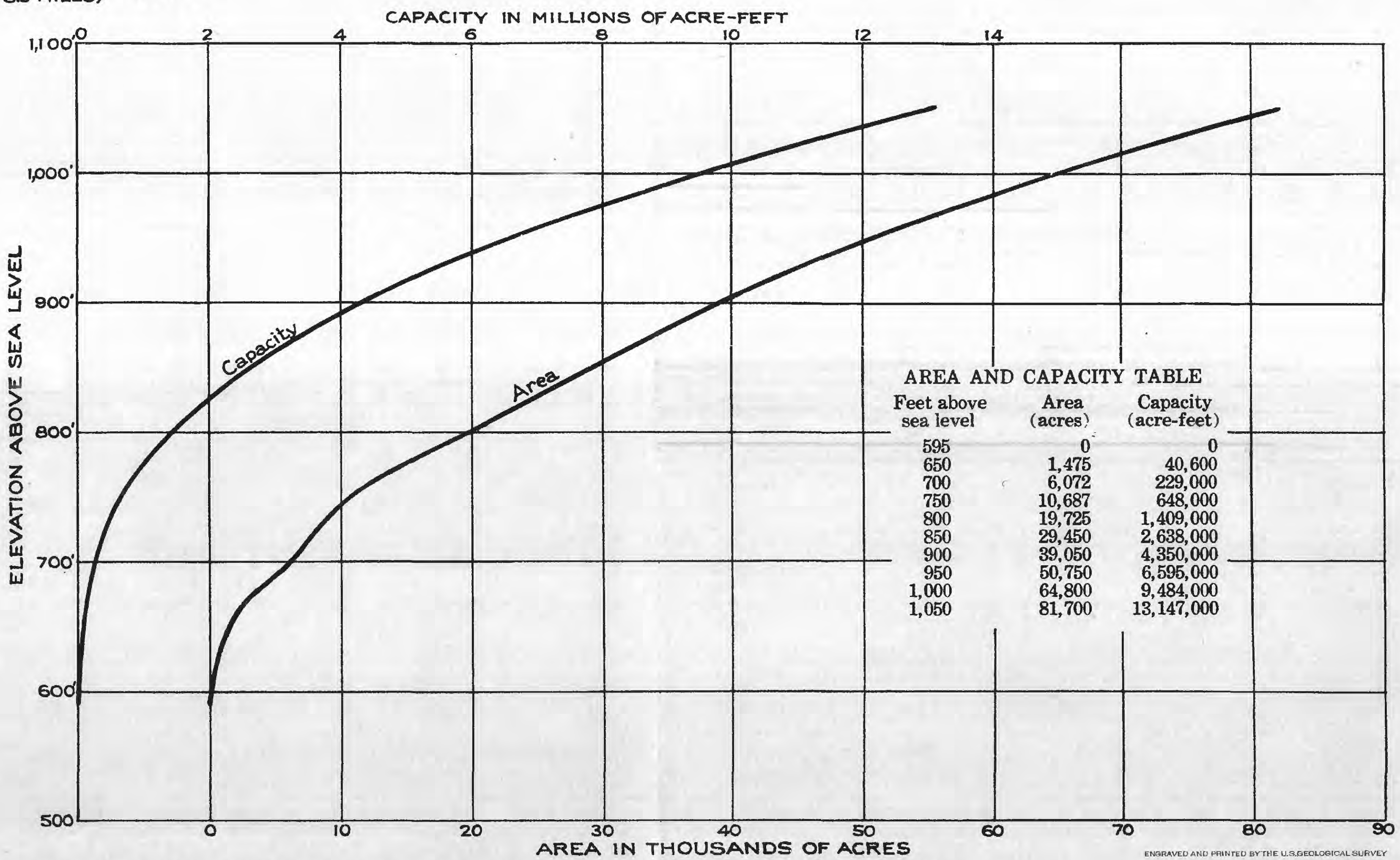


B. BOULDER BAR IMMEDIATELY ABOVE HUALPAI RAPIDS DAM SITE

Geology by E. C. La Rue



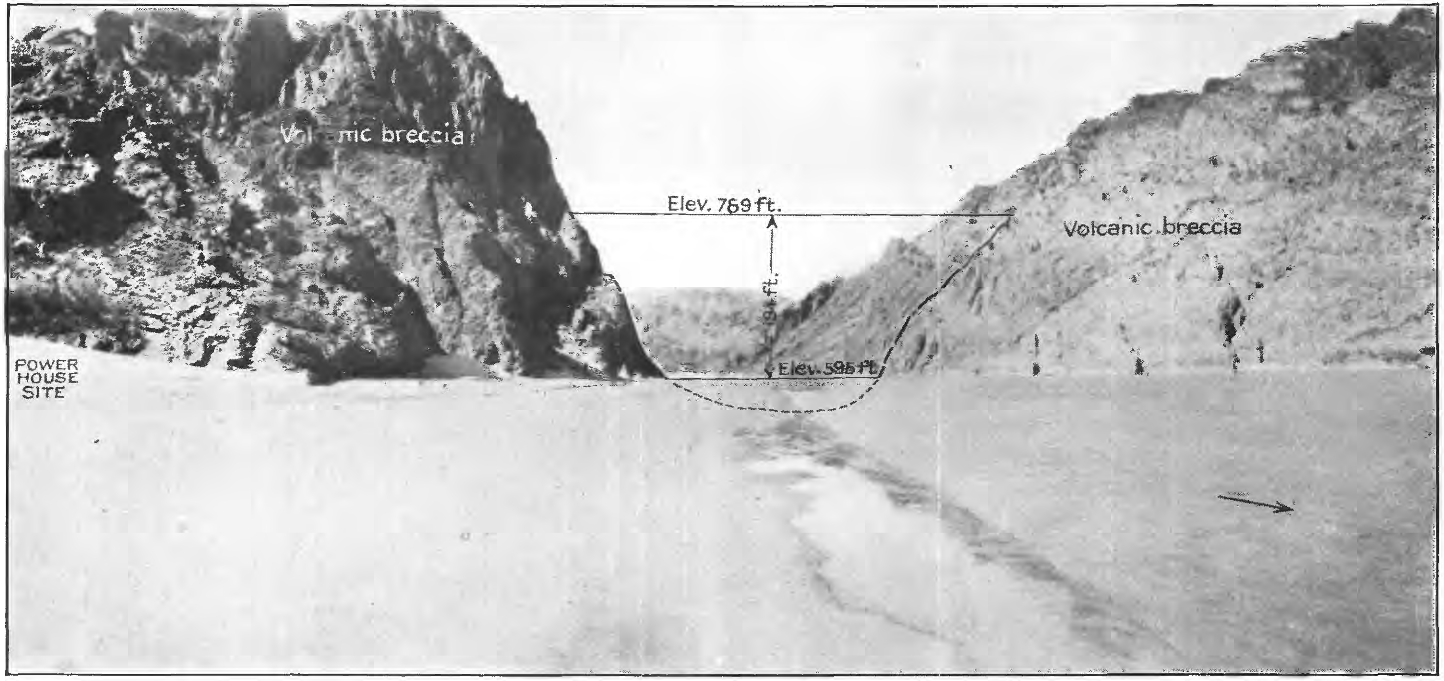
Contour interval 20 feet
Surveyed October 2-3, 1924
Water surface elevations probably correct within 3 feet



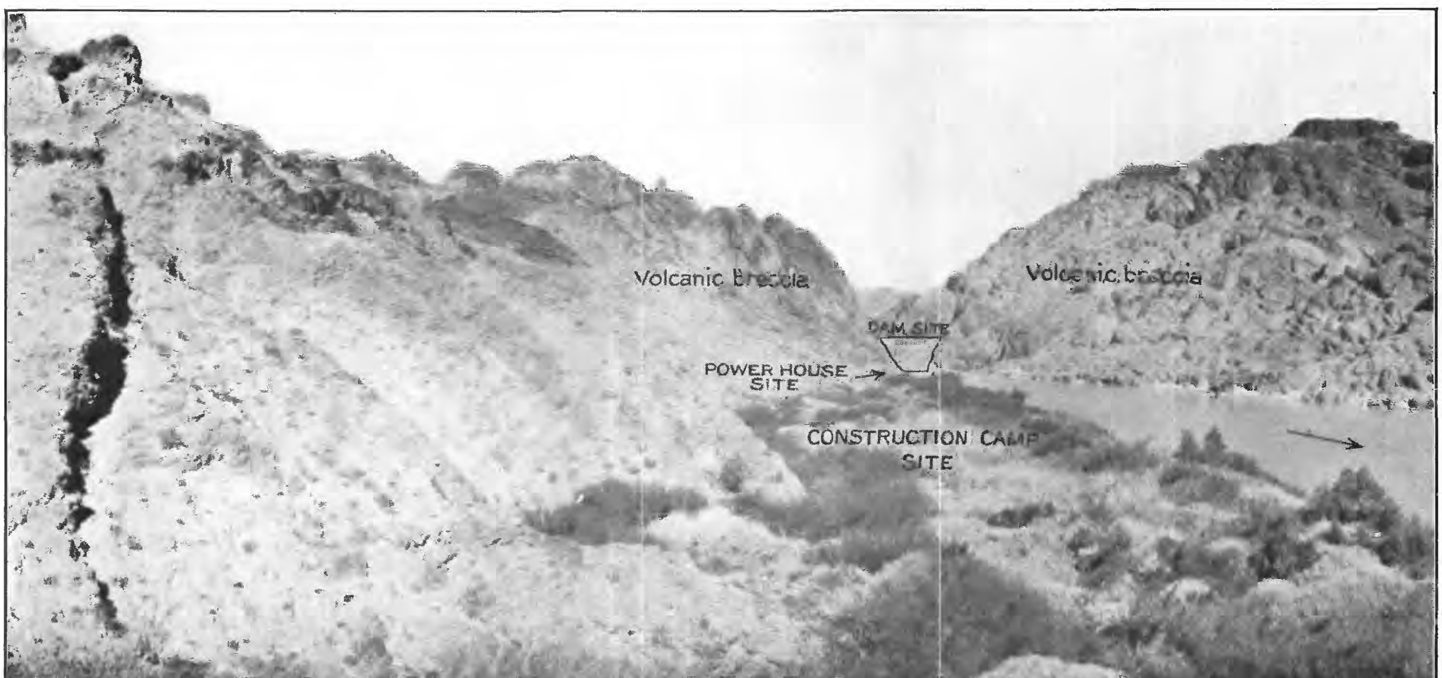
AREA AND CAPACITY TABLE

Feet above sea level	Area (acres)	Capacity (acre-feet)
595	0	0
650	1,475	40,600
700	6,072	229,000
750	10,687	648,000
800	19,725	1,409,000
850	29,450	2,638,000
900	39,050	4,350,000
950	50,750	6,595,000
1,000	64,800	9,484,000
1,050	81,700	13,147,000

MAP, CROSS SECTION, AND AREA AND CAPACITY CURVES FOR LOWER BLACK CANYON POWER SITE



A. GENERAL VIEW



B. VIEW SHOWING SITES FOR POWER HOUSE AND CONSTRUCTION CAMP

LOWER BLACK CANYON DAM SITE, 6 MILES ABOVE THE MOUTH OF ELDORADO WASH

Geology by E. C. La Rue

	Horsepower
Without storage and with irrigation and power development in upper basin as in 1922:	
Capacity 50 per cent of time	200, 000
Capacity 90 per cent of time	132, 000
With storage in Glen Canyon and with irrigation and power development in upper basin as in 1922:	
Continuous power available	407, 000
With storage and with ultimate irrigation and power development in upper basin:	
Continuous power available	263, 000
Installed capacity (load factor 60 per cent)	438, 000

Right of way.—If a dam were built at the Hualpai Rapids dam site, a few mining claims and a small ranch at Greggs Ferry would be submerged. The lake above the dam would be 73 miles long and cover an area of 9,700 acres. The flowage damage would be small.

Accessibility.—The Hualpai Rapids dam site is easily accessible from the south. At the present time an automobile may be driven to the site over the Greggs Ferry road. The site may be connected with the main line of the Atchison, Topeka & Santa Fe Railway by constructing a branch road 43 miles long. This branch would start from the main line near Antares, Ariz. The first 30 miles of the railroad in Hualpai Valley could be built at a minimum cost, as very little grading would be necessary. The last 13 miles, which would be in Hualpai Wash, would require somewhat heavier work. Kingman, Ariz., 64 miles from the dam site by automobile road, is the nearest important town.

Adaptability of plan.—The Hualpai Rapids site is one of the best dam sites on the lower river, if the depth to bedrock is not too great. As explained under "Outline of plan," its utilization in connection with sites above and below will permit a maximum development of the water resources of the river. If this site were utilized as suggested here, the net additional loss of water due to evaporation from the lake formed by the dam would be about 55 second-feet.

LOWER BLACK CANYON POWER SITE

Location.—The lower Black Canyon dam site is 19½ miles below the upper Black Canyon site, suggested by the Bureau of Reclamation (p. 29), 6 miles above the mouth of Eldorado Wash, and 24 miles northeast of Searchlight, Nev. (See Pl. II, in pocket.)

Physical characteristics.—For several miles above and below the dam site the river has carved its channel in a massive formation which has been classified as volcanic tuff-breccia. This formation is hard and resists erosion remarkably well. The character of the rock appears to be satisfactory for the construction of a dam of any height up to 450 feet above the river. A map and cross section of the dam site and the area and capacity curves for the reservoir are given in Plate LV.

The width between the canyon walls at the water surface is 325 feet, and a dam to raise the water 194 feet would have a length on top of 750 feet. A view of the dam site is presented in Plate LVI, *A*. The depth to bedrock in the river channel is unknown but may be as great as 100 feet.

As there is a deposit of fine silt in the river channel, the diversion of the water during the construction period would be more difficult than at the Hualpai Rapids site. A 10-acre flat on the right bank immediately below the dam site and a 40-acre flat about half a mile farther downstream afford excellent locations for a railroad terminal and the construction camp.

The volcanic breccia when crushed would be satisfactory for the coarser concrete aggregate. Sand and gravel of suitable quality may be found in the wash on the Nevada side about 2 miles south of the dam site. There is an excellent location for a power house on the right bank at the upper end of the 10-acre flat. (See Pl. LVI, *B*.)

Plan of development.—As there is no natural site for a spillway at the lower Black Canyon dam site, the overflow type of dam is suggested. The power house may be placed on the right bank 600 feet below the dam, as shown in Plate LV. The dam would raise the water 194 feet, or to an elevation of 789 feet above sea level; this height would not prevent the utilization of the Hualpai Rapids power site, where the water surface is 799 feet above sea level.

Water supply.—With the use of water in the upper basin of Colorado River as in 1922 and without storage, the water supply available at the lower Black Canyon dam site would be 7,330 second-feet 90 per cent of the time, or 11,100 second-feet 50 per cent of the time. Under the same conditions of development but with storage in Glen Canyon, the available water supply would be 22,600 second-feet. With ultimate development in the upper basin and with the canyon section of the river developed as outlined in this report, the water supply will be reduced to 14,480 second-feet.

Power capacity.—The static head at the lower Black Canyon site would be 194 feet. The power capacity with this head and the water supply given in the preceding paragraph would be as follows:

	Horsepower
Without storage and with irrigation and power development in upper basin as in 1922:	
Capacity 50 per cent of time	172, 000
Capacity 90 per cent of time	114, 000
With storage in Glen Canyon and with irrigation and power development in upper basin as in 1922:	
Continuous power available	351, 000
With storage and with ultimate irrigation and power development in upper basin:	
Continuous power available	225,000
Installed capacity (load factor 60 per cent)	375, 000

Right of way.—If a dam were built at the lower Black Canyon site to raise the water to an elevation of 789 feet above sea level, the surface area of the reservoir would be 17,500 acres. A narrow strip of land on each side of the river between the dam site and Virgin Canyon would be submerged. The backwater would extend up the channel of Virgin River to a point 3 miles above its mouth. Some placer claims near the river would be affected. However, the flowage damage would be relatively small, for there are no towns, railroads, improved farm lands, or mining properties that are being operated within the flowage line of the proposed reservoir. This plan may be compared with the one that calls for the construction of a dam near the head of Black Canyon to raise the water 605 feet, or to an elevation of 1,252 feet above sea level. (See p. 29.) If such a dam were built 160,000 acres of land would be submerged, including, in addition to mining properties, the towns of St. Thomas and Overton, Nev., improved farm lands, and about 8 miles of railroad.

Accessibility.—The conditions at the lower Black Canyon dam site are favorable for carrying on construction work. The dam site proper is easily accessible, as immediately below the site the canyon widens out, so that it would be possible to locate the railroad terminal, shops, storage rooms, and other buildings close to the dam site.

The dam site is also favorably located with respect to a connection with a main-line railroad. A railroad from either Las Vegas or Searchlight, Nev., could be built to the site at a reasonable cost. A railroad from Searchlight, which was the terminus of a former branch of the Atchison, Topeka & Santa Fe Railway, could be built to the dam site without the necessity of any heavy construction work except on the last 8 or 9 miles. Such a railroad would be about 39 miles long. Although the rails on the branch to Searchlight have been taken up, they could be relaid at small expense.

Adaptability of plan.—As this site is near the lower end of Black Canyon, it is possible to develop a head for power with a minimum loss of water (90 second-feet) due to evaporation from the water surface of the reservoir. The flowage damage would also be reduced to a minimum, as the area of land that would be submerged is relatively small.

The dam site is well located with respect to the Mohave Canyon storage site, as it would permit the development of 10,200,000 acre-feet of available storage capacity at the Mohave Canyon site.

With upstream storage and with a 60 per cent load factor, an installed capacity of nearly 600,000 horsepower at the lower Black Canyon site would be justified. It is thus seen that power may be developed in sufficient quantity to permit its being transmitted economically over distances of 300 miles or more.

As shown in the discussion of the comprehensive plan on pages 68–73, development of the lower Black Canyon site, in connection with a diversion dam at Parker, a storage dam at Mohave Canyon, and power dams at Hualpai Rapids, Devils Slide, and Bridge Canyon, will permit a maximum use of the water for irrigation and a maximum development of power and provide adequate flood control and irrigation storage.

MOHAVE CANYON DAM SITE

Two miles below the lower Black Canyon dam site the river passes into Cottonwood Valley, through which it flows for 43 miles. Below Cottonwood Valley the river passes through a short stretch of canyon and then follows a circuitous course 50 miles long through the great Mohave Valley. The river has its outlet from this valley through Mohave Canyon. A dam built in this canyon would submerge the valleys just mentioned and form a reservoir with far greater storage capacity for a given height of dam than any other known site in the Colorado River basin. Owing to its position on the river and its great storage capacity the Mohave Canyon site has been selected by the writer as chiefly valuable for flood control. A detailed description of the site is given in the discussion of the flood-control problem (pp. 30–34).

PARKER DIVERSION DAM SITE

After the water of Colorado River has been used to develop more than 4,000,000 horsepower it may be diverted at Parker to reclaim by irrigation approximately 1,000,000 acres of land in Arizona and California. With this project developed, and with the extension of the irrigation system at Yuma and Imperial Valley, the entire flow of Colorado River may ultimately be used for the irrigation of lands in the United States. Under this plan the return flow reaching Colorado River below the Laguna dam would be sufficient to irrigate about 200,000 acres in Mexico, which is about the amount of land irrigated in that country from Colorado River in 1924. The plan of development is shown on the map (Pl. II, in pocket). The amount of water that may ultimately pass into Mexico may be amicably determined by negotiation between the two Governments.

Location.—The Parker dam site is 5 miles northeast of Parker, Ariz., and three-quarters of a mile above the east boundary of the Colorado River Indian Reservation. (See Pl. II.)

Physical characteristics.—At the Parker dam site the low hills close in, confining the river to a relatively narrow section. A dam to raise the water 99 feet, or to an elevation of 457 feet above sea level, would have a bottom length of about 600 feet and a crest length of 1,200 feet. On the California side about 1,000 feet from the west end of the proposed dam there is a low saddle which may be used as a spillway site. A view of the Parker dam site, looking upstream, is presented in Plate LVII, *A*.

Plan of development.—The Parker dam site has been investigated by the Beckman & Linden Engineering Corporation, of San Francisco, Calif. This firm has suggested the rock-fill type of dam as being best adapted to fit the conditions at the dam site. The design calls for the construction of a reinforced-concrete core wall resting on a pile foundation, and a double row of steel sheet piling, to prevent the flow of water under the core wall. The back fill on the upstream side of the core wall is to be composed of a clayish material, and on the downstream side a loose rock fill is to be used. A spillway capacity of 200,000 second-feet is to be provided by building a concrete structure in a low saddle on the California side 1,000 feet from the west end of the proposed dam. The spillway crest of 1,000 feet is to be provided with gates, so that the water level in the reservoir can be regulated through a range of 15 feet. This plan calls for a power house to be built on the Arizona side near the east end of the proposed dam.

At some future time a dam at the Parker site may be used as the point of diversion for the irrigation of an aggregate area of about 1,000,000 acres of land in Arizona and California. The water that must be diverted for the irrigation of lands under the Yuma project and in the Imperial Valley could be used for the development of power. An average head of about 90 feet could be utilized. The amount of water to be diverted at the Parker dam would vary in accordance with the demand for water for irrigation. It is suggested that an installation of 70,000 horsepower would be justified, so that a large part of the flow might be utilized during the months when the demand for water for irrigation is greatest. The plan of development is shown in Plate LVIII.

Adaptability of plan.—The data now available indicate that a diversion dam should be built at the Parker site, for it seems probable that with such a dam in operation, in connection with an adequate irrigation system, the entire flow of Colorado River may ultimately be used for the irrigation of land in the United States.

ALTERNATIVE DAM SITES

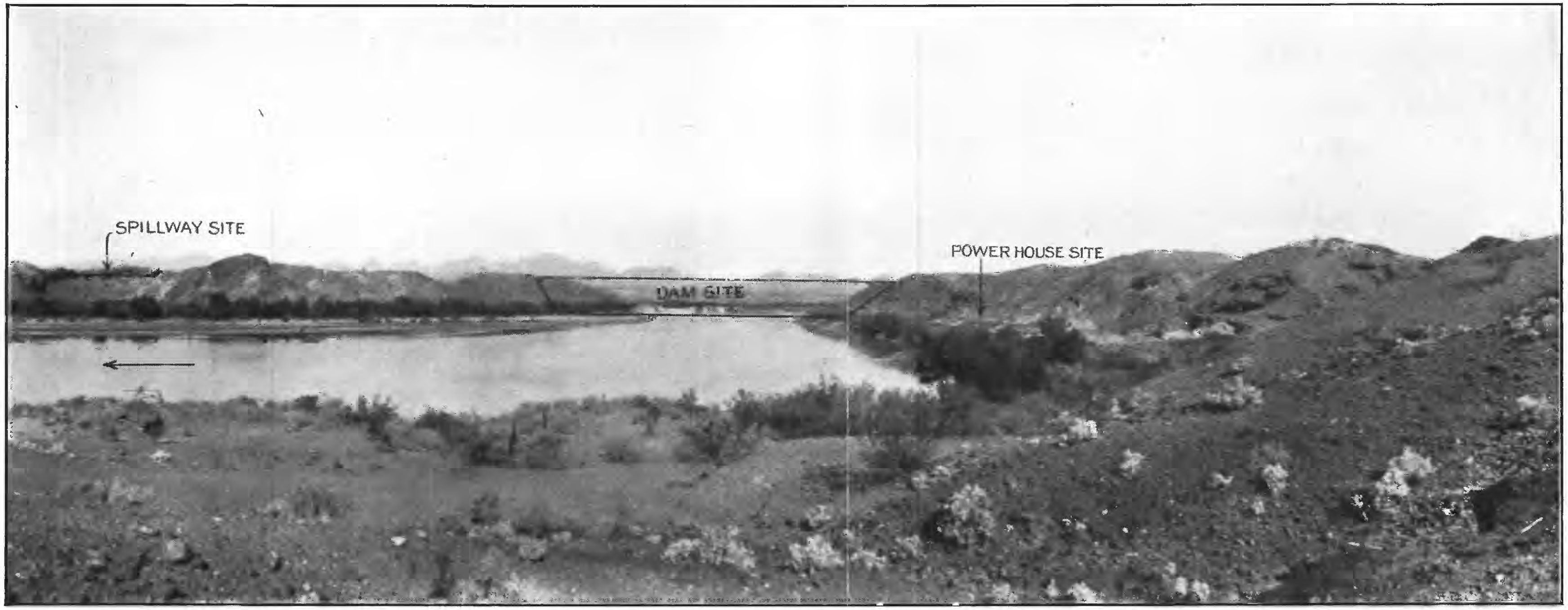
The sites listed here as alternative dam sites are those between the west boundary of the Grand Canyon National Park and Parker not included in the writer's suggested plan of development described above. Although the character of the rock at the six dam sites included in the writer's plan has been determined, these sites have not been drilled to determine the depth to bedrock. If the foundation at some of these sites should be found unfavorable, it would be necessary to change the plan by substituting sites where the conditions are favorable. The data at hand relative to the physical conditions at the alternative dam sites will be presented, so that anyone who desires to study the problem may have all the facts available before him. The Boulder and upper Black Canyon dam sites are described on pages 28 and 29.

PROSPECT SITE

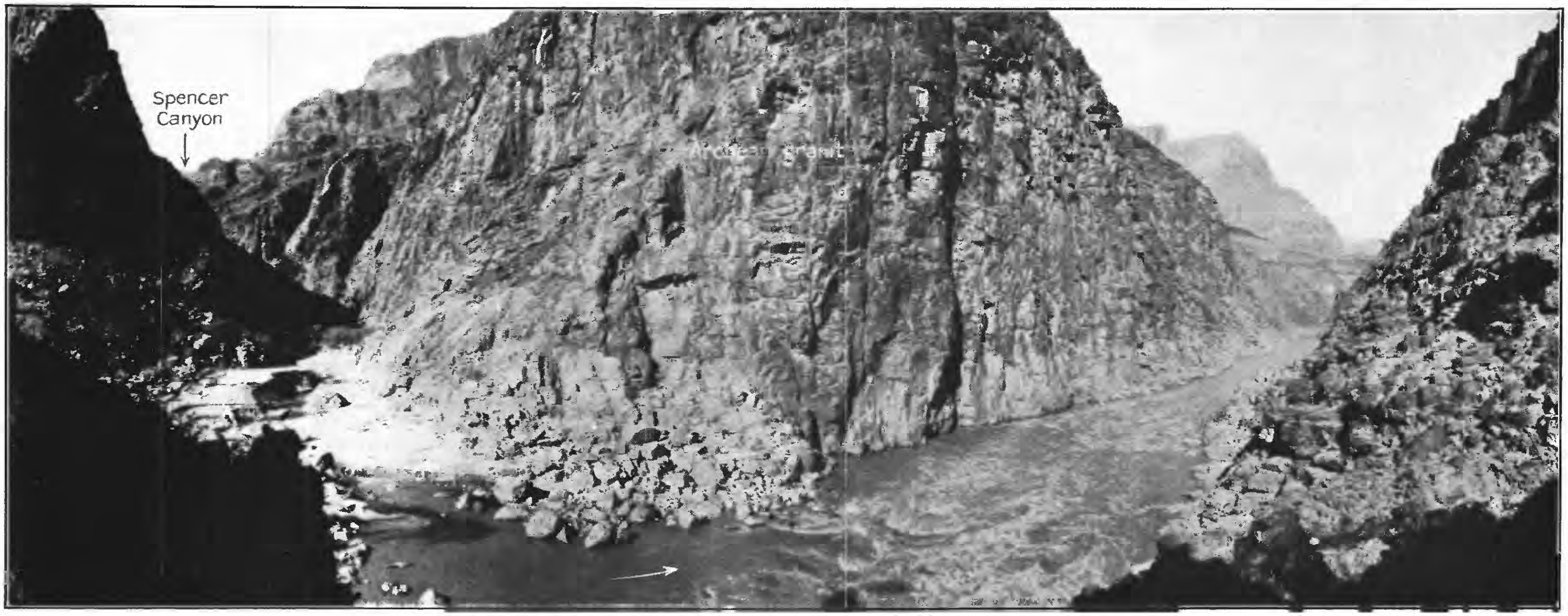
General features.—As a result of the river survey, the water surface at the Havasu dam site (p. 65) was found to be 1,783 feet above sea level. The water surface at the mouth of Diamond Creek was known to be 1,335 feet above sea level. The fall between these points is therefore 448 feet. When the 69 miles of canyon between Havasu and Diamond creeks was being surveyed, the writer made a careful search for a dam site at an elevation of about 1,560 feet above sea level. A dam site midway between Havasu and Diamond creeks is desirable in order to avoid the necessity of constructing a high dam at Diamond Creek to utilize the 448 feet of fall below Havasu Creek.

Immediately below Havasu Creek the Muav limestone begins to rise, and at a point 9 miles below this creek the Bright Angel shale appears in the river channel. The shale is exposed in the wall and river channel for a distance of 10 miles, and then the top of the Tapeats sandstone appears above the water surface. For the next 14 miles alternating beds of sandstone, limestone, and shale appear in the canyon next to the river.

Owing to the width of the canyon and the character of the rocks, no possible dam sites were found until the Prospect site was reached, 33.5 miles below Havasu Creek. Here the formations have been raised sufficiently by faulting to expose the pre-Cambrian crystalline rocks in the river channel. For a distance of 1 mile the Archean granite appears in the walls, but at no place does it rise more than 80 feet above the river. A dam-site survey was made near the upper end of this granite gorge. Below the gorge the Bright Angel shale reappears in the river channel. At a point 39.5 miles below Havasu Creek a fault crosses the river, and for a short distance the Muav limestone appears next above the water; this is followed by the Bright Angel shale, which gradually rises until the Tapeats sandstone is exposed. Here the inner walls spread apart for a mile or more, forming an open basin to which the name Granite Park was given, granite being exposed in the side canyons on the left bank. Granite Park is 52 miles below Havasu Creek. Below Granite Park the Tapeats sandstone rises gradually until the whole of this formation is exposed above the river 10 miles above Diamond Creek. The crystalline rocks appear above the water surface at this point and remain continuously exposed for a distance of 51 miles. At a

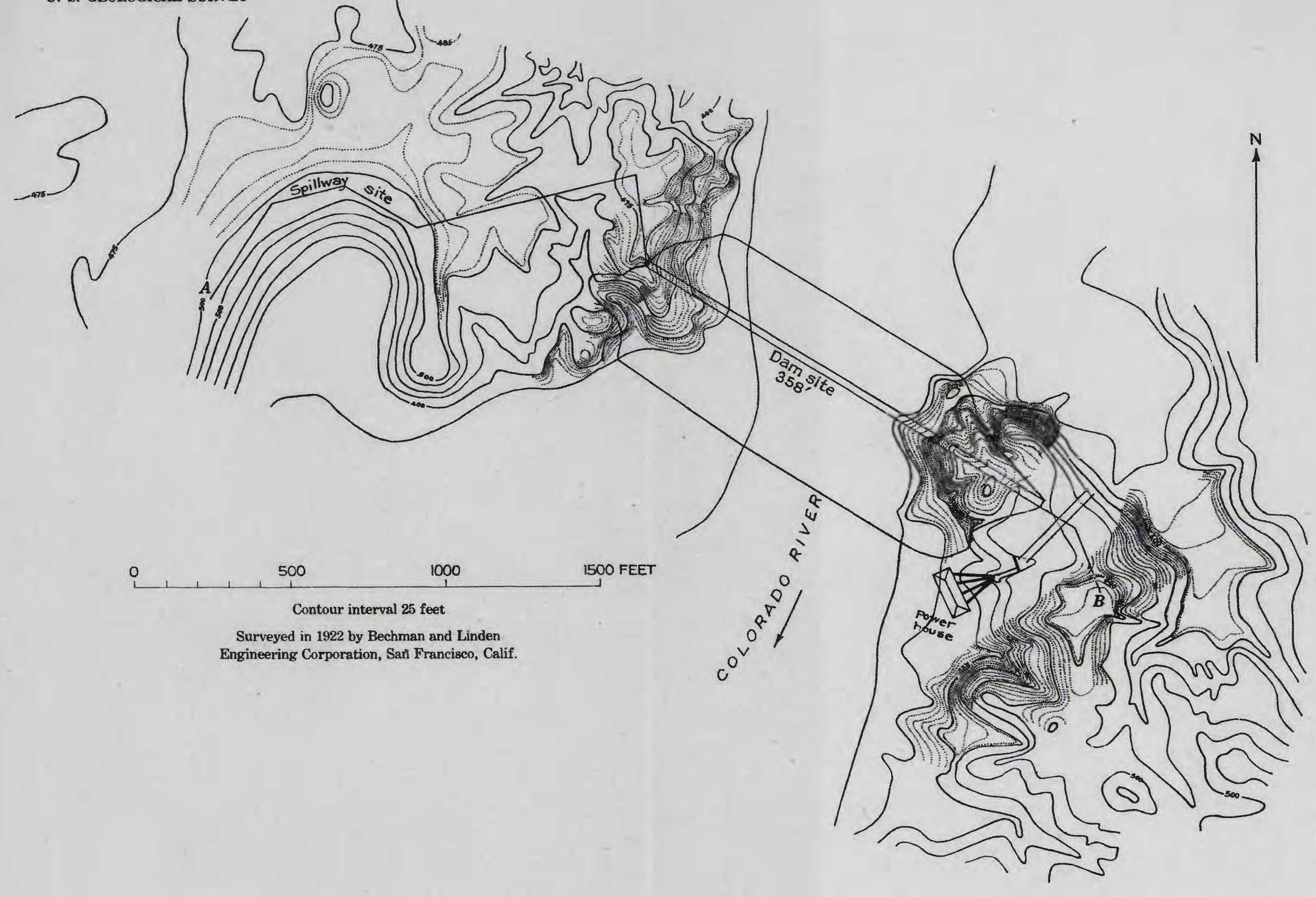


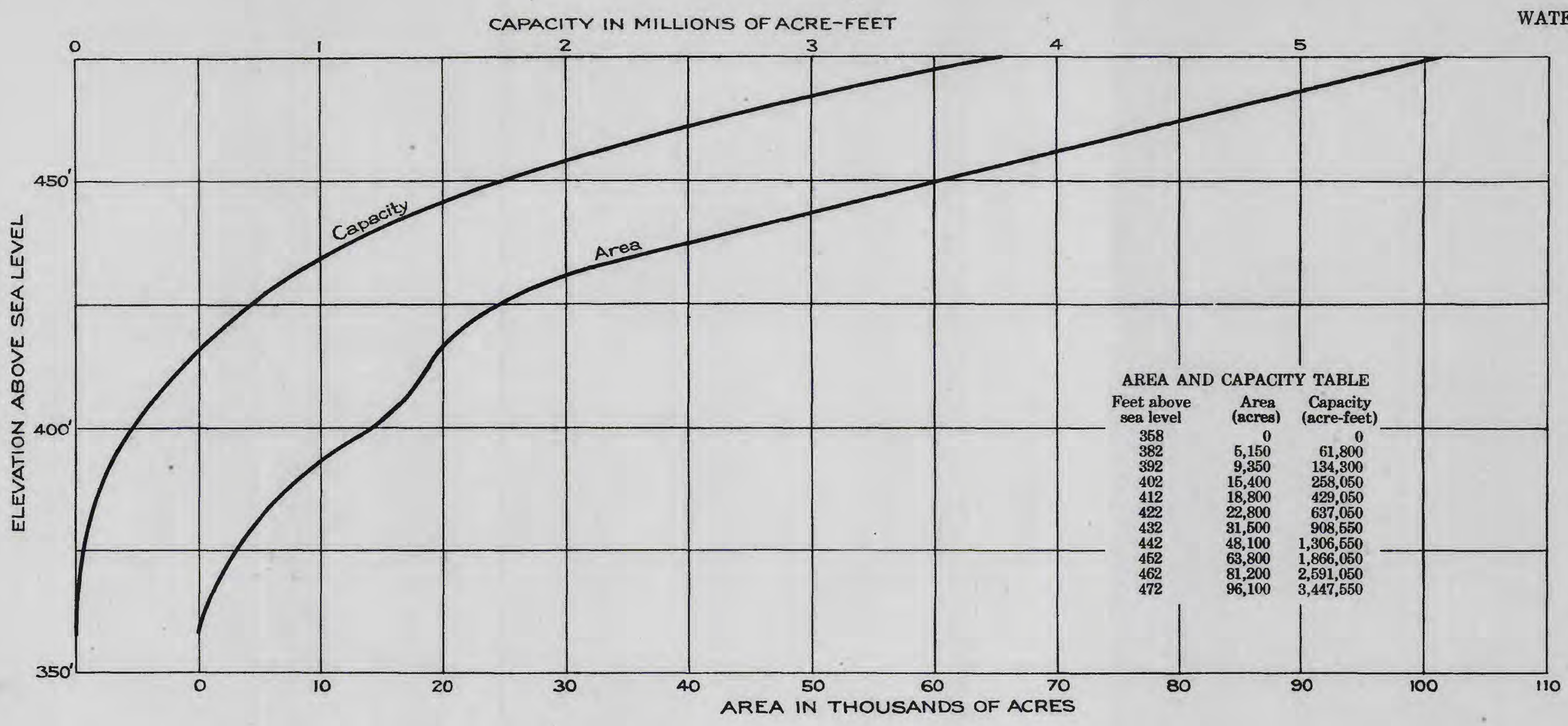
A. PARKER DAM SITE, 5 MILES NORTHEAST OF PARKER



B. SPENCER CANYON DAM SITE, GRAND CANYON, 20 MILES BELOW THE MOUTH OF DIAMOND CREEK

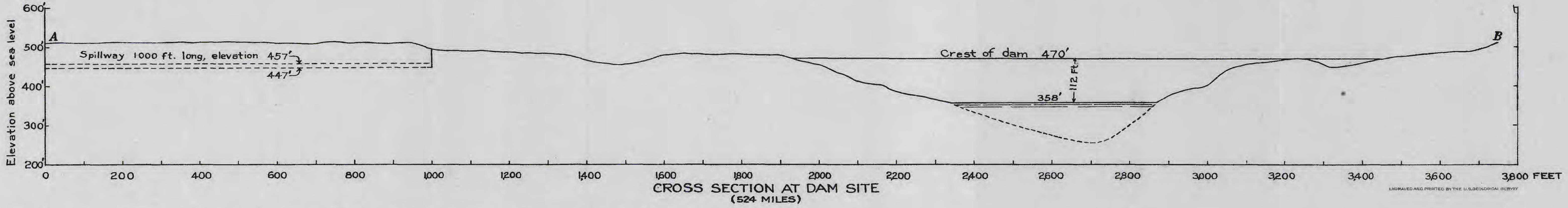
Geology by R. C. Moore



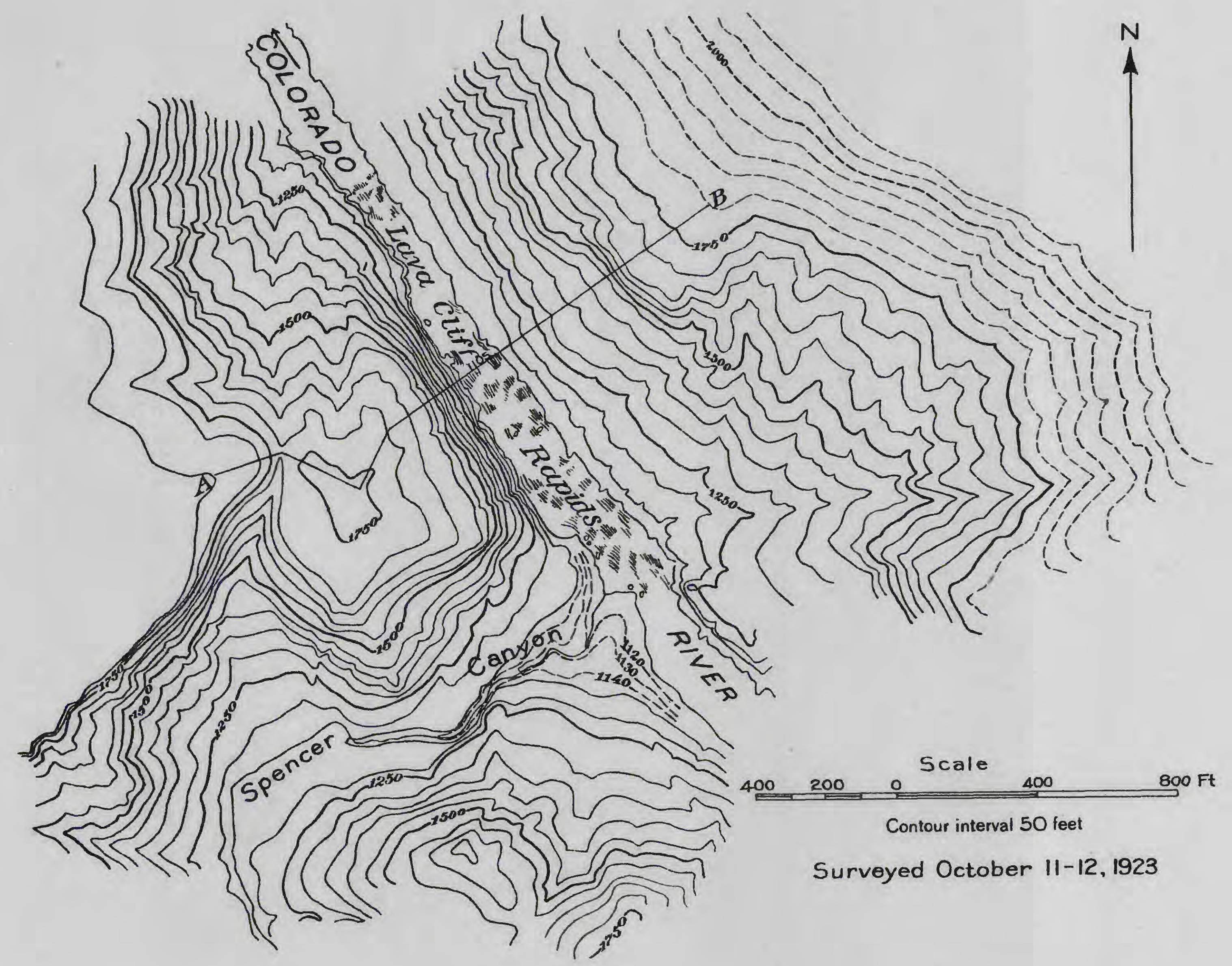


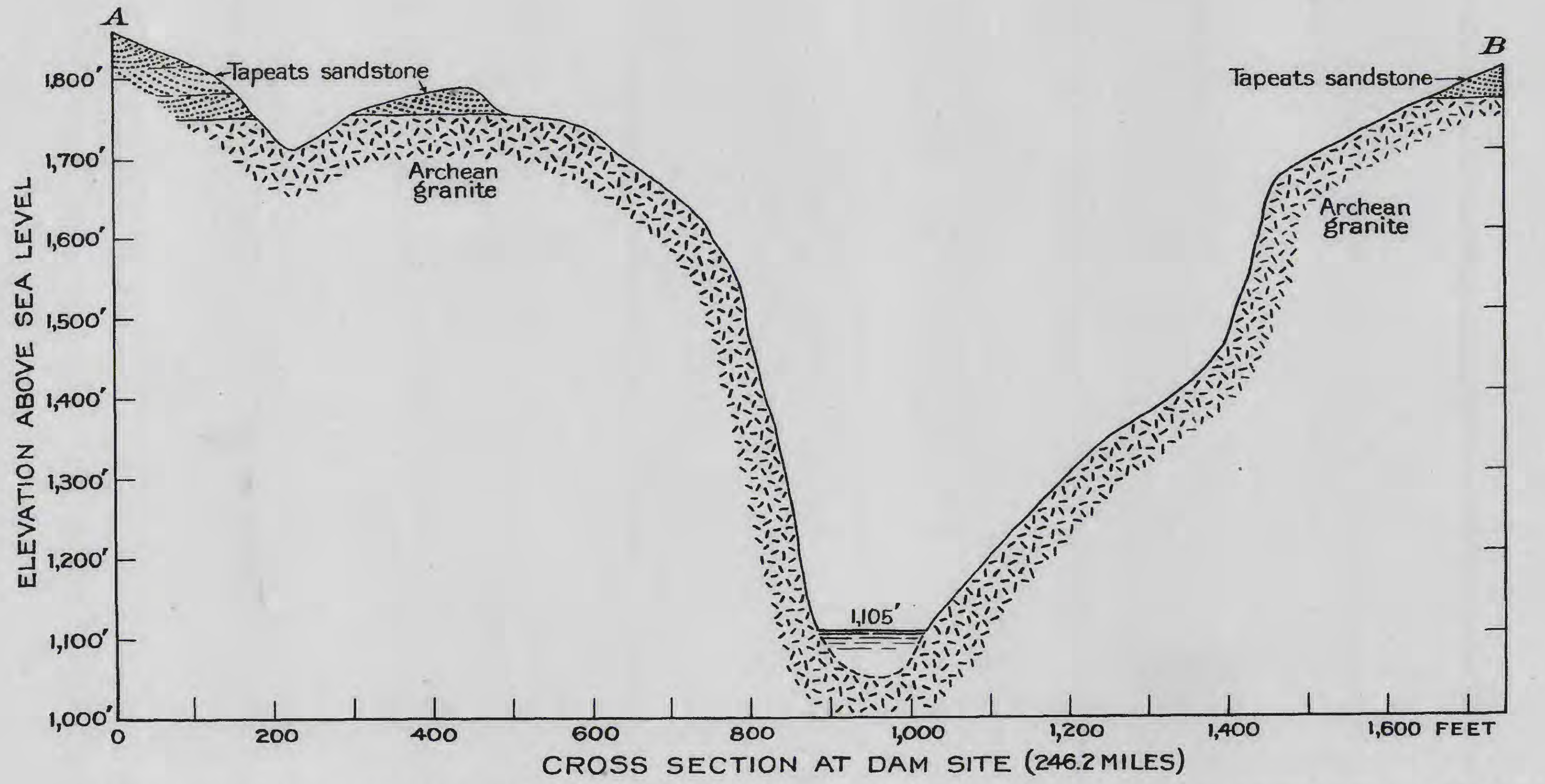
AREA AND CAPACITY TABLE

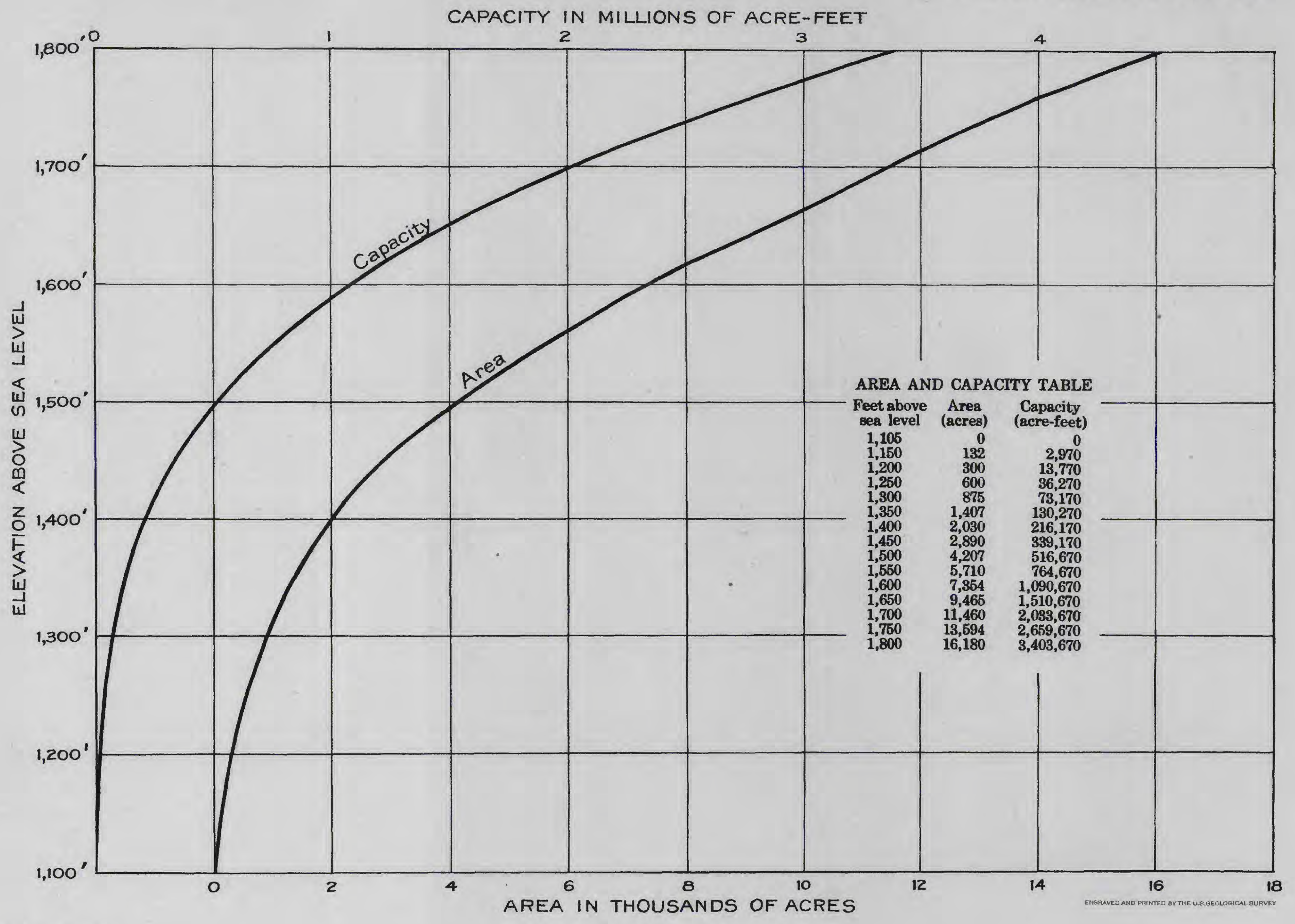
Feet above sea level	Area (acres)	Capacity (acre-feet)
358	0	0
382	5,150	61,800
392	9,350	134,300
402	15,400	258,050
412	18,800	429,050
422	22,800	637,050
432	31,500	908,550
442	48,100	1,306,550
452	63,800	1,866,050
462	81,200	2,591,050
472	96,100	3,447,550



MAP, CROSS SECTION, AND AREA AND CAPACITY CURVES FOR PARKER DIVERSION DAM SITE







AREA AND CAPACITY TABLE

Feet above sea level	Area (acres)	Capacity (acre-feet)
1,105	0	0
1,150	132	2,970
1,200	300	13,770
1,250	600	36,270
1,300	875	73,170
1,350	1,407	130,270
1,400	2,030	216,170
1,450	2,890	339,170
1,500	4,207	516,670
1,550	5,710	764,670
1,600	7,354	1,090,670
1,650	9,465	1,510,670
1,700	11,460	2,033,670
1,750	13,594	2,659,670
1,800	16,180	3,403,670

MAP, CROSS SECTION, AND AREA AND CAPACITY CURVES FOR SPENCER CANYON POWER SITE point 4 miles below Diamond Creek the granite and associated crystalline rocks rise in the canyon wall to a height of 725 feet above the river. More detailed information relative to the rock formations in the canyon between Havasu and Diamond creeks will be found in Appendix B (pp.155–159). The reader is also referred to Plate XV (in pocket).

The preceding data show clearly that the geologic formations are decidedly unfavorable for the location of a dam on Colorado River between Havasu and Diamond creeks except possibly at the Prospect site.

Location.—The Prospect site is in a short granite gorge 33 miles below Havasu Creek and 36 miles above Diamond Creek. (See Pl. II, in pocket.)

Physical characteristics.—In the 1-mile gorge that contains the Prospect dam site, the Archean granite gneiss is exposed in the left wall to a height of 65 feet above the river and in the right wall to a height of about 80 feet above the river. The granite gneiss, which would form an excellent foundation for a dam, is capped by the Tapeats sandstone. A downstream view of the dam site showing the granite outcrop in the river channel is presented in Plate XLI, *B*. To utilize the fall below the Havasu dam site, it would be necessary to raise the water to an elevation of 1,773 feet above sea level. The top of the granitic rock on the left bank at the dam site is 1,644 feet above sea level. It is thus clear that the Tapeats sandstone, which here shows more than the usual surface jointing, would have to form the abutment wall for the upper 129 feet of the dam. The appearance of the sandstone raises some doubt in the writer's mind as to whether a safe dam can be constructed at this point at a reasonable cost.

More detailed information relative to the rock formations at the site and the materials available for the construction of a dam is given in Appendix B (p. 157).

Plan of development.—If a safe dam can be built at the Prospect site, no doubt a concrete dam of the overflow type would be chosen as the best adapted to fit the existing conditions. The power house may be built on the left bank near the mouth of a side canyon 1,000 feet below the dam.

The water may be raised to an elevation of 1,773 feet above sea level without interfering with the Havasu site above. As the water surface at the Prospect site is 1,579 feet above sea level, it would be possible to utilize a head of 194 feet for the development of power. The plan of development is shown on Plate XLIII.

Water supply.—With development in the upper basin as in 1922, the water supply available at the Prospect dam site would be 7,000 second-feet 90 per cent of the time, or 10,800 second-feet 50 per cent of the time. Under the same conditions but with storage in Glen Canyon, the available water supply would be about 22,000 second-feet continuously. With ultimate development in the upper basin, the available supply would be reduced to 14,200 second-feet.

Power capacity.—The static head at the Prospect site would be 194 feet. The power capacity with this head and the water supply given in the preceding paragraph would be as follows:

	Horsepower
Without storage and with irrigation and power development in upper basin as in 1922:	
Capacity 50 per cent of time	168, 000
Capacity 90 per cent of time	109, 000
With storage in Glen Canyon and with irrigation and power development in upper basin as in 1922:	
Continuous power available	357, 000
With storage and with ultimate irrigation and power development in upper basin:	
Continuous power available	222, 000
Installed capacity (load factor 60 per cent)	370, 000

Right of way.—If a dam should be built at the Prospect site, the flowage damage would be negligible.

Accessibility.—The Prospect site may be more easily accessible from the south rim of the canyon than the dam sites in the canyon above. A wagon road approaches within 4½ miles of the site, and from the end of this road there is a trail leading to a mine 1½ miles from the site. If the construction of a dam at this site should be found feasible, however, the site may prove to be most accessible by means of the backwater from a dam built at or below Diamond Creek.

Adaptability of plan.—As explained above, a head of 194 feet may be utilized at the Prospect site without interfering with the Havasu site. The next site below is at Diamond Creek, where a head of 234 feet may be utilized without interfering with the Prospect site.

The writer believes that the plan of utilizing the Prospect dam site is of doubtful feasibility. Attention is called to the site so that it may be investigated further, if at some future time it should be decided that this site must be utilized in order that the power resources of the river may be fully developed. In the writer's opinion the fall in the river between Havasu and Diamond creeks can best be utilized by building a relatively high dam at Diamond Creek or at Bridge Canyon. (See p. 68.)

UPPER DIAMOND CREEK SITE

More than 10 years ago James B. Girand, of Phoenix, Ariz., filed with the Federal Government an application for a permit to develop power on Colorado River at Diamond Creek. The dam site was surveyed, and the depth to bedrock in the river channel was determined by means of diamond-drill borings. An investigation of the project was made by the firm of Barclay Parsons & Klapp, consulting engineers, of New York City.

Location.—The upper of the two dam sites in this vicinity is just above the mouth of Diamond Creek, 225.6 miles below Paria River and 17 miles north of Peach Springs, Ariz., a station on the main line of the Atchison, Topeka & Santa Fe Railway. (See Pl. II, in pocket.)

Physical characteristics.—For a dam of moderate height, the upper dam site at Diamond Creek has several favorable features. As disclosed by diamond-drill borings, the maximum depth to bedrock is 50 feet below the water surface at low-water stage. The distance between the canyon walls at the water surface is 235 feet, and a dam to raise the water 234 feet would have a crest length of 750 feet.

The granitic rock that would form the foundation and abutment walls is satisfactory for a dam of any reasonable height. Unfortunately, there are two weak zones in the wall on the left bank, due to faulting. (See Pl. XLIV.) In constructing the spillway or pressure tunnels, these fault zones should be avoided. A detailed description of the rocks and information regarding building materials will be found in Appendix B (p. 159).

Plan of development.—The water surface may be raised to an elevation of 1,773 feet above sea level without interfering with the development of the Havasu power site, which is at the west boundary of the Grand Canyon National Park. A dam to raise the water that much would be 488 feet in height above its foundation. The dam site is not well adapted to the building of a dam of this height, as the wall on the left bank is not high enough. Unless a new site were selected farther upstream, it would be necessary to construct the upper part of the dam on a narrow ridge crossing over the two faults which have been referred to. The position of the faults, shown on the map in Plate XLIV, indicates that it would not be desirable to select a dam site 400 to 600 feet farther upstream. It is not probable, therefore, that the site immediately above Diamond Creek will be selected for a dam that would raise the water to an elevation of 1,773 feet above sea level.

Attention is called above to a possible dam site at 1,579 feet above sea level. (See Prospect dam site, p. 86.) Utilization of this site would limit any development at Diamond Creek to an elevation of 1,569 feet. It would not only be feasible to build a dam at the upper site at Diamond Creek to raise the water 234 feet, or to an elevation of 1,569 feet above sea level, but the project would have several attractive features. The favorable section and satisfactory rock walls have been referred to. In building a dam no higher than

234 feet the fault zone could be avoided, and the tunnels leading to a power house on the flat at the mouth of Diamond Creek need not enter the fault zone. The suggested plan of development is shown in Plate XLIV. A view of the upper dam site at Diamond Creek is presented in Plate XLV, *A*.

Water supply.—With the water in the upper basin used as in 1922, and with storage in Glen Canyon, it would be possible to maintain at Diamond Creek a flow of 22,300 second-feet. Under the same conditions, but without storage, the flow of Colorado River at Diamond Creek would be about 10,900 second-feet 50 per cent of the time, or 7,180 second-feet 90 per cent of the time. With full development in the upper basin, the uniform flow at the Diamond Creek power site may be about 14,400 second-feet. (See Appendix A, p. 113.)

Power capacity.—The static head at the upper Diamond Creek site would be 234 feet. The power capacity with this head and the water supply given in the preceding paragraph would be as follows:

	Horsepower
Without storage and with irrigation and power development in upper basin as in 1922:	
Capacity 50 per cent of time	204, 000
Capacity 90 per cent of time	134, 000
With storage in Glen Canyon and with irrigation and power development in upper basin as in 1922:	
Continuous power available	418, 000
With storage and with ultimate irrigation and power development in upper basin:	
Continuous power available	270, 000
Installed capacity (load factor 60 per cent)	450, 000

Right of way.—The building of a dam at Diamond Creek to raise the water 234 feet would form a lake about 28 miles long, the surface area of which would be 3,700 acres. There are no improvements on the land that would be submerged. The flowage damage would therefore be negligible.

Accessibility.—In contrast with the power sites in the Grand Canyon above Diamond Creek, this site is fairly accessible. A branch from the main line of the Atchison, Topeka & Santa Fe Railway at Peach Springs, Ariz., to the construction-camp site at the mouth of Diamond Creek could be built at a reasonable cost. The length of such a railroad would be about 37 miles, and the last 10 miles would involve heavy construction work. The upper Diamond Creek site is accessible by automobile at the present time (1925), the distance from the highway at Peach Springs being about 22 miles.

Adaptability of plan.—If the upper dam site at Diamond Creek were utilized as suggested above, it would be necessary to develop the Prospect dam site also in order to utilize all of the fall in the river between the west boundary of the Grand Canyon National Park and Diamond Creek. The development of the upper site at Diamond Creek in the manner described in the preceding pages would fit in well with a development at the Prospect site. However, the feasibility of developing the Prospect site is doubtful. It therefore seems better to select a dam site below Diamond Creek, at some point where a dam can be built of sufficient height to back the water to the west boundary of the Grand Canyon National Park. Such a site is described in the next section.

LOWER DIAMOND CREEK SITE

On the completion of the survey of the canyon between the west boundary of the Grand Canyon National Park and Diamond Creek (October 2, 1923) the writer made a thorough study of the upper Diamond Creek dam site. After deciding that it would not be desirable to build at the upper site a dam of sufficient height to utilize the fall in the river below the park, he recommended that the dam site immediately below the mouth of Diamond Creek should be surveyed. At that time nothing was known with respect to dam sites in the canyon for a distance of 50 miles below Diamond Creek.

Location.—The lower Diamond Creek dam site is about 600 feet below the mouth of the creek. (See Pl. XLIV.)

Physical characteristics.—A topographic map and cross section of the lower dam site at Diamond Creek are shown in Plate XLIV. Here the river has carved its channel in granitic rock, which rises in the canyon walls to an elevation of 1,950 feet above sea level, or more than 600 feet above the river. This rock is capped by a vertical wall of Tapeats sandstone about 100 feet thick. The relative position of the rock formations is clearly shown in the view presented in Plate XLVI, *A*. The vertical wall of sandstone is very hard and well adapted to form the abutment for the upper part of a high dam. So far as the cross section and rock formations at this site are concerned, it would be feasible to build a dam of any height up to 700 feet above the water surface of the river. There are no fault zones near the dam site that might be expected to cause trouble. (See Appendix B, p. 159.)

The width of the river at the dam site is 190 feet, and a dam to raise the water 450 feet, or to an elevation of 1,773 feet above sea level, would have a length on top of 1,120 feet. The maximum depth to bedrock below the water surface is estimated at 50 feet.

Building material in abundance is available near the dam site, though it would be necessary to obtain the cement elsewhere. (See Appendix B, p. 159.)

Plan of development.—If a relatively low dam is to be built near Diamond Creek to back the water to the Prospect dam site, such a dam should be located at the upper site. However, if the Prospect dam site is not to be utilized, then it would be necessary to build a high dam at Diamond Creek or at some site below in order to utilize all of the fall in the river below the Grand Canyon National Park. The site 600 feet below Diamond Creek is well adapted to the construction of a high dam. At this site the water may be raised 450 feet without interfering with the development of power at the Havasu site, at the west boundary of the park. There is a good site for a power house on the flat 900 feet below the dam site. (See Pl. XLV, *B*.) The construction of a dam of the overflow type is suggested for this site, but in order that the discharge over the dam may not be long continued, it may be advisable to provide discharge tunnels in the dam in order to hold the water level at or near the crest except during the peak of a flood.

As shown by the reservoir capacity curve (Pl. XLIV), the capacity of the reservoir would be 1,780,000 acre-feet. The storage capacity provided by the upper 50 feet of the dam would be 480,000 acre-feet. Such a dam could be so operated as to equalize the flow of the highest recorded flood which has entered Colorado River from tributaries below Lees Ferry.

There is an excellent site for a construction camp and permanent buildings for housing the power-house operators on the flat above the dam site on the left bank. (See Pl. XLIV.)

Water supply.—The water supply would be the same as that available at the dam site just above Diamond Creek. (See p. 90.)

Power capacity.—The static head at the lower Diamond Creek site would be 450 feet. The power capacity with this head and the water supply given in the preceding paragraph would be as follows:

	Horsepower
Without storage and with irrigation and power development in upper basin as in 1922:	
Capacity 50 per cent of time	393, 000
Capacity 90 per cent of time	258, 000
With storage in Glen Canyon and with irrigation and power development in upper basin as in 1922:	
Continuous power available	803, 000
With storage and with ultimate irrigation and power development in upper basin:	
Continuous power available	518, 000
Installed capacity (load factor 60 per cent)	863, 000

Right of way.—A dam to raise the water 450 feet would form a reservoir 67 miles long, the water-surface area of which would be 10,700 acres. No valuable improved property would be submerged, and the flowage damage would therefore be negligible.

Accessibility.—The lower dam site at Diamond Creek is reasonably accessible. A railroad constructed to this site would be about 2 miles shorter than one constructed to the upper dam site, as it would not be necessary to cross Diamond Creek. (See p. 90.)

Adaptability of plan.—The lower dam site at Diamond Creek is well adapted to the construction of a power plant to utilize the full head available between Diamond Creek and the west boundary of the Grand Canyon National Park. For a relatively low dam to back the water to the Prospect dam site, the conditions here are less favorable than those that prevail at the dam site immediately above Diamond Creek.

Although the conditions are favorable for the construction of a high dam below Diamond Creek, there is another site 10 miles farther down the river, at Bridge Canyon, where the conditions for the construction of a dam of any height up to 800 feet are even more favorable. The data presented on pages 74–77 show that possibly a high dam should be built at the Bridge Canyon site. If this should be done, the dam sites at Diamond Creek, as well as the Prospect dam site, would be submerged.

TRAVERTINE CANYON SITE

As the survey was carried down the river from Diamond Creek a careful watch was kept for a site where it would be feasible to build a dam high enough to raise the water to an elevation of 2,000 or 2,100 feet above sea level. Such a site was found 3 miles below Diamond Creek. Here the Archean granitic gneiss rises in the walls to a height of 700 feet above the river. A view of the dam site is presented in Plate XLVI, *B*. The gneiss is capped by a bed of Tapeats sandstone 200 feet thick.

Travertine Canyon is a narrow gorge carved through a massive deposit of travertine by a small stream of water that enters the Colorado from the left at a point half a mile below the dam site. A map and cross section of the dam site are shown in Plate XLVII. A more detailed description of the rocks at the dam site will be found in Appendix B (p. 162).

Although this site has some favorable features, yet, owing to its position on the river, it is not likely that the Travertine Canyon dam site will form a unit of a comprehensive plan for the full development of the water resources of the river.

SPENCER CANYON SITE

Location.—The Spencer Canyon dam site is in the Grand Canyon immediately below the mouth of Spencer Canyon and 20 miles below Diamond Creek. (See Pl. II, in pocket.)

Physical characteristics.—At this site the river has carved the lower part of its canyon in hard granitic rock. The granite is capped by the Tapeats sandstone at a height of 650 feet above the river. A detailed description of the rocks will be found in Appendix B (p.164).

The center line of the proposed dam is located in a rapid which is beset with large rocks (see Pl. LVII, *B*), some of which appear to be granite in place, and it seems likely that the maximum depth to bedrock will not exceed 40 feet.

The work of taking care of the water during the construction period would be simple, as the obstruction in the river channel that causes the rapid would afford a shallow and firm foundation for the cofferdams.

The distance between the canyon walls at the water surface is only 130 feet. The wall on the left bank is nearly vertical, but the slope of the right wall would render the dam site reasonably accessible during construction.

As shown by the cross section in Plate LIX, the slope of the walls becomes very flat above an elevation of 1,700 feet above sea level. The practicable height of a dam at this site is about 650 feet. A dam of that height would raise the water to an elevation of 1,755 feet above sea level. If the dam were built much higher, the cost would be excessive.

If a dam were built to raise the water to an elevation of 1,700 to 1,750 feet above sea level, the saddle on the left side of the river, shown on the map in Plate LIX, could be used as a spillway site. To raise the water only 200 to 300 feet a dam of the overflow type would probably be best adapted to fit the conditions that prevail at the site.

There is a fair site for a power house on the left bank about 700 feet below the dam site. Water could be conveyed to the power house by means of tunnels leading from Spencer Canyon.

Right of way.—There are no improvements in Lower Granite Gorge that would be affected by the building of a dam at the Spencer Canyon dam site. The flowage damage would therefore be negligible.

Accessibility.—The Spencer Canyon dam site is reasonably accessible from a main-line railroad. A branch from the Atchison, Topeka & Santa Fe Railway near Peach Springs, Ariz., could be built to the dam site by way of Spencer Canyon. Such a branch would be about 36 miles long, and about 16 miles of it would entail heavy construction. The ruling grade would probably be about 6 per cent.

FLOUR SACK RAPIDS SITE

Location.—The Flour Sack Rapids dam site is in the Grand Canyon 41 miles below the mouth of Diamond Creek and about 13 miles above Pierces Ferry (now abandoned). (See Pl. II, in pocket.)

Physical characteristics.—The Flour Sack Rapids dam site was examined by the writer September 16, 1924, in connection with a search for favorable dam sites between Devils Slide and Pierces

Ferry. The surveying instruments having been lost, owing to the capsizing of the boat, the investigation was confined to estimates of the width of the river and the distance between the canyon walls and a study of the rocks. With the river-survey map as a basis, a cross section was prepared for the Flour Sack Rapids dam site. (See Pl. LX.) The distance between the canyon walls at 965 feet above sea level is about 270 feet, and on September 16, 1924, the river was confined to a channel 100 feet wide. Granite is exposed for a distance of 160 feet on the left bank and for about 10 feet on the right bank. The granite is capped by a layer of the Tapeats sandstone, above which is the Bright Angel shale. A view of the dam site is presented in Plate LXI, *A*.

The foundation of a dam at this site would be in granite, and the Tapeats sandstone cliff would form the abutment walls to a height of about 55 feet above the river (Pl. LX). A dam to raise the water more than 55 feet would extend into a weaker formation. By constructing adequate cut-off walls into this formation a safe dam could undoubtedly be built here, but its cost would be relatively high. The dam site is described in this report only as a possibility.

PIERCES FERRY SITE

Location.—The Pierces Ferry dam site is near the lower end of the Grand Canyon, 1½ miles above the abandoned Pierces Ferry and 52 miles below the mouth of Diamond Creek. (See Pl. II, in pocket.)

Physical characteristics.—At this site Colorado River has cut through the Tapeats sandstone and well into the Archean crystalline rocks. Here the canyon is boxed next to the river, forming an inner gorge with low walls. (See Pl. LXI, *B*.) The granite appears in the walls to a height of 100 feet above the river. Above the granite the Tapeats sandstone rises precipitously about 100 feet. By means of soundings made September 18, 1924, under the direction of the writer, the maximum depth of the water at the dam site was found to be 70 feet. The sounding weight was resting on silt at a depth of 70 feet below the water surface. Soundings made some years ago by James B. Girand, of Phoenix, Ariz., are reported to have shown a maximum depth of water of 90 feet. The depth to bedrock is unknown.

The height of the walls and the character of the rocks are favorable for the construction of a dam to raise the water 200 feet. However, the cost of the cofferdams necessary to by-pass the water during the construction period would be very high. The dam site is reasonably accessible, and materials for the construction of a dam are near at hand.

A detailed description of the rocks at the dam site will be found in Appendix B (p. 168). A map of the dam site is shown in Plate LXII.

GRAND WASH CANYON SITE

Location.—The Grand Wash Canyon dam site is 5 miles below Pierces Ferry (abandoned) and 2,000 feet above the mouth of Grand Wash. (See Pl. II, in pocket.)

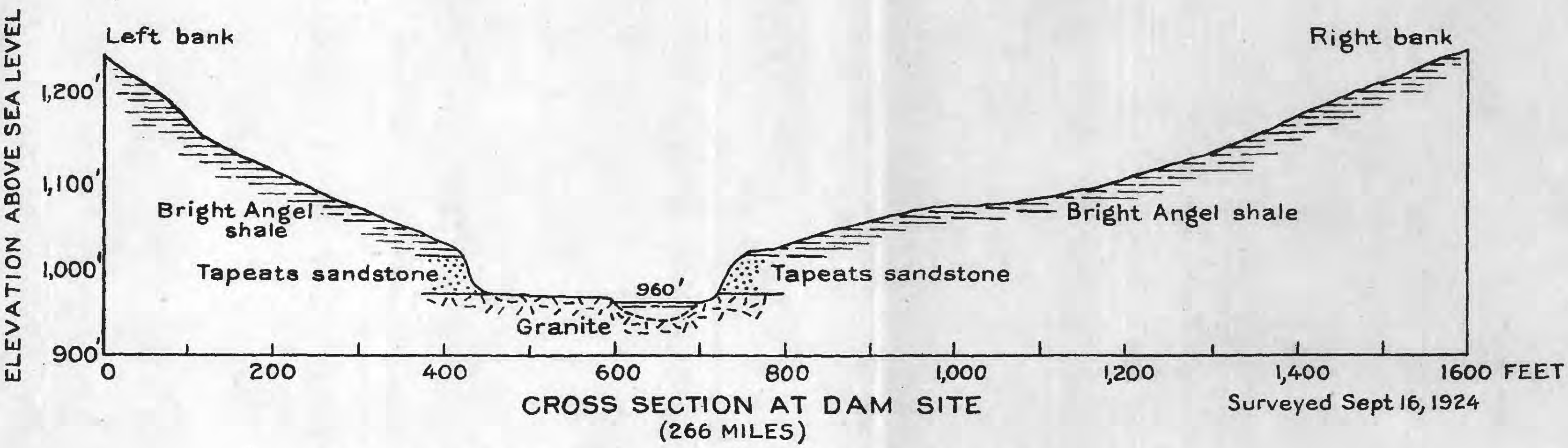
Physical characteristics.—This site was surveyed September 24, 1924. As no geologist was in the party, it was necessary for the writer to make a study of the rocks, and he is responsible for the statements relating to the geologic formations in the vicinity of this dam site.

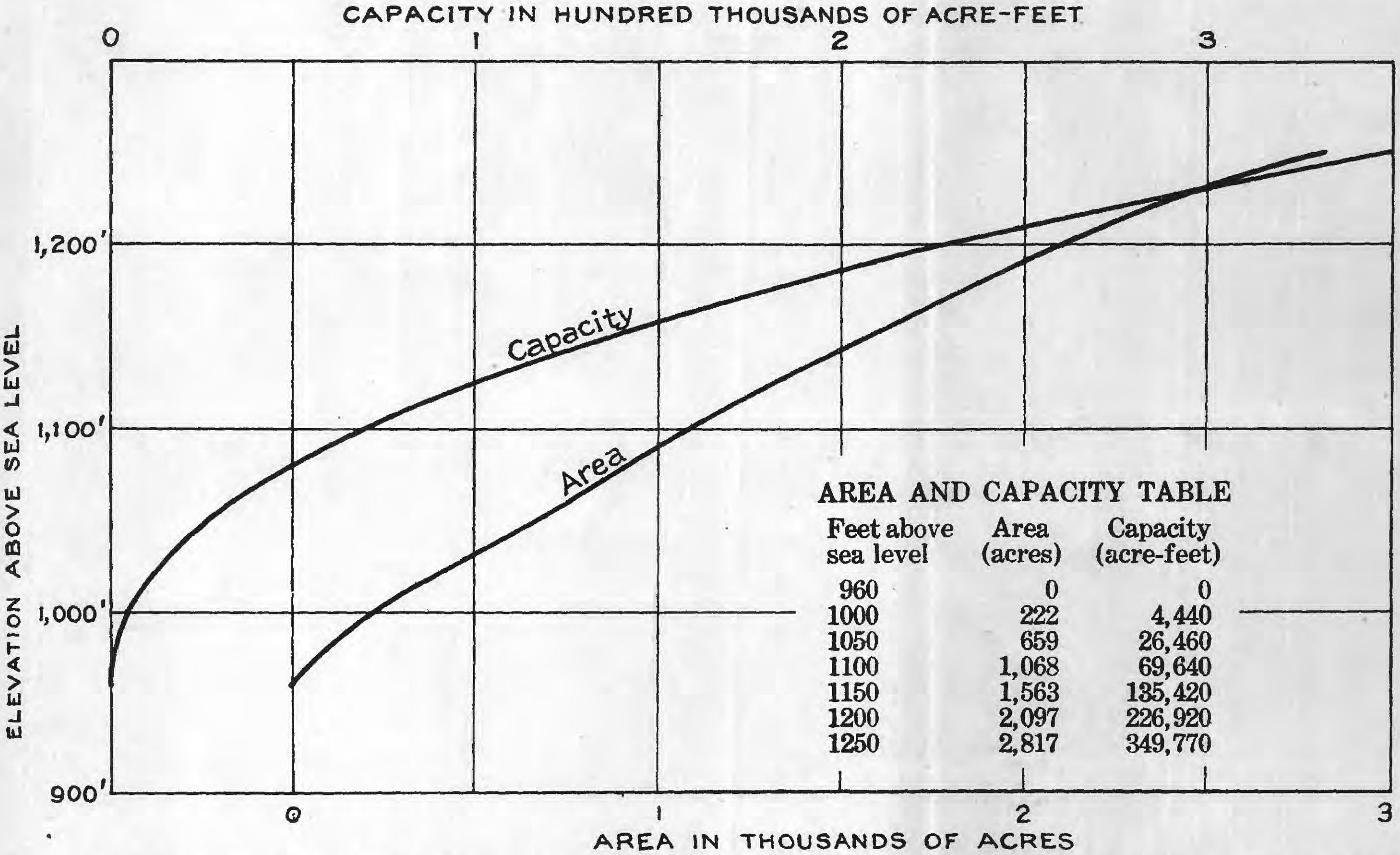
Beginning at a point 1½ miles above the mouth of Grand Wash the following formations are exposed in the canyon walls or on the sky line: Kaibab limestone, Coconino sandstone, Supai shale, Redwall limestone, and Muav limestone. Plate LXIII, *B*, shows the formations on the right bank of the river just above the entrance to Grand Wash Canyon. In Grand Wash Canyon the Redwall and Muav limestones form the canyon walls. At the dam site the formation next to the river is believed to be the Muav limestone, which is overlain by the Redwall limestone. As a result of excessive faulting, the formerly horizontal bedding planes lie at an angle of about 45°. (See Pl. LXIII.)

By soundings made at the dam site the greatest depth of water was found to be 20 feet. Here the river flows over a bed of sand and silt, and the depth to bedrock in the river channel is unknown.

The topographic features of the site are favorable. There is a good site for a power house on the right bank at the mouth of Grand Wash, about 2,000 feet below the dam site. The cost of taking care of the water during the construction period would not be excessive if a suitable foundation is found at a reasonable depth. The character of the rocks in the canyon walls and the height of the walls would permit the construction of a dam of any height up to 400 feet above the river. A cross section and map of the dam site and curves showing the area and capacity of the reservoir basin are presented in Plate LXIV.

Accessibility.—The Grand Wash Canyon dam site is reasonably accessible. By building a railroad 56 miles long, the site could be connected with the main line of the Atchison, Topeka & Santa Fe Railway at Antares, Ariz. The route of such a branch leading to the Hualpai Rapids dam site is described on page 81. The extension of this branch from Hualpai Wash to the Grand Wash Canyon dam site would not be difficult.





AREA AND CAPACITY TABLE

Feet above sea level	Area (acres)	Capacity (acre-feet)
960	0	0
1000	222	4,440
1050	659	26,460
1100	1,068	69,640
1150	1,563	135,420
1200	2,097	226,920
1250	2,817	349,770

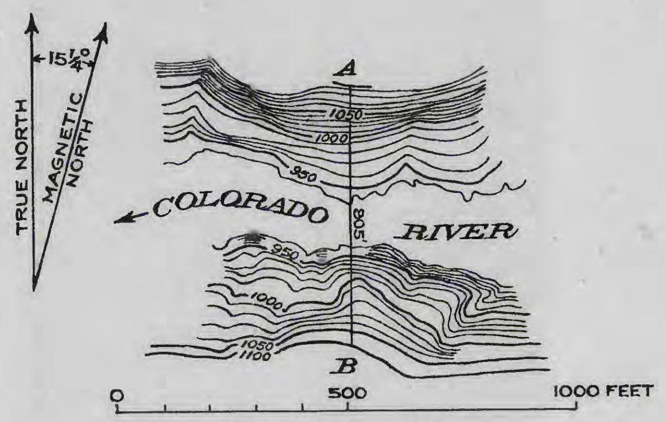
CROSS SECTION AND AREA AND CAPACITY CURVES FOR FLOUR SACK RAPIDS POWER SITE

A. FLOUR SACK RAPIDS DAM SITE, GRAND CANYON, 13 MILES ABOVE PIERCES FERRY

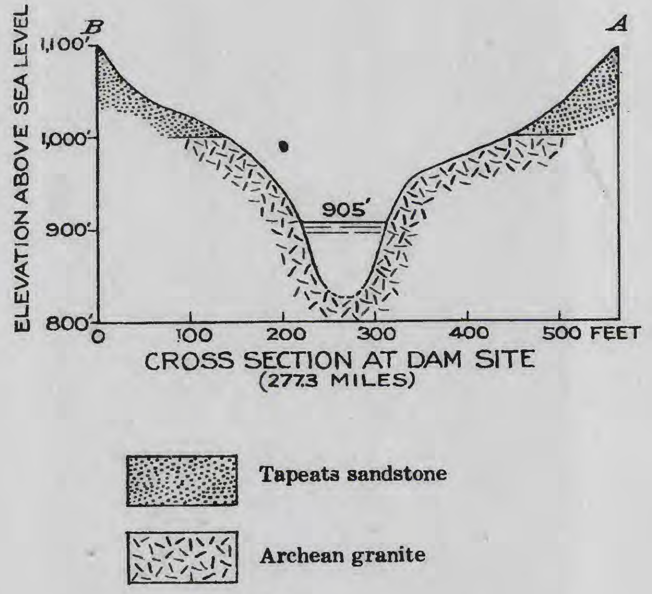
Geology by E. C. La Rue

B. PIERCES FERRY DAM SITE, GRAND CANYON, 1.5 MILES ABOVE PIERCES FERRY

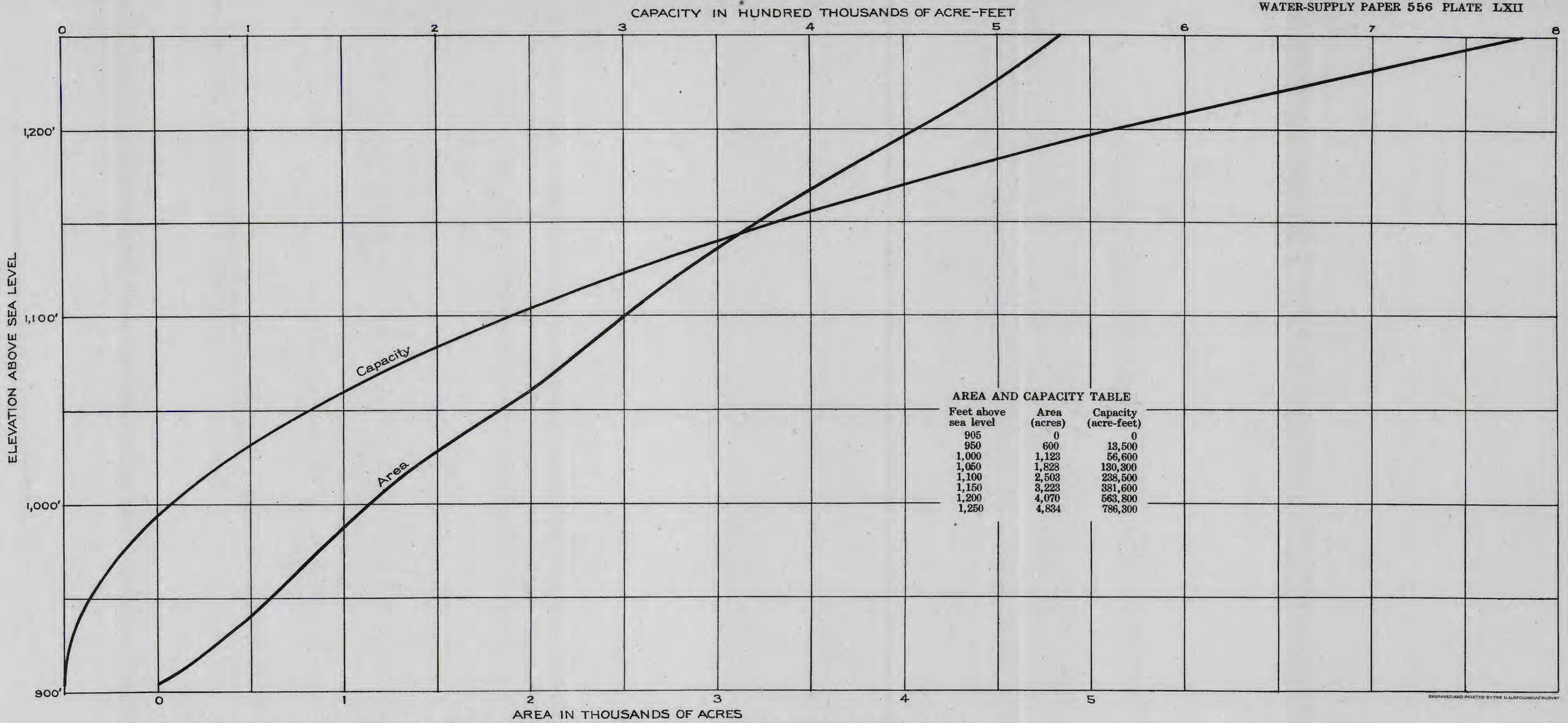
Geology by R. C. Moore



Contour interval 10 feet
Surveyed Oct. 15, 1923



CROSS SECTION AT DAM SITE
(277.3 MILES)



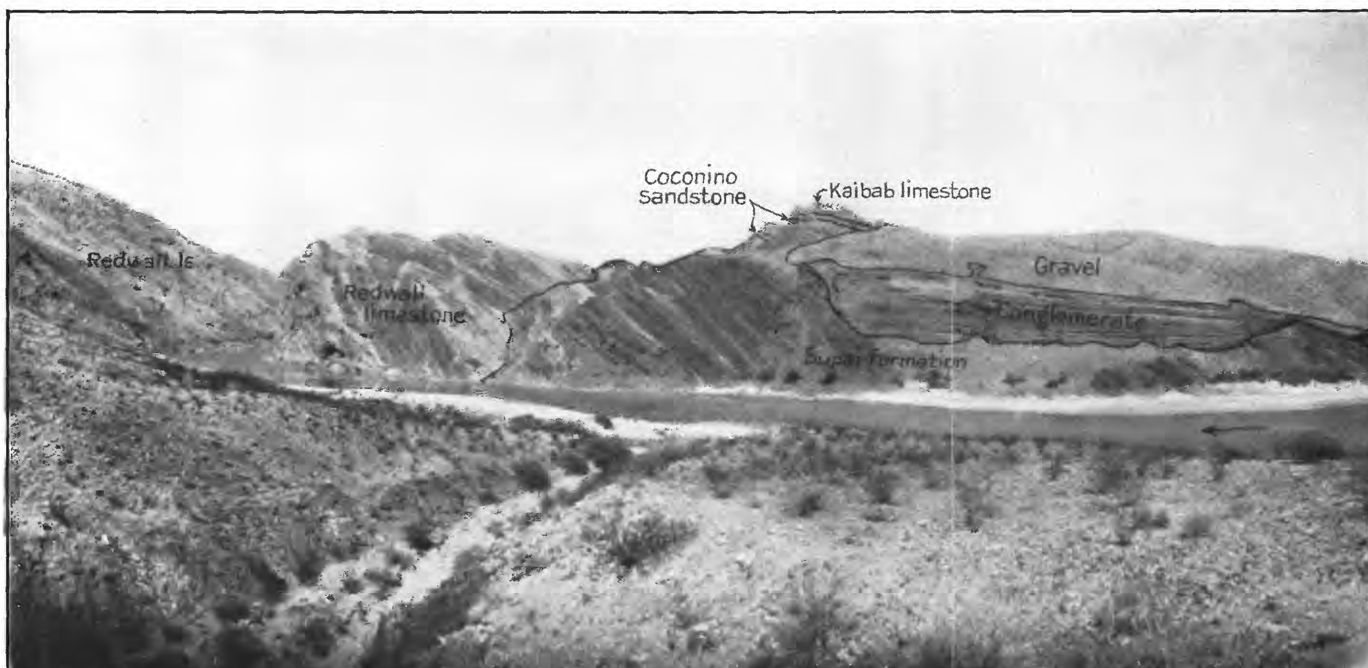
AREA AND CAPACITY TABLE

Feet above sea level	Area (acres)	Capacity (acre-feet)
905	0	0
950	600	13,500
1,000	1,123	56,600
1,050	1,828	130,300
1,100	2,503	238,500
1,150	3,223	381,600
1,200	4,070	563,800
1,250	4,834	786,300

MAP, CROSS SECTION, AND AREA AND CAPACITY CURVES FOR PIERCES FERRY POWER SITE

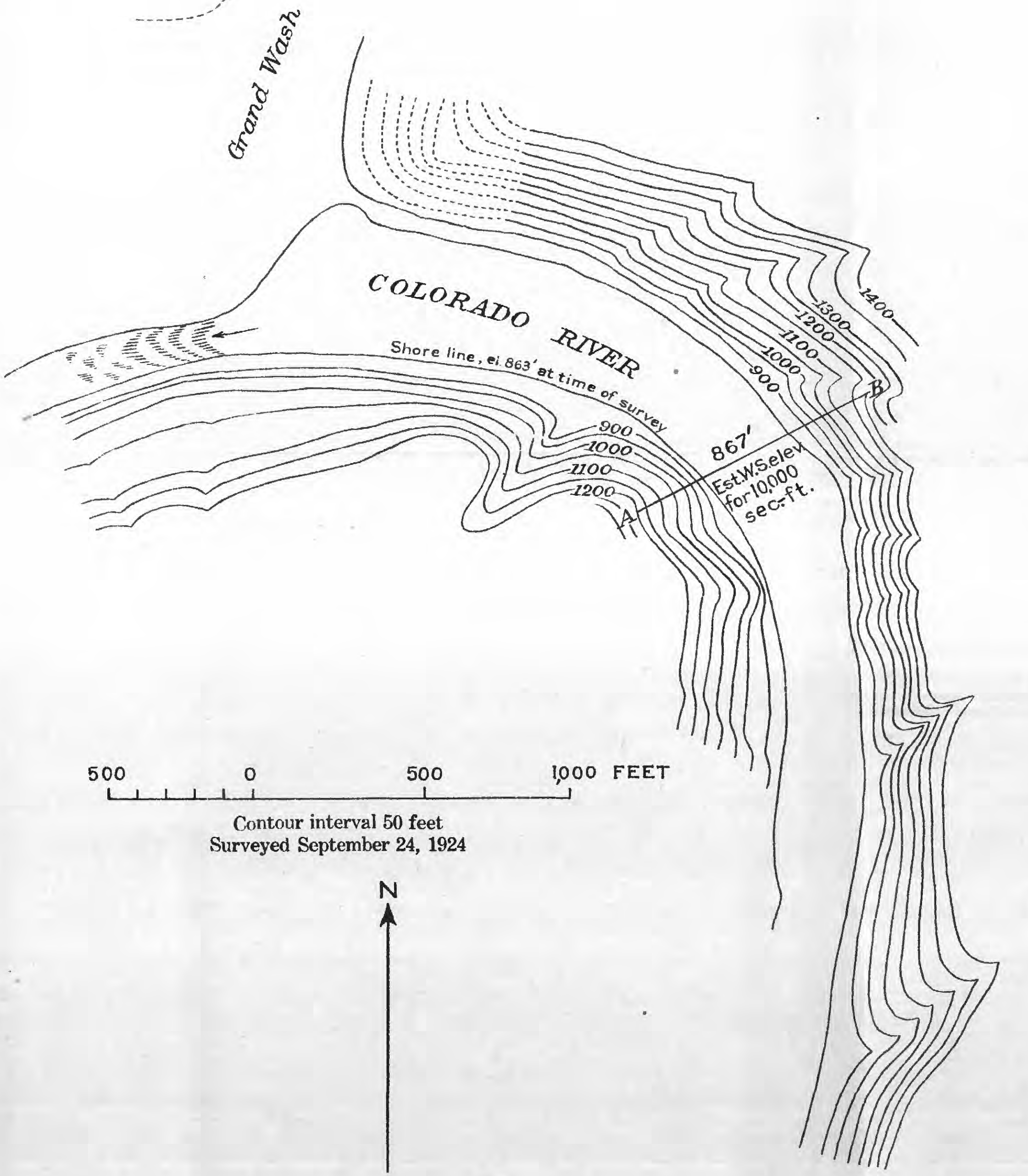
A. GRAND WASH CANYON DAM SITE, 5 MILES BELOW PIERCES FERRY

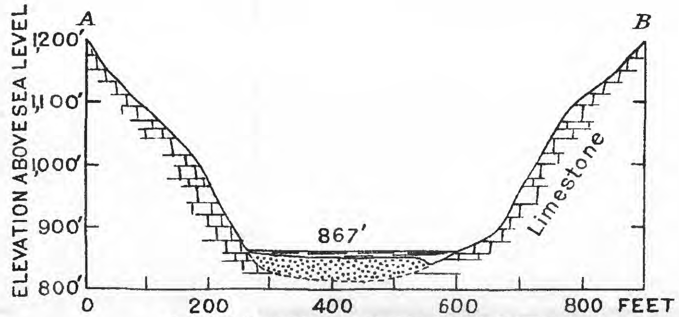
Geology by E. C. La Rue



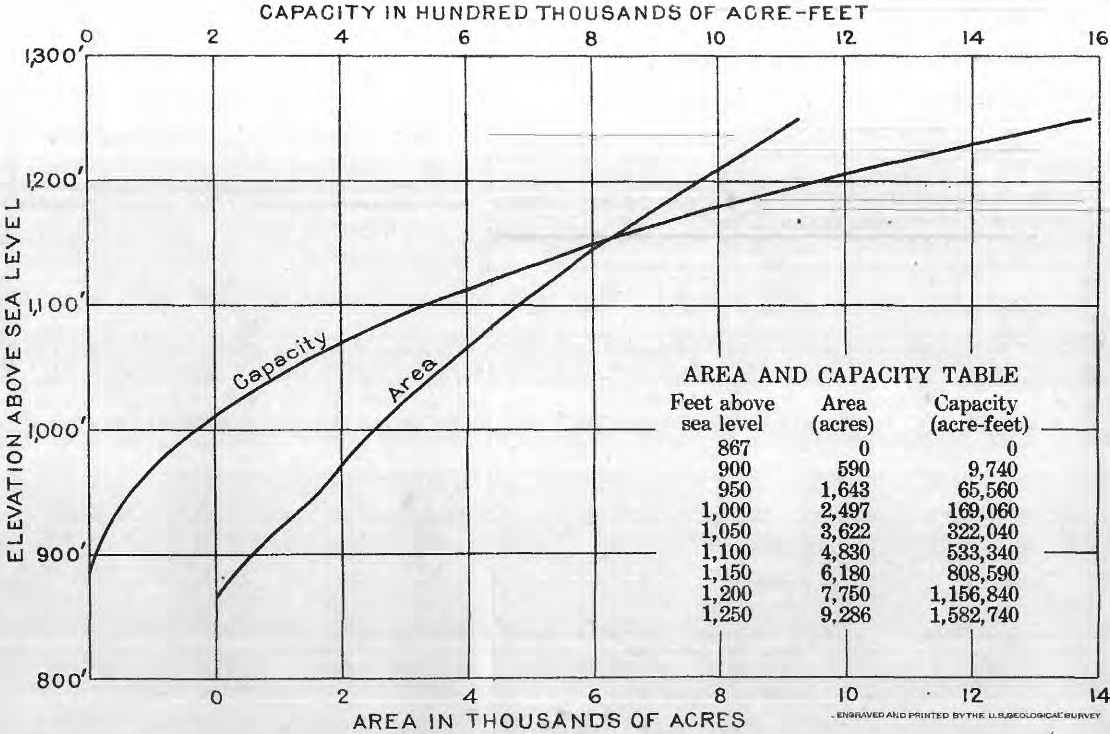
B. ROCK FORMATIONS ON RIGHT BANK OF COLORADO RIVER JUST ABOVE ENTRANCE TO GRAND WASH CANYON

Geology by E. C. La Rue





CROSS SECTION AT DAM SITE
(284.2 MILES)



AREA AND CAPACITY TABLE

Feet above sea level	Area (acres)	Capacity (acre-feet)
867	0	0
900	590	9,740
950	1,643	65,560
1,000	2,497	169,060
1,050	3,622	322,040
1,100	4,830	533,340
1,150	6,180	808,590
1,200	7,750	1,156,840
1,250	9,286	1,582,740

ENGRAVED AND PRINTED BY THE U.S.GEOLOGICAL SURVEY

MAP, CROSS SECTION, AND AREA AND CAPACITY CURVES FOR GRAND WASH CANYON POWER SITE

VIRGIN CANYON SITE

Location.—The Virgin Canyon dam site is in Virgin Canyon of Colorado River, 3 miles below the mouth of Hualpai Wash and 6 miles below Greggs Ferry. (See Pl. II, in pocket.)

Physical characteristics.—At 3 miles below Greggs Ferry Colorado River enters Virgin Canyon, cut in the hard crystalline rocks of the Virgin Mountains. The canyon is about 4 miles long and more than 1,000 feet deep. A relatively narrow cross section was observed about 3 miles below the mouth of Hualpai Wash. Here the topography of a narrow strip was mapped. (See Pl. LXV.) The distance between the canyon walls near the water surface is 400 feet. If a favorable foundation should be found a dam could be built to raise the water 400 feet. Such a dam would have a length on top of 1,150 feet.

Soundings made by the writer September 28, 1924, indicated that the river was flowing on a bed of silt, and the greatest depth of water was found to be 9½ feet. The depth to bedrock in the river channel is unknown.

Accessibility.—As the dam site is in a deep canyon, where the canyon walls are precipitous, the accessibility of the site for carrying on the work of construction is unfavorable. There are no good sites for a power house or construction camp. A view of the dam site is presented in Plate LXVI, *A*. The cost of a railroad built to the dam site from Antares, Ariz., would not be excessive. Such a railroad would be about 46 miles long. A branch from Antares to the Hualpai Rapids dam site is described on page 81. To reach the Virgin Canyon dam site from Hualpai Rapids it would be necessary to extend the road 3 miles down Virgin Canyon. The cost of this 3-mile extension would be relatively high.

CALLVILLE SITE

Location.—The Callville dam site is at the lower end of Boulder Canyon, 1½ miles above the Callville ruins. (See Pl. II, in pocket.)

Physical characteristics.—This site has many favorable features. The granitic rock in the walls and river channel is satisfactory. The foundation has been tested by the Southern California Edison Co. The maximum depth to bedrock as determined by three holes drilled in the river channel is 80 feet. The canyon walls are low and would permit easy access to the dam site during the construction period. A view of the dam site is presented in Plate LXVI, *B*.

Immediately below the dam site on the Nevada side of the river is a flat tract of land comprising about 400 acres. This flat affords an ideal location for a power house, railroad terminal, and construction camp. (See Pl. LXVII.)

A low saddle on the Nevada side of the river limits the maximum practicable height of a dam at the Callville site to about 240 feet. Such a dam would raise the water to an elevation of 924 feet above sea level. Even then it would be necessary to build an auxiliary dam in the saddle just mentioned.

A railroad could be built to the site from a point on the Union Pacific system near Las Vegas, Nev. There are two feasible routes, by Las Vegas Wash or Callville Wash. The railroad, which would be 35 to 40 miles long, could be built at a reasonable cost.

Although the Callville site is one of the best power sites on lower Colorado River, it does not fit in well with any plan thus far suggested for the full development of the river.

MIDDLE BLACK CANYON SITE

Location.—The middle Black Canyon dam site is in Black Canyon, 2 miles above the mouth of Jumbo Wash, 9 miles above the lower Black Canyon site (p. 81), and 33 miles northeast of Searchlight, Nev. (See Pl. II, in pocket.)

Physical characteristics.—The writer examined the middle Black Canyon dam site October 1, 1924. A map showing the topography of the site was made from an enlargement of a section of the Bulls Head reservoir survey (Pl. LXVIII).

A side canyon that may be used as a spillway site joins the main canyon a few hundred feet below the dam site. About 2,000 feet below the dam site the high walls are succeeded by low hills. These conditions make the dam site accessible from the lower side. There is a good site for a power house and construction camp on the right bank about 1,300 feet below the dam site. (See Pl. LXIX, *A*.)

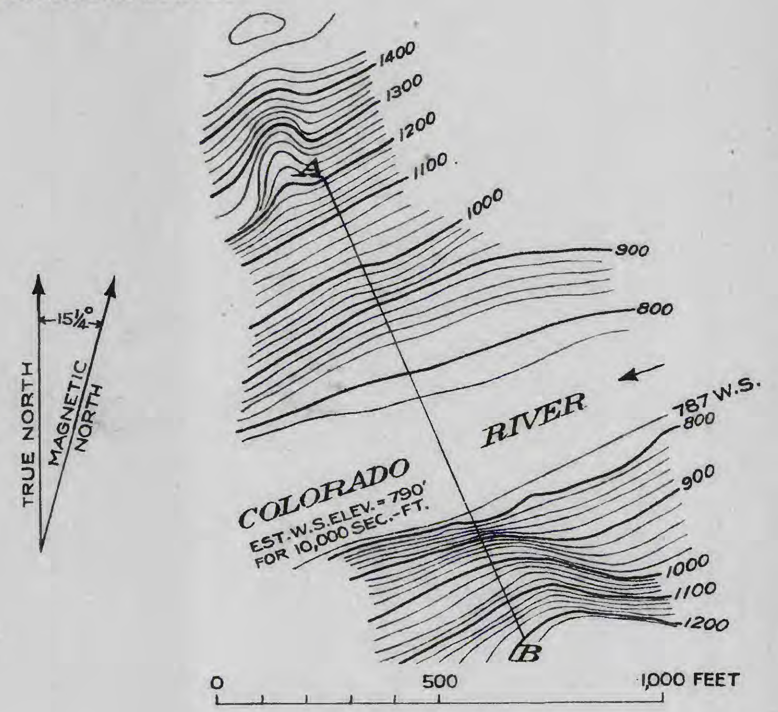
It is the writer's belief that the rock exposed in the walls at the dam site is volcanic tuff-breccia and that granitic rocks are exposed near the water surface a few hundred feet below the dam site. He is of the opinion that the depth to bedrock in the river channel may be as great as 100 feet and that the foundation of a dam at this site may be in granite.

Accessibility.—The site is reasonably accessible from Searchlight, Nev., and Chloride, Ariz. An automobile may be driven from Chloride to the mouth of Jumbo Wash, which is 2 miles downstream from the dam site.

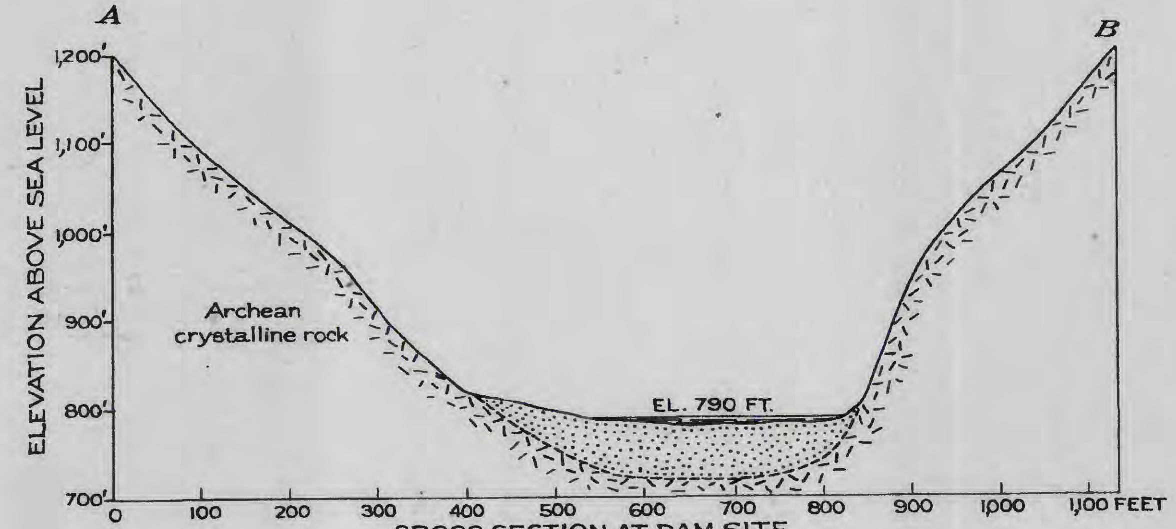
ELDORADO SITE

Location.—The Eldorado dam site is at the lower end of Black Canyon, 3½ miles above Eldorado Wash, and about 24 miles northeast of Searchlight, Nev. (See Pl. II, in pocket.)

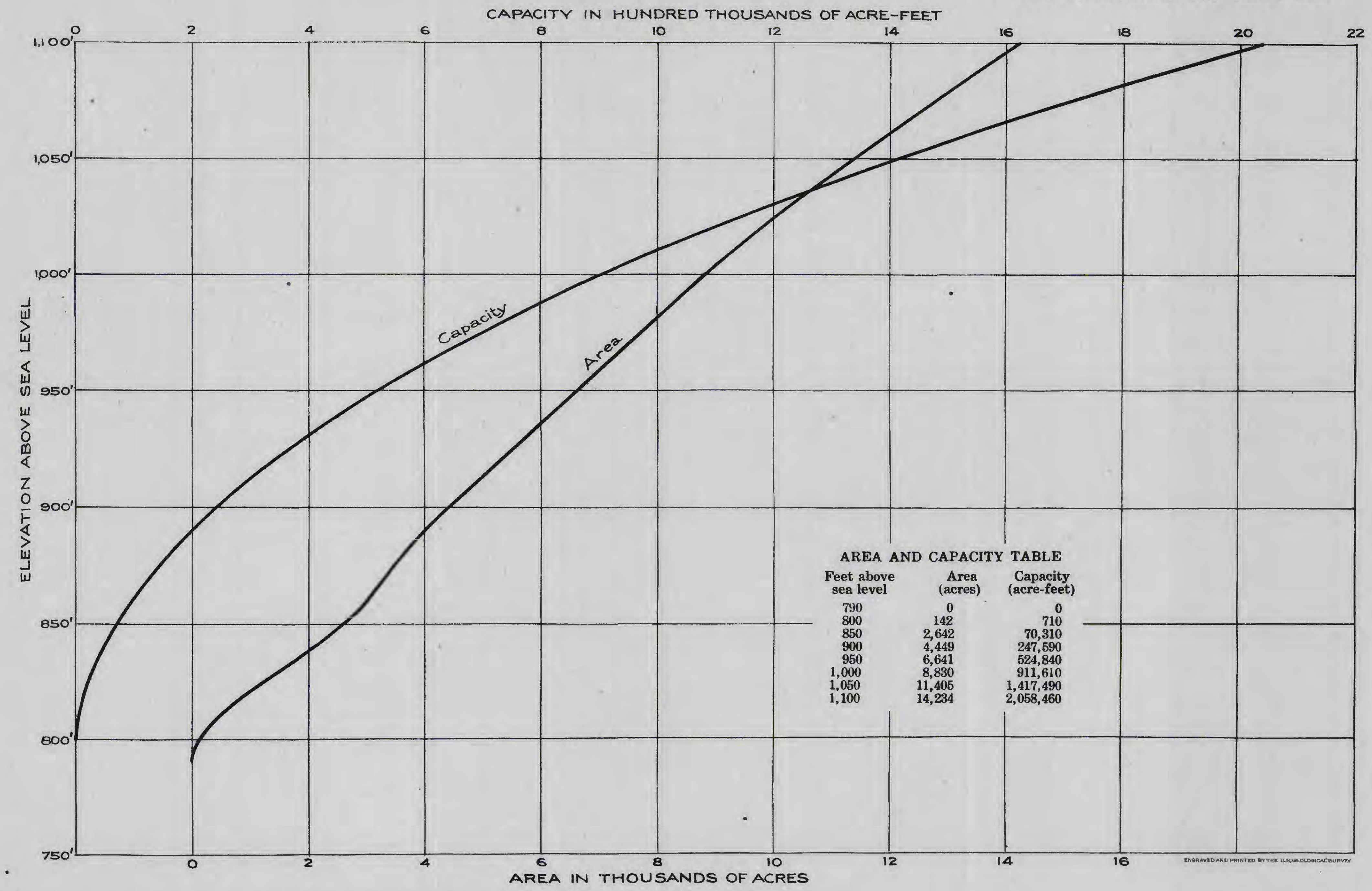
Physical characteristics.—The Eldorado dam site was surveyed October 4–5, 1924, and a detailed study of the rocks at the dam site



Contour interval 50 feet
Surveyed September 28, 1924



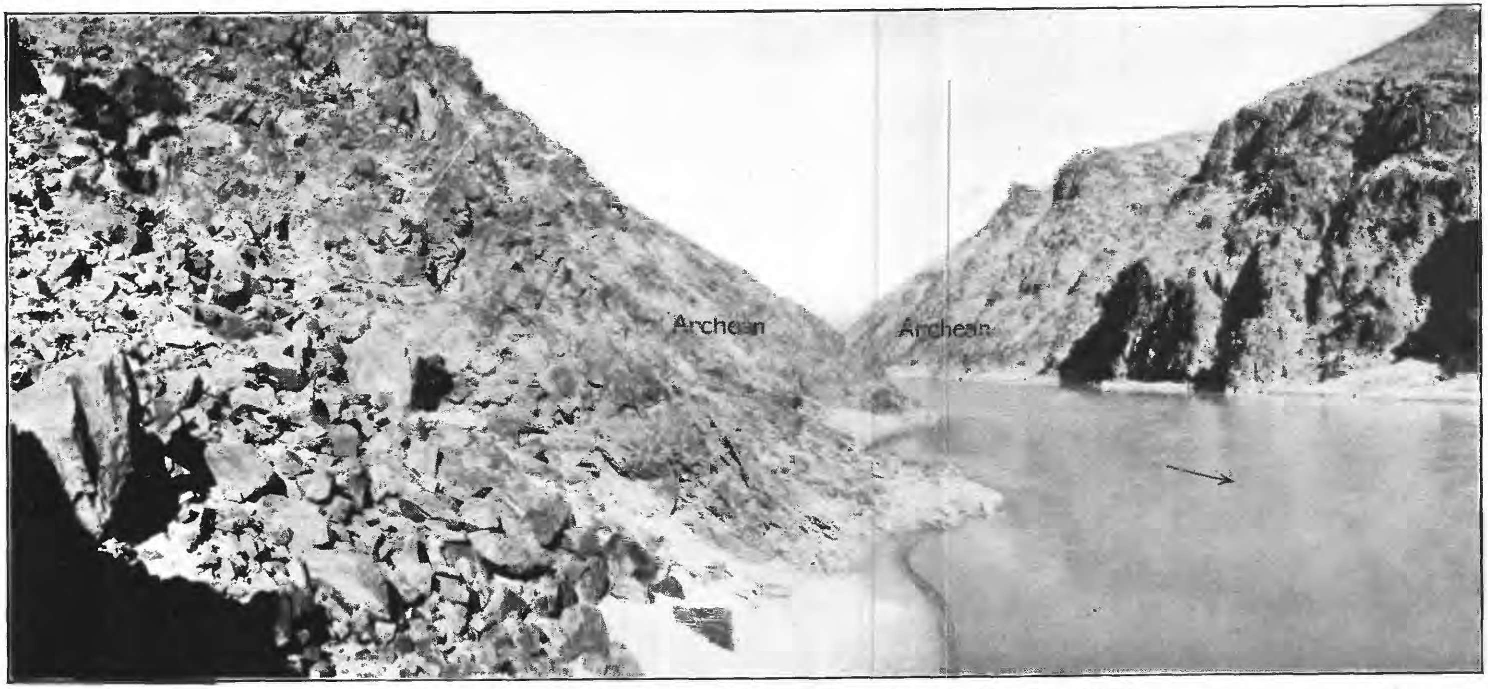
CROSS SECTION AT DAM SITE
(304.7 MILES)



AREA AND CAPACITY TABLE

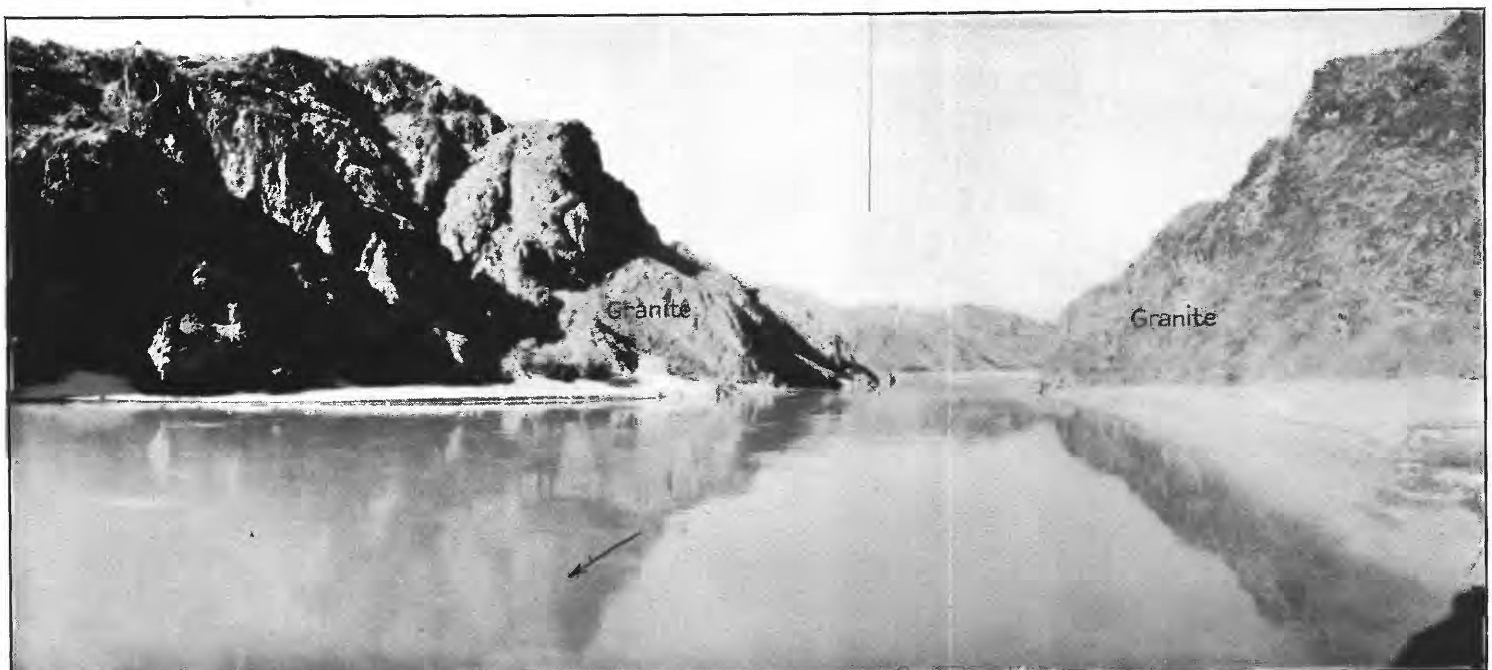
Feet above sea level	Area (acres)	Capacity (acre-feet)
790	0	0
800	142	710
850	2,642	70,310
900	4,449	247,590
950	6,641	524,840
1,000	8,830	911,610
1,050	11,405	1,417,490
1,100	14,234	2,058,460

MAP, CROSS SECTION, AND AREA AND CAPACITY CURVES FOR VIRGIN CANYON POWER SITE



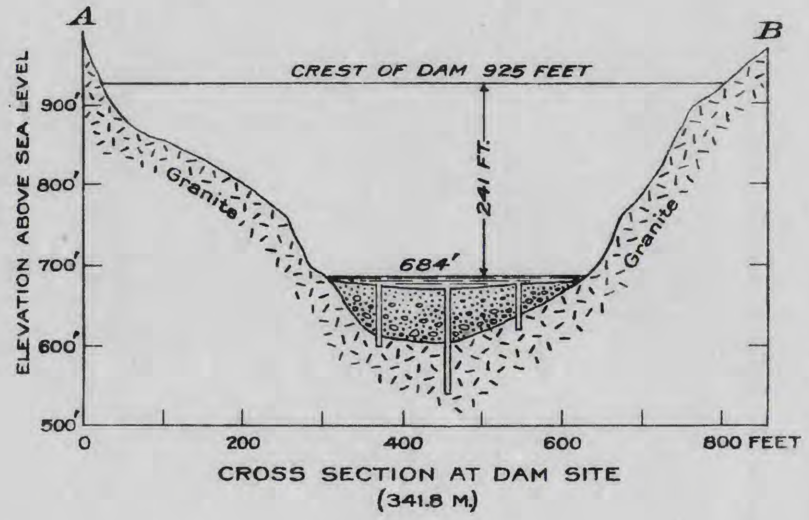
A. VIRGIN CANYON DAM SITE, 3 MILES BELOW MOUTH OF HUALPAI WASH

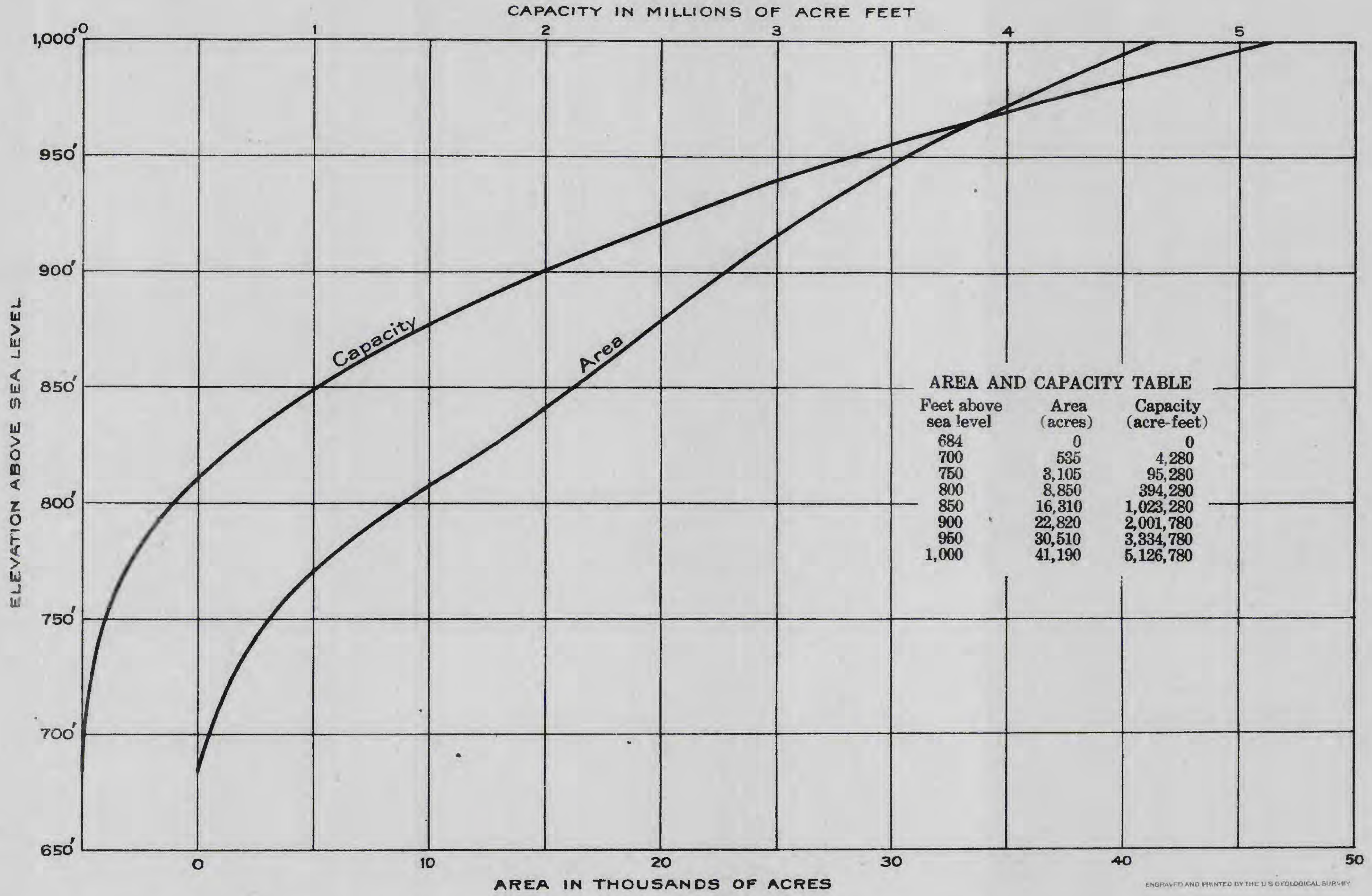
Geology by E. C. La Rue



B. CALLVILLE DAM SITE, AT LOWER END OF BOULDER CANYON, 1.5 MILES ABOVE CALLVILLE RUINS

Geology by E. C. La Rue





AREA AND CAPACITY TABLE

Feet above sea level	Area (acres)	Capacity (acre-feet)
684	0	0
700	535	4,280
750	3,105	95,280
800	8,850	394,280
850	16,310	1,023,280
900	22,820	2,001,780
950	30,510	3,334,780
1,000	41,190	5,126,780

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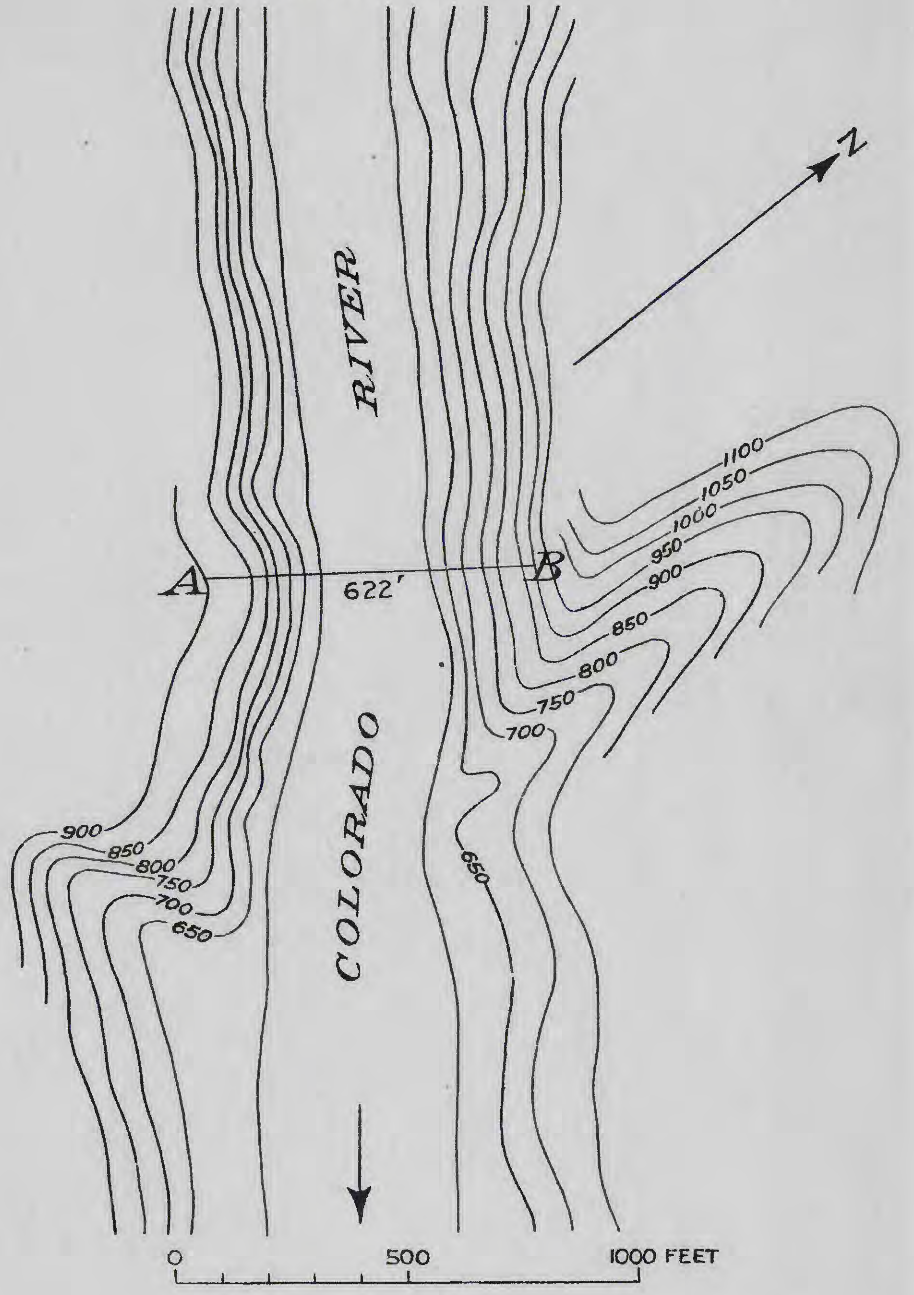
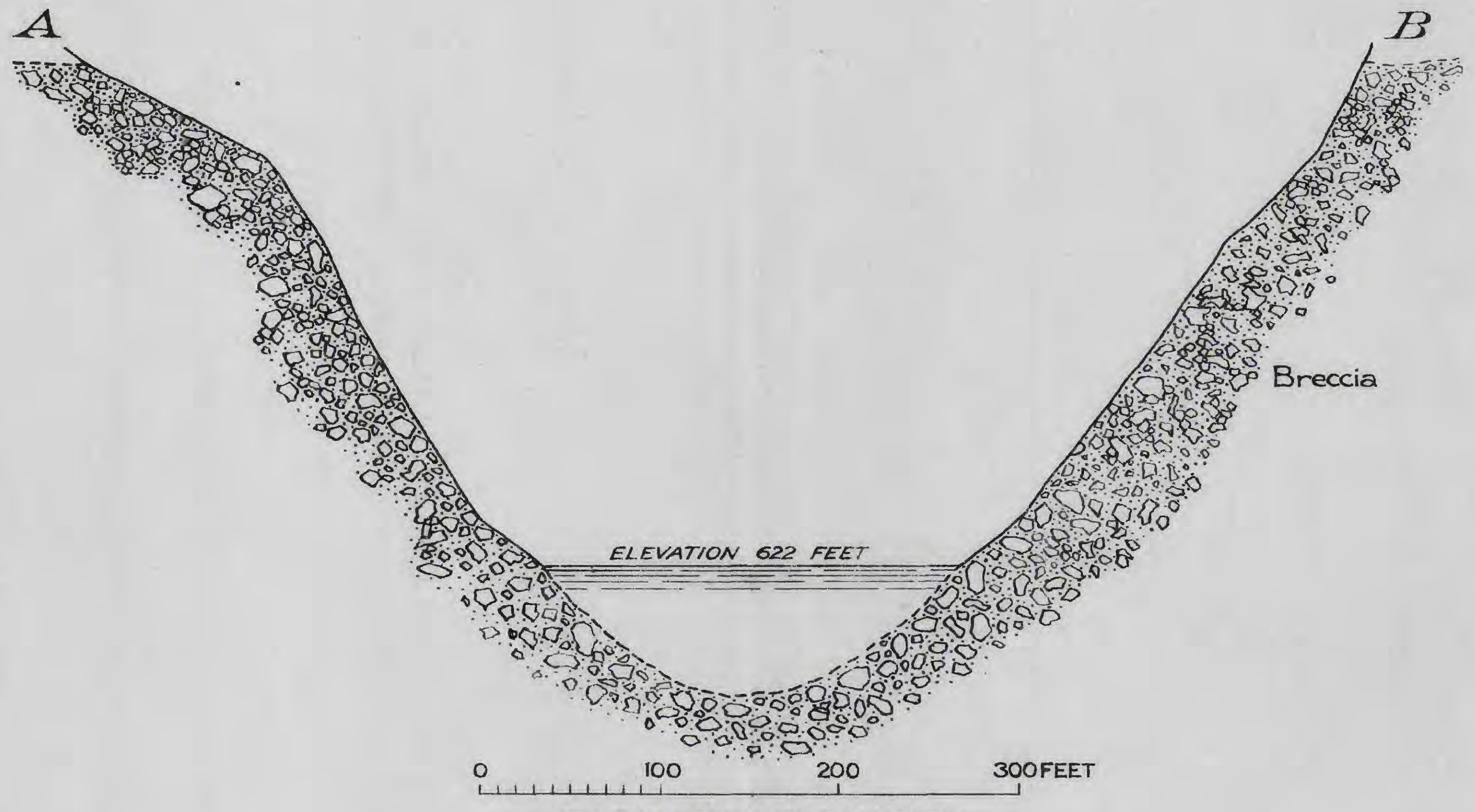
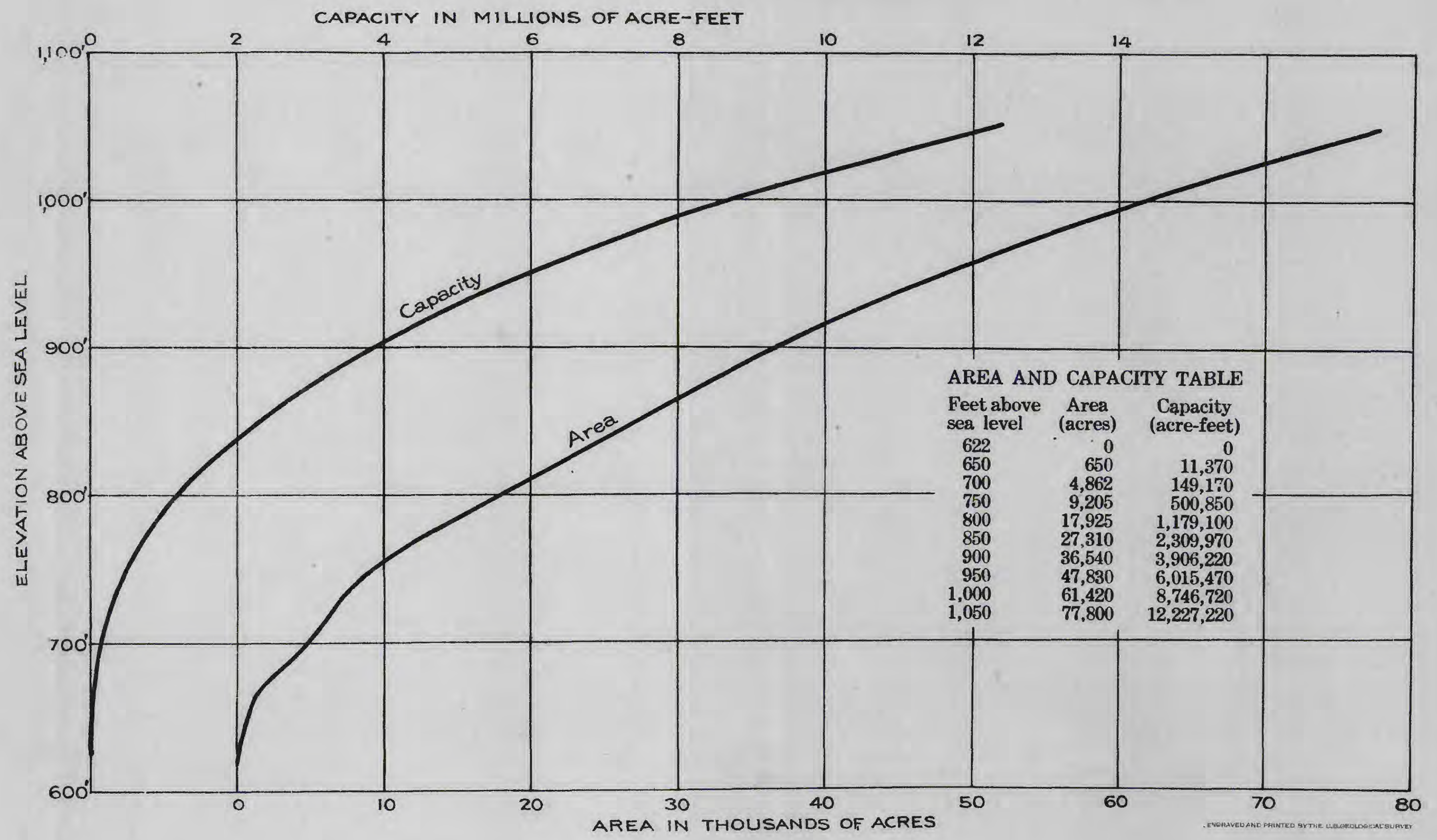
MAP, CROSS SECTION, AND AREA AND CAPACITY CURVES FOR CALLVILLE POWER SITE



Contour interval 50 feet
Surveyed December 1920



CROSS SECTION AT DAM SITE
(364.9 MILES)

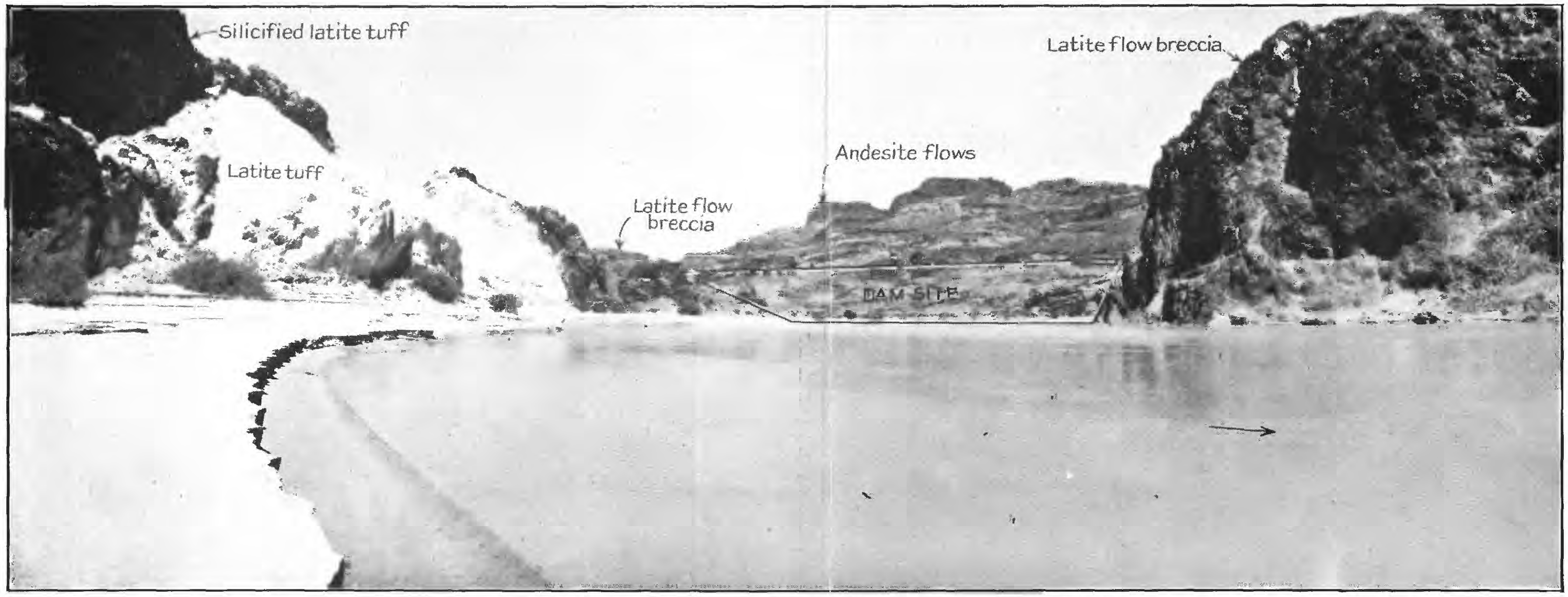


AREA AND CAPACITY TABLE

Feet above sea level	Area (acres)	Capacity (acre-feet)
622	0	0
650	650	11,370
700	4,862	149,170
750	9,205	500,850
800	17,925	1,179,100
850	27,310	2,309,970
900	36,540	3,906,220
950	47,830	6,015,470
1,000	61,420	8,746,720
1,050	77,800	12,227,220

MAP, CROSS SECTION, AND AREA AND CAPACITY CURVES FOR MIDDLE BLACK CANYON POWER SITE

A. MIDDLE BLACK CANYON DAM SITE, 2 MILES ABOVE MOUTH OF JUMBO WASH



B. ELDORADO DAM SITE, 3.5 MILES ABOVE MOUTH OF ELDORADO WASH

Geology by D. F. Hewett

was made September 26, 27, and 28, 1924, by D. F. Hewett, geologist, United States Geological Survey. Mr. Hewett has classified the rock in both abutment walls as latite flow-breccia (Pl. LXIX, *B*) and is of the opinion that these rocks are sufficiently resistant and strong to serve as the abutments for a dam to raise the water 100 feet. He noted a gravel deposit 600 feet west of the right abutment wall that would permit serious leakage if a dam were built to raise the water higher than 100 feet. Aside from this gravel deposit, the walls on the right bank are relatively low, a condition which in itself renders the site unsuitable for the construction of a dam higher than 100 feet above the present low-water level.

The width of the river at the dam site is 580 feet, and a dam to raise the water 100 feet would have a length on top of about 950 feet. The depth to bedrock in the river channel is unknown. The dam site is reasonably accessible from Searchlight, Nev.

A map and cross section of the dam site and curves showing the area and capacity of the basin above the dam site are shown in Plate LXX.

EAGLE ROCK SITE

Location.—The Eagle Rock dam site is in Eagle Rock Canyon, near the head of Cottonwood Valley, about 60 miles by river above Needles, Calif.

Physical characteristics.—Eagle Rock Canyon was surveyed by the United States Reclamation Service in 1903. Lee[22] describes the conditions at Eagle Rock Canyon as follows:

> At Eagle Rock, near the southern end of Round Island, the river leaves the flood plain and flows through a narrow rock gorge about a mile long and 150 feet deep. * * * The gravel-filled channel to the east connects the Round Island Valley with the Cottonwood Valley proper. In other words, Colorado River, during one of its periods of canyon cutting, * * * failed to reexcavate its old gravel-filled channel at Eagle Rock and cut a new channel in the rock west of the old one.

Lee classifies the rock in the narrow gorge as andesite, and in his map, reproduced here as part of Plate LXXI, he shows the relation of the rock gorge to the old gravel-filled river channel on the Arizona side of the river.

Under the direction of the writer, a survey was made October 29, 1922, to determine accurately the cross section at the dam site. It was found that a dam to raise the water 100 feet, or to an elevation of 650 feet above sea level, would have a length at the water surface of 730 feet and a length on top of 940 feet. However, if a dam were built in the present river channel to raise the water 100 feet, serious leakage would probably occur in the old gravel-filled channel shown

[22] Lee, W. T., Geologic reconnaissance of a part of western Arizona: U. S. Geol. Survey Bull. 352, p. 39, 1908.

on the map in Plate LXXI. The depth to bedrock in the old channel, as well as in the present channel, is unknown. The dam site seems of doubtful practicability, and is mentioned here only as a possible site which may be investigated further if there is urgent need for a dam at an elevation of about 550 feet above sea level. A view of the dam site is presented in Plate LXXII, *A*.

BULLS HEAD SITE

Location.—The Bulls Head dam site is near the lower end of Pyramid Canyon, 25 miles due north of Needles, Calif. (See Pl. II, in pocket.)

Physical characteristics.—This site was thoroughly investigated by the United States Reclamation Service in 1902–3.[23] Three sites were investigated by means of diamond-drill borings. The first one was abandoned owing to an unsatisfactory foundation for a dam 100 feet high Tests at the other two sites also gave unsatisfactory results. The engineers of the Reclamation Service found no suitable place for the construction of a dam 100 feet high at Bulls Head, but they reached the conclusion that the conditions were favorable for the construction of a diverting weir 20 feet in height above low water, with a waste weir founded on solid rock on the Arizona side. With this conclusion the writer is in full accord. However, engineers of the Bureau of Reclamation have recently prepared tentative designs and estimates for an earth dam to raise the water 170 feet at this site.

Lee[24] has clearly described the geologic history of Pyramid Canyon below Bulls Head Rock. Using the data furnished by the Reclamation Service, supported by facts obtained on the ground, he constructed a map showing the present river channel in relation to the old gravel-filled channel and cross sections showing the probable depth to bedrock at the three sites which were tested by drilling. These data are presented in Plate LXXIII. At the three dam sites investigated the gravel filling in the river channel was found to be more than 100 feet deep.

In Plate LXXII, *B*, is presented a view of Bulls Head Rock, showing the present river channel, the old gravel-filled channel, and Bulls Head dam site No. 1, as seen from the south.

As the foundations at the three dam sites at Bulls Head Rock are unsatisfactory, the cost of a dam of any type built here would be relatively high.

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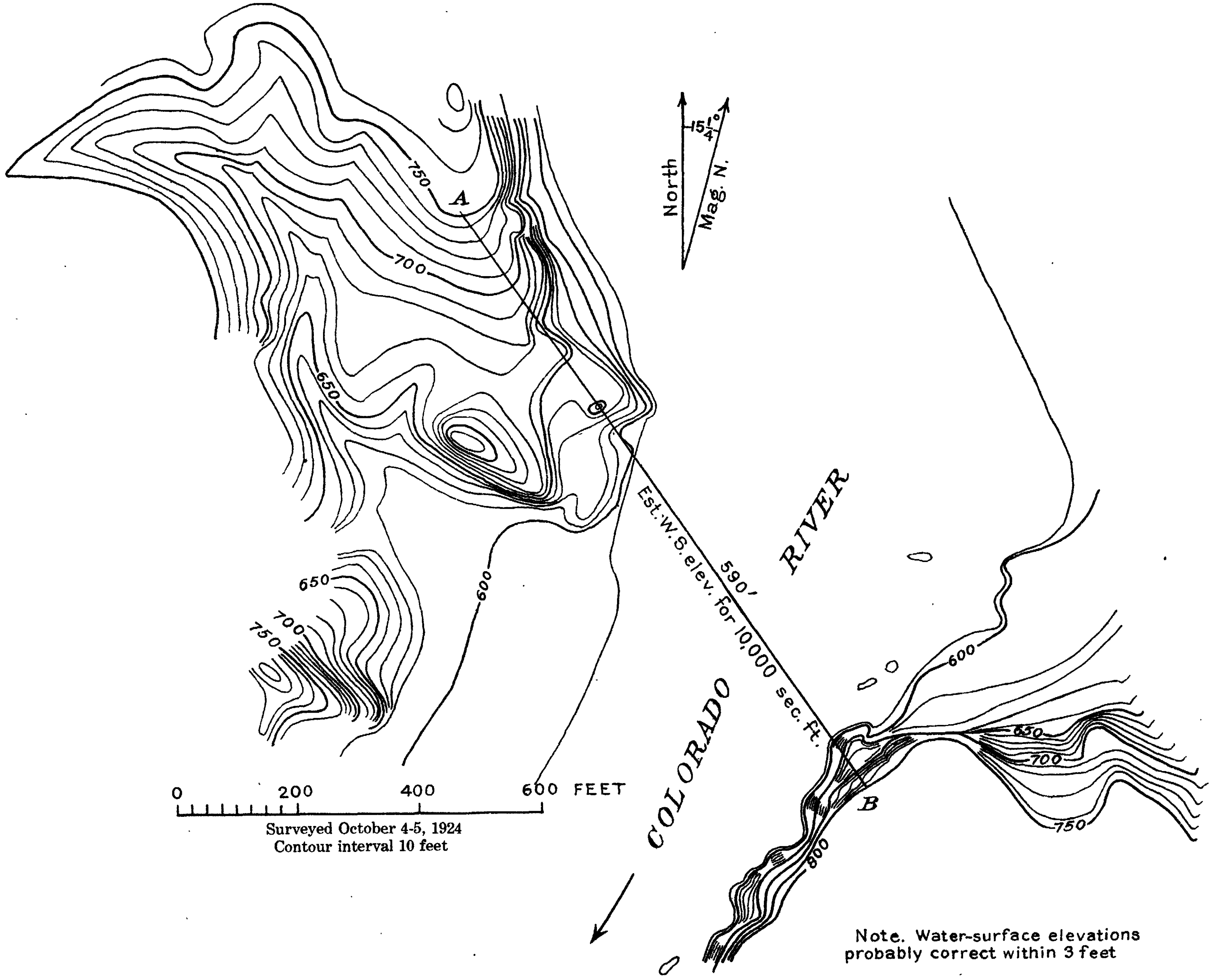
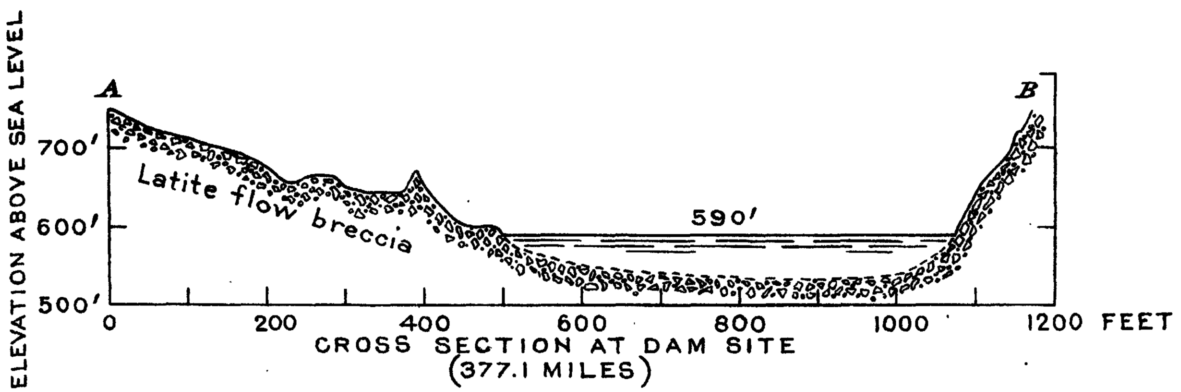
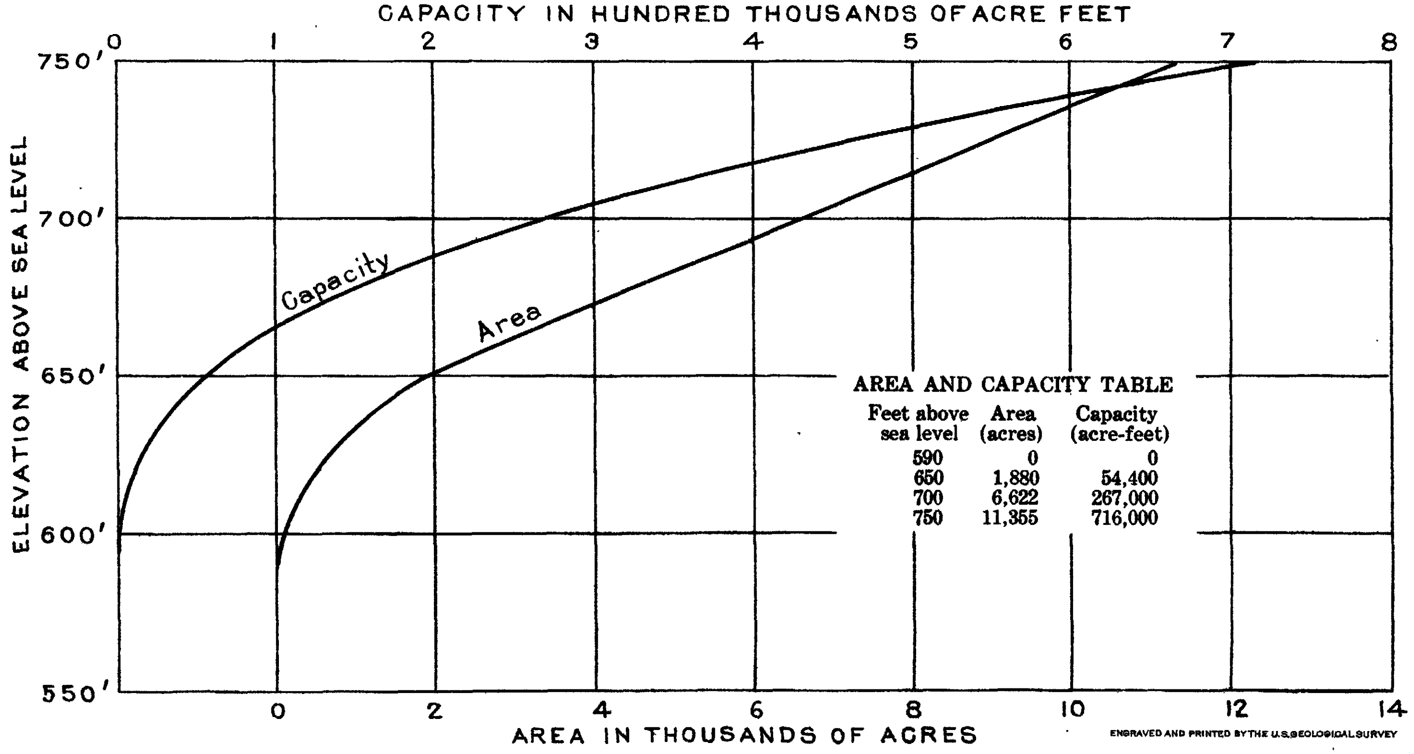
[23] U. S. Recl. Service Second Ann. Rept., p. 134, 1904.

[24] Op. cit., p. 39.





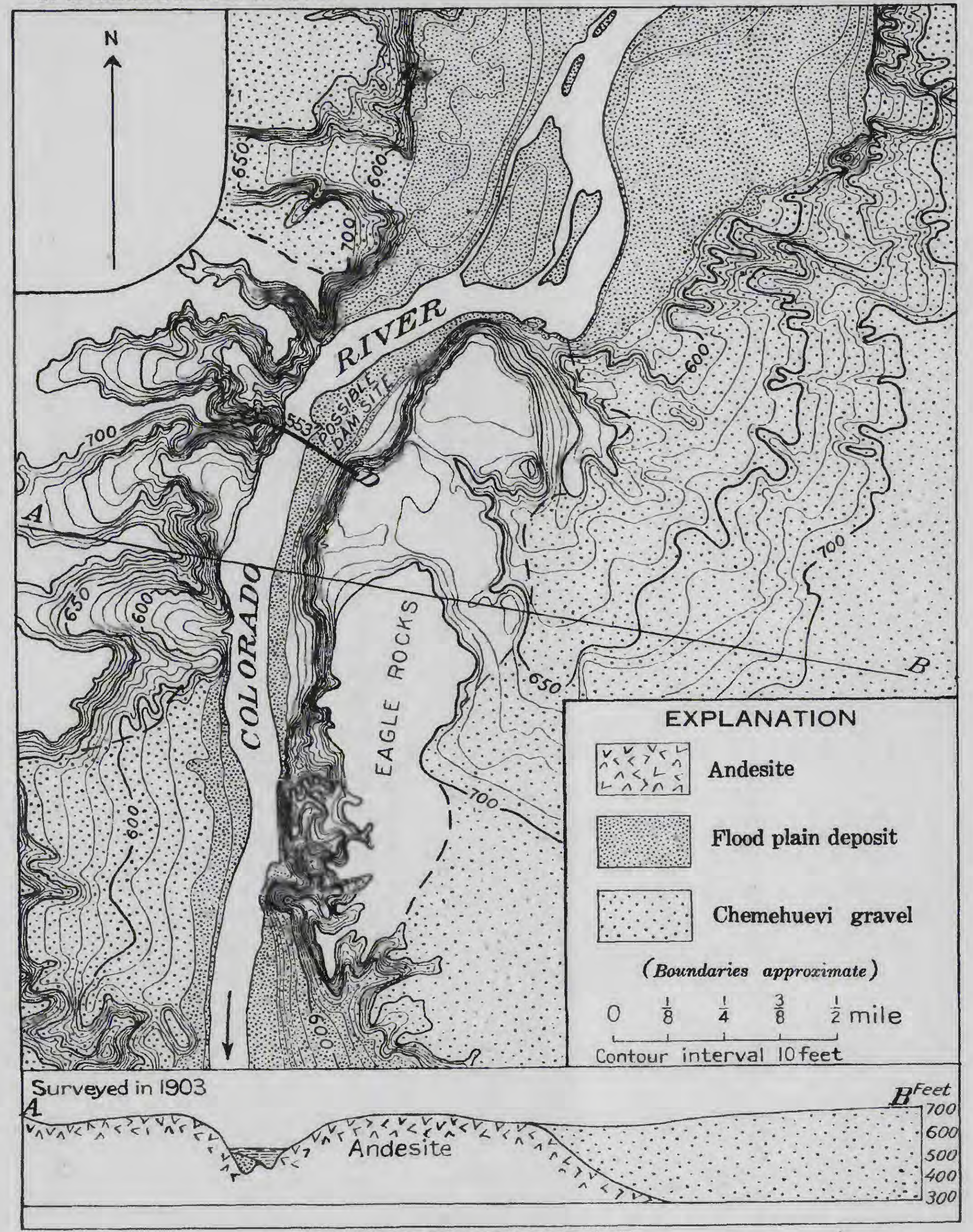


AREA AND CAPACITY TABLE

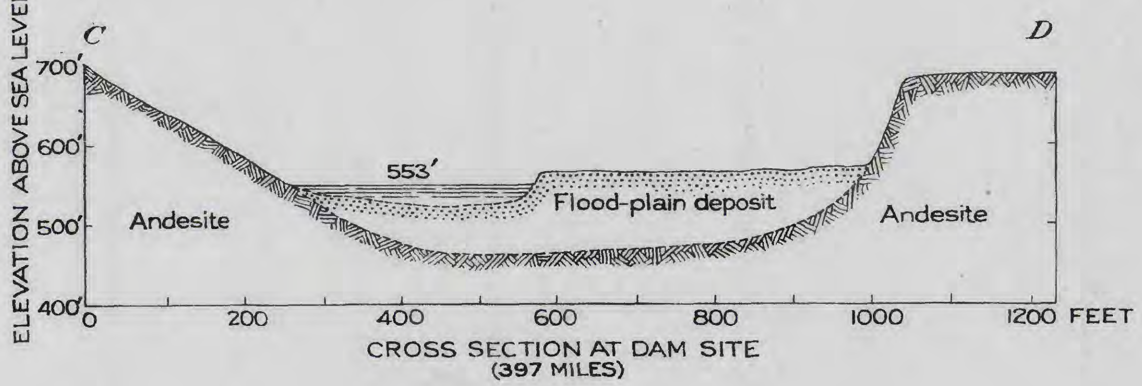
Feet above sea level	Area (acres)	Capacity (acre-feet)
590	0	0
650	1,880	54,400
700	6,622	267,000
750	11,355	716,000

ENGRAVED AND PRINTED BY THE U.S. GEOLOGICAL SURVEY

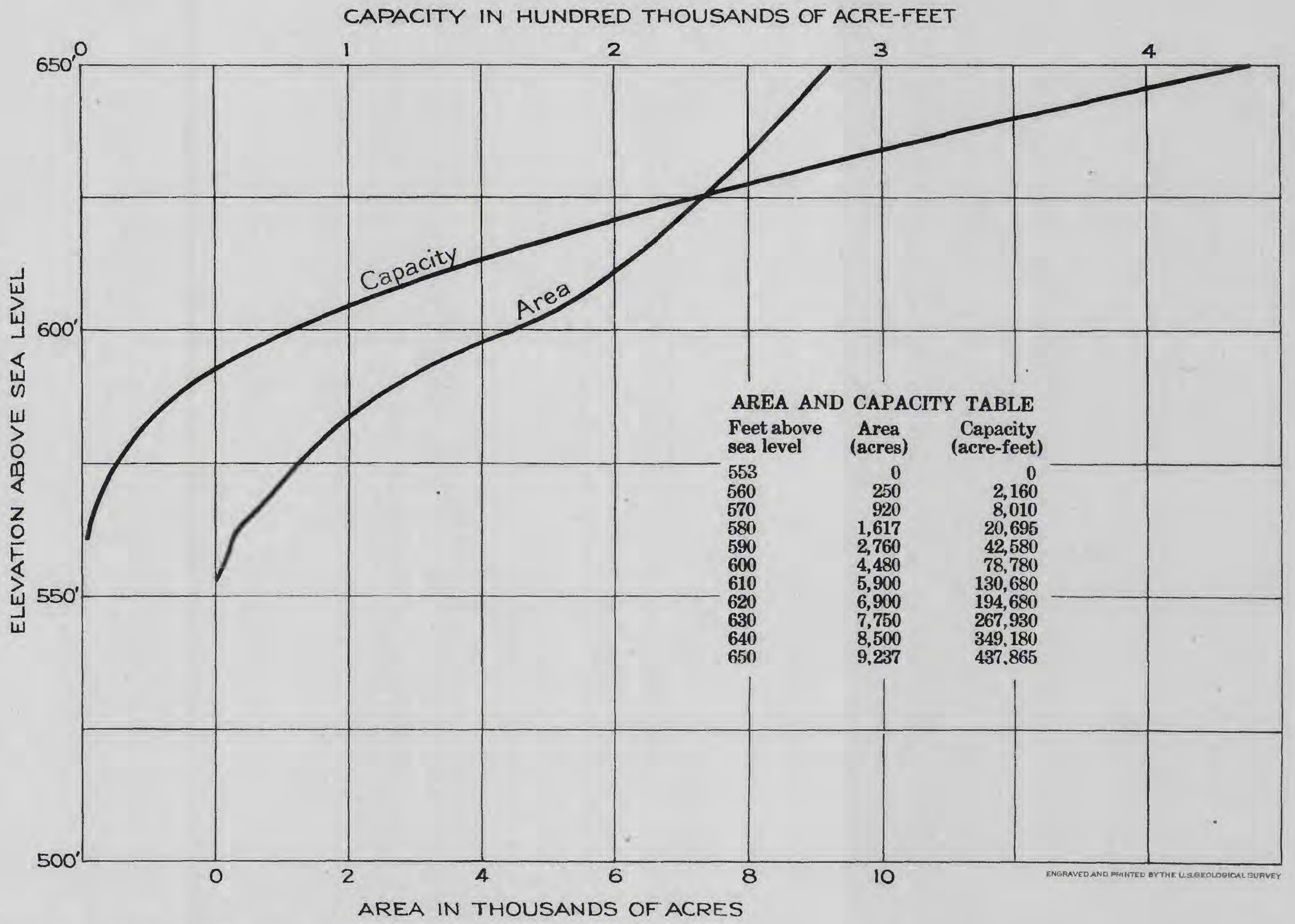
MAP, CROSS SECTION, AND AREA AND CAPACITY CURVES FOR THE ELDORADO POWER SITE



SECTION ALONG LINE A-B



CROSS SECTION AT DAM SITE
(397 MILES)

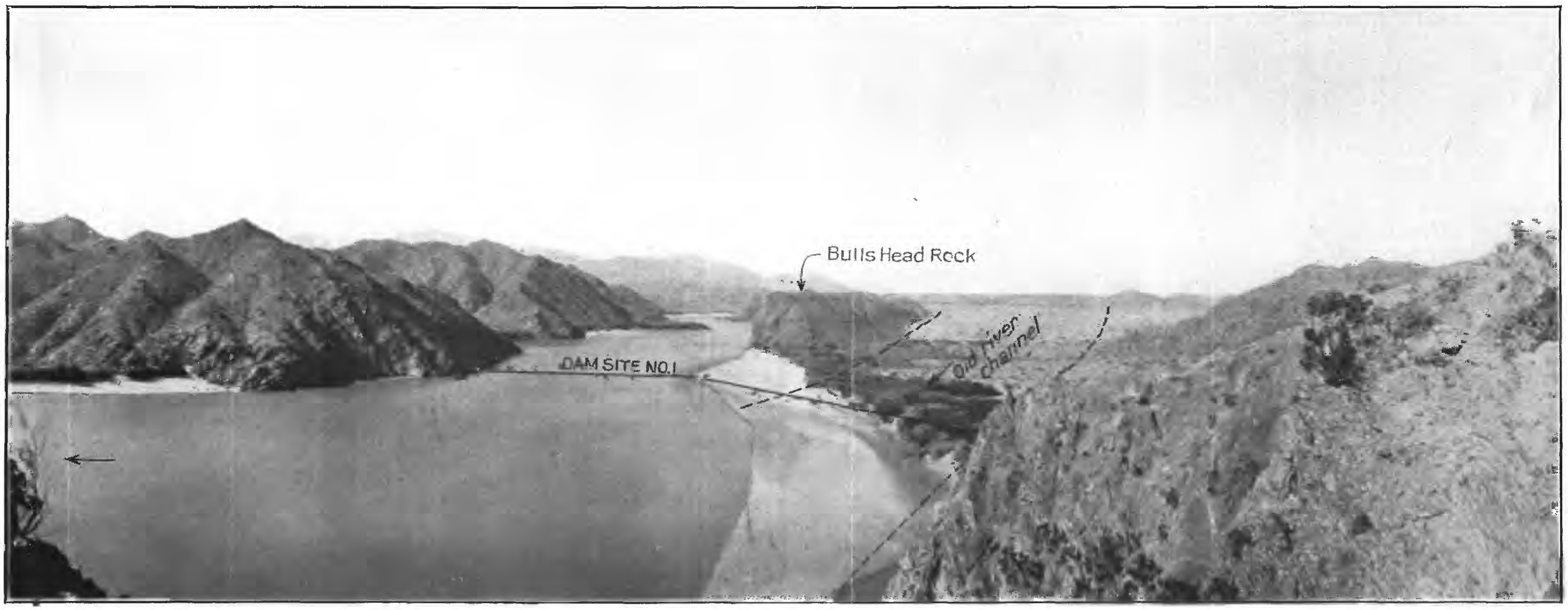


AREA AND CAPACITY TABLE

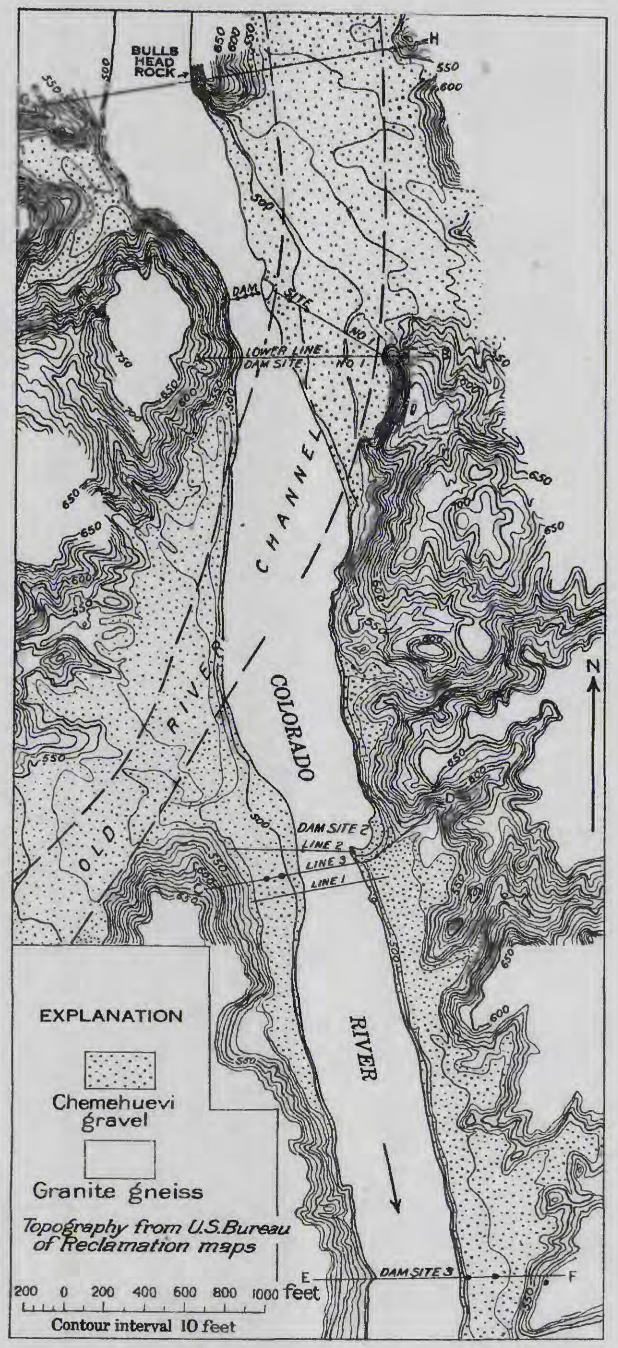
Feet above sea level	Area (acres)	Capacity (acre-feet)
553	0	0
560	250	2,160
570	920	8,010
580	1,617	20,695
590	2,760	42,580
600	4,480	78,780
610	5,900	130,680
620	6,900	194,680
630	7,750	267,930
640	8,500	349,180
650	9,237	437,865

MAP, CROSS SECTION, AND AREA AND CAPACITY CURVES FOR EAGLE ROCK POWER SITE

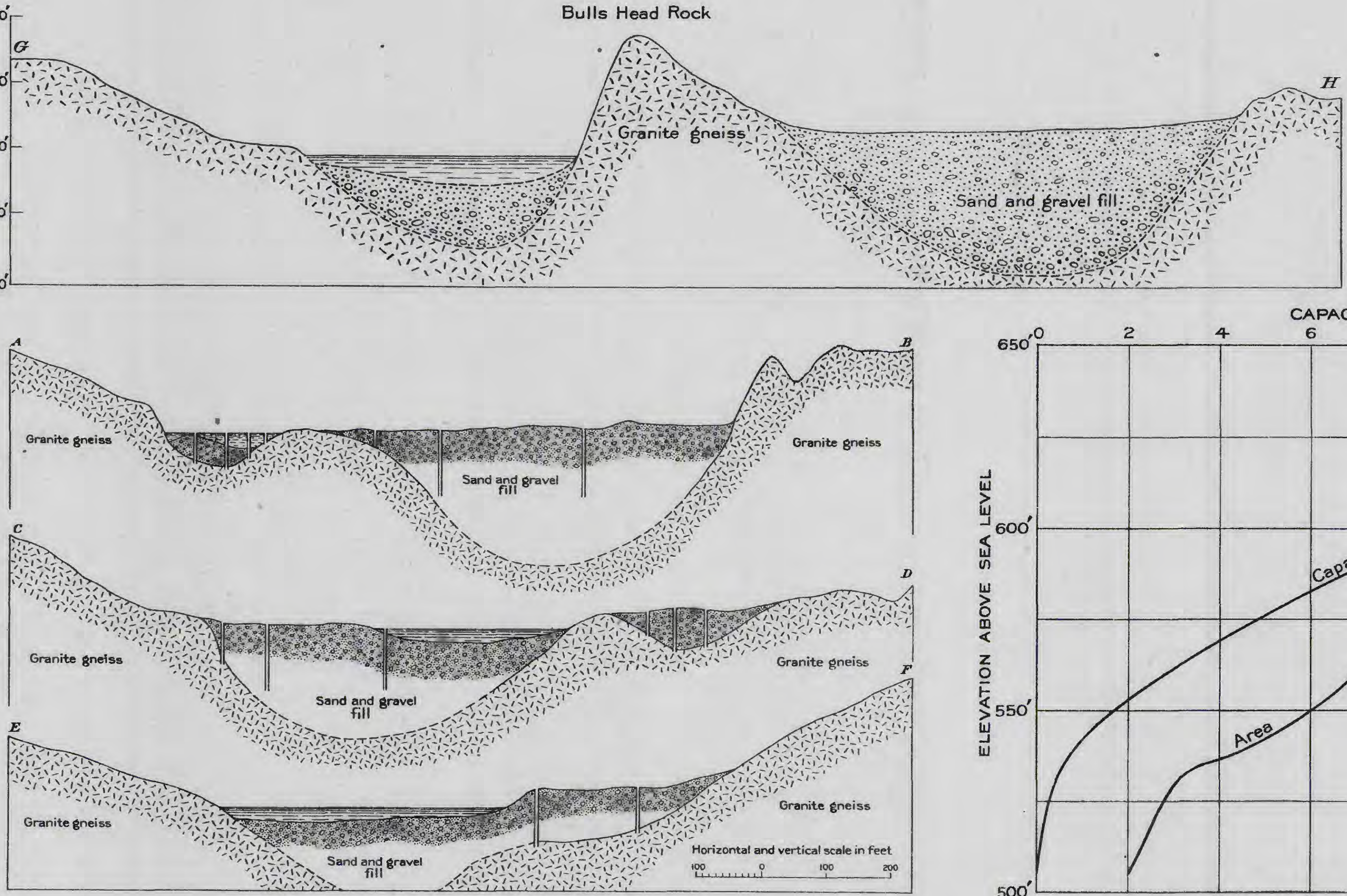
A. EAGLE ROCK DAM SITE, AT THE HEAD OF COTTONWOOD VALLEY, 60 MILES BY RIVER ABOVE NEEDLES



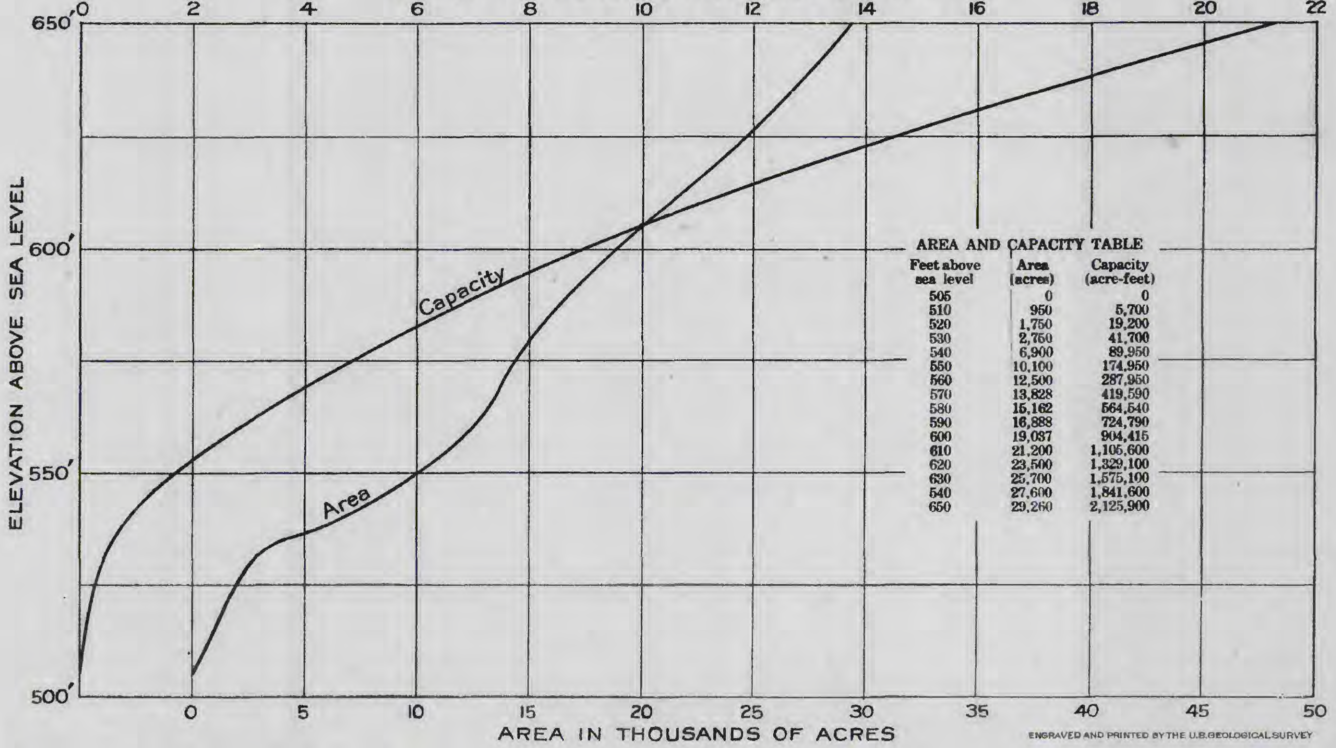
B. BULLS HEAD DAM SITE, 25 MILES DUE NORTH OF NEEDLES



Surveyed in 1903



CROSS SECTIONS AT DAM SITES (421 M.)



AREA AND CAPACITY TABLE

Feet above sea level	Area (acres)	Capacity (acre-feet)
505	0	0
510	950	5,700
520	1,750	19,200
530	2,750	41,700
540	6,900	89,950
550	10,100	174,950
560	12,500	287,950
570	13,828	419,590
580	15,162	564,540
590	16,888	724,790
600	19,037	904,415
610	21,200	1,105,600
620	23,500	1,329,100
630	25,700	1,575,100
540	27,600	1,841,600
650	29,260	2,125,900

MAP, CROSS SECTIONS, AND AREA AND CAPACITY CURVES FOR BULLS HEAD POWER SITE

APPENDIX A.—WATER SUPPLY

By E. C. LA RUE and GEORGE F. HOLBROOK

STREAM-FLOW RECORDS

The middle section of the basin of the Colorado is probably the most remote and inaccessible region within the domain of the United States exclusive of Alaska. Throughout the canyon region, from the mouth of Green River to the Grand Wash, a distance of 500 miles, there are only three points at which it is possible to reach the river with a wheeled vehicle. At a few other places pack animals may be taken to the water's edge. Because of the inaccessibility and the absence of permanent inhabitants in this region, no stream-gaging stations have been established here until recent years.

In the summer of 1921 the Geological Survey, in cooperation with the Southern California Edison Co., established a gaging station at Lees Ferry, Ariz. Early in 1923 a station was established at the mouth of Bright Angel Creek, in the Grand Canyon. The records obtained at these stations are good but cover only short periods. Estimates of the water supply available in this section of the river must be based on stream-flow records obtained in the upper basin or the record of discharge obtained by the Bureau of Reclamation at Yuma, Ariz. The short-time records obtained at Lees Ferry and Bright Angel have proved very useful in connection with the work of estimating the inflow to the river in the canyon section.

The Yuma record is continuous from the year 1902, the date of the beginning of construction on the Yuma project of the Bureau of Reclamation. The chief difficulty in applying this record to the canyon section lies in the fact that there is a large and variable loss of water by evaporation from the stream channel, especially from the overflowed lands in the valleys between Yuma and Pierces Ferry. These lands are submerged and saturated by the annual summer floods. The area thus flooded varies from year to year, and the considerable amount of water passing into the dry, heated desert air by evaporation and transpiration from the rank growth of vegetation also varies. It is impossible to estimate accurately the amount of water thus lost. A more accurate estimate of the water supply for the canyon section can be obtained from the records of the flow of the main stream and its tributaries in the upper basin.

The lowest gaging station on the Colorado above the Green at which a continuous record has been obtained is that at Fruita, Colo. This station, however, is above the mouth of Dolores River. Stations have been maintained for periods of a few years near Cisco and Moab, Utah. Both of these stations are low enough to catch practically all the run-off from the basin of the Colorado above the mouth of Green River. The records at Cisco and Moab, extended by comparison with the continuous record at Fruita, have therefore been used to represent the discharge of Colorado River above Green River from 1911 to 1923. This record is presented in column 3, Table 2.

Green River has been measured continuously at Little Valley, near Green River, Utah, from 1910 to 1923. San Rafael River, which is the only considerable tributary of the Green below Little Valley, has been measured near its mouth from 1909 to 1918, and stations were being maintained in its upper basin in 1923. By comparing the record of discharge of the San Rafael at its mouth with the sum of the records of its three largest tributaries, Huntington, Cottonwood, and Ferron creeks, the figures for the San Rafael have been extended through the years 1919 to 1923. These figures, added to those for the Green at Little Valley, give a reliable estimate of the total contribution of the Green River to the Colorado. It is presented in column 1, Table 2. The sum of the discharge of the Green at its mouth and of the Colorado above the mouth of the Green is given in column 4 of Table 2 and represents the flow of Colorado River in the section between Green and Fremont rivers. It is assumed that any slight inflow from springs or intermittent surface drainage between the principal tributaries above Lees Ferry, Ariz., will be balanced by the evaporation from the broad surface of the river through Glen Canyon.

The only tributaries to the river of any importance between the mouth of Green River and Lees Ferry are Fremont, Escalante, and San Juan rivers. Gaging stations were maintained on the headwaters of Fremont and Escalante rivers during the period 1909–1914. From the records of these stations it has been estimated that the average annual discharge of the Fremont is about 200,000 acre-feet. These streams flow out from the mountains of southern Utah, and their basins are adjacent to that of San Rafael River, for which there is an accurate record of discharge from 1911 to 1923. It is believed that the annual discharge of Fremont and Escalante rivers for any year of this period will bear the same relation to their mean annual discharge as the annual discharge of the San Rafael for that year bears to its mean annual discharge. A percentage factor based upon the San Rafael record has therefore been applied to the estimated mean annual discharges of Fremont and Escalante rivers to give an estimate of the annual run-off for each year of the period 1911–1923.

Figures for monthly run-off were obtained by applying to the annual discharge a percentage factor for each month of each year determined from the San Rafael record. Estimates of monthly discharge so obtained may, of course, be considerably in error for any individual month, but such errors will be compensating, and as the quantities involved are relatively small in comparison with the discharge of Colorado River, the errors become negligible when such quantities are added to the record of that stream.

Column 5, Table 2, which represents the flow in Colorado River in the section from the Fremont to the San Juan, is derived directly from column 4, by adding the computed flows of Fremont and Escalante rivers.

In the San Juan River basin stream-flow records have been obtained at several stations since 1904. For the purpose of this study it has been assumed that the record of discharge at any station below the mouth of Animas River would represent the flow of the San Juan at its mouth. This involves the same assumption as that made on the Colorado, namely, that inflow from springs and small intermittent streams is balanced by evaporation. From 1912 to 1923 the record is continuous at Farmington and Shiprock, N. Mex., and at Bluff, Utah. All these stations are below the mouth of the Animas. For the period 1907 to 1912 it is necessary to add the discharge of the Animas at Aztec, N. Mex., to that of the San Juan as measured at a station above the Animas. The monthly discharge record of the San Juan thus obtained is given in column 2, Table 2. The figures in column 2, added to those in column 5, which is the record of Colorado River above San Juan River, give column 6, which represents the flow of Colorado River from the mouth of the San Juan to Lees Ferry, Ariz.

At Lees Ferry a gaging station has been in operation since the summer of 1921. On September 30, 1923, two full climatic years of record were completed at this station. Table 1 is presented to show the variation between the figures computed as outlined above for these two years and the measured record:

TABLE 1.—*Comparison of measured record and computed figures showing the discharge of Colorado River at Lees Ferry, Ariz., 1922–23*

Climatic year	Measured discharge	Computed discharge	Error in computation	
			Acre-feet	Percentage of measured record
	Acre-feet	*Acre-feet*		
1922	16,372,000	16,422,000	+50,000	+0.3
1923	16,135,000	15,889,000	−246,000	−1.5

TABLE 2.—*Monthly discharge, in acre-feet, of Green, San Juan, and Colorado rivers, 1911–1923*

Month	Green River at mouth	San Juan River at mouth	Colorado River			
			Above mouth of Green River	Green River to Fremont River	Fremont River to San Juan River	San Juan River to Lees Ferry
	1	2	3	4	5	6
1911						
January	157,000	34,600	165,000	322,000	343,000	377,000
February	202,000	54,400	161,000	363,000	379,000	434,000
March	396,000	270,000	327,000	723,000	738,000	1,010,000
April	336,000	422,000	432,000	768,000	783,000	1,200,000
May	749,000	658,000	1,540,000	2,290,000	2,340,000	2,990,000
June	1,190,000	631,000	1,840,000	3,030,000	3,080,000	3,710,000
July	526,000	615,000	941,000	1,470,000	1,480,000	2,090,000
August	185,000	70,100	299,000	484,000	492,000	562,000
September	126,000	51,900	217,000	343,000	357,000	409,000
October	256,000	371,000	469,000	725,000	758,000	1,130,000
November	137,000	79,700	220,000	357,000	363,900	442,000
December	105,000	59,300	183,000	288,000	294,000	353,000
The year	4,365,000	3,317,000	6,794,000	11,163,000	11,407,000	14,707,000
1912						
January	109,000	60,000	172,000	281,000	286,000	346,000
February	108,000	57,000	156,000	264,000	270,000	327,000
March	233,000	70,700	225,000	458,000	467,000	538,000
April	396,000	99,900	387,000	783,000	791,000	891,000
May	1,020,000	461,000	2,000,000	3,020,000	3,060,000	3,520,000
June	2,330,000	557,000	2,710,000	5,040,000	5,180,000	5,740,000
July	1,010,000	278,000	1,400,000	2,410,000	2,430,000	2,710,000
August	427,000	110,000	487,000	914,000	921,000	1,030,000
September	219,000	54,000	251,000	470,000	475,000	529,000
October	249,000	58,100	280,000	529,000	564,000	622,000
November	221,000	64,900	229,000	450,000	468,000	533,000
December	96,400	30,600	198,000	294,000	298,000	329,000
The year	6,418,400	1,901,200	8,495,000	14,913,000	15,210,000	17,115,000
1913						
January	143,000	28,500	200,000	343,000	347,000	376,000
February	127,000	26,200	166,000	293,000	297,000	328,000
March	264,000	42,000	273,000	537,000	549,000	591,000
April	782,000	277,000	690,000	1,470,000	1,500,000	1,780,000
May	1,080,000	493,000	1,310,000	2,390,000	2,490,000	2,980,000
June	1,180,000	350,000	1,180,000	2,360,000	2,400,000	2,750,000
July	912,000	109,000	475,000	1,390,000	1,400,000	1,510,000
August	269,000	38,200	180,000	449,000	454,000	492,000
September	242,000	86,300	245,000	487,000	508,000	594,000
October	223,000	91,000	249,000	472,000	479,000	570,000
November	200,000	55,500	215,000	415,000	426,000	482,000
December	107,000	42,100	142,000	249,000	255,000	297,000
The year	5,529,000	1,638,800	5,325,000	10,855,000	11,105,000	12,745,000
1914						
January	123,000	36,700	180,000	303,000	308,000	345,000
February	151,000	104,000	152,000	303,000	308,000	412,000
March	401,000	213,000	224,000	625,000	633,000	846,000
April	765,000	267,000	584,000	1,350,000	1,370,000	1,640,000
May	1,850,000	488,000	2,080,000	3,930,000	4,080,000	4,570,000
June	2,220,000	589,000	2,810,000	5,030,000	5,180,000	5,770,000
July	854,000	262,000	1,130,000	1,980,000	2,010,000	2,270,000
August	287,000	124,000	499,000	786,000	790,000	914,000
September	158,000	95,800	265,000	423,000	425,000	521,000
October	253,000	189,000	374,000	627,000	642,000	831,000
November	164,000	94,000	209,000	373,000	377,000	471,005
December	97,800	62,700	144,000	242,000	248,000	310,000
The year	7,323,800	2,525,200	8,651,000	15,972,000	16,371,000	18,900,000
1915						
January	95,200	62,100	130,000	225,000	229,000	291,000
February	101,000	129,000	141,000	242,000	246,000	375,000
March	199,000	137,000	176,000	375,000	394,000	531,000
April	455,000	478,000	578,000	1,030,000	1,050,000	1,530,000
May	699,000	570,000	1,120,000	1,820,000	1,860,000	2,430,000
June	955,000	601,000	1,550,000	2,500,000	2,540,000	3,140,000
July	381,000	399,000	615,000	996,000	1,000,000	1,400,000

TABLE 2.—*Monthly discharge, in acre-feet, of Green, San Juan, and Colorado rivers, 1911–1923*—Continued

Month	Green River at mouth	San Juan River at mouth	Colorado River: Above mouth of Green River	Colorado River: Green River to Fremont River	Colorado River: Fremont River to San Juan River	Colorado River: San Juan River to Lees Ferry
	1	2	3	4	5	6
1915						
August	128,000	102,000	184,000	312,000	312,000	414,000
September	188,000	62,500	129,000	317,000	320,000	382,000
October	242,000	57,900	172,000	414,000	415,000	473,000
November	175,000	39,700	165,000	340,000	351,000	391,000
December	113,000	39,200	156,000	269,000	275,000	315,000
The year	3,731,200	2,677,400	5,116,000	8,840,000	8,992,000	11,672,000
1916						
January	110,000	80,600	181,000	291,000	296,000	377,000
February	134,000	80,500	186,000	320,000	327,000	407,000
March	581,000	382,000	422,000	1,000,000	1,030,000	1,420,000
April	637,000	450,000	756,000	1,390,000	1,410,000	1,860,000
May	1,320,000	574,000	1,680,000	3,000,000	3,050,000	3,620,000
June	1,430,000	625,000	2,010,000	3,440,000	3,520,000	4,150,000
July	645,000	317,000	855,000	1,500,000	1,520,000	1,840,000
August	375,000	438,000	633,000	1,010,000	1,040,000	1,480,000
September	157,000	154,000	286,000	443,000	449,000	603,000
October	359,000	483,000	424,000	783,000	861,000	1,340,000
November	157,000	61,900	206,000	363,000	370,000	432,000
December	132,000	41,100	167,000	299,000	307,000	348,000
The year	6,037,000	3,687,100	7,806,000	13,839,000	14,180,000	17,877,000
1917						
January	81,000	42,700	123,000	204,000	206,000	249,000
February	122,000	69,400	139,000	261,000	269,000	339,000
March	214,000	84,200	193,000	407,000	419,000	503,000
April	720,000	352,000	530,000	1,250,000	1,270,000	1,620,000
May	1,660,000	560,000	1,520,000	3,180,000	3,260,000	3,820,000
June	2,890,000	833,000	3,300,000	6,190,000	6,390,000	7,230,000
July	1,740,000	521,000	1,510,000	3,250,000	3,290,000	3,810,000
August	417,000	177,000	422,000	839,000	849,000	1,030,000
September	252,000	111,000	231,000	483,000	502,000	613,000
October	204,000	39,700	188,000	392,000	398,000	438,000
November	189,000	28,700	186,000	375,000	382,000	411,000
December	171,000	25,400	205,000	376,000	382,000	407,000
The year	8,660,000	2,844,100	8,547,000	17,207,000	17,617,000	20,470,000
1918						
January	147,000	28,200	185,000	332,000	337,000	365,000
February	140,000	43,600	175,000	315,000	321,000	365,000
March	258,000	115,000	270,000	528,000	538,000	653,000
April	391,000	182,000	430,000	821,000	831,000	1,010,000
May	857,000	364,000	1,550,000	2,410,000	2,420,000	2,780,000
June	1,760,000	470,000	2,590,000	4,350,000	4,410,000	4,880,000
July	741,000	173,000	727,000	1,470,000	1,520,000	1,690,000
August	210,000	94,600	206,000	416,000	427,000	522,000
September	161,000	117,000	243,000	404,000	415,000	532,000
October	231,000	29,600	220,000	451,000	459,000	489,000
November	183,000	48,100	215,000	398,000	404,000	452,000
December	134,000	33,800	170,000	304,000	310,000	343,000
The year	5,213,000	1,698,900	6,981,000	12,199,000	12,392,000	14,081,000
1919						
January	90,900	33,600	138,000	229,000	234,000	268,000
February	101,000	48,300	122,000	223,000	229,000	277,000
March	282,000	172,000	220,000	502,000	509,000	681,000
April	488,000	342,000	558,000	1,050,000	1,070,000	1,410,000
May	980,000	576,000	1,410,000	2,390,000	2,490,000	3,060,000
June	569,000	448,000	940,000	1,510,000	1,530,000	1,980,000
July	115,000	481,000	372,000	487,000	497,000	978,000
August	79,000	144,000	205,000	284,000	292,000	436,000
September	113,000	99,200	135,000	248,000	257,000	356,000
October	126,000	66,600	146,000	272,000	278,000	345,000
November	129,000	55,900	172,000	301,000	307,000	363,000
December	94,400	63,000	160,000	254,000	260,000	323,000
The year	3,167,300	2,529,600	4,578,000	7,750,000	7,953,000	10,477,000

TABLE 2.—*Monthly discharge, in acre-feet, of Green, San Juan, and Colorado rivers, 1911–1923*—Continued

Month	Green River at mouth	San Juan River at mouth	Colorado River: Above mouth of Green River	Colorado River: Green River to Fremont River	Colorado River: Fremont River to San Juan River	Colorado River: San Juan River to Lees Ferry
	1	2	3	4	5	6
1920						
January	112,000	132,000	165,000	277,000	282,000	414,000
February	144,000	212,000	180,000	324,000	330,000	542,000
March	249,000	262,000	192,000	441,000	448,000	710,000
April	394,000	429,000	272,000	666,000	674,000	1,100,000
May	1,710,000	1,000,000	2,830,000	4,540,000	4,640,000	5,640,000
June	2,090,000	879,000	3,090,000	5,180,000	5,280,000	6,160,000
July	639,000	337,000	1,060,000	1,700,000	1,710,000	2,050,000
August	286,000	151,000	374,000	660,000	672,000	823,000
September	156,000	62,400	198,000	354,000	361,000	423,000
October	164,000	64,800	240,000	404,000	410,000	475,000
November	201,000	50,100	230,000	431,000	437,000	487,000
December	121,000	34,700	178,000	299,000	305,000	340,000
The year	6,266,000	3,614,000	9,009,000	15,276,000	15,549,000	19,164,000
1921						
January	125,000	38,000	180,000	305,000	311,000	349,000
February	173,000	61,600	160,000	333,000	339,000	400,000
March	477,000	109,000	272,000	749,000	756,000	865,000
April	449,000	161,000	325,000	774,000	783,000	944,000
May	1,590,000	399,000	2,000,000	3,590,000	3,650,000	4,050,000
June	2,920,000	850,000	3,660,000	6,580,000	6,790,000	7,640,000
July	686,000	476,000	1,040,000	1,730,000	1,760,000	2,240,000
August	350,000	377,000	535,000	885,000	903,000	1,280,000
September	210,000	179,000	321,000	531,000	540,000	720,000
October	152,000	34,200	198,000	350,000	362,000	396,000
November	153,000	51,500	215,000	368,000	379,000	430,000
December	140,000	59,000	214,000	354,000	364,000	423,000
The year	7,425,000	2,795,300	9,120,000	16,549,000	16,937,000	19,737,000
1922						
January	114,000	36,400	164,000	278,000	288,000	324,000
February	142,000	120,000	134,000	276,000	283,000	403,000
March	401,000	237,000	245,000	646,000	656,000	893,000
April	369,000	298,000	434,000	803,000	816,000	1,110,000
May	1,720,000	837,000	2,280,000	4,000,000	4,100,000	4,940,000
June	2,320,000	780,000	2,120,000	4,440,000	4,570,000	5,350,000
July	547,000	149,000	485,000	1,030,000	1,060,000	1,210,000
August	263,000	46,400	247,000	510,000	529,000	576,000
September	179,000	22,700	151,000	330,000	340,000	363,000
October	131,000	20,700	138,000	269,000	275,000	296,000
November	159,000	23,300	188,000	347,000	354,000	377,000
December	139,000	34,300	189,000	328,000	338,000	372,000
The year	6,484,000	2,604,800	6,775,000	13,257,000	13,609,000	16,214,000
1923						
January	146,000	55,400	184,000	330,000	340,000	395,000
February	126,000	39,900	154,000	280,000	287,000	327,000
March	227,000	29,800	172,000	399,000	408,000	438,000
April	615,000	131,000	432,000	1,050,000	1,060,000	1,190,000
May	1,630,000	484,000	1,750,000	3,380,000	3,430,000	3,920,000
June	1,910,000	474,000	2,210,000	4,120,000	4,200,000	4,680,000
July	828,000	204,000	1,040,000	1,870,000	1,900,000	2,100,000
August	364,000	152,000	521,000	885,000	901,000	1,050,000
September	202,000	235,000	295,000	497,000	509,000	744,000
The period	6,048,000	1,805,100	6,758,000	12,811,000	13,035,000	14,844,000

The 13-year period from 1911 to 1923 is known to be an incomplete cycle of precipitation and run-off in the southwestern part of the United States. It does not include any period of years of abnormally low run-off such as occurred in the period 1900–1905. In the Colorado River basin a study of stream-flow records reveals the fact that the period 1911 to 1923 yielded a mean annual discharge 6 per cent larger than that of the 29-year period 1895 to 1923, even without making any allowance for the increased consumption of water by irrigation in the upper basin in recent years over that of the earlier years of the 29-year period. If such a correction for increased irrigation consumption is applied, the mean annual discharge for the 13-year period is 11 per cent larger than that for the 29-year period. Therefore, to obtain a more reliable estimate of water supply, it is necessary to extend the 13-year period of continuous stream-flow records back to include the preceding period of years of low run-off. This can be done in terms of estimated annual discharge only, as the measured records in the upper basin during these years, upon which such an estimate must be based, are incomplete. The annual discharge in acre-feet of Green and Colorado rivers for the period 1895 to 1910 is taken from Water-Supply Paper 395, published by the United States Geological Survey, 1916. These estimates are given in columns 1, 3, and 4 of Table 3. The figures in Table 3 for the years 1911 to 1922 are the totals for those years as given in Table 2.

Column 2, Table 3, gives the discharge of San Juan River at its mouth from 1895 to 1922. From 1907 to 1922 these figures represent measured records on lower San Juan River. Such records are lacking for the period 1895 to 1907, and except for the one year, 1905, during which a measured record was obtained at Farmington, N. Mex., an estimate of the annual discharge of San Juan River was made by three separate methods, and an average of these three was assumed to be the most probable figure. These methods were (1) by comparison with Colorado River below the mouth of Green River; (2) by comparison with Arkansas River at Canon City, Colo.; (3) by comparison with an average of the Rio Grande records near Del Norte, Colo., and near San Marcial, N. Mex.

The computed records of Fremont and Escalante rivers for the period 1911–1922 were extended back to 1895 by comparison with Colorado River below the Green, and, as in Table 2, the discharge of these streams added to that of the Colorado below the Green gives an estimate of the water supply in the Colorado from Fremont River to San Juan River. (See column 5, Table 3.) The addition of the San Juan record (column 2, Table 3) gives figures that represent the flow of the Colorado from San Juan River to Lees Ferry, as presented in column 6, Table 3.

TABLE 3.—*Annual discharge, in acre-feet, of Green, San Juan, and Colorado rivers for calendar years 1895–1922*

Year	Green River at mouth	San Juan River at mouth	Colorado River: Above mouth of Green River	Colorado River: Green River to Fremont River	Colorado River: Fremont River to San Juan River	Colorado River: San Juan River to Lees Ferry
	1	2	3	4	5	6
1895	4,520,000	2,080,000	6,360,000	10,900,000	11,100,000	13,200,000
1896	4,320,000	1,530,000	6,790,000	11,100,000	11,300,000	12,800,000
1897	6,460,000	2,660,000	8,260,000	14,700,000	15,000,000	17,700,000
1898	5,430,000	1,880,000	4,850,000	10,300,000	10,500,000	12,400,000
1899	8,480,000	2,380,000	8,900,000	17,400,000	17,900,000	20,300,000
1900	3,820,000	1,800,000	6,880,000	10,700,000	10,900,000	12,700,000
1901	4,600,000	1,700,000	7,010,000	11,600,000	11,800,000	13,500,000
1902	3,600,000	847,000	4,280,000	7,880,000	8,010,000	8,850,000
1903	4,960,000	2,030,000	5,650,000	10,600,000	10,800,000	12,800,000
1904	5,320,000	1,500,000	5,070,000	10,400,000	10,600,000	12,100,000
1905	4,120,000	2,790,000	6,490,000	10,600,000	10,800,000	13,600,000
1906	6,670,000	2,700,000	7,690,000	14,400,000	14,700,000	17,400,000
1907	9,250,000	3,430,000	7,900,000	17,200,000	17,700,000	21,100,000
1908	4,390,000	1,860,000	4,660,000	9,050,000	9,200,000	11,100,000
1909	9,040,000	3,270,000	8,470,000	17,500,000	18,000,000	21,200,000
1910	4,900,000	1,610,000	5,830,000	10,700,000	10,900,000	12,500,000
1911	4,360,000	3,320,000	6,790,000	11,200,000	11,400,000	14,700,000
1912	6,420,000	1,900,000	8,500,000	14,900,000	15,200,000	17,100,000
1913	5,530,000	1,640,000	5,320,000	10,900,000	11,100,000	12,700,000
1914	7,320,000	2,530,000	8,650,000	16,000,000	16,400,000	18,900,000
1915	3,730,000	2,680,000	5,120,000	8,840,000	8,990,000	11,700,000
1916	6,040,000	3,690,000	7,810,000	13,800,000	14,200,000	17,900,000
1917	8,660,000	2,840,000	8,550,000	17,200,000	17,600,000	20,500,000
1918	5,210,000	1,700,000	6,980,000	12,200,000	12,400,000	14,100,000
1919	3,170,000	2,530,000	4,580,000	7,750,000	7,950,000	10,500,000
1920	6,270,000	3,610,000	9,010,000	15,300,000	15,500,000	19,200,000
1921	7,420,000	2,800,000	9,120,000	16,500,000	16,900,000	19,700,000
1922	6,480,000	2,600,000	6,780,000	13,300,000	13,600,000	16,200,000
Mean	5,730,000	2,350,000	6,870,000	12,600,000	12,900,000	15,200,000

PAST DEPLETION

Table 3 represents the flow of Colorado River during the period 1895–1922. At the beginning of that period the irrigated areas in the upper basin were much smaller than in 1922. A large part of the water consumed by growing crops in 1922 was running to waste in the river channel in 1895. Each new development in the upper basin took its toll of the waters of the river. If the same climatic conditions that occurred in the 28-year period 1895 to 1922 were to be repeated in the succeeding 28 years and if there were no further increase in irrigation, the quantity of water discharged by the stream in any year in the later period would be less than that of the recorded discharge for the corresponding year in the earlier period by an amount equal to the increase of irrigation consumption in 1922 over that in the given year. Therefore, to obtain an estimate of the water supply in the river in 1923, for example, it would be necessary to deduct from the recorded discharge for each year in the period 1895 to 1922 an amount sufficient to satisfy the consumptive use of the area placed under irrigation since that year. Thus a decreasing minus correction must be applied to the record, ranging from 1,810,000 acre-feet in 1895 to zero in 1922. (See Table 6.)

This "correction for past depletion" is based on a consumptive use of 1½ acre-feet annually per acre irrigated. The following table, taken from an unpublished report of the Bureau of Reclamation,[1] shows the distribution through the year of the past irrigation depletion in the upper basin of the Colorado:

TABLE 4.—*Monthly irrigation depletion, in acre-feet per acre, in upper basin of Colorado River, 1895–1922*

	Average diversion	Return flow	Consumptive use	
			Acre-feet	Per cent of total
January	0	0.05	−0.05	−3.3
February	0	.05	−.05	−3.3
March	0	.05	−.05	−3.4
April	.2	.05	.15	+10
May	.4	.10	.30	+20
June	.7	.20	.50	+33.3
July	.8	.30	.50	+33.3
August	.6	.30	.30	+20
September	.3	.20	.10	+6.7
October	0	.10	−.10	−6.7
November	0	.05	−.05	−3.3
December	0	.05	−.05	−3.3
	3	1.50	1.50	100

Data obtained from the United States Census Bureau and other sources were used by the Bureau of Reclamation to estimate the area that has been irrigated in the upper basin of the Colorado. The results of these estimates are given in Table 5:

TABLE 5.—*Increase in area of land under irrigation in upper basin of Colorado River, 1899–1922*

Year	Total area irrigated	Year	Total area irrigated
	Acres		*Acres*
1899	530,000	1919	1,400,000
1902	650,000	1922	1,500,000
1909	1,000,000		

By interpolating between the dates given in Table 5 and applying a consumptive use of 1½ acre-feet to the acre, an estimate is made of the water consumed each year in the upper basin. Transmountain diversions from the upper basin, which began in 1906, increased slowly for several years, increased rapidly through the period 1914–1917, and reached 115,000 acre-feet by 1922.

[1] Presented to the Committee on Irrigation and Reclamation, House of Representatives, February, 1924.

TABLE 6.—*Correction for past depletion in upper basin of Colorado River, 1895–1922*

Year	Area irrigated above Lees Ferry, Ariz.	Water consumed at 1.5 acre-feet per acre	Transmountain diversion	Total water consumed	Total past depletion applicable at Lees Ferry, Ariz.
	1	2	3	4	5
	Acres	*Acre-feet*	*Acre-feet*	*Acre-feet*	*Acre-feet*
1895	370,000	555,000		555,000	1,810,000
1896	410,000	615,000		615,000	1,750,000
1897	450,000	675,000		675,000	1,690,000
1898	490,000	735,000		735,000	1,630,000
1899	530,000	795,000		795,000	1,570,000
1900	570,000	855,000		855,000	1,510,000
1901	610,000	915,000		915,000	1,450,000
1902	650,000	975,000		975,000	[a]1,043,000
1903	700,000	1,050,000		1,050,000	[a]986,000
1904	750,000	1,125,000		1,125,000	[a]930,000
1905	800,000	1,200,000		1,200,000	1,165,000
1906	850,000	1,275,000	1,000	1,276,000	1,089,000
1907	900,000	1,350,000	2,000	1,352,000	1,013,000
1908	950,000	1,425,000	2,000	1,427,000	938,000
1909	1,000,000	1,500,000	3,000	1,503,000	862,000
1910	1,040,000	1,560,000	4,000	1,564,000	801,000
1911	1,080,000	1,620,000	5,000	1,625,000	740,000
1912	1,120,000	1,680,000	6,000	1,686,000	679,000
1913	1,160,000	1,740,000	11,000	1,751,000	614,000
1914	1,200,000	1,800,000	16,000	1,816,000	549,000
1915	1,240,000	1,860,000	36,000	1,896,000	469,000
1916	1,280,000	1,920,000	66,000	1,986,000	379,000
1917	1,320,000	1,980,000	86,000	2,066,000	299,000
1918	1,360,000	2,040,000	86,000	2,126,000	239,000
1919	1,400,000	2,100,000	96,000	2,196,000	169,000
1920	1,433,000	2,150,000	103,000	2,253,000	112,000
1921	1,467,000	2,200,000	109,000	2,309,000	56,000
1922	1,500,000	2,250,000	115,000	2,365,000	

[a] Reduced 25 per cent because of extremely low run-off.

Column 5 of Table 6 gives the total past depletion by which the record of discharge of the river at or below Lees Ferry, Ariz., must be corrected to make it applicable to present-day conditions. The years 1902, 1903, and 1904 cover a period of unusually low run-off, and as it is probable that less than the normal amount was diverted in those years the correction for past depletion is accordingly reduced 25 per cent.

FUTURE DEPLETION

As irrigation and the development of power in the upper basin continue to advance, there will be still greater demands for water from the upper tributaries of Colorado River. Losses by evaporation from new power reservoirs will occur, and new irrigated areas will consume their share of the total run-off.

In the past irrigation has been confined mainly to the valleys of the streams from which the water was diverted. The irrigated lands are usually well drained, and the surplus water used has not had far to go before appearing as return flow. Much of the area remaining to be reclaimed lies at some distance from the streams that will supply the water, giving greater opportunity for losses by evaporation from canals and drainage ditches. Future diversion to lands outside the basin will yield no return flow to the Colorado. Many regulating reservoirs will be required to insure an adequate water supply in years of scant precipitation, and each of these reservoirs will contribute to the increased evaporation losses. The consumptive use of water for these new projects must accordingly be variably estimated to fit the conditions of each project or area.

From information furnished by the States in the upper basin and gathered from other sources, the Bureau of Reclamation[2] has made an estimate of the areas in which future reclamation by irrigation from Colorado River is feasible. Classified into drainage areas and somewhat condensed, this estimate is reproduced in Table 7:

TABLE 7.—*Summary of future irrigation development, in acres, in upper basin of Colorado River*

Drainage area	Near future	Distant future	Total
Green River in Wyoming	373,000	135,000	508,000
White and Yampa rivers	360,000	30,000	390,000
Uinta Basin	140,000	29,000	169,000
Colorado River in Colorado	602,000	288,000	890,000
San Juan Basin	193,000	460,000	653,000
Colorado River in southeastern Utah	103,000	27,000	130,000
	1,771,000	969,000	2,740,000

The consumptive use of water by these areas will vary. An estimate by the Bureau of Reclamation gives a total consumption of 5,376,000 acre-feet of water annually, which is equal to an average rate for the total area of 1.96 acre-feet to the acre. This figure includes losses by evaporation from power and irrigation reservoirs to be constructed in the upper basin above the Glen Canyon reservoir site. The Bureau of Reclamation estimates that ultimately the total transmountain diversion from the Colorado River basin will be 554,000 acre-feet of water a year, or 439,000 acre-feet more than was diverted in 1922. This increased diversion, added to the future consumption for irrigation and power within the upper basin, gives a total future annual depletion of 5,815,000 acre-feet.

In estimating past depletion it was recognized that during the period of dry years 1902–1904 it would have been difficult to divert as much water at many points high in the basin as was used in a normal year, and accordingly the past depletion was reduced 25 per cent for those years. It is believed that this effect will occur even more frequently in the future, when the irrigation demand shall have equaled or exceeded the normal low-water flow of many of the streams. Therefore, the estimated correction for future irrigation depletion (5,815,000 acre-feet) has been reduced 15 per cent for those years in which the flow available at Lees Ferry with development as in 1922 (column 3, Table 8) fell below the arbitrary amount

[2] Unpublished report presented to the Committee on Irrigation and Reclamation, House of Representatives, February, 1924.

of 12,000,000 acre-feet. As this shortage occurred in 11 years in the 28-year period, or only 40 per cent of the time, and under the same climatic conditions would be experienced by only a part of the increased irrigated area, a reduction of 15 per cent in the depletion estimate seems ample.

Column 1, Table 8, represents the flow of Colorado River at Lees Ferry as computed from records of discharge in the upper basin. Column 2 gives the estimated past irrigation depletion in the upper basin, which deducted from column 1 gives column 3. Column 3 therefore represents the water supply at Lees Ferry that will be available for future irrigation and power development. It is the water left in the river with development at the stage reached in 1922. Column 4 gives the correction for future depletion in the upper basin, the estimated depletion being reduced 15 per cent for certain years, as explained in the preceding paragraph. This subtracted from column 3 yields column 5, which shows the flow that it is estimated will be available at Lees Ferry when the demand for future development within and diversions from the upper basin shall have been satisfied.

TABLE 8.—*Annual discharge of Colorado River at Lees Ferry, in acre-feet, corrected for past and future irrigation depletion*

Year	Flow as measured (column 6, Table 3)	Correction for past depletion (column 5, Table 6)	Flow corrected for past depletion (column 1 minus column 2)	Correction for future depletion	Flow corrected for past and future depletion (column 3 minus column 4)
	1	2	3	4	5
1895	13,200,000	1,810,000	11,390,000	4,943,000	6,450,000
1896	12,800,000	1,750,000	11,050,000	4,943,000	6,110,000
1897	17,700,000	1,690,000	16,010,000	5,815,000	10,200,000
1898	12,400,000	1,630,000	10,770,000	4,943,000	5,830,000
1899	20,300,000	1,570,000	18,730,000	5,815,000	12,900,000
1900	12,700,000	1,510,000	11,190,000	4,943,000	6,250,000
1901	13,500,000	1,450,000	12,050,000	5,815,000	6,240,000
1902	8,850,000	[a]1,040,000	7,810,000	4,943,000	2,870,000
1903	12,800,000	[a]986,000	11,814,000	4,943,000	6,870,000
1904	12,100,000	[a]930,000	11,170,000	4,943,000	6,230,000
1905	13,600,000	1,160,000	12,440,000	5,815,000	6,620,000
1960	17,400,000	1,090,000	16,310,000	5,815,000	10,500,000
1907	21,100,000	1,010,000	20,090,000	5,815,000	14,300,000
1908	11,100,000	938,000	10,162,000	4,943,000	5,220,000
1909	21,200,000	862,000	20,338,000	5,815,000	14,500,000
1910	12,500,000	801,000	11,699,000	4,943,000	6,760,000
1911	14,700,000	740,000	13,960,000	5,815,000	8,140,000
1912	17,100,000	679,000	16,421,000	5,815,000	10,600,000
1913	12,700,000	614,000	12,084,000	5,815,000	6,270,000
1914	18,900,000	549,000	18,351,000	5,815,000	12,500,000
1915	11,700,000	469,000	11,231,000	4,943,000	6,290,000
1916	17,900,000	379,000	17,521,000	5,815,000	11,700,000
1917	20,500,000	299,000	20,201,000	5,815,000	14,400,000
1918	14,100,000	239,000	13,861,000	5,815,000	8,050,000
1919	10,500,000	169,000	10,331,000	4,943,000	5,390,000
1920	19,200,000	112,000	19,088,000	5,815,000	13,300,000
1921	19,700,000	56,000	19,644,000	5,815,000	13,800,000
1922	16,200,000		16,200,000	5,815,000	10,400,000
Mean	15,200,000		14,400,000		8,880,000

[a] Reduced 25 per cent because of extremely low run-off.

WATER SUPPLY FOR POWER

A study of the data now available indicates that about 13 projects will be necessary for complete development of the power resources of Colorado River between the mouth of Green River, Utah, and Parker, Ariz. The exact location of these power sites may not be determined for some time, but for the purpose of studying the power value of the stream the writer has selected a series of dam sites so located that their development to full capacity would utilize practically all the fall in that section of the river. In Table 9 an attempt has been made to estimate the water supply available for power at these sites.

TABLE 9.—*Water supply of Colorado River available below mouth of Green River, in second-feet*

Dam site	With development as in 1922 (corrected for past depletion)			With ultimate development (corrected for past and future depletion)
	With storage in Glen Canyon	Without storage		
		50 per cent of time	90 per cent of time	
	1	2	3	4
Dark Canyon	----------	7,540	4,650	9,840
Glen Canyon	19,300	9,540	5,780	12,000
Redwall	19,500	9,640	5,880	12,200
Mineral Canyon	20,500	10,200	6,400	12,800
Ruby Canyon	20,800	10,200	6,500	13,000
Specter Chasm	21,000	10,300	6,580	13,200
Havasu	21,700	19,700	6,920	13,900
Prospect	22,000	10,800	7,000	14,200
Diamond Creek	22,300	10,900	7,180	14,400
Travertine Canyon	22,300	10,900	7,230	14,400
Bridge Canyon	22,400	10,900	7,270	14,440
Devils Slide	22,500	11,000	7,330	14,540
Pierces Ferry	22,600	11,100	7,330	----------
Hualpai Rapids	22,600	11,100	7,330	14,600
Lower Black Canyon	22,600	11,100	7,330	14,480
Mohave Canyon	22,100	11,100	7,330	13,970
Parker	22,100	11,100	7,330	13,940

Columns 1, 2, and 3 of Table 9 show the water supply available with development in the upper basin as it existed in 1922. These figures represent the water that would have been available for the generation of power in the canyon section of the river in 1923.

Column 1 shows the water supply available at Lees Ferry and below, with storage in the Glen Canyon reservoir sufficient for complete regulation of the river. A mass diagram of the discharge at Lees Ferry from 1895 to 1922, corrected for past depletion (column 3, Table 8), indicates that, evaporation being neglected, a storage capacity of about 27,000,000 acre-feet will be required to yield a regulated flow of 19,900 second-feet, the mean annual discharge under these conditions. Computing from the same diagram the mean quantity of water in storage and applying to the corresponding area an annual evaporation of 5 acre-feet per acre of water surface gives an estimated evaporation loss of 440,000 acre-feet a year, or 600 second-feet continuous flow. Thus 19,300 second-feet should be available at Lees Ferry if sufficient storage were provided in Glen Canyon to regulate the river completely.

It should be kept in mind, however, that if storage were provided in the basin above Lees Ferry, the amount of storage required at Lees Ferry to effect complete regulation of the flow would be greatly reduced. Probably the cost of such regulation would be greater than would be warranted by the benefits accruing from it at any time in the near future, and therefore an estimate of water supply available at the present time, as affected by such complete regulation, may have no bearing upon the problems that are pressing for early solution. It is possible that if large power developments are made in the canyon section below Lees Ferry, a large regulating and desilting reservoir below San Juan River will be an important factor in the economy of operation and maintenance of the power plants. The estimate given in column 1 may therefore be considered to represent the maximum water supply that it is possible to develop in the Grand Canyon section of the river. Some portion of this greater supply may be utilized if the rate of power development in the canyon should much exceed that of future irrigation development in the upper basin.

Columns 2 and 3 of Table 9 show the flow at Lees Ferry that may be expected under present conditions of development, without regulation, to be maintained for 50 per cent and 90 per cent, respectively, of the time. These figures are based upon the monthly discharge for 1911–1923 presented in Table 2 in columns 4 and 6. The figures in these columns, corrected for past depletion by quantities derived by computation from those given in column 5, Table 6, indicate that the unregulated flow at Lees Ferry for 50 and 90 per cent of the time is 9,540 and 5,780 second-feet, respectively.

Between Lees Ferry and Bright Angel Creek there is considerable inflow to Colorado River. The greater part of this comes from the basin of the Little Colorado. The records of the gaging stations at Lees Ferry and Bright Angel for the year ending September 30, 1923, indicate that 911,000 acre-feet of water entered the river between these gaging stations. For the same period the Topock record shows a gain of 1,129,000 acre-feet over the Bright Angel record. As there is practically no inflow to the river between Virgin and Williams rivers, the gain at Topock should be credited to the innumerable side canyons and springs in the bottom of the Grand Canyon below the Bright Angel gaging station.

The Grand Canyon section of Colorado River ends at the Grand Wash Cliffs, near the Pierces Ferry dam site, about 45 miles above the mouth of Virgin River. Below this point the stream flows alternately between canyon walls and in open valleys. The grade of the river here is comparatively slight, and in the valleys the course is meandering and the channel wide and shallow. A slight increase above the low-water stage is sufficient to flood thousands of acres of bottom land in these valleys. It has been estimated that the annual loss of water by evaporation from these overflowed lands between Pierces Ferry and Topock is 380,000 acre-feet. Thus the 1,129,000 acre-feet of water gained in 1923 between Bright Angel Creek and Topock is the net result of the inflow in the canyon section minus the large evaporation losses in the open valleys. The actual inflow between Bright Angel and Pierces Ferry in that year was about 1,509,000 acre-feet.

It is apparent that the total net gain between gaging stations is not a true measure of the increase in the water-power value of the stream as it descends from Lees Ferry. Some of this inflow is discharged as sudden, flashy floods from the larger tributary canyons and therefore would not be available for the development of power except at certain reservoir sites that might be operated partly for flood control. The erratic distribution through the year of this gain between the stations is shown in Table 10:

TABLE 10.—*Discharge of Colorado River at Lees Ferry, Bright Angel Creek, and Topock for the year ending September 30, 1923, in acre-feet, showing increase between stations*

Month	Lees Ferry	Bright Angel Creek		Topock	
		Increase	Total	Increase	Total
October	289,000	35,000	324,000	43,000	367,000
November	399,000	27,000	426,000	43,000	469,000
December	397,000	40,000	437,000	89,000	526,000
January	373,000	28,000	401,000	39,000	440,000
February	339,000	30,000	369,000	45,000	414,000
March	447,000	52,000	499,000	50,000	549,000
April	1,270,000	40,000	1,310,000	−20,000	1,290,000
May	3,510,000	60,000	3,570,000	−270,000	3,300,000
June	4,560,000	80,000	4,640,000	480,000	5,120,000
July	2,320,000		2,320,000	390,000	2,710,000
August	1,350,000	90,000	1,440,000	160,000	1,600,000
September	881,000	429,000	1,310,000	80,000	1,390,000
	16,135,000	911,000	17,046,000	1,129,000	18,175,000

The large gain in September, 1923, between Lees Ferry and Bright Angel Creek was caused by an unusual flood of several days' duration which came out of the basin of the Little Colorado. It will be noted that the increases from October to March are fairly consistent in the two sections of the river, being somewhat larger in the lower section, but that from April to September the increase is very erratic, ranging in July from nothing in the upper section to 390,000 acre-feet in the lower section, and in May from 60,000 acre-feet in the upper section to a decrease of 270,000 acre-feet in the lower section.

This erratic effect is caused partly by the time required for the water to flow between the gaging stations but chiefly by the influence of change in the amount of water stored in the river channel with wide changes in the stage of the river. As the annnal summer flood is large in volume and of long duration, the disturbing effect of fluctuations in channel storage is chiefly apparent during the months April to September. However, the increments of increase in discharge below Lees Ferry from one power site to the next that affect the power value of the stream 50 and 90 per cent of the time, without storage at the respective sites, are not the large gains occurring during the floods of the summer but the more uniform gains occurring during the winter.

An inspection of the gage-height records of the three stations shows that from December 1, 1922, to March 31, 1923, there was only a slight change in stage of the river at these stations; therefore during that period there could have been no pronounced change in channel storage. The increase in flow between stations during that period has therefore been accepted as a measure of the increase in the power value of the stream for 50 and 90 per cent of the time.

The total increase in discharge between Lees Ferry and Bright Angel Creek during the four-month period was 150,000 acre-feet, equal to a uniform flow of 620 second-feet. That between Bright Angel Creek and Topock was 223,000 acre-feet, or a continuous flow of 930 second-feet.

During the progress of the topographic surveys of the Grand Canyon in 1923 the discharge of all tributaries from Lees Ferry to Virgin River was measured or estimated. (See Table 11.) Such miscellaneous measurements, of course, form no basis for an accurate estimate of monthly or annual discharge of a stream, but they may be and have been used here to indicate in a general way the tributaries from which the inflow came that was measured at the gaging stations on the main river. In apportioning this inflow to obtain the figures given in columns 2 and 3, Table 9, consideration was also given to the areas of the several tributary basins.

TABLE 11.—*Discharge of tributaries of Colorado River between Lees Ferry and Topock, Ariz.*

[Measurements and estimates made by E. C. La Rue]

Tributary	Distance below Paria River	Discharge	Date (1923)
	Miles	*Sec.-ft.*	
Paria River	0	[a]3	Aug. 1
Threemile Wash	3	0	1
Fourmile Wash	4	0	1
Fivemile Wash	5	0	1
Sixmile Wash	6	0	1
Badger Creek	8	0	1
Soap Creek	11	0	2
House Rock Canyon	17	0	4
Eighteen Mile Wash	18	0	5
Nineteen Mile Canyon	19	0	5
North Canyon	20	0	5
Twentytwo Mile Wash	22	0	6
Twentyfour Mile Wash	24	0	6
Cave Springs	25.2	[a].5	6
Twentynine Mile Canyon	29	0	6
Springs	30.2	[a].5	7
Paradise Canyon	31.6	0	7
Vaseys Paradise Springs	32	[a]10	8
South Canyon	41	0	9
Saddle Canyon	47	0	11
Little Nankoweap Creek	52	0	12
Nankoweap Creek	52.3	3.13	12
Kwagunt Creek	56	Seep.	12
Malgosa Canyon	57.5	0	13
Awatubi Canyon	58	0	13
Sixty Mile Canyon	60	0	13
Little Colorado River	61.5	[a]1,500	13
Carbon Canyon	64.6	0	14
Lava Canyon	65.5	0	14
Comanche Creek	67	0	14
Tanner Canyon	68.6	0	14
Basalt Creek	69.5	0	14
Cardenas Creek	71.3	0	14
Unkar Creek	72.5	0	14
Seventyfive Mile Creek	75.5	0	15
Seventysix Mile Canyon	76	0	15
Red Canyon	77	0	16
Mineral Canyon	77.8	0	17
Asbestos Canyon	78	0	21
Hance Creek	78.6	[a].2	21
Cottonwood Creek	80.5	0	21
Vishnu Creek	81	0	21
Grapevine Creek	81.4	0	22
Boulder Creek	82.7	0	22
Lonetree Canyon	83.9	0	22
Clear Creek	84.1	[a]3.0	22
Zoroaster Canyon	84.6	0	22
Cremation Canyon	86	0	23
Bright Angel Creek	87.7	32.8	25
Pipe Creek	89	1.0	28
Horn Creek	90	0	28
Ninetyone Mile Creek	91	0	28
Trinity Creek	91.5	0	28
Salt Creek	92.5	0	28
Monument Creek	93.5	0	28
Ninetyfour Mile Creek	94	0	28
Hermit Creek	95	[a]1.0	30
Boucher Creek	96.5	.6	30
Crystal Creek	98	2.0	30
Slate Creek	98	0	30
Tuna Creek	99	.5	31
Agate Canyon	100.5	0	31

Tributary	Distance below Paria River	Discharge	Date (19)
	Miles	*Sec.-ft.*	
Sapphire Canyon	101	0	Aug. 31
Turquoise Canyon	102	0	31
Ruby Canyon	104.5	0	Sept. 1
Serpentine Canyon	106	0	1
Bass Canyon	107.5	0	1
Hotauta Canyon	107.7	0	2
Shinumo Creek	108.5	15.5	3
Copper Canyon	110	0	4
Hakatai Canyon	111	0	4
Walthenberg Canyon	112	0	5
Garnet Canyon	114.5	0	5
Elves Chasm	116.5	[a].5	5
Hundred and Nineteen Mile Creek	119	0	5
Hundred and Twenty Mile Creek	120	0	5
Hundred and Twenty-two Mile Creek	122	0	6
Forster Canyon	123	0	6
Fossil Canyon	125	0	6
Hundred and Twenty-seven mile Creek	127	0	6
Hundred and Twenty-eight Mile Creek	127	0	6
Specter Chasm	129	0	6
Hundred and Thirty Mile Creek	130.4	[a]2.0	7
Galloway Canyon	131.6	[a].9	7
Stone Creek	131.8	[a]1.2	8
Hundred and Thirty-three Mile Creek	133	0	8
Tapeats Creek	133.6	93.9	9
Deer Creek	136.2	8.2	10
Springs 300 feet below Deer Creek	136.3	[a]4.0	10
Fishtail Canyon	139	0	10
Hundred and Forty Mile Canyon	140	0	10
Kanab Creek	143.5	3.8	11
Olo Canyon	145.5	0	12
Matkatamiba Canyon	148	1.0	12
Hundred and Fifty Mile Canyon	150	0	13
Green Alcove, small spring	151.8	[a].2	13
Sinyala Canyon	153.3	0	13
Havasu Creek	156.7	74.5	13
Hundred and Sixty-four Mile Canyon	164.5	0	15
Cataract Canyon	166.5	[a]1.0	16
Fern Glen Canyon	168.1	[a].5	16
Stairway Canyon	171	0	17
Gateway Canyon	171.5	[a].5	17
Red Slide Canyon	174.3	0	17
Lava Falls, Warm Springs	179.3	[a]15.0	18
Hundred and Eighty-eight Mile Canyon	188	0	23
Hundred and Ninety-two Mile Canyon	192	0	23
Hundred and Ninety-three Mile Canyon	192.7	0	23
Boulder Wash	193.1	0	24
Hundred and Ninety-four Mile Canyon	194.5	0	24
Hundred and Ninety-six Mile Creek	196.5	0	24

[a] Estimated.

TABLE 11.—*Discharge of tributaries of Colorado River between Lees Ferry and Topock, Ariz.*—Continued

Tributary	Distance below Paria River	Discharge	Date (1923)
	Miles	*Sec.-ft.*	
Parashont Wash	198.5	0	Sept. 25
Spring Canyon	204.3	[a].3	26
Indian Canyon	206.6	0	27
Two Hundred and Nine Mile Canyon	208.7	0	27
Granite Park Canyon	209	0	28
Fall Canyon	211.6	0	29
Two Hundred and Fourteen Mile Creek	214	0	29
Two Hundred and Fifteen Mile Creek	215	0	92
Three Springs Canyon	215.6	[a].2	30
Two Hundred and Seventeen Mile Canyon	217.4	0	30
Trail Canyon	219.3	0	30
Two Hundred and Twenty Mile Canyon	219.8	0	Oct. 1
Granite Spring Canyon	220.4	Seep.	1
Two Hundred and Twentytwo Mile Creek	222	0	1
Two Hundred and Twentyfour Mile Canyon	223.7	0	2
Diamond Creek	225.8	2.2	4
Two Hundred and Twentyeight Mile Canyon	228	Seep.	Oct. 6
Travertine Canyon	229	[a]1.5	7
Travertine Falls	230.5	[a].5	8
Bridge Canyon	235	[a].2	8
Gneiss Canyon	235.7	0	9
Separation Canyon	239.5	[a].2	9
Spencer Canyon	246	4.4	11
Surprise Canyon	248.4	[a].5	13
Lost Creek	249	[a].7	13
Reference Point Creek	252.3	[a].2	13
Salt Creek	255.3	0	13
Small Waterfall	259.8	([b])	15
Travertine Warm Spring	267.7	([b])	15
Do	268.7	([b])	15
Do	269.2	([b])	15
Do	274.2	([b])	15
Travertine Warm Spring, long series	276	([b])	15
Grapevine Wash	279.3	0	15
Grand Wash	284.6	[a].5	15
Hualpai Wash	301.4	[a].3	16
Salt Springs Wash	307.4	0	16
Virgin River	323	Seep.	16
Detrital Wash	325.5	0	17
Callville Wash	343	0	17
Las Vegas Wash	348.3	0	17

[a] Estimated. [b] No estimate.

Column 4 of Table 9 is an estimate of the water supply that will be available in the canyon section when ultimate development for power and irrigation has been reached in the upper basin. At that time there will be more or less complete regulation of every large tributary in the upper basin, incidental to the development of water supply for many new power and irrigation projects. As a result, a very moderate amount of storage will be necessary in Glen Canyon to afford complete regulation of the flow at that point for power.

The mean given in column 5 of Table 8 (p. 112) represents the estimated amount of water that will be available at Lees Ferry after complete development in the upper basin has been reached. The figures in this column indicate that the annual flow at Lees Ferry might range from 2,870,000 to 14,500,000 acre-feet. Probably, however, no such range would occur. As the flow would be regulated for the development of power and as there would be only a small variation in the amount of return flow from year to year, it is apparent that there would be but a relatively small annual variation in the amount of water reaching Lees Ferry. A small amount of storage in Glen Canyon would make possible a fairly complete regulation of the flow at Lees Ferry. It therefore seems reasonable to believe that in the distant future 12,000 second-feet or more can be made available for developing power at Lees Ferry and in the canyon section below.

If the power plants that may be built below Lees Ferry are to be operated in conjunction with a plant at that place to develop a maximum of power from the stream it would be possible to regulate the flow of the river at Lees Ferry in such a way that the maximum use could be made of the inflow from the streams below that point. For this reason the figures showing the increments of increase in flow from site to site in columns 1 and 4, Table 9, are based upon the total annual inflow to the river. The only exception to this is in the section between the Redwall dam site and the Mineral Canyon dam site. The Little Colorado enters the main stream in this section, and it is believed that future irrigation development in the basin of the Little Colorado will decrease the mean annual discharge of the stream about 50 per cent at its mouth.

In column 4, Table 9, allowance has been made for losses by evaporation from the reservoir in Glen Canyon. Power reservoirs through the Grand Canyon will change the character of the stream in that section to such an extent by reducing velocities and smothering rapids that it is difficult to determine their effect upon evaporation from the water surface. The total reservoir area between Lees Ferry and Havasu Creek will be about 14,200 acres, or 9,500 acres greater than the natural stream surface, but any tendency to increase of evaporation because of the larger surface area may be offset by a lower rate of evaporation from the quiet water. Therefore, no allowance has been made for losses by evaporation in the canyon region between Lees Ferry and Havasu Creek.

The figures given in column 4 of Table 9 represent the water supply available at each of the several dam sites after that part of the river above the site has been developed in accordance with the plan outlined in this report. For the sites below Havasu Creek a correction was made for losses due to evaporation from the water surface of reservoirs. The methods used in estimating the water supply available at the dam sites below Havasu Creek are explained in the next paragraph.

For the year ending September 30, 1923, the measured discharge of Colorado River at Topock, Ariz., was 1,129,000 acre-feet, or 1,560 second-feet, greater than the measured discharge at the Bright Angel gaging station for the same period. With ultimate development, the inflow from Virgin River and other tributaries below Bright Angel will have been reduced. The amount of such reduction in inflow can not be estimated accurately, but it seems reasonable to assume that the net measured inflow between Bright Angel and Topock will be reduced from 1,560 second-feet to 1,300 second-feet.

The flow of the river at the Bright Angel gaging station, with ultimate development above this point, has been estimated at 12,900 second-feet; adding the net inflow of 1,300 second-feet just referred to gives 14,200 second-feet as the flow available at Topock. Between Pierces Ferry and Topock losses by evaporation estimated at 530 second-feet occur. In this section of the river there are large areas subject to overflow during floods, and even at ordinary stages the width of the river is relatively large. The area of the land subject to overflow and the area of the river channel were measured, and by applying figures showing monthly rates of evaporation to these areas, the total annual loss of water by evaporation between Pierces Ferry and Topock was found to be 384,000 acre-feet, which is equivalent to a uniform flow of 530 second-feet. The flow at Pierces Ferry would thus be equal to the flow at Topock (14,200 second-feet) plus the loss of water between Pierces Ferry and Topock (530 second-feet), or 14,730 second-feet.

By applying the net gain in water supply between the successive dam sites, figures were obtained that represent the water supply that would be available at each dam site below Havasu Creek without development on this section of the river. If dams were built at the sites below Havasu Creek, as outlined in this report, the available supply would be reduced through the loss of water due to the fact that the water-surface area of the reservoirs would be greater than the area exposed to evaporation under natural conditions. Table 12 is presented to show how the water supply would be affected by the construction of dams on the lower river. The figures given in the first and last columns of this table are rounded, and those in the last column are the same as those given for the respective dam sites in column 4 of Table 9.

TABLE 12.—*Water supply, in second-feet, of Colorado River between Bright Angel gaging station and Parker, Ariz., with ultimate development of the water resources*

Site	With ultimate development in upper basin but without development below Havasu Creek	Net inflow between sites	Present evaporation loss between sites	With ultimate development below Bright Angel gaging station: Reservoir loss by evaporation between sites		
				Gross	Net	Net water supply available
Bright Angel gaging station	12,900	1,000				12,900
Havasu	13,900	600	25	86	61	13,900
Bridge Canyon	14,500	100	4	6	2	14,440
Devils Slide	14,600	130	4			14,540
Pierces Ferry	14,730	−8	8	67	55	
Hualpai Rapids	14,720	−31	31	121	90	14,600
Lower Black Canyon	14,690	−487	487	508	21	14,480
Mohave Canyon	14,200	125	25	180	155	13,970
Parker	14,320					13,940

WATER SUPPLY FOR IRRIGATION

A gage-height record for Great Salt Lake has been kept since 1875. Prior to that date the value of such a record was not appreciated, and the early settlers in that region kept no systematic records. Their farming and stock-raising activities, however, brought them into close contact with the shores of the lake, and the location of the shore line on gently sloping beaches at several definite dates before 1875 is very clearly fixed in the memories of some of the pioneers. This traditional evidence has been gathered, and the levels so obtained have been referred to the datum of the existing gages in the lake, thereby extending the hydrograph of lake levels back to 1851. From these lake levels, with proper allowance for evaporation from the lake surface by the aid of an area diagram, has been computed the annual inflow to Great Salt Lake from 1851 to 1922. Practically all of this inflow has come from areas immediately adjoining the upper basin of Colorado River and therefore may be expected to show a definite relation to the run-off from the Colorado basin. A study of this relation through the 28-year period 1895 to 1922 shows that the greatest variation in that period occurred in 1908, a variation of 29 per cent from the curve. In three other years the variation was more than 20 per cent, but for 16 years of the 28-year period the discharge of Colorado River varied from that given by the curve less than 10 per cent.

By means of this relation with the inflow to Great Salt Lake, the figures showing the discharge of Colorado River at Lees Ferry have been extended back to the year 1851. It is recognized that estimates so made may be considerably in error for any single year, especially prior to 1875, but it is believed that they are sufficiently reliable to indicate in a general way the periods of high and low run-off from the upper basin of the Colorado. The 72-year figures thus obtained have been corrected for past and future depletion and are presented in the form of a hydrograph. (See Pl. LXXIV.)

What would have been the mean annual discharge of Colorado River through this 72-year period under conditions of present development and also under conditions of ultimate development in the upper basin does not differ materially from the corresponding figures for the 28-year period 1895 to 1922, which were presented in Table 8, the actual difference between the two sets of means being less than 1 per cent. However, the hydrograph (Pl. LXXIV, *C*) for conditions of ultimate development discloses the very significant fact that the 20-year period 1886 to 1905 was an unusually long period of low run-off, the mean annual discharge for this period under those conditions being but 6,750,000 acre-feet.

The hydrograph in Plate LXXIV, *D*, shows the flow at Lees Ferry under conditions of ultimate development in the upper basin, in 10-year progressive periods. This diagram indicates two groups or series of five 10-year progressive periods each, in which the run-off was less than 75,000,000 acre-feet during each 10-year period. It also indicates that the flow of the river when annual fluctuations are eliminated by considering long-time progressive periods may show a tendency to run in cycles of high and low average run-off. Thus for the first five periods it is very uniform and moderate. In the next seven periods it rises steadily, and not until 18 periods have been completed does the 10-year total recede to its former amount. Then follows a series of 23 periods of moderate or low flow, which extend through the dry years 1900 to 1905. For the last 17 periods the hydrograph shows a gently ascending slope and indicates that the flow in the river during the last 20 years has been greater than might reasonably be expected to be maintained as a basis for a reliable water supply.

ADEQUACY OF WATER SUPPLY

In Table 9 the last column represents the regulated discharge of Colorado River at a time when ultimate irrigation development shall have been reached in and adjacent to the upper basin. The lowest point on the river for which this discharge has been computed is Parker, Ariz. With the Mohave reservoir in use to re-regulate the flow to conform to the seasonal variation in demand for irrigation in the lower basin, the annual discharge at Parker may be taken as the total supply available for irrigation in and adjacent to the lower basin of the Colorado. This discharge, 13,940 second-feet, is equivalent to 10,093,000 acre-feet a year.

TABLE 13.—*Irrigable areas and water needed for ultimate development in the United States below Parker, Ariz.*

Area	Irrigable areas	Water diverted (gross duty 4.5 acre-feet per acre)	Return flow (1.5 acre-feet per acre)	Water consumed
Parker-Gila Valley project:	*Acres*	*Acre-feet*	*Acre-feet*	*Acre-feet*
Between Parker and Palo Verde Valley	50,000	225,000	75,000	150,000
Palo Verde Valley, gravity	79,000	355,500	118,500	237,000
Palo Verde Mesa, gravity	20,000	90,000	30,000	60,000
Palo Verde Mesa, pump	25,000	112,500	37,500	75,000
Chuckwalla Valley, pump	136,000	612,000	0	612,000
Parker Mesa, gravity	4,000	18,000	6,000	12,000
Parker Mesa, pump	8,000	36,000	12,000	24,000
Parker bottom land, gravity	104,000	468,000	156,000	312,000
Cibola Valley, gravity	16,000	72,000	24,000	48,000
Gila Valley, pump	632,000	2,844,000	[a] 948,000	2,844,000
Yuma project:				
Gravity	69,000	310,500	[a] 103,500	310,500
Pump	61,000	274,500	[a] 91,500	274,500
Imperial irrigation district	515,000	2,317,500	0	2,317,500
Imperial Valley extension:				
Gravity	385,000	1,732,500	0	1,732,500
Pump	200,000	900,000	0	900,000
	2,304,000	10,368,000	----------	9,909,000

[a] Return flow available to lands in Mexico only.

TABLE 14.—*Annual supply and demand in acre-feet for Colorado River water below Parker, Ariz.*

	Demand	Supply
Regulated supply at Parker ultimate irrigation development in the upper basin		10,093,000
Loss in channel below Parker	500,000	
Total ultimate demand in United States	9,909,000	
Return flow from Gila Valley		948,000
Return flow from Yuma project		195,000
Present demand for irrigation of 190,000 acres in Mexico at 4.5 acre-feet per acre	855.000	
	11,264,000	11,236,000

As shown in the preceding tables the total ultimate demand in the United States below Parker, plus the loss in the river channel below Parker, will exceed the total supply at Parker by about 300,000 acre-feet. If 60,000 or 70,000 acres in the lower part of the Imperial Valley should receive a water supply from the return flow and waste water from lands higher in the valley, this apparent shortage for lands within the United States might be eliminated.

When the Yuma project is completed and when 600,000 acres is irrigated in the lower Gila Valley, the return flow from these lands should be ample to irrigate about 200,000 acres in Mexico. This is approximately the area in that country irrigated from Colorado River in 1924. The total area in Mexico upon which it is feasible to use Colorado River water is estimated at 1,000,000 acres. If all of this land should be irrigated, the deficiency in the water supply for lands within the United States would amount to about 3,600,000 acre-feet, or enough to irrigate 800,000 acres.

It is recognized that the use of water by municipalities for domestic purposes is a higher use than that of irrigation. There are over 50 cities in the coastal region of southern California, most of which within a few years will have outgrown their local water supplies. If the population of this region continues to increase, a new source of domestic water must be found. The city of Los Angeles is planning to carry 1,500 second-feet of Colorado River water across the desert and through the mountains for the use of its citizens. The diversion of 2,000 second-feet from the river for domestic consumption in southern California may be an accomplished fact before ultimate irrigation development shall have been attained in the upper basin of the Colorado. This use of water may further deplete the supply for irrigation in the lower basin by 1,450,000 acre-feet annually.

From these estimates it appears that when ultimate irrigation development is reached in the upper basin of Colorado River there will be an annual shortage of 5,000,000 acre-feet in the lower basin, an amount sufficient to irrigate 1,100,000 acres of land.

Appendix B.—GEOLOGIC REPORT ON THE INNER GORGE OF THE GRAND CANYON OF COLORADO RIVER

By Raymond C. Moore

INTRODUCTION

SCOPE AND PURPOSE OF THE REPORT

The following account of the rock formations of the Grand Canyon of Colorado River undertakes primarily to describe those geologic features which are involved in any plan to control the floods and develop the water power along this stream. Connecting with surveys and geologic studies on the river above and below, this report covers the canyon country between Lees Ferry, Ariz., and the Grand Wash Cliffs, near the Nevada boundary, a distance along the river of nearly 280 miles. Through all of this distance the river flows in a continuous deep canyon.

PREVIOUS GEOLOGIC WORK

The earliest exploration and geologic study in the Grand Canyon was undertaken by John Wesley Powell in 1869–1872.[1] The general geographic and geologic information gathered by this pioneer geologist was of great value, but detailed information concerning the canyon has come mainly from subsequent investigators.

In 1871 G. K. Gilbert[2] accompanied an expedition that ascended the Grand Canyon from the Grand Wash Cliffs to the mouth of Diamond Creek, and in his report he described the rock formations and structure of this part of the canyon. The general geologic features of the canyon, especially those that may be seen in the more easily accessible Kaibab division, near Grand Canyon station, are known from the reports of a number of able observers.[3]

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[1] Powell, J. W., Exploration of the Colorado River of the West and its tributaries, 1875.

[2] Gilbert, G. K., Report on the geology of portions of Nevada, Utah, California, and Arizona, examined in the years 1871 and 1872: U. S. Geol. Surveys W. 100th Mer. Rept., vol. 3, pt. 1, pp. 17–187, 1875.

[3] Darton, N. H., Reconnaissance of parts of northern New Mexico and northern Arizona: U. S. Geol. Survey Bull. 435, 1910. Dutton, C. E., Tertiary history of the Grand Canyon district, with atlas: U. S. Geol. Survey Mon. 2, 1882. Walcott, C. D., Pre-Carboniferous strata in the Grand Canyon of the Colorado, Ariz.: Am. Jour. Sci., 3d ser., vol. 26, pp. 437–442, 1883. Ransome, F. L., Algonkian rocks of the Grand Canyon of the Colorado: Jour. Geology, vol. 3, pp. 312–330, 1895. Noble, L. F., The Shinumo quadrangle, Grand Canyon district, Ariz.: U. S. Geol. Survey Bull. 549, 96 pp., 1914 (contains a detailed bibliography); A section of the Paleozoic formations of the Grand Canyon at the Bass trail: U. S. Geol. Survey Prof. Paper 131, pp. 23–73, 1922. Noble, L. F., and Hunter, J. F., Reconnaissance of the Archean complex of the Granite Gorge, Grand Canyon, Ariz.: U. S. Geol. Survey Prof. Paper 98, pp. 95–113, 1916.

Except Powell and Gilbert, no geologist has previously had opportunity to study the rock formations along the river for any distance, and none of the previous investigations have been concerned with the problems connected with control of floods and development of water power.

FIELD WORK

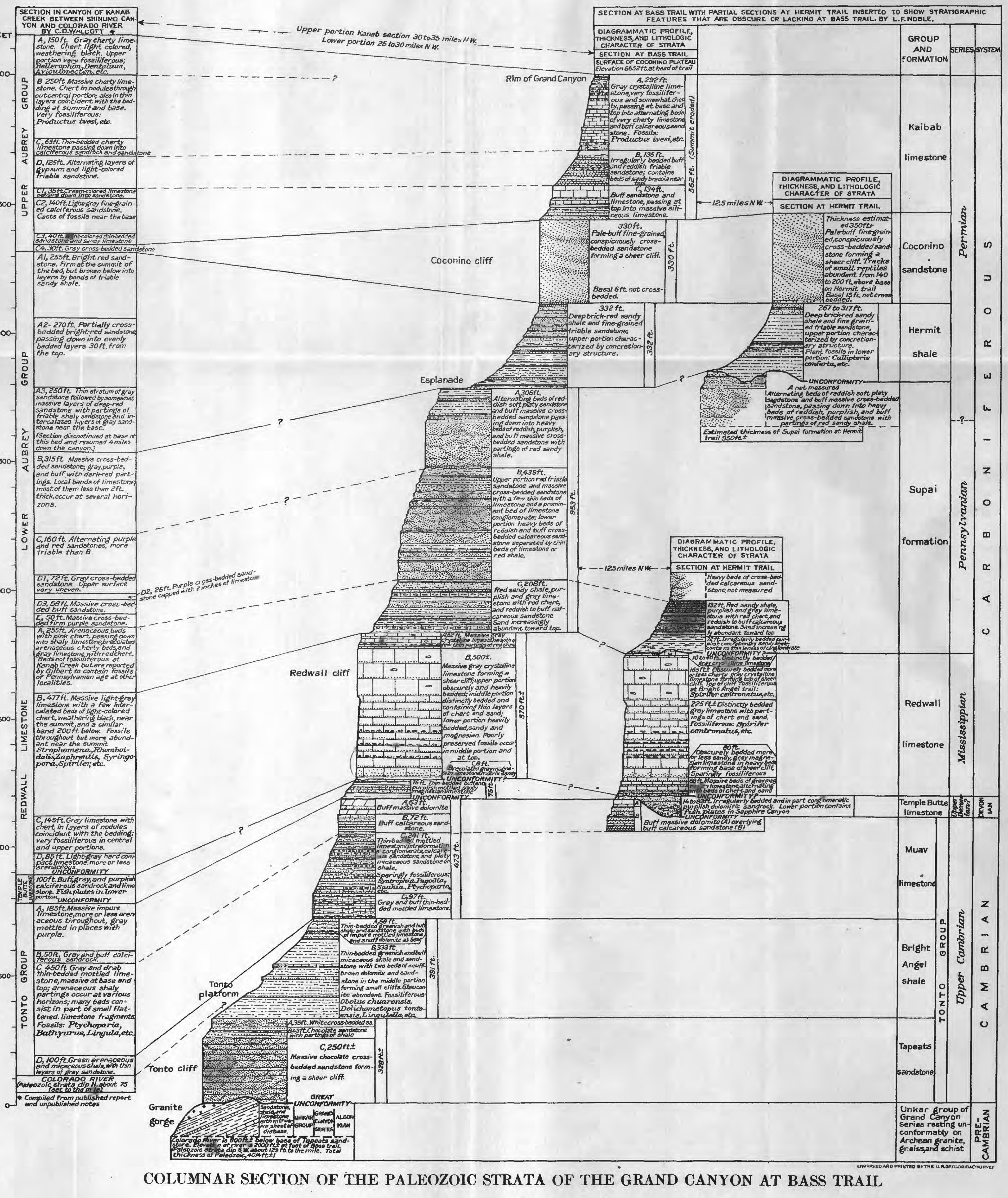
Accompanying the expedition under the direction of C. H. Birdseye, which between August 1 and October 19, 1923, traveled by boat down the river from Lees Ferry to Needles, a distance of 456 miles, the writer had opportunity to make careful observations of the rocks in the bottom portion of the canyon. Besides studying all geologic features along the route in as much detail as was permitted by the available time, he gave special attention to all sections of possible importance in connection with river control and development. Certain features were advantageously discussed on the ground with the hydraulic engineers, Messrs. E. C. La Rue and Herman Stabler, and the writer desires here to acknowledge their assistance and that of the topographic engineers, Messrs. Birdseye and R. W. Burchard.

ROCK FORMATIONS OF THE GRAND CANYON DISTRICT

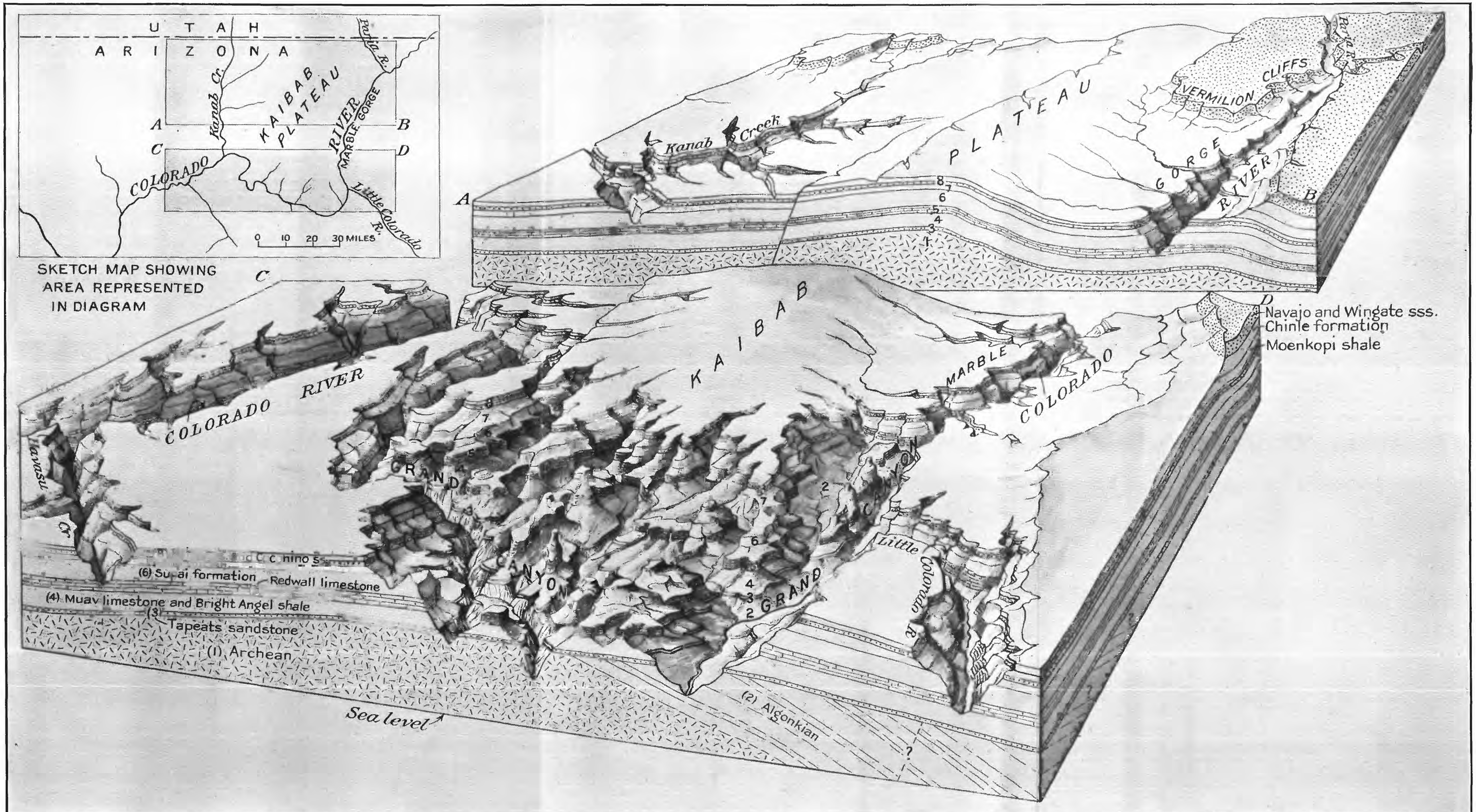
GENERAL SECTION

Because previous detailed descriptions are readily available, and because all the rock formations that make up the walls of the Grand Canyon do not have important bearing on the subject of this report, it is unnecessary to record minutely and in systematic order the rocks of these formations. A brief summary, accompanied by a diagrammatic geologic section (Pl. LXXV), is presented here, and further consideration is reserved for the discussion of river development.

The rocks of the Grand Canyon district comprise (1) a slightly warped and locally broken but nearly flat-lying series of alternating limestone, sandstone, and shale, about 4,000 feet in average total thickness; (2) an older sedimentary series of great thickness, in which the beds are now considerably inclined; (3) a complex mass of crystalline rocks, chiefly granite and schist. The first series rests in some places upon the beveled edges of the second and in others upon the crystalline complex, which also underlies the inclined sedimentary series. (See Pl. LXXVI.) These three series represent respectively the Paleozoic, the Algonkian, and the Archean divisions of geologic time. The hardness of the several rock formations in these divisions and hence their resistance to erosion differ greatly, and to these differences practically all the features in the sculptured canyon wall are due. The hard rocks form cliffs, and the soft formations make slopes; the portions of the valleys carved in weak beds are wide, and those in resistant rocks are steep-sided and



COLUMNAR SECTION OF THE PALEOZOIC STRATA OF THE GRAND CANYON AT BASS TRAIL



DIAGRAMMATIC REPRESENTATION OF A PART OF THE GRAND CANYON AND THE ADJACENT PLATEAU COUNTRY

narrow. This general relation between the strength of the rock formations and their topographic expression prevails throughout the Grand Canyon district.

The stratigraphic position and general lithologic character of the rocks in this region are shown in the following summary:

Rock formations in the Grand Canyon district

Age	Group and formation.		Thickness (feet)	Lithologic character
Jurassic.	Navajo sandstone.		1,100–1,200	Massive buff reddish to cross-bedded sandstone; forms high precipitous cliffs.
Jurassic or Triassic.	Wingate sandstone.			
Triassic.	Chinle formation.		1,000±	Blue and variegated sandy and limy shale, with included thin sandstones; forms slopes.
	Shinarump conglomerate.		50–100	Medium to coarse-grained hard light-gray grit and conglomerate; forms escarpments.
	Moenkopi formation.		500	Dark reddish-brown sandy shale and shaly sandstone, with thin beds and veins of gypsum; forms slopes.
Permian.	Kaibab limestone.		400–600	Dense, hard crystalline cherty and magnesian limestone, fossiliferous, massive; forms sheer cliffs.
	Coconino sandstone.		50–600	Massive buff cross-bedded sandstone; forms cliffs.
	Hermit shale.		150–550	Soft red sandy shale and shaly sandstone; forms slopes.
(?) Pennsylvanian.	Supai formation.		900–1,200	Hard fine-grained cross-bedded yellow and reddish-brown sandstone, with interbedded red sandy shale and in lower part hard bluish limestone; forms cliffs.
Mississippian.	Redwall limestone.		500–700	Massive bluish limestone, obscurely bedded; forms sheer cliffs.
Devonian.	Temple Butte limestone.		0–125	Light tan to white and variegated purplish limestone and limy sandstone, present only locally.
Upper Cambrian.	Tonto group	Muav limestone.	350–900 (?)	Massive to thin-bedded bluish-green mottled magnesian limestone, shaly and sandy in lower part.
		Bright Angel shale.	52–400	Soft greenish to brown micaceous sandy shale, with beds of massive hard magnesian limestone in upper part, in western part of district.
		Tapeats sandstone.	0–300	Tan to brown massive, irregularly cross-bedded hard quartzitic sandstone and grit; forms cliffs; contains slope-forming sandy shale and shaly sandstone in upper part to the west.

Rock formations in the Grand Canyon district—Continued

Age	Group and formation.		Thickness (feet)	Lithologic character
Algonkian (Grand Canyon series).	Chuar group.		0-5,120	Reddish-brown sandstone and shale.
	Unkar group	Dox sandstone.	2,300	Micaceous greenish-gray to red-brown and vermilion shaly sandstone, ripple-marked and cross-bedded.
		Shinumo quartzite.	1,560	Hard, compact cross-bedded sandstone and quartzite; forms cliffs.
		Hakatai shale.	580	Clayey to sandy red shale and sandstone; forms slopes.
		Bass limestone.	335	White to bluish hard, dense, massive to medium-bedded magnesian crystalline limestone; forms cliffs.
		Hotauta conglomerate.	0-30	Arkose, coarse conglomerate.
Archean.	Vishnu schist.		1,000+	Complex of crystalline rocks, including quartz, mica, and hornblende schist, gneiss, granite, amphibolite, greenstone, and pegmatite.

MESOZOIC ROCKS

The Mesozoic formations included in the foregoing table are mostly lacking in the immediate vicinity of the Grand Canyon, but they are prominent near the head of Marble Gorge, and in places, as at Shinumo Altar and Cedar Mountain, near Marble Gorge, outliers of Triassic rocks occur not far from the canyon rim. The Mesozoic rocks are exposed in a broad eastward-trending band just north of the Grand Canyon upwarped area and in the Echo Cliffs, which extend southeastward from the head of Marble Gorge. Notice of these rocks is desirable here, first to indicate the relations of the main rock formations of the Grand Canyon to those of Glen Canyon, in which Colorado River flows for a long distance above Lees Ferry. The geology of Glen Canyon has been described by Longwell and others.[4] In the second place, the Mesozoic rocks are sufficiently near the Grand Canyon, especially the Marble Gorge division, to warrant an examination of their possible value in furnishing materials for use in constructing dams at places within the canyon.

Navajo and Wingate sandstones.—A very prominent high sandstone escarpment (Vermilion Cliffs) that trends irregularly westward from the head of Marble Gorge at Lees Ferry and an equally notable straight line of cliffs (Echo Cliffs) that extends southward from Lees Ferry are formed by the resistant massive cross-bedded sandstones which elsewhere in the Colorado Plateau country have been differen-

[4] Longwell, C. R., and others, Rock formations in the Colorado Plateau of southeastern Utah and northern Arizona: U. S. Geol. Survey Prof. Paper 132, pp. 1-23, 1923.

tiated, from the top down, as the Navajo sandstone, Todilto formation, and Wingate sandstone. These subdivisions are not clearly defined in the vicinity of Lees Ferry. The sandstone cliffs mark the boundary of the plateau in which Glen Canyon is carved. The sandstone is not of a high crushing strength. The constituent grains are fine and well rounded. These formations have no value for use in construction at any of the Grand Canyon dam sites.

Chinle formation.—The Chinle formation, consisting of variegated clayey and sandy shale with some thin beds of sandstone and impure limestone, crops out west and south of the sandstone cliffs and forms long slopes. Some of the clays that occur here appear to be suitable for use in the manufacture of cement, and these are the only deposits in the whole Grand Canyon district that are not much too sandy for this purpose. The nearest fuel is coal in the Cretaceous formations of the Warm Creek region, in southern Utah. This could be transported the short distance to Colorado River and floated down to Lees Ferry, about 15 miles, but nowhere in the vicinity is any satisfactory limestone found, the nearest being the Redwall limestone, far down in the canyon.

Shinarump conglomerate.—Below the Chinle is a hard conglomerate or coarse grit which makes an escarpment. This formation, the Shinarump conglomerate, contains subangular coarse quartz fragments and other material suitable for use in making concrete, but most of the rock is too hard to permit crushing at reasonable expense. The exposures are very near the Lees Ferry dam site but distant from those in the Grand Canyon.

Moenkopi formation.—The Moenkopi formation consists of chocolate-brown gypsiferous shale and shaly sandstone. It forms slopes between the overlying Shinarump conglomerate and the underlying Kaibab limestone, but throughout most of the Grand Canyon district it has been stripped by erosion. It has no value for use in construction.

PALEOZOIC FORMATIONS

Kaibab limestone.—The youngest subdivision of the Paleozoic is the Permian Kaibab formation, which consists mainly of hard cherty magnesian limestone. It averages about 500 feet in thickness. The Kaibab appears at the surface at the head of Marble Gorge, a short distance below Lees Ferry, and thence southward and westward it is the capping formation of most of the plateau as far as the Grand Wash Cliffs. Except in the upper part of Marble Gorge it is several hundreds or even thousands of feet above the bed of Colorado River. Its resistance to erosion is shown by its widespread occurrence as the capping formation in the Grand Canyon district and by the narrow, nearly vertical-walled box canyon in the head portion of Marble Gorge. In places the rock is more or less extensively channeled by ground-water solution, as shown by sinks on the plateau and by cavities seen in the canyon walls. However, this rock would make a very satisfactory foundation for the base and abutments of a dam, and it affords any desired quantity of suitable material for concrete aggregate or for rough ashlar or rubble masonry.

Coconino sandstone.—Next beneath the Kaibab is a massive cross-bedded sandstone, ranging in thickness from about 60 feet at the north to more than 600 feet in part of its exposures at the south. This is the Coconino sandstone. Its outcrop commonly forms a very light-colored sheer cliff, which can be traced in the canyon walls for great distances. Like the Kaibab it can be found near the river only in the upper part of Marble Gorge. The sandstone has a fine-grained and even texture, and the rather well-rounded grains are held together by a siliceous cement. The relatively porous character of the formation is shown by the occurrence of springs at a number of places at its base.

Hermit shale.—Beneath the Coconino occurs a very persistent soft red sandy shale with thin interbedded sandstones, the Hermit (Permian) shale, about 300 to 500 feet thick. The shale commonly forms a prominent slope, and where the formation is thick, as in the Kanab division of the Grand Canyon, it has produced a wide platform or bench, which is known as the Esplanade. The Hermit occurs in the bottom of the Grand Canyon only in the upper part of Marble Gorge.

Supai formation.—The Hermit shale is underlain by medium to massive bedded reddish and light tan-brown sandstones with some shale, known as the Supai formation, of Pennsylvanian and Permian (?) age. The Supai has an average thickness of 700 to 900 feet and commonly forms precipitous cliffs, which, however, are not so prominent and continuous as those made by the underlying Redwall formation.

Redwall limestone.—The Redwall limestone, of Mississippian age, is a very massive, resistant formation, which commonly crops out in a vertical cliff 500 to 600 feet in height. In succession downstream through the upper and middle portions of Marble Gorge, the Supai and the Redwall are found to compose a large part of the precipitous inner walls. Where the river has not eroded below the base of the Redwall the canyon sides rise almost vertically from the water's edge.

Temple Butte limestone.—In some parts of the Grand Canyon there are small remnants of a limestone formation, including some calcareous sandstone, which belongs to the Devonian period. This is the Temple Butte limestone. It is of very local distribution, and its maximum thickness, so far as known, is little more than 100 feet.

Cambrian formations.—The lowermost part of the Paleozoic succession, comprising about 1,000 feet of strata, belongs to the Tonto group and consists of three formations—the Muav limestone at the top, about 400 feet thick; the Bright Angel shale in the middle, about 400 feet thick; and the Tapeats sandstone at the base, about 200 to 300 feet thick. All these formations are of Cambrian age. The Muav limestone and Tapeats sandstone commonly form persistent cliffs, but the Bright Angel shale crops out uniformly in a slope or bench, which in some places is more than a mile in width. These rocks occur near the level of the river in the lower part of Marble Gorge and for a short distance below the mouth of the Little Colorado. Farther downstream, where the river is carved in Algonkian and Archean rocks, the Cambrian formations occur at various elevations above the river, in some places nearly 1,500 feet above it; but in the middle portion of the Grand Canyon, between the mouths of Tapeats and Diamond creeks, and again near the mouth of the canyon, in a stretch of about 20 miles east of the Grand Wash Cliffs, the Cambrian formations occur along the river, at the bottom of the canyon.

ALGONKIAN ROCKS

Rocks belonging to the Algonkian system are more or less widely exposed in the bottom portions of the canyon in at least three places—(1) a considerable area in the eastern part of the Kaibab division of the Grand Canyon, near the mouth of Little Colorado River; (2) an extensive but smaller area in the vicinity of Shinumo Creek; and (3) an area extending for several miles along the river near the mouth of Tapeats Creek. The Algonkian rocks consist mainly of reddish-brown sandy shale, which is rather easily eroded, and sandstone, which is partly hard and quartzitic. A persistent hard magnesian limestone associated with dark-colored intrusive rock (diabase) occurs near the base, and elsewhere there are considerable masses of basaltic lava. As indicated by the topography, the Algonkian formations are in few places sufficiently resistant to hold the river in a narrow canyon, and there are few if any possible dam sites in the areas where the river flows on Algonkian strata.

ARCHEAN ROCKS

Underneath all the other rocks is a complex mass of crystalline rocks, consisting in considerable part of schist and in part of granite, gneiss, pegmatite, and other crystalline rocks. Almost certainly a large part, perhaps most of the schist, represents a profoundly altered series of old sedimentary rocks, which have been severely compressed, crumpled, and physically changed. The schist and gneiss have a more or less readily evident parallel bedding or banding, which commonly stands nearly vertical. The massive igneous rocks are intruded irregularly into the schist and gneiss and one into another. Almost all the Archean rocks are very resistant to erosion, as is shown by the narrow, steep-sided gorges formed where the river has been carved into them. In three main sections and a number of minor stretches the river is carved in Archean rock, and each of the resulting inner canyons which is produced is commonly called a "granite gorge." The uppermost, for which the United States Geographic Board has adopted the name Granite Gorge, begins near the mouth of Red Canyon, in the eastern part of the Kaibab division of the Grand Canyon, and extends westward about 40 miles to a point a short distance below the mouth of Elves Chasm. A few miles farther downstream, on the west side of Powell Plateau, is the Middle Granite Gorge, a little less than 4 miles long. The third main Archean gorge, called the Lower Granite Gorge, is in the vicinity of Diamond Creek, extending from a point several miles above the mouth of the creek to a point within about 20 miles of the Grand Wash Cliffs, a total length of more than 50 miles. The massive structure and the hardness of the Archean rocks and the consequent steep-sided narrow gorges which have been carved in them by the river afford conditions that are very favorable to construction projects in connection with river development.

STRUCTURE OF THE GRAND CANYON DISTRICT

Of essentially equal importance to the nature of the rocks in the Grand Canyon district is the geologic structure, which controls the position of each of the rock formations in the canyon. As shown in the diagrammatic representation of a part of the Grand Canyon and adjacent plateau country (Pl. LXXVI) the rocks have been raised several thousand feet above sea level, warped and flexed, and locally broken by faults. The degree of uplift and the direction and amount of inclination of the rocks obviously control the manner in which the river and its tributaries have been able to attack them in carving the canyon. The highest portion of the uplifted rock mass, across which the canyon has been eroded, is a part of the Kaibab Plateau, north of the canyon (Pl. XXI, *B*). From this plateau the rocks slope somewhat steeply eastward and more gently southward and westward. In the western part of the Grand Canyon district the rock strata have been displaced by a series of great faults, in some of which the movements had a vertical component measured in thousands of feet. Although the structure of the region largely controls the rock formations that occur along the course of the river, a detailed account of it is not necessary at this place.

GEOLOGIC FACTORS INVOLVED IN RIVER DEVELOPMENT

The selection of dam sites and the making of plans most effectively to control and develop for the uses of man the waters of Colorado River must take account of a number of geologic features. In the first place, the selection of dam sites must take into account the rock formations that will furnish the side and bottom foundations for the dam. Strong, massive, impervious rocks extending below the greatest depth of river excavation and above the elevation of the crest of the proposed dam afford satisfactory foundations and commonly also a minimum cross section in the lower part of the river valley. Although height of dam, reservoir capacity, and relation to adjacent developments in a comprehensive scheme of maximum river utilization are primarily engineering considerations, they are all necessarily based on the conditions that control the possible location of a competent dam. If hard rock formations that furnish the required conditions for good dam sites are found at suitable intervals through the Grand Canyon, a plan of complete control and development can be worked out readily. When a site is found that has the necessary rock formations for good foundations and a favorable cross section, a detailed examination of the site with reference to spillway facilities, power-house location, and construction problems may be undertaken.

In the Grand Canyon there are long stretches where hard, impervious rocks afford many favorable dam sites, and in such stretches the choice of a site rests chiefly on engineering considerations. In other parts of the canyon stretches of relatively weak rocks alternate with stretches of hard rock, and in such parts geologic considerations are of paramount importance. The wide cross sections and incompetent foundations of soft rocks are naturally unfavorable for dam construction, and the dam sites must be chosen where the best conditions are found in the intervening hard-rock stretches. Besides the strength of the rocks, the possibility of leakage and the availability of local materials for construction are important geologic factors.

Examination of the reservoir basin that is to be made by a dam may be quite as essential as that of the dam site itself, for serious leakage at some point in the reservoir, though it might not in any way endanger the dam, would obviously endanger the effectiveness of the project. In the Grand Canyon, however, this consideration is entirely negligible, for in none of the reservoirs that would be created by dams built in the canyon would there be any possibility of sufficient leakage through the rocks of the plateau to affect even slightly the stability of the reservoirs. This phase of the subject will therefore be omitted in the following discussion of designated dam sites.

THE BOTTOM PORTION OF THE COLORADO RIVER CANYON WITH SPECIAL REFERENCE TO DAM SITES

The following description of the bottom portion of the Grand Canyon of Colorado River is presented in order downstream, from the head of Marble Gorge at Lees Ferry to the lower end of the canyon at Grand Wash Cliffs. Observations not important to considerations of river development are not included. Although it is possible to identify certain localities in the quadrangles that have been accurately surveyed topographically (Vishnu, Bright Angel, Shinumo, Supai) by recognized place names, it will be convenient in the main to indicate location along the river by mileage measured from Paria River, just above the head of Marble Gorge. This procedure is especially needful in the long sections of the canyon where few or no recognized place names have been applied.

MARBLE GORGE DIVISION, PARIA RIVER TO LITTLE COLORADO RIVER

Head of Marble Gorge.—The Kaibab limestone first appears above the water line of Colorado River at the point where Paria River enters from the north. For a short distance downstream the Kaibab is well exposed in the short tributaries entering from the west, in the low bluffs along the river, and on the opposite side of Colorado River near the old dugway leading to Lees Ferry. Within less than a mile from the Paria the top of the Kaibab has risen about 200 feet above Colorado River, and the bluffs formed by the outcrop of the formation have closed in so that the river flows in a practically vertical-sided box canyon, the beginning of Marble Gorge. Downstream the formation continues to rise, although somewhat more slowly, and about 6 miles below the mouth of the Paria the walls of the canyon are nearly 600 feet high (Pl. XXII).

Suggested dam site near the head of Marble Gorge.—In this part of the canyon, where the walls rise abruptly on both sides of the river, it has been proposed to build a bridge across the river. Because of the comparatively easy accessibility of this locality and the apparently satisfactory character of the canyon walls, which rise sufficiently high to make possible a dam with a storage reservoir approximately equal to that of the site selected by Mr. La Rue near the lower end of Glen Canyon, above Lees Ferry, special attention was given to the possibility of locating a dam here. As shown in the accompanying diagram (Pl. XXIII), which gives a cross section of the river at the bridge site, it was found that the walls of the canyon above the water level include practically all of the Coconino and Kaibab formations, and it follows, therefore, that the bed of the river has already reached and has been cut into the soft Hermit shale, which underlies these more resistant rocks. Indeed, only a few hundred feet downstream from the bridge site the Hermit shale appears above the level of the river, and it continues to rise uninterruptedly southward. The Hermit is a soft shale entirely unsuited for the foundation of a high dam. Wherever it is exposed throughout the canyon it forms weak slopes and wide benches, as it disintegrates readily under the attack of weathering. The occurrence of this formation in the bed of the stream near the bridge site so strongly condemns the project of building a dam here as to make further detailed consideration unnecessary. Although the Coconino sandstone and the overlying sandy and shaly beds that with interbedded limestone make up the lower part of the Kaibab are rather porous and, as shown by the persistent development of a slope beginning about 300 feet below the top of the Kaibab, are not wholly satisfactory as abutments for a dam, it would be possible to build a dam a short distance upstream, at a point where the entire structure would be within the Kaibab and Coconino. However, at this point the walls of the canyon are much lower and the advantages of large reservoir storage would be lost.

Mile 4.6 to Vaseys Paradise.—From the point where the top of the Hermit shale appears above the water level, 4.6 miles below the mouth of the Paria, the thickness of the exposed portion of this formation gradually increases until at the mouth of Badger Creek a slope 300 feet in height is formed by the outcrop of the formation. The nearly vertical cliff above the Hermit shale slope, a little less than 600 feet in height, represents the combined thickness of the Coconino and Kaibab formations.

Southward from Badger Creek the rock formations continue to rise and the river slightly to lower its level, so that just below the mouth of Soap Creek (mile 11.5) the Hermit shale is exposed to its full thickness, which, as determined by measurement here, is 537 feet.

Near the foot of the Soap Creek rapids the top of the Supai sandstone makes its appearance, and from this point downstream the river is again inclosed in a steep but not vertical sided box canyon, which gradually deepens until several hundred feet of the Supai is exposed in its walls. The Supai consists mainly of massive beds of hard cross-bedded red, yellowish-brown, or buff sandstone, with interbedded thinner layers of sandstone and in some places thin beds of sandy shale. In the lower part of the formation are interbedded limestone, sandstone, and thin red shale. The upper part of the formation is in general more massive and forms prominent cliffs; the lower part consists of thin or medium-thick beds that weather in broken slopes. The total thickness of the Supai formation, including the shale and limestone at its base, about 800 feet, is exposed above river level at and south of a point a little over 24 miles below Paria River.

The weak strata included in the Supai formation detract from its suitability as a foundation for dams and cause an increase in the width of the canyon.

The top of the Redwall limestone appears above water level at mile 24.2, and here, as in similar places where the river enters a resistant formation, the bottom portion of the canyon is narrow and has steep sides, which gradually increase in height as the rock formations rise above the river. The limestone is dense, fine grained, and hard and in places is smoothly polished by water. Although it is this formation that has given rise to the name Marble Gorge, no part of the Redwall limestone is a true marble.[5] The rock is mostly a pure limestone; a few beds are of medium-coarse crystalline texture, but much the greatest part is finely crystalline and dense. In any fresh exposure the color of the limestone is a light bluish gray or blue, and most of the Redwall limestone of Marble Gorge has this hue, but in many places, particularly in the middle and lower parts of the Grand Canyon, the limestone cliffs are stained red by wash from the overlying red Supai and Hermit beds—hence the name Redwall.

At about the same rate as in the upper part of Marble Gorge the rock formations continue to rise and the river to lower its level. Only a few miles from the point where the top of the Redwall appears between 200 and 300 feet of massive limestone is exposed in essentially vertical walls, which hem the river very narrowly. A landmark in this part of the canyon is Vaseys Paradise (mile 31.8), so named by Major Powell, a striking patch of green trees and shrubs clustered about large springs that cascade down the lower part of the rock wall.

Redwall dam site.—About 2 miles above Vaseys Paradise, at a point where the narrow box canyon carved in the Redwall limestone appears to offer favorable conditions for placement of a dam, the river level is approximately 250 feet below that at Lees Ferry. The site for a dam that would back water to the Lees Ferry dam was selected by Mr. La Rue at mile 30 and designated by him the Redwall dam site.

The Redwall formation, which would constitute the side walls and bottom foundation for a dam, consists of hard, resistant limestone. The formation is so massive that almost no bedding planes appear in the cliff, although there are some changes in color, mainly shown by parallel color banding. So far as construction would be concerned the formation is a unit, and in the nearly complete absence of bedding planes and joint cracks it is admirably fitted to serve as foundation for a dam. The smooth, practically vertical limestone walls rise 275 feet above river level at the dam site. There are a few places in the several miles of limestone exposure above the site

[5] See footnote 8, p. 19.

where the Redwall has been attacked by percolating ground waters, which have dissolved out cavities a few inches to several feet in width. In a formation like the Redwall the chief danger of serious leakage is along solution channels that may have been previously formed or along solution cavities that may be developed along lines of weakness in the formation. However, for a considerable distance along the river above and at the dam site there is no indication of solution of the limestone. Although the rock is not protected immediately above by an impervious shale covering, there is so little natural percolating water at this locality and the formation is so massive and so unaffected by prominent joints or other lines of weakness that there is, it is believed, a minimum danger of leakage from this source.

At the lower end of a rapid some 400 yards below the site selected for the dam a fault striking northeast with downthrow on the southeast crosses the river obliquely. (See Pl. XXV.) The main fault is accompanied by two or three minor fractures, the total displacement of the strata being about 200 feet. On both sides of the river tributary streams have followed the lines of weakness produced by the faults and have carved more or less open canyons. The cliffs near the river are broken down, and for a short distance the characteristic topography of this general section of Marble Gorge is lost. Springs that follow fractures in the vicinity of the faults enter the river from both sides, and one on the left bank has a considerable flow. South of the faults for some distance there is considerable evidence of solution of the Redwall limestone, some of the cliffs showing the limestone to be very cavernous. The position of the springs and the character of the local geologic structure indicate that the water is derived essentially from the country south of the fault, and accordingly there is no indication that these features on the downstream side of the dam site would affect the stability of a dam at the site selected north of the fault. Except that the fault has guided the course of underground water, and that the limestone adjacent to it is more or less cavernous, no special attention need be given to the existence of the fault unless tunnels are designed to cross it, when precaution in construction should be taken to safeguard against leakage.

Although the depth to bedrock can only be estimated, it is believed, from the narrowness of the canyon, its straight course in the vicinity of the dam site, and the absence of any alluvial deposits along the side of the stream throughout this section, that there is probably very little sediment on the stream bed. The general character of the stream and canyon suggests that probably 60 feet is the maximum distance to bedrock. As the thickness of the Redwall as shown in the cliff some miles below the dam site is more than 500 feet, and, further, as the Redwall is underlain by the hard Muav limestone, the bedrock in the river at this site is massive limestone, entirely satisfactory as a foundation for a high dam.

The Redwall limestone will furnish abundant material satisfactory for use as concrete aggregate, also large blocks, easily dressed, if desired. Because of the comparative steepness of the slope above the top of the Redwall cliff (see Pl. XXIV) quarrying probably can not be done profitably in the immediate vicinity of the dam site, but in the open section of the canyon 1,200 feet below the site there are very satisfactory quarry sites. Abundant sand is available in the lower part of the Supai formation, which forms a slope above the Redwall, but this sand will have to be obtained mainly by crushing and is somewhat finer than would be desirable. Pure limestone of satisfactory quality for the manufacture of Portland cement is available in unlimited quantities, but other requisites, such as shale of suitable quality and fuel, are lacking.

Alternative Redwall dam sites.—Two other sites suitable for such a dam as is required in this part of Marble Gorge by a scheme of complete river development were considered. One of these is at a point 29 miles below the mouth of Paria River, just a mile above the Redwall site; the other is at mile 32.2, a little over 2 miles below the Redwall site and half a mile downstream from Vaseys Paradise. The conditions as regards side wall and bottom foundations at these alternative sites are essentially identical with those at the site already described, but the walls are a trifle lower at the upstream site and higher at the downstream site. In all three places the massive limestone extends considerably above the elevation required for the crest of a dam.

The alternative site at mile 29 is in a long, comparatively straight stretch of the canyon in which the inner gorge carved in the limestone is almost unbroken by side canyons. (See Pl. XXVI, *A*.) No evidence of solution of the limestone or of jointing or shattering that would render the side walls liable to leakage is found near the site. Construction materials here are the same as at the main site but because of topographic difficulties are much less easily procurable.

At the alternative site at mile 32.2 Colorado River flows eastward between nearly vertical smooth cliffs composed of the Redwall limestone. (See Pl. XXVI, *B*.) Above the inner cliff the lower beds of the Supai form a steeply stepped slope. At Vaseys Paradise a large spring of water issues high on the right wall of the canyon and tumbles in a picturesque fall into the river, but in the vicinity of the dam site the walls are not pierced by any solution channels or cavities. The character of the wall therefore indicates no likelihood of excessive leakage around a dam built here. As only about 300 feet of the approximately 500 feet of total thickness of the Redwall is exposed above water level at this site, the bed of the river is here in limestone. The conditions generally are comparable to those at the alternative site at mile 29, for the canyon is continuously narrow.

Vaseys Paradise to Little Colorado River.—Below Vaseys Paradise the river is for several miles narrowly inclosed between vertical cliffs of Redwall limestone, which gradually increase in height until the full thickness of the formation is exposed. At a point about 35 miles below the mouth of Paria River the top of the Muav limestone appears, and within 2 or 3 miles 100 feet or more of this formation is exposed above the water. At intervals there are exposures of the Temple Butte limestone filling depressions in the top of the Muav. The contact between the Redwall and the Muav is commonly marked by a narrow slope or bench, but as the upper limestones of the Muav are hard and resistant, they tend to form a cliff beneath the Redwall and practically continuous with it. The middle and lower parts of the Muav limestone are here very thin-bedded and sandy and tend to crop out in a slope, which accordingly produces an increase in the width of the canyon. At 45.8 miles below the Paria the full thickness of the Muav, here nearly 500 feet, is exposed above the river, and a short distance downstream the very dark green sandy shale and shaly sandstone of the upper part of the Bright Angel shale appear. The Bright Angel shale is a very weak formation, which crops out uniformly in a slope or bench. Throughout the lower part of Marble Gorge these weak rocks of the Bright Angel shale and the lower and middle portions of the Muav are near the bottom of the canyon, and no dam site is available. At the mouth of Little Colorado River (Pl. XXI, *A*) the complete thickness of the Bright Angel shale and the top of the Tapeats sandstone, which underlies the Bright Angel, are shown. Here theriver is entering a gorge carved in the Tapeats

KAIBAB DIVISION, LITTLE COLORADO RIVER TO SHINUMO CREEK

Little Colorado River to head of Granite Gorge.—The Tapeats sandstone, which is the lowermost formation in the canyon for 4 or 5 miles in the vicinity of the mouth of the Little Colorado, is a hard, coarse-grained sandstone or grit in medium-thick to massive, more or less lenticular beds, which are irregularly cross-bedded. Wherever it is exposed in the Grand Canyon the Tapeats sandstone characteristically forms strong, generally vertical cliffs, an indication of its resistance to erosion. Such cliffs, surmounted by slopes of the Bright Angel shale, inclose the river narrowly below the mouth of the Little Colorado, but within a distance of 2 miles from this point the total thickness of the Tapeats, about 275 feet, is seen above the river. The sandstone gradually rises, exposing beneath it an increasing thickness of soft brown shaly sandstone and sandy shale of Algonkian age. Four miles below the Little Colorado, just above the mouth of Lava Canyon, the Tapeats is abruptly moved upward several hundred feet by a fault that crosses the river in a northwesterly direction. Owing to the relative weakness of the Algonkian rocks, which are widely exposed on the west or downstream side of the fault, the bottom part of this portion of the Grand Canyon is broad and open, and the river, though swift in places and not lacking rapids, is wide and follows a winding course. East of The Tabernacle and Solomon Temple, on the southeast spur from Vishnu Temple (in the Vishnu quadrangle), hard sandstone in the lower part of the Algonkian is encountered. Accordingly, the bottom portion of the canyon is narrowed and the slopes next to the river are steepened in places to nearly vertical walls. Just below Red

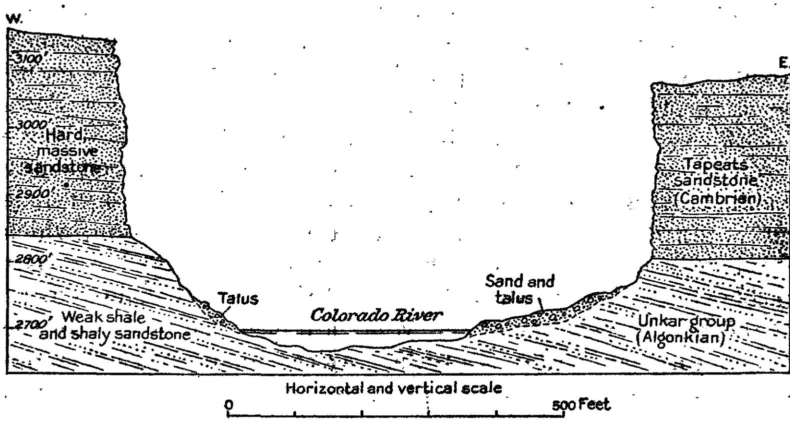


FIGURE 1.—Geologic cross section east of Temple Butte

Canyon the base of the Algonkian rocks is reached and the Colorado plunges into a narrow, rapidly deepening gorge carved in the underlying crystalline Archean rocks.

Possible dam sites between the mouth of Little Colorado River and Granite Gorge.—In the Tapeats gorge, below the mouth of the Little Colorado, careful observations were made to find, if possible, a satisfactory dam site. The total thickness of the Tapeats sandstone here is between 275 and 290 feet, and beneath this formation occurs soft, incompetent shaly sandstone belonging to the Algonkian. The top of the Algonkian beds first appears above water level 1½ miles below the mouth of the Little Colorado, and as these rocks are not at all suitable for a dam foundation, a location in the Tapeats gorge below this point should not be considered as a dam site. A geologic cross section measured at a narrow place in the gorge east of Temple Butte, about 3 miles below the mouth of Little Colorado River, is shown in Figure 1.

Head of Granite Gorge to Grapevine Creek.—Near the end of Hance Rapids, 15 miles below the mouth of Little Colorado River and due south of Sheba Temple (in the Vishnu quadrangle), Archean granite first appears in the lower side walls of the Grand Canyon. As shown in Plate XXIX, *A*, the unconformable contact between the Algonkian and Archean rocks, which runs smoothly parallel to the beds of the lower Algonkian, rises steeply downstream, so that within a mile of the point where the Archean first appears nearly 500 feet of these hard crystalline rocks are exposed above the river. The steep-sided, V-shaped gorge that is carved in the resistant Archean rocks extends downstream for about 40 miles. The river, narrowly constricted, fills the bottom of the gorge from wall to wall, and only at the mouths of certain tributary streams where accumulations of boulders have permitted the lodgment of sand are there found narrow sandy beaches. The Algonkian rocks wedge out within a very short distance from the head of the Granite Gorge, and the Tapeats sandstone, the basal formation of the Paleozoic succession, comes to rest on the smoothly beveled surface of the Archean rocks. Consequently, throughout almost all of the Granite Gorge there is a nearly vertical sandstone cliff, about 200 to 300 feet high, on each side of the gorge at its top. Beyond and above this cliff are the alternating slopes and cliffs of the soft and hard overlying Paleozoic rocks.

The rocks that compose the walls of the Granite Gorge are not by any means uniform in character and really include comparatively little true granite. These Archean rocks are a complex of crystalline schist and gneiss, with intruded pegmatite, granite, and basic igneous rocks and in places considerable injected quartz.

In the uppermost part of the gorge, as far as the mouth of Grapevine Creek, the chief rock is a much contorted pinkish gneiss in which there are numerous irregular injections of pink pegmatite and milky quartz. The gneiss is so crumpled that no prevailing structure is determinable. Slight variations in the hardness of the rocks and the complex, irregular structure are expressed in the craggy, patternless roughness of the canyon walls.

Throughout the many miles of the Granite Gorge the rocks of the bottom and side walls are almost anywhere satisfactory in strength and resistance to leakage for the construction of dams. In a considerable part of the gorge the massive crystalline rocks rise more than 1,000 feet above the river level.

Mineral Canyon dam site.—A point just below the mouth of Mineral Canyon, which enters the main gorge from the south at mile 77.8, slightly less than a mile from the point where the Granite Gorge begins, has been designated as the location for a dam that may raise the water level to the foot of the Redwall site, in the middle portion of Marble Gorge. The rocks in the walls in the main gorge of Colorado River and in the lower part of Mineral Canyon consist of a strongly compressed complex of granitic rocks of varying composition, in which the prevailing type is a granite gneiss. In places there are prominent irregular bands of gray micaceous gneiss and scattered bands and lenses of garnet-bearing mica schist and dark-colored biotite schist. All these rocks are medium to coarse grained and have a prominent cleavage parallel to the banding. In parts of the main gorge the rocks are so contorted that no prevailing strikes and dips can be determined, but in the lower part of Mineral Canyon the cleavage shows a tendency to a northeast strike and a nearly vertical dip. The gneiss and schist are irregularly intruded by younger igneous rocks, which consist mainly of coarse pink pegmatite and in part of fine-grained light-colored aplite. These irregular dikes stand more or less vertical and trend predominantly northeast, parallel to the general cleavage of the granitic rocks where this can be determined. Except for the more highly micaceous rocks, which disintegrate somewhat readily where long exposed to weathering, the rocks are resistant to erosion. In the bed of Mineral Canyon and near the water level of Colorado River the rocks are smoothly polished by the action of the water. The rock is traversed by irregular joint cracks, which influence breaking down and weathering of the rocks. The joints do not run in any definite direction but appear in the main to extend through the rocks subvertically, and observations indicate a slightly predominant trend a little west of north and another about N. 60° E. The general character and the structure of the rocks indicate a minimum of possible leakage at any point around the dam.

Resting unconformably on a remarkably even erosion surface, developed in pre-Unkar time across the granite schist and gneiss, are Algonkian sedimentary rocks belonging to the Unkar group. Near the dam site the base of these beds is approximately 500 feet above the river, and consequently they have no relation to such matters as the foundation of a dam. However, as they have considerable effect on the local topography, and as they contain materials that may be used in part of the dam construction, their character may be described briefly. As shown in the cross section (Pl. XXX), the Unkar rocks consist from the base upward of a rather tightly cemented conglomerate (Hotauta) with numerous well-rounded coarse pebbles, extending as a resistant cap rock along the borders of the gorge at its top; shaly to massive yellowish-gray to light-blue fine-grained pure magnesian limestone (Bass ?), dense and hard, in the middle portion of which is intruded a persistent thick bed of very dark igneous rock (diabase), which commonly crops out in a cliff; and shaly to massive red sandstone (Hakatai ?), succeeded above by a thick red sandy shale that forms a wide bench and a long slope. Deposits of asbestos occur in the shaly parts of the limestone adjacent to the diabase. The topography of these sedimentary rocks is clearly shown in Plate XXIX, *A*.

Construction materials for use at the Mineral Canyon dam site are readily available. Very satisfactory concrete aggregate may be procured from the dense limestone in the Bass (?) formation just above and below the diabase. This rock is easily quarried along the joints, which intersect the beds at nearly right angles. The diabase also is sufficiently strong, for the most part, and may be quarried readily for use in the same way if desired. Much of this rock is excellently adapted for rubble or cyclopean masonry, and some beds of the limestone may be used for dimension stones, for the rocks can be so quarried as to need very little tool dressing. If desired, some of the sandstone that is hard and quartzitic can also be used for construction.

Granite Gorge between Grapevine and Clear creeks.—Between Grapevine Creek and a point half a mile west of the mouth of Clear Creek the rocks of the Granite Gorge consist almost wholly of mica schist and mica quartzite, which exhibit a pronounced parallel structure. They have, indeed, the appearance of an exceedingly thick, well-stratified series of sedimentary beds, in which the strata stand practically vertical and have a dominant northeast strike. It is to these rocks, southeast of Vishnu Temple, that the name Vishnu schist as the designation for a geologic terrane has been applied. Numerous features indicate that the Vishnu schist comprises a highly metamorphosed sedimentary series. In places there are pink intrusive rocks and veins and stringers of quartz, but this section of the Granite Gorge is noteworthy on account of the general absence of these intrusive rocks. Most of the schist, especially the quartzitic portion, is fine grained, dense, and hard, and the gorge is accordingly narrow and steep sided. As the river crosses the schist almost at right angles to the strike of the rocks, the hardest beds stand out more or less prominently as spurs or ridges, and the intervening softer beds sink back as slight depressions. The walls of the gorge are therefore corrugated rather than smooth, a feature which is suggested on the topographic map.

Clear Creek dam site.—The rock walls of the gorge at the Clear Creek dam site, at mile 84.4 (Pl. XXXVI), are composed of nearly black quartz-mica schist, which is very fine grained and dense. The rocks have a very strong parallel structure, the planes of schistosity or cleavage standing practically vertical and trending at right angles across the river—that is, about N. 35° E. Some of the beds or bands are very finely laminated, and others are massive; some are very fine grained, and others are medium or coarse grained. The general mineral composition, texture, and structure of the rocks as well as the variations in each of these features indicate strongly that the schist represents an altered sedimentary series, in which the original bedding is generally followed by the planes of the present schist cleavage. In accordance with the variations in different beds of the schist, some parts weather in large, massive blocks defined by planes of schistosity and joints, whereas other parts weather in thin slabs. All the rocks contain rather numerous thin veins and irregular lenses of white milky quartz, and in places there are veins and lenses of pink granite and pegmatite; the latter, however, form a very minor constituent in the rocks of the gorge. The rocks are thoroughly competent as foundation material for the bottom and sides of a dam. The strength of the rock is shown not only in features of local topography, but by the resistance of masses of the schist, which, though smooth and polished by the swift current, project irregularly many feet into the river. The structure of the schist is such as to make leakage around the dam almost impossible.

Material for concrete can best be obtained from parts of the schist, probably on the north side of the river, where quarrying operations and construction incident to tunneling and spillway work will supply an abundance of material satisfactory for use in building the dam. Large rocks for plums can be readily procured. About half a mile back from the gorge on both sides are enormous quantities of easily obtainable hard, pure limestone (Redwall). A coarse sand can be obtained by crushing the Tapeats sandstone, which crops out at the top of the gorge, but this formation is rather too hard to be crushed readily.

Granite Gorge between Clear and Bright Angel creeks.—A short distance west of the mouth of Clear Creek there is a sharp change in the nature of the rocks composing the walls of the gorge. Beginning approximately at Zoroaster Canyon, half a mile below Clear Creek, and extending within a short distance of the mouth of Bright Angel Creek, massive pink granite and granite gneiss take the place of schist. The resistance of these granitic rocks is shown by the extreme steepness and relative smoothness of the walls, the very narrow width of the gorge, the comparatively small amount of erosion by fair-sized tributary streams, and the unusual projection of parts of the granite at the base of the Tapeats sandstone. This is one of the narrowest sections of the whole Granite Gorge.

Granite Wall and Cremation dam sites.—The rock walls of the gorge at the Granite Wall dam site, mile 85.1 (Pl. XXXVI), consist of medium coarse-grained hard massive pink granite. The rock lacks the parallel structure due to compression that is characteristic of most of the rocks in the gorge and is traversed by only a few major joint planes. It is evidently owing to the massiveness and hardness of the granite that this part of the Archean rocks projects above the remarkably smooth erosion surface that marks the unconformity at the base of the Paleozoic. The granite reaches upward into the lower part of the Bright Angel shale, cutting out all of the Tapeats sandstone for a short distance on the right bank of the river and making the highest mass of Archean rocks that is known in the Kaibab division of the Grand Canyon. The main joints in the granite are generally inclined obliquely, dipping steeply to the north, so that the south wall, following the joint planes, slopes in great smooth surfaces at angles of 50° to 60° down toward the river, whereas the north wall stands more nearly vertical.

At the Cremation dam site, mile 86.3 (Pl. XXXVII), the gorge is exceedingly narrow and the walls are nearly vertical. The rocks consist chiefly of very fine grained hornblende-biotite schist, the parallel planes of which strike southeast, at an acute angle with the river. The schist is traversed by numerous rather thick, irregular veins of coarse-grained pink granite and pegmatite. An unusually massive dike of granite pegmatite, nearly 200 feet thick, runs vertically to the rim of the gorge just below the dam site, As a whole the rocks are very resistant and are not highly jointed. No question can be raised as to the adequacy of the rocks at the sites in this section as a foundation for dams, and at neither place is there any possibility of leakage through the side walls of the canyon.

Because of the steepness of the gorge and the character of the rock, material for construction can not be obtained readily from the crystalline rocks within the gorge in the vicinity of the dam sites. Such material can be procured most easily from the limestones of the Redwall and Muav, in the cliffs on both sides of the gorge.

Granite Gorge between Bright Angel and Hermit creeks.—Granite gneiss crowded with pink pegmatitic injections, more or less gneissoid pink granite, amphibolite, and hornblende schist, which on the whole are somewhat less resistant to erosion than the rocks in the gorge above Bright Angel Creek, extend to a point about 1 mile below the mouth of Hermit Creek. In parts of this stretch the rocks are so greatly contorted that no dominant trend to the structure can be discerned, but downstream from a point just above the mouth of Horn Creek there is a fairly well marked, nearly vertical banding, the strike of which ranges from slightly east of north to northeast.

Pipe Creek dam site.—Near the mouth of Bright Angel Creek, a short distance below the Cremation dam site, the Granite Gorge increases in width and the walls become somewhat less steep. This change is due mainly to a local change in the hardness of the rocks.

Near the mouth of Pipe Creek, however, a little over a mile below Bright Angel Creek, the canyon is again moderately narrow and steep sided (Pl. XXXIX, *A*), and the conditions warrant consideration of a dam site. Because of the course of the lower part of Pipe Creek and of a bend in Colorado River near this point, a fairly long ridge between the side canyon and the main gorge extends northeastward from Plateau Point (in the Bright Angel quadrangle).

The walls of the inner gorge of Colorado River at the Pipe Creek site consist mainly of a very hard dark gneissoid granite which near the river level, where it is subject to scouring, is smoothly polished and carved in numerous small potholes and other curved surfaces. In some places this rock shows a well-defined banding, but elsewhere it is massive and apparently unbanded. It is crossed by joints, which generally define the large angular blocks produced by weathering. The gneiss contains irregular injections of pink granite pegmatite and veins of white quartz. Much of the pegmatite is very coarse grained, containing feldspar crystals as large as 6 inches in diameter, and the rock is made up almost wholly of quartz and red orthoclase. Because of its coarsely crystalline character, the pegmatite weathers more easily than the associated rocks. The quartz occurs in thin or medium thick irregular veins and here and there in irregular masses 6 to 10 inches in diameter.

The dark gneiss and the associated rocks form the walls and bed of the gorge at the dam site, but east of the mouth of Pipe Creek there are softer rocks, chiefly dark hornblende schist. The dominant strike of the schist is about N. 30° W., and the dip about 80° NE. Associated with the schist are irregular masses of gneiss and pegmatite. Opposite Plateau Point, just below the dam site, the gorge is cut in massive pink granite gneiss and granite. The character and structure of the rocks at the site near Pipe Creek are entirely satisfactory. The rocks have ample strength for the foundation and abutments, and there is no possibility of serious leakage.

Construction materials for use at the Pipe Creek site can be obtained adjacent to the site, within the inner gorge, and from rock formations above the granite, not far away. The crystalline rocks near the river can be used in concrete but are much harder to quarry and crush than the limestone to be had from the Muav and Redwall formations, about a mile from the site. Large rocks for plums can readily be obtained from the Tapeats sandstone, which crops out at the top of the gorge, a few hundred yards from the dam site.

Granite Gorge between Hermit Creek and Turquoise Canyon.—From a point a mile below Hermit Creek nearly to the mouth of Tuna Creek the rocks in the gorge consist chiefly of dark micaceous and quartzitic schist with a very prominent parallel structure. Some of the schist resembles phyllite, as suggested by the name Slate Creek, one of the tributary streams in this section. These rocks are hard, and the gorge is narrow. The dominant strike of the rocks is north of east.

Between Tuna Creek and Turquoise Canyon granite and hornblende gneiss predominate, with much pink pegmatite west of the mouth of Agate Canyon. In topographic character this part of the gorge resembles the section carved in granite between Clear and Bright Angel creeks.

Ruby Canyon dam site.—The Ruby Canyon dam site is at mile 103.9 (Pls. XXIX, *B*, and XXXI), between the mouths of Ruby and Turquoise canyons, directly northeast of the projecting spur called Le Conte Plateau (in the Shinumo quadrangle). It is in a fairly narrow, steep-sided section of the Granite Gorge, the walls of which are made up almost entirely of dark massive coarse-grained igneous rock (diorite) showing little or no evidence of parallel structure. This rock is hard and resistant to erosion. In places it is intersected by dikes of very coarse to medium grained pink pegmatite composed of microcline, muscovite, and quartz. Some of the microcline crystals in the pegmatite reach 36 inches in diameter, muscovite 8 inches, and quartz masses more than 12 inches. At one point a band of gneissoid granite several feet thick was observed. The pink intrusive rocks make up only about 15 per cent of the walls of the gorge. The hardness of the rocks and their massive dense texture indicate very satisfactory dam foundations and effectually preclude the possibility of serious leakage.

Construction problems at the Ruby Canyon dam site are essentially similar to those at Pipe Creek and other sites in the Granite Gorge. The igneous rock is somewhat more uniform in texture than the crystalline rocks at the dam sites previously described, and it can be quarried without great difficulty. However, it is difficult to break with the hammer and accordingly would be less easily handled than limestone from the cliff a short distance back from the gorge, the nearest in Le Conte Plateau, a mile from the river. Large blocks for cyclopean masonry can be procured from the Tapeats sandstone, which crops out on the rim of the inner gorge above the dam site.

Granite Gorge between Turquoise Canyon and Shinumo Creek.—From a point near Turquoise Canyon to the Bass cable crossing, just below Bass Canyon, the Granite Gorge is cut chiefly in massive basic intrusive rocks, which in part exhibit a more or less well-defined parallel structure but in the main show almost no evidence of dynamic metamorphism. Near Turquoise Canyon the basic rocks are intruded by an abundance of pink pegmatite, and the resistance of the rocks is indicated by the narrow steep-sided character of the gorge. Below Ruby Canyon the rocks are more readily attacked by weathering, and the width of the inner gorge increases. The section between Ruby and Bass canyons is moderately narrow, owing to the strength of the quartz diorite which is exposed there.

A sharp contact between the basic igneous rocks and mica schist that resembles some of the typical Vishnu schist found farther upstream occurs near the Bass cable crossing. The mica schist continues to and beyond the mouth of Shinumo Creek, which marks the approximate boundary between two of the broad, structurally defined divisions of the Grand Canyon district, the Kaibab and Kanab.

In the vicinity of Bass Canyon the crystalline rocks are for a short distance sharply depressed, and a great wedge of Algonkian sedimentary rocks, which is extensively exposed in the canyon of Shinumo Creek and its tributaries, forms relatively gentle slopes near the river. This area has been described and mapped in detail by Noble.[6]

Investigation for dam site near mouth of Shinumo Creek.—In this section of the canyon an examination was made to ascertain the feasibility of constructing a dam just below the mouth of Shinumo Creek, where the topography suggests that advantageous spillway facilities would be offered from the lower part of the Shinumo Creek canyon to the river on the west. The examination showed, however, somewhat too wide a cross section of the main canyon for a dam and rather weak micaceous rock walls. The rocks in the projecting points between the mouth of Shinumo Creek and the main river are shattered by two or more cross faults, and the site for a dam and spillway is considered undesirable.

KANAB DIVISION, SHINUMO CREEK TO THE TOROWEAP VALLEY

Granite Gorge between Shinumo Creek and Walthenberg Canyon.—A short distance below Shinumo Creek the inner gorge of the Colorado regains its typical narrow width and steep walls, the change in topography being coincident with the appearance of hard rocks in the bottom of the canyon near the river. These rocks consist mostly of fine-grained dull reddish to pinkish mica schist, which is cut in places by dikes of pegmatite. The amount of intrusive rock is, however, rather small. Like the schist in the vicinity of Clear Creek, the mica schist of this section appears to be of sedimentary origin. In many places the structure is so complex that no prevailing strike or dip is determinable, but for the greater part the rocks have a fairly well defined parallel structure with nearly vertical dip

[6] Noble, L. F., The Shinumo quadrangle, Grand Canyon district, Ariz.: U. S. Geol. Survey Bull. 549, 1914.

and prevailing northeast strike. Westward toward Walthenberg Canyon the height of the walls of the Granite Gorge gradually decreases, for the Paleozoic strata above are inclined westward here at an angle materially greater than the grade of the stream.

Hakatai dam site.—At Hakatai Canyon, mile 110.7 (Pls. XXXIX, *B*, and XL), 2 miles below Shinumo Creek, conditions favorable for a dam were found. The walls of the Granite Gorge are here composed of hard bluish-gray micaceous schist, some portions of which are harder, finer grained, denser, and more quartzitic than others. Thin lenticular injections of milky quartz and of pegmatite composed of quartz, orthoclase, and muscovite have been forced into parts of the schist, but this section of the gorge is in general lacking in intrusive material. Some zones are highly contorted, and injected quartz veins are very irregularly folded and squeezed; such zones are in the main moderately hard. They are essentially parallel to the general structure as a whole.

The south wall of the gorge is steep and unbroken except for slight projections of harder zones and faint depressions marking a little softer rock. The strike of the schist here is around N. 50° E., and the dip is 70°–80° NW. The direction of cleavage in the schist hence intersects obliquely (at an angle of about 40°) the course of the river gorge, which here trends nearly due west. There are numerous irregular joints and fractures, but these do not constitute an appreciable weakness so far as the construction of a dam is concerned.

The north wall is somewhat rougher and apparently more jaggedly fractured than the south wall, owing to the angle at which its slope intersects the planes of schistosity. The structure on this side also is less regular and evident. Upstream, near the point where the projecting spur of schist east of Hakatai Canyon meets the Tapeats sandstone cliff, the strike is N. 80° W. and the dip 45° N. Southwestward along the spur the strike of the schistosity swings to N. 40° E. and the dip to about 80° NW. The surface of the spur is jagged and irregular, and joint and schist planes are very prominent. Slight excavation will reveal satisfactory rock for dam abutments, and it is not believed that the joints or other cracks constitute a hazard from leakage. The structure of the schist on both sides of the river is favorable as affording natural stoppage to seepage downstream.

The extension of projecting spurs of bedrock nearly halfway across the river just above Hakatai Canyon and the swift current here indicate a channel scoured of sediment and probably not more than 50 feet deep at any part of the cross section.

The fine-grained hard schist in the walls of the main canyon and in the Hakatai Canyon may be quarried and crushed for concrete, although here, as at other sites along the Granite Gorge, limestone from the formations about a thousand feet above the top of the inner gorge and at a distance of a mile or less from the river would be more easily quarried and worked. The Tapeats sandstone, which forms a cliff capping the gorge, furnishes thick-bedded, massive sandstone that may be used as plums or quarried for cyclopean masonry.

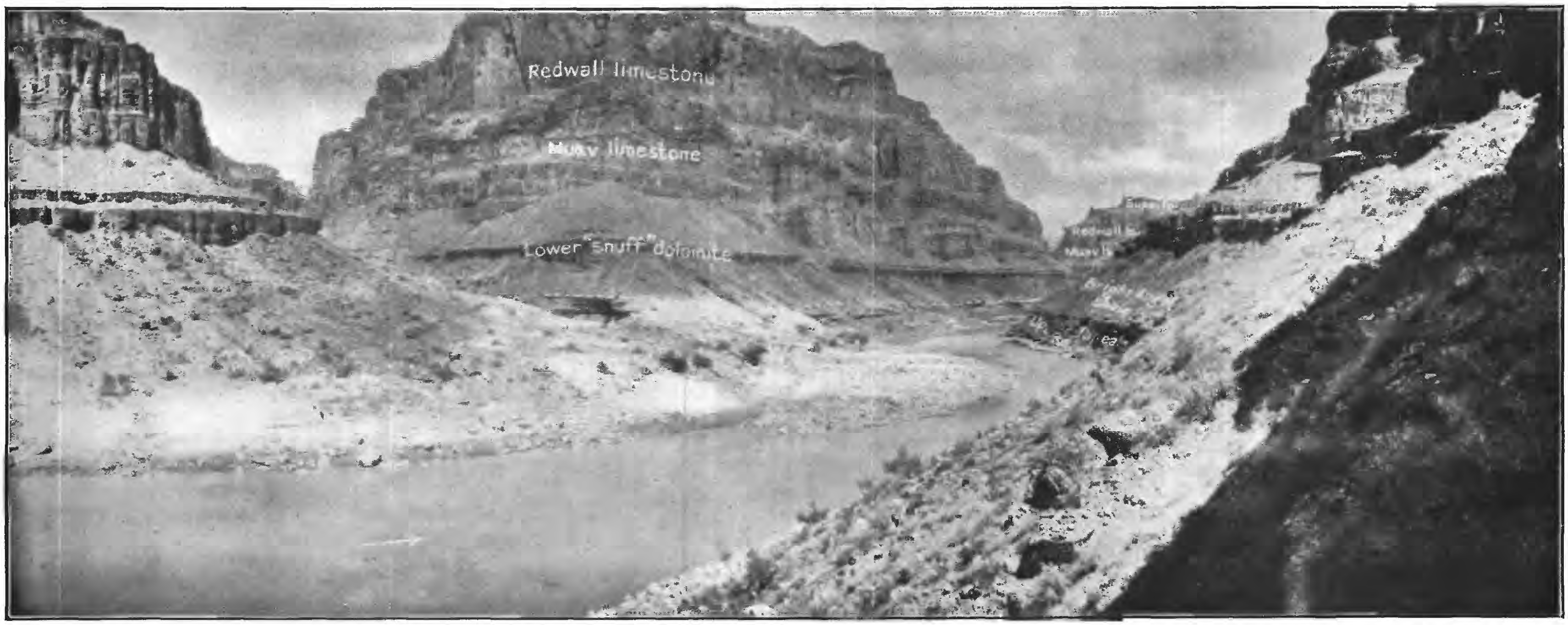
Granite Gorge from Walthenberg Canyon to Stephen Aisle.—The lower portion of the Granite Gorge is carved mostly in hard bluish-gray even-textured banded granite gneiss. Granite schist and amphibolite are exposed in places but form a minor part of the canyon walls. In response to the general resistance which these rocks offer to erosion, the width of the gorge is narrowed and the walls somewhat steepened, but the prevailing slope of the stratified rocks, which carries all the formations lower toward the west and south, decreases very considerably the height of the crystalline-rock gorge. Where the river turns nearly due south, on the east side of Marcos Terrace, the height of the walls of the inner gorge is little more than 300 feet, of which over 100 feet is made up by the cliff of Tapeats sandstone. Granite is exposed above the level of the river entirely around the southern part of the big bend that nearly encircles Marcos Terrace. It disappears rather abruptly at mile 117.8, at a small fault that crosses the river in the middle part of Stephen Aisle, on the west side of Marcos Terrace.

Big Bend dam site.—The walls of the gorge at the Big Bend dam site, mile 113.3 (Pls. XLI, *A*, and XLII), are composed of very hard massive bluish-gray granite gneiss, intersected irregularly by thin dikes of pink granite, granite pegmatite, and dark amphibolite. The gneiss weathers in steep walls, which in places are sheer. Joints traverse the gneiss irregularly, defining blocks of various sizes and shapes. This rock is not shattered and will unquestionably afford highly satisfactory dam foundations and abutments and tunnels. Near water level the rock is finely polished and is in places irregularly carved into potholes.

The gneiss is unconformably overlain by the massive, irregularly cross-bedded Tapeats sandstone, the base of which is here 310 feet above the river. The thickness of the massive, cliff-forming lower part of the sandstone is slightly less than 100 feet (98 feet at one point measured by alidade). This rock is rather coarse grained but is hard and rather tightly cemented and is regarded as satisfactory also for abutments if a dam were constructed high enough to reach it.

A. DOWNSTREAM VIEW OF GRAND CANYON FROM POINT ON RIGHT BANK IN CONQUISTADOR AISLE ABOUT 60 MILES BELOW LITTLE COLORADO RIVER, OR 5 MILES BELOW ELVES CHASM

Geology by R. C. Moore



B. DOWNSTREAM VIEW OF GRAND CANYON FROM POINT ON RIGHT BANK ABOUT 64 MILES BELOW LITTLE COLORADO RIVER, OR 4 MILES ABOVE SPECTER CHASM

Geology by R. C. Moore

Grand Canyon between Granite Gorge and Middle Granite Gorge.—For 8½ miles along the river below the end of Granite Gorge the rocks in the bottom of the canyon are mostly sedimentary. In the next 4 miles, however, the Archean crystalline rocks reappear and form a deep, narrow gorge which on the Shinumo topographic map is designated "Lower Granite Gorge." That name has now been adopted by the United States Geographic Board for the third main granite gorge of the Grand Canyon, which is 50 miles long and extends from a point several miles above Diamond Creek to a point within a few miles of the Grand Wash cliffs. The term Middle Granite Gorgs has been adopted for the short Archean gorge that begins 8½ milee below the Granite Gorge.

For a mile below the Granite Gorge cliffs of Tapeats sandstone, about 150 feet high, occur on both sides of the river at water level. Within the next mile and a third, where the river beneath De Vaca Terrace swings from north to west, Archean schist appears in the very bottom of the canyon. At hardly any point does the base of the Tapeats sandstone reach a height of 100 feet above the river. The schist disappears at the mouth of Hundred and Twenty Mile Creek. Westward through Conquistador Aisle the rock formations are gently inclined to the west at a rate slightly greater than the westward drop of the stream (Pl. LXXVII), so that before the mouth of Hundred and Twentytwo Mile Creek is reached the top of the lower part of the Tapeats sandstone has disappeared beneath the river. Around Alarcon Terrace the bottom of the canyon is carved in the upper part of the Tapeats, here consisting of rather soft sandstone and shaly beds, and the overlying Bright Angel shale.

Middle Granite Gorge.—About 0.2 mile above the mouth of Hundred and Twentyseven Mile Creek dark fine-grained hard pre-Cambrian schist appears and gradually rises above the water until an inner gorge comparable to the Granite Gorge is formed. This is the Middle Granite Gorge. A short distance below Specter Chasm the inner gorge is several hundred feet deep and is very steep sided and narrow. The rocks of the gorge consist mostly of very hard quartzite and quartzitic mica schist, which have a pronounced banding or bedding. This bedding stands nearly vertical and with a dominant northwest strike crosses the river, here flowing northeastward, almost at right angles. The narrowest and steepest parts of the gorge are the parts where the hard quartzite predominates. In the lower part of the gorge granite pegmatite is much more abundant than in the upper part.

Specter Chasm dam sites.—The Specter Chasm dam sites, near mile 130 (Pls. XXXII and XXXIII), are in the highest narrow section of the Middle Granite Gorge. The walls here are composed of very hard dark reddish-brown to bluish-black schistose quartzite and quartzitic schist, with some black amphibolite, somewhat extensively injected with medium to coarse grained pink granite pegmatite in irregular veins from a few inches to 15 or 20 feet thick and with thin veins of milky quartz. The average strike of the schistose rocks is N. 55° E., but there are local variations, due to folds, of about 20°. This strike is essentially parallel to the course of the river here. The dip is 55°–75° NW. The rocks are almost without exception very hard, being broken by the hammer only with considerable difficulty. This feature and the very dense, impermeable texture make the rock very satisfactory for the foundations and abutments of a dam. The excessive hardness, however, will increase the cost of drilling and quarrying. The schistose structure is not so well developed as to be of much aid in working the rock. The dark rocks are undoubtedly an indurated, somewhat metamorphosed sedimentary series which has been closely folded, squeezed, and in places more or less broken. The bedding apparently is parallel to the schistosity.

The southeast (right) wall of the gorge is in general rather smoother than the northwest wall, for in many places the planes of schistosity define the slope. For this reason exposures of the pink granitic intrusive rocks are less conspicuous on the southeast side of the river. The northwest wall is steep but is jaggedly rough, as the slope cuts across the schistose structure. Intrusive pink granite pegmatite is abundant, composing according to estimate about 20 per cent of the wall. The intrusive bodies follow the planes of schistosty in the main and hence extend for considerable distances subhorizontally.

The walls are capped by a cliff about 100 feet high, composed of the Tapeats sandstone, which is medium to coarse grained, irregularly cross-bedded, and hard.

The walls of the Specter Chasm dam sites are so dense and relatively so unshattered by joints or fractures that in spite of the trend of the schist, subparallel to the river's course, they are believed to be entirely satisfactory as a foundation for a dam and to be impermeable to water under pressure.

This section of the river has a quiet, rather even rapid flow, which fills the canyon from wall to wall. The estimated depth to bedrock is 30 to 50 feet. The quartzite of the rock walls is more than sufficiently dense and hard for use as concrete aggregate. It is rather difficult to get at and expensive to crush. The higher parts of the canyon walls, above the gorge, furnish an abundance of suitable, fairly easily accessible, and readily quarried material for concrete. The massive brown hard dolomite about 25 feet thick in the Bright Angel shale, 170 feet above the top of the Tapeats sandstone and only a few hundred yards distant from either dam site, will furnish large quantities of suitable material and will be most easily obtained, as this bed forms extensive benches with gentle slopes below and little cover above. The limestones of the Muav and Redwall formations, higher in the cliffs, are satisfactory but more difficult to work.

Sand is probably most readily obtainable by crushing the Tapeats sandstone, which is about 250 feet in total thickness. The grains of this sandstone are medium coarse to very coarse and gritty and are subangular, and the cementing material is not such as to make crushing expensive. There are unlimited quantities of this easily worked sandstone at the top of the inner gorge, immediately above the quartzite.

Grand Canyon between Middle Granite Gorge and Havasu Creek.—On both sides of the river just below the lower Specter Chasm dam site and in the lower part of Hundred and Thirty Mile Creek, the basal beds of the Unkar group, of Algonkian age, appear between the Archean schist and gneiss and the Tapeats sandstone. A fault that runs parallel to the lower course of Hundred and Thirty Mile Creek, striking about N. 50° W., intersects the pre-Cambrian rocks, dropping the beds north of the fault about 100 feet. The Archean rocks disappear beneath river level about 200 yards north of the fault, for here, as in the vicinity of Shinumo Creek, the top of the crystalline rocks is beveled off smoothly, and this surface, parallel to the bedding in the Algonkian rocks, is inclined at an angle of 10° to 12°, in accordance with the northeasterly dip of the Algonkian strata. From this point for a distance of a little over 3 miles, to a point just below the mouth of Tapeats Creek, the lower portion of the canyon is carved in Algonkian rocks (Pl. LXXVIII, *A*). These rocks consist of a basal deposit of conglomerate (Hotauta), followed by 100 to 150 feet of dense, hard fine-grained yellowish limestone (Bass limestone), a very massive sill of diabase 300 or 400 feet thick, the remainder of the Bass limestone, the Hakatai shale, and in places the Shinumo quartzite. These rocks are beveled off more or less evenly above and are overlain by the Tapeats sandstone. Although a possible dam site may be found in this section of the river, especially between the walls composed of diabase, it does not compare favorably with the Specter Chasm sites, just described.

The inner gorge of the Grand Canyon is sharply constricted about halfway between the mouths of Tapeats and Deer creeks. For a little more than a mile above Deer Creek the river has carved a narrow canyon, which in places is several hundred feet deep, in Archean crystalline rocks, mostly hard granite. Minor exposures of crystalline rocks or of the Bass limestone appear at several points between Deer Creek and Fishtail Canyon, but as far as Hundred and Forty Mile Canyon the formation at the bottom of the gorge is mostly the Tapeats sandstone. Beyond this point for many miles the Bright Angel shale crops out along the stream and in the bottom of the canyon walls. The rock strata continue to descend westward, however, at an angle slightly greater than the drop of the river, so that 3½ miles below the mouth of Kanab Creek the top of the Bright Angel shale disappears, and thence to a point about 9 miles below Havasu Canyon the bottom formation of the canyon is the Muav limestone (Pl. LXXVIII, *B*).

Havasu dam site.—For some distance above and below the mouth of Havasu Creek Colorado River flows in a narrow, deep, steep-sided gorge in the Muav limestone. The Havasu dam site, mile 156.6 (Pls. XXXIV and XXXV, *A*), is a short distance above the mouth of Havasu Creek, in a section slightly narrower than the average. The canyon wall on the right bank is vertical for about 250 feet from the water, and that on the left is composed of two essentially vertical cliffs separated by a 60-foot slope above the lower cliff, which is approximately 100 feet high.

The rock at the dam site, from a level probably below the scour depth of the river to a level considerably above the projected height of the dam, is all limestone, which is more or less magnesian and grades in part into true dolomite. The rock is very fine grained, hard, and dense and is little affected by solution. It is variously mottled dark bluish drab and greenish brown, the mottlings following for the most part branching calcareous seaweeds (algae and fucoids). In contrast to the Redwall limestone, which is a very massive pure limestone, more or less commonly channeled by solution cavities, the Muav is regularly and evenly stratified horizontally, its beds are on the average very thin (1 to 6 inches), and there is a general absence of solution cavities. In spite of the thin bedding, which is revealed on weathered exposures, the formation makes massive, essentially sheer cliffs. Aside from the thinnest-bedded portions of the Muav, noted below, the formation offers excellent conditions for the foundations and abutment walls of a dam.

Certain portions of the Muav limestone in this part of the canyon appear less resistant to weathering than others. Accordingly the canyon walls show two or three alternating series of cliff walls and slopes. The cliffs are composed of the more massive, solid limestone. Examination of the material composing the slopes shows here also limestones not very different lithologically from the cliff limestones, but between the thin limestone beds is a slight parting of sandy material which permits the attack of weathering agencies to disrupt the formation somewhat more readily. The individual thin limestone beds remain hard and dense. In places where weathering has not proceeded for a long time these weaker beds make sheer cliffs that are indistinguishable from adjoining more resistant portions of the formation.

Although the right wall at the dam site is a single cliff, the canyon walls adjacent and on the opposite side show the presence of a slightly less resistant portion of the Muav about 60 feet thick, beginning about 100 feet above water level. Another thin-bedded zone with partings, generally a zone of slopes, about 80 feet thick, appears farther upstream, its top dipping southwest beneath the river just at the dam site. Accordingly, the foundation and lower part of the dam here will be in part of the limestone that is less strong. Measurement of the thickness of the Muav limestone indicates, as shown in the geologic cross section at the dam site (Pl. XXXIV), that the limestone extends considerably below the possible depth of river scour. The disadvantage of the thinner-bedded, less resistant parts of the Muav formation may be offset satisfactorily by increase in the width of concrete construction. The lack of danger from seepage through the formation or from solution largely counterbalances, in the writer's judgment, the disadvantageous conditions noted.

An abundance of highly satisfactory rock for concrete is available in the limestones of the Muav and Redwall formations, which form the canyon walls in this part of the gorge. This rock can be shot down and quarried at any place desired. No sand except that obtainable from crushing the sandstones of the Supai formation, which caps the cliffs of the Redwall limestone along Colorado River and Havasu Creek, or from the Coconino sandstone, near the canyon rim, is readily available. This sand is rather fine grained but may be obtained cheaply in any quantities desired.

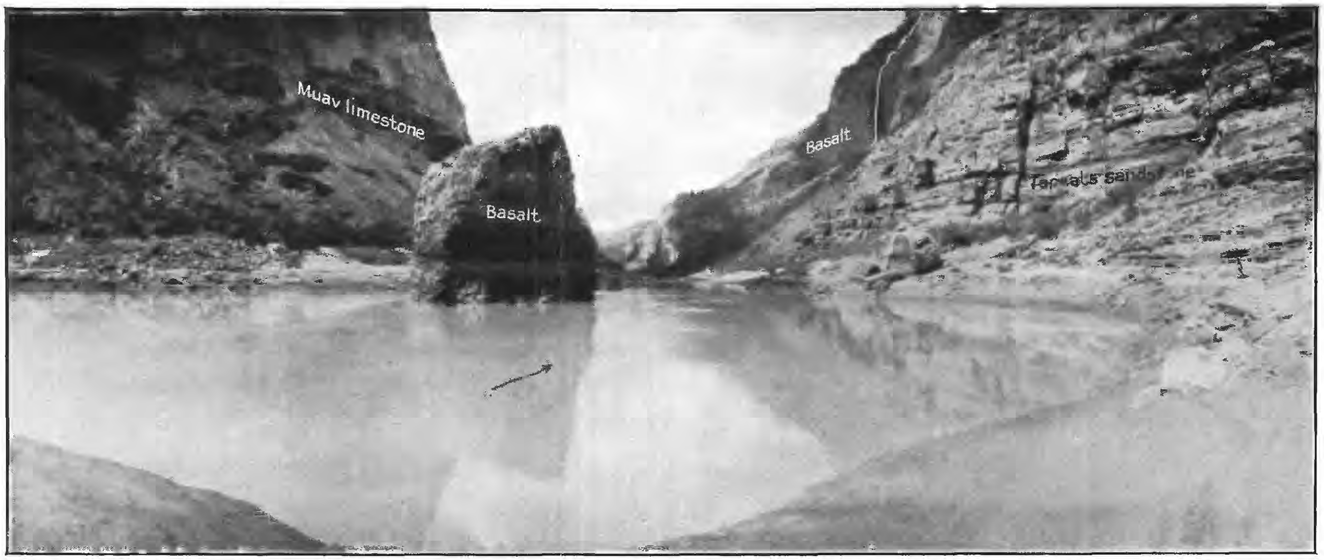
Grand Canyon between Havasu Creek and Toroweap Valley.—Downstream from the mouth of Havasu Creek the river for nearly 20 miles flows in a steep-walled, narrow canyon which swings to the right and left in gentle curves. At the Havasu dam site the lower part of the Muav limestone crops out next to the river, at the bottom of the cliffs on each side. At mile 165.7, about 9 miles below the mouth of Havasu Creek and just above Cataract Canyon, the top of the Bright Angel shale appears above the river, and downstream, as this formation continues to rise, a slope appears between the river and the first cliffs of the canyon, the height of this slope marking essentially the amount of Bright Angel shale exposed. Both because of the increased width of the canyon and because of the unsuitability of the shale for abutments and foundations, favorable dam sites are lacking for many miles. Near mile 171, 14½ miles below the mouth of Havasu Creek, are the two opposite side canyons named Stairway and Gateway canyons. The courses of the tributaries in these two canyons follow very closely a line of displacement that crosses the river obliquely, trending a little east of north, and raises the beds on the west about 100 feet. This is the first of numerous displacements, including some of considerable magnitude, that have affected the rocks of the western part of the Grand Canyon plateau. Almost without exception the faults have had a controlling influence on the erosion of tributary canyons, but the position and topography of Colorado River itself have not been perceptibly affected. The top of the Tapeats sandstone appears a little more than 19 miles below Havasu Creek. At 21 miles below Havasu Creek is found the first of several considerable masses of lava (basalt) which flowed down over the canyon rim to the bottom of the gorge and thence along the canyon. Near this point a lava pinnacle forms an island in the river, known as Vulcans Forge, a prominent landmark for voyagers, which represents a remnant of the lava flow (Pl. LXXIX, *A*). At one time the lava undoubtedly dammed the lower part of the canyon to a height of some hundreds of feet, but the river has long since cut away most of the obstructing material (Pl. LXXIX, *B*).

At mile 179, 22 miles below Havasu Creek, is Lava Falls Rapids, one of the most difficult barriers to travel by boat along the river. Here a large northward-trending fault, which is known to extend along Toroweap Valley and hence is called the Toroweap fault, is crossed by the river. The measured amount of the displacement here is 580 feet.

UINKARET DIVISION, TOROWEAP VALLEY TO HURRICANE FAULT

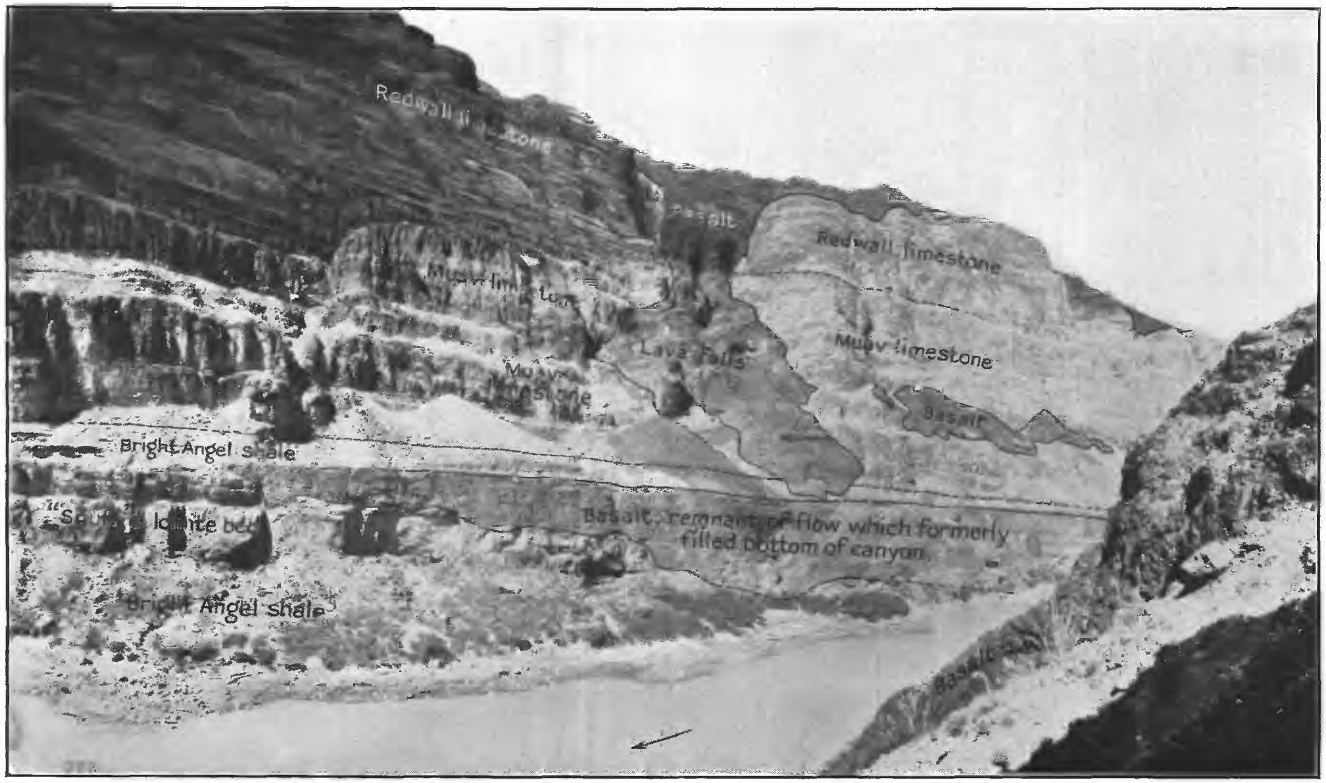
West of the Kanab Plateau, and separated from it in the region of Colorado River by the Toroweap fault, is a segment of the Grand Canyon structural province which is designated the Uinkaret Plateau. This plateau is bounded on the west by the great Hurricane fault, which is traceable for more than 200 miles in a general north-south direction. The surface of the plateau is largely covered by volcanic material, especially near Colorado River, and this covering, together with its structural demarcation from the adjoining plateaus, is its chief characteristic. At the Grand Canyon the Hurricane fault is not far west of the Toroweap Valley, and the Uinkaret division of the canyon is hence very short. From Lava Falls Rapids, at mile 179, to a point near mile 191, a distance of a little more than 11 miles, the canyon is carved in the Uinkaret Plateau.

For about half a mile below the Toroweap fault the Muav limestone appears in the bottom of the Grand Canyon at river level. Within a short distance the slight eastward inclination of the strata and the westward gradient of the river bring the top of the Bright Angel shale to the surface. For a number of miles the thickness of shale exposed gradually increases, and a slope with height corresponding to the thickness of the shale appears above the river. On the left (south) bank of the stream the shale, more or less concealed by



A. DOWNSTREAM VIEW SHOWING LAVA REMNANT KNOWN AS VULCANS FORGE, 21 MILES BELOW HAVASU CREEK, NEAR THE UPPERMOST POINT WHERE THE CANYON HAS BEEN INVADED BY RECENT LAVA

Geology by R. C. Moore

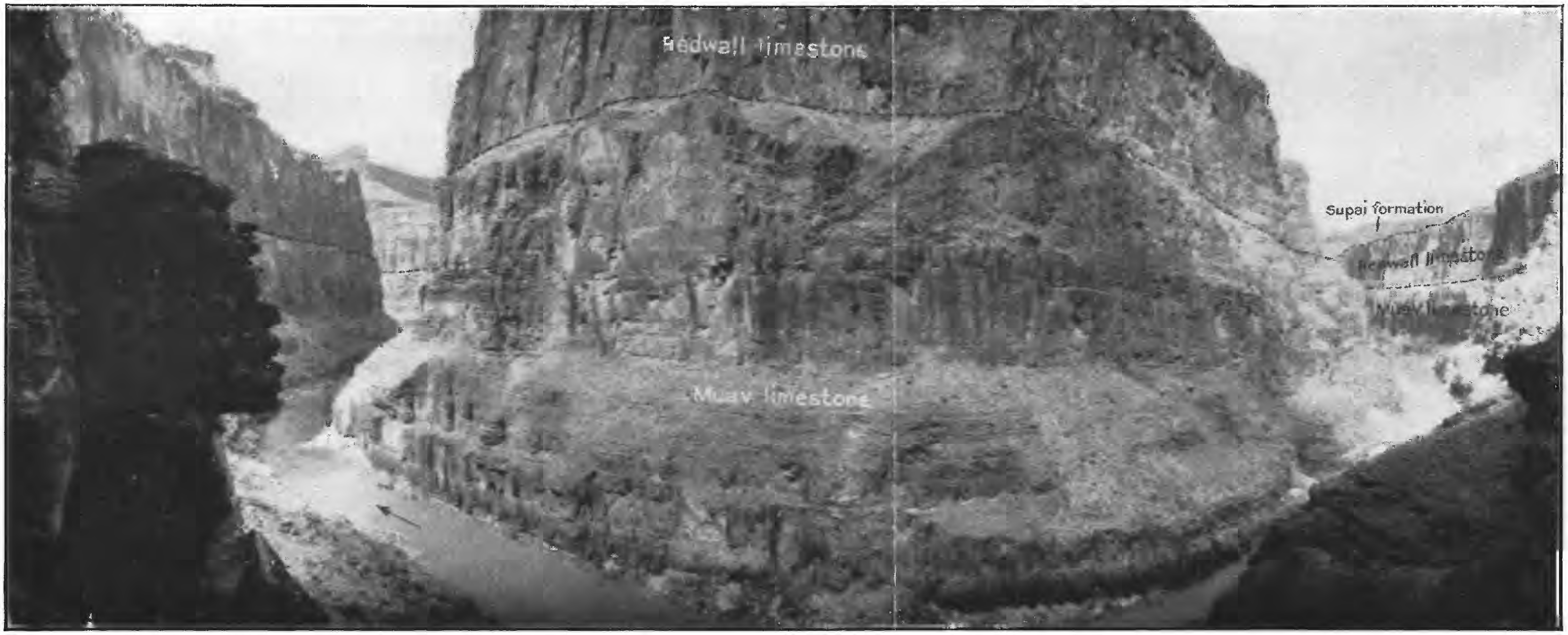


B. LAVA FALLS, A BASALT FLOW FROM THE PLATEAU, 28.3 MILES BELOW HAVASU CREEK

The upper and lower lavas have no immediate relation to each other. Geology by R. C. Moore

A. UPSTREAM VIEW OF GRAND CANYON FROM LEFT BANK ABOUT HALF A MILE ABOVE TAPEATS CREEK

The rocks in the lower part of the canyon are Algonkian. Geology by R. C. Moore



B. VIEW FROM LEFT BANK ABOUT 500 FEET ABOVE THE RIVER, SHOWING BIG BEND IN GRAND CANYON 5 MILES ABOVE KANAB CREEK

Geology by R. C. Moore

talus, is exposed almost continuously, but on the right bank it is covered in many places by lava. At 6½ miles below the Toroweap Valley the top of the Tapeats sandstone reappears above the river, and the moderately steep inner cliffs formed by it gradually increase in height as more of the formation is exposed.

At mile 189.5 the river, flowing east of south, crosses a northeasterly fault along the east side of which the rocks have been raised about 300 feet, sufficiently to expose above the river some 80 feet of the pre-Cambrian crystalline rocks. This fault is apparently one of the series of faults that in this locality mark the Hurricane displacement. In common with all the other gorges carved in the Archean rocks, the inner gorge here is narrow and steep sided, the resistant crystalline rocks being capped by a nearly vertical cliff of Tapeats sandstone. Within little more than a mile the river recrosses the fault and the granite disappears. Notwithstanding the fact that the depth of the inner gorge east of the fault is not very great, the rocks have the necessary strength and the river a sufficiently narrow cross section for a dam within the gorge.

Prospect dam site.—The foundation of a dam in the gorge at mile 190 (Pl. XLIII) will rest on hard Archean granite gneiss, the abutments partly on gneiss and partly on the Tapeats sandstone. The gneiss is pink, brown, and dark blue, is medium to fine grained, and consists of irregular contorted bands whose general trend is about N. 60° E., crossing the river obliquely. The resistance of the rocks is indicated by the constriction of the river in its passage through the short crystalline gorge, in the persistence at several places of little islands composed of the crystalline rock, and in the polished, irregularly carved surfaces of the rock near the river level (Pl. XLI, *B*). No seepage through the crystalline rocks need be anticipated. The Tapeats sandstone, about 300 feet in total thickness here, rests on a surface that bevels very smoothly across the gneiss. The lower part of the formation is composed of medium to coarse grained quartz tightly cemented to form massive beds, each on the average several feet in thickness, the whole cropping out in a nearly vertical cliff a little more than 100 feet high. The rock is traversed by irregular but not numerous joints. So far as strength in anchoring the upper part of a dam abutment is concerned, the Tapeats sandstone is entirely satisfactory, but there is a possibility of some seepage through more porous zones in the sandstone and along joint cracks. In order to obtain suitable massive, unbroken abutment foundations in the Tapeats it will be necessary to remove the outer, more highly jointed portion of the formation. This work may involve excavation into the cliff for 20 to 30 feet. It is believed that with precautions in construction, no seepage will be sufficiently large or localized to endanger the dam. The fault to which the short granite gorge is due intersects the wall of the canyon at a distance of nearly 0.2 mile back from the right side of the dam site and is in no way a possible weakness. Conceivably some seepage might occur along the fault around the dam, but the distance from the point above the dam where the fault crosses the river to an outlet below the dam and the apparently well sealed nature of the fault zone render danger from such seepage very unlikely.

On the right (west) wall of the canyon, at a height of a little more than 100 feet above the river, a remnant of basalt conceals for some distance a part of the Tapeats sandstone, at one place extending over the Tapeats down to the granite. The site of the dam is at the point where the lower part of the Tapeats sandstone appears from beneath the lava, which covers the entire outcrop of the Tapeats for some distance upstream. The thickness of the lava still covering the Tapeats at the dam site is probably not more than a few feet. As a dam with a height of more than 115 feet above the present river level will reach the lava, it will be necessary in building such a dam to excavate the lava in order that the upper part of the right abutment may rest upon the sandstone. The contact between the lava and the underlying rock is by no means water-tight.

Satisfactory material for concrete can be most readily procured at this site from the massive beds of dolomite in the Bright Angel shale, several hundred feet above the river, and from the limestone of the Muav formation, which crops out on both sides of the gorge only a short distance back from the cliff of Tapeats sandstone. Stone for cyclopean masonry can be quarried from the Tapeats sandstone or from the more easily worked dolomite in the Bright Angel shale.

SHIVWITS DIVISION, HURRICANE FAULT TO GRAND WASH CLIFFS

Grand Canyon from Hurricane fault to Diamond Creek.—For several miles below the short granite gorge in which the Prospect dam site is situated the river flows on the Bright Angel shale. Because of the weakness of this formation and because of the occurrence of a number of faults that have aided erosion in breaking down the rock walls, the canyon is somewhat wider at the bottom, and the confining upper walls, which are broken at many places, hem the river less closely. At short intervals, first on one side and then on the other, are low-lying remnants of basaltic lava. At mile 196, about 40 miles below the mouth of Havasu Creek, a fault with downthrow on the west displaces the stratified rocks about 450 feet, and to the west the Muav limestone succeeds the Bright Angel shale as the lowest exposed formation in the canyon. Only a short distance west of the fault, however, the top of the Bright Angel shale reappears above river level, and it continues gradually to rise as the river flows southward. At mile 205 the top of the Tapeats sandstone appears and climbs rather rapidly above the river. Just above mile 208 the river swings eastward to the line of a prominent northward-trending fault, on the east side of which 500 or 600 feet of Archean granite and schist are brought into view at this place. Owing mainly to this and associated smaller faults, which have raised the weak Bright Angel shale zone high above the river, where it may be readily attacked by erosion, and which by fracturing the massive formations have aided in carving a number of prominent side canyons, a conspicuous irregular amphitheater has been formed, to which has been given the name Granite Park. West of the fault in Granite Park the Bright Angel shale appears next above the river. There are no places suitable for dam sites anywhere along the river in this section.

About a third of a mile below the island in Granite Park the top of the Tapeats sandstone appears beneath the Bright Angel shale, and downstream more and more of the formation is exposed until at mile 215 the top of the Archean crystalline rocks appears beneath the Tapeats cliff. Although the granite and associated crystalline rocks are continuously exposed from this point downstream to a point within about 20 miles of the Grand Wash Cliffs, the inner gorge, which has conveniently and appropriately been named the Lower Granite Gorge, increases only very gradually in depth. In this part of its course, extending as far as Diamond Creek, the river flows nearly parallel to and only a short distance west of a large northward-trending fault which here appears to represent the main Hurricane displacement. The rocks east of the fault have been raised from 1,000 to 1,500 feet, so that considerable areas of granite are exposed east of the fault line.

Diamond Creek dam sites.—The inner gorge of Colorado River in the vicinity of the mouth of Diamond Creek is carved in massive light bluish-gray Archean granite and hard cliff-forming sandstone. The granite, which extends downward indefinitely below water level, rises above the river in steep slopes about 600 feet high and is surmounted by a cliff, generally sheer, a little more than 100 feet in height, composed of the Tapeats sandstone (Pl. XLVI, *A*). Above the Tapeats cliff is a bench of varying width formed by shaly sandstone and sandy shale. The granite slopes are scored by shallow subparallel gullies, which follow slightly weaker parts of the rock and joints. These depressions and the intervening shoulders trend slightly west of north, oblique to the course of the river.

Low water exposes a few rather narrow bars of sand on each side of the river, and at the mouth of Diamond Creek there is a large accumulation of sand and boulders which lies in general above the high-water level of the river. The rapids just below the mouth of

Diamond Creek result essentially from the boulders brought down by this tributary.

Foundations for any dam up to about 600 feet in height above the present water level would consist of the granite of the inner gorge (Pl. XLV). The granite is in the main a very massive hard medium-textured rock composed essentially of quartz, white or nearly colorless feldspar, hornblende, and biotite; the average size of the grains is less than 3 millimeters. The dark minerals (hornblende and biotite) show a more or less well-defined parallel arrangement, with the longer crystal axes in one direction. This gneissoid structure is not sufficiently well developed to appear in marked banding, nor does it have any great effect on weathering of the rock. Evidently this rock has not been subjected to pressure and shearing stresses that would develop notable weakness at different places. Some of the granite of the gorge is finer textured than the gray rock just described, is darker and more reddish in color, and appears to weather more easily. Rock of this type forms a minor part of the gorge and is rather irregularly distributed. It offers no difficulty for dam construction but will require somewhat deeper surface stripping to reach fresh, unweathered rock. Both types of granite weather brown. The granite is crossed by rather irregular joints, which generally define large blocks. The rock is not closely or finely fractured; hence weathering produces angular or rounded blocks and projecting points that are rather large. The joints do not have a well-defined trend, but the most prominent ones bear slightly west of north, along the line of the shallow depressions at places on the walls of the canyon. Intrusive bodies of other igneous rocks, such as pegmatite, in the granite are almost entirely absent. Dark thin dikes of amphibolite a few feet in width appear opposite Diamond Creek. The foundation material of the dam is hence all the same kind of rock, hard and strong, well adapted to the construction of a high dam. There is no likelihood of seepage around or under a dam at the lower site, a short distance below the mouth of Diamond Creek, at mile 225.9. At the site above the mouth of the creek some difficulties may be expected from faults and prominent fracture zones which affect the walls of the canyon, as noted below.

The accompanying map (Pl. XLIV) indicates the presence of certain faults which have fractured and displaced the rocks. A fault that may be called the West fault cuts the rocks back of the river gorge on the west, with a trend about N. 14° E. It intersects the Tapeats sandstone and granite in the small side canyon which joins Colorado River 2,000 feet above the mouth of Diamond Creek and cuts the cliffs north of the side canyon. It does not affect the stability of a dam in the Colorado River gorge but should be taken into account if a plan is made to construct tunnels or spillways on the west side of the river near the point where it displaces the rocks of the canyon wall. Seepage along the fault plane from ponded water extending up the tributary canyon above Diamond Creek into the river below is improbable and even if it occurred would not in any way weaken the dam.

A fault trending N. 20° E. crosses Diamond Creek about half a mile above its mouth. It follows a prominent but short side canyon of Diamond Creek on the south and a smaller indentation of the wall on the north. The beds south of Diamond Creek are displaced about 40 feet, those on the west being raised; but the dislocation diminishes northward. This fault will have no effect on tunnels from Diamond Creek into the Colorado River canyon for a dam below the mouth of the creek, as such tunnels will presumably be located west of the fault. No seepage along it around the dam is to be expected.

So far as indicated by other geologic considerations, a site above the mouth of Diamond Creek, at mile 225.5, is possible, as well as one below, but the presence of several zones of prominent fracturing or faulting running through the southwestward-projecting spur of crystalline rocks north of Diamond Creek promises possibly serious leakage, which, however, might be prevented by special precautions in construction. The difficulties and dangers from this source increase rapidly in proportion to the height of the dam proposed. For a dam south of the mouth of Diamond Creek (Pl. XLV, *B*), tunnels from Diamond Creek to the river gorge below the dam would be carried entirely in granite.

Abundant material suitable for construction is conveniently available for a dam near the mouth of Diamond Creek. In the lower parts of Peach Springs Wash and Diamond Creek canyon there are unlimited quantities of hard crystalline rocks, but the massive beds of dolomitic limestone in the upper part of the Bright Angel shale and in the lower part of the Muav formation can be quarried more easily, and if, as is probable, the railroad and construction camps are located on the plateau bench above the granite gorge, this source will be more accessible, as the outcrops of the limestone occur a short distance back of the cliffs that rim the gorge. The limestone may be used very satisfactorily in concrete or in ashlar, rubble, or cyclopean masonry, or large blocks can be used as plums. Large quantities of sand and gravel are found in the lower part of the Diamond Creek canyon. The sand is medium to fine in texture, and the grains are more or less rounded. Much coarser and somewhat more angular sand can be obtained by crushing beds of the Tapeats sandstone, which crops out at the rim of the gorge above the dam site.

Although pure limestone (Redwall) is to be had near by in the canyon cliffs, the other materials needed for the local manufacture of Portland cement are not found here.

Lower Granite Gorge from Diamond Creek to Travertine Canyon.—Downstream from the mouth of Diamond Creek, as the river flows first westward and then northwestward, the bottom portion of the Grand Canyon is essentially similar in character to that at the Diamond Creek dam sites, described above (Pl. XLVI, *A*). The walls, which are uniformly very steep, are for many miles several hundred feet in height. Although composed in part of dark fine-grained hard schistose rocks, most of the rock is medium-grained massive granite or granite gneiss. The side canyons from the south or north are narrow and deep, and their descent toward the river is steep. Here, as in each of the other granite gorges along the river, the persistent Tapeats sandstone forms a vertical cliff surmounting the steep wall of the crystalline rocks. About 3 miles below the mouth of Diamond Creek the walls of the Lower Granite Gorge are extremely steep and are approximately 1,000 feet high.

Travertine Canyon dam site.—In the narrow, steep-sided section of the gorge at mile 228.6, near the lower end of a tributary named Travertine Canyon, are found favorable conditions for a dam (Pls. XLVI, *B*, and XLVII). The walls of the gorge here consist of very hard, massive, rather fine grained pink to bluish-gray granite gneiss. The hardness of the rock is shown by the unusual narrowness of the gorge and by the nearly vertical cliffs that occur in places on both sides of the river, especially on the right, where the entire wall is remarkably steep. Near the river level the hard, dense rock is smoothly polished and in places is irregularly carved into potholes by the action of the water. Its joints are irregular. The gneiss is more or less prominently banded, and the banding crosses the river almost at right angles. The texture, composition, and structure of the rocks at this dam site preclude all possibility of leakage around the dam. A minimum of work in the removal of surface-weathered and more or less jointed rock would be required to give foundations of the utmost stability. The base of the Tapeats sandstone is approximately 700 feet above river level. As the Tapeats is here a very massive, hard formation, almost a quartzite, it would be readily possible, so far as the character of the rocks is concerned, to construct a dam more than 900 feet high at this place.

Just below the narrow section selected for a dam site, where small canyons enter from each side, the character of the walls changes very abruptly, the gneiss being replaced by dark micaceous schist. Most of the schist is dense and hard, being composed largely of fine quartz with more or less abundant fine mica along cleavage planes. Some of the schist is highly garnetiferous. As a whole the schist is much less resistant than the gneiss, but water spilled down either side canyon and downstream will not erode it rapidly. The strike of the schist is almost at right angles to the course of the river.

Construction materials at the Travertine Canyon dam site are practically the same as those at Diamond Creek, for the same formations are found here in essentially the same relations.

Lower Granite Gorge from Travertine Canyon to Bridge Canyon dam site.—Between Travertine Canyon and the Bridge Canyon dam site, mile 236.3, there are no marked changes in the general character of the rocks exposed in the lower part of the Grand Canyon, nor in the topography. The blue granite gneiss that forms the narrows at the Travertine Canyon dam site extends only to the mouth of Travertine Canyon. Below this point are dark-colored dense quartzite and mica schist, in part highly garnetiferous, with very pronounced banding. The schist closely resembles a rather thinly stratified sedimentary series upturned nearly on end. The strike of the schistose structure is slightly east of north, almost at right angles to the course of the river. Farther downstream the structure of the schist is more irregular, and in places no dominant trend to the banding can be clearly distinguished. There are also sections of the gorge in which granite, granite gneiss, and more or less abundant pegmatite appear. Most of the rock is very hard, and the walls rise steeply from the river's edge.

Bridge Canyon dam site.—In a very narrow, steep-walled portion of the Lower Granite Gorge, at mile 236.3, 10.4 miles below the mouth of Diamond Creek, is the Bridge Canyon dam site (Pls. XLIX and XLVIII, *B*). The rocks here consist of a rather complex mass of dark-bluish granite gneiss with thin, irregular veins of pink granite and granite pegmatite and thick intrusions of massive pink granite. All of the rock, irrespective of details of kind and structure, is hard and dense and is admirably fitted for foundation material in a high dam. No danger from lack of strength or from leakage around the dam through the rocks need be anticipated. There are small, irregular masses of dark schist in the lower part of the gorge, near the mouth of the side canyon that has been considered as part of a spillway. The schist is only slightly less satisfactory than the gneiss. The parallel structure in the gneiss and schist is irregular but tends to follow a direction nearly due north. The side canyon on the left that offers facilities for a spillway is carved in the schist, its course following the strike of the schistose structure. Though not so strong as the gneiss which is the predominating rock at the dam site, the schist in the side canyon will not yield with undue rapidity to erosion from spillway overflow. It is not deemed necessary to take special precautions in utilizing the side canyon for a spillway.

The construction materials available here are practically the same as to kind, availability, and unlimited quantity as at Diamond Creek.

Lower Granite Gorge between Bridge Canyon dam site and Spencer Canyon.—Below Bridge Canyon the walls of the Lower Granite Gorge consist mainly of medium to coarse grained pinkish granite and granite gneiss. The granite is very massive and is traversed by relatively few major joints, so that it weathers in cliffs and great rough crags. A small amount of schist, into which the granite is evidently intruded, occurs in places. Some parts of the massive crystalline rocks are intruded by irregular, mainly rather thin dikes of a very dark igneous rock which appears to be amphibolite. Near the mouth of Separation Canyon the rock is chiefly a very hard bluish granite gneiss, the banding of which strikes north, approximately at right angles to the course of the river. The rocks of the gorge are almost everywhere more than sufficiently strong for the foundations of a dam. The average depth of the gorge in this section is lower than at points upstream, for the Paleozoic strata are here inclined very gently to the west, descending at a rate slightly greater than the gradient of Colorado River.

Spencer Canyon dam site.—The lower part of the canyon of Colorado River at the Spencer Canyon dam site, mile 246.2 (Pls. LIX and LVII, *B*), is carved in very hard, dense medium-grained bluish-gray granite. The granite gorge is narrow, and its walls are on the left nearly vertical and on the right steeply sloping. The granite is massive and is not traversed by zones of weaker rocks. It is coarsely jointed, and the main joints run irregularly in subhorizontal, nearly vertical, and steeply oblique (about 45°) directions, dipping downstream. These joints control the weathering, the rock breaking into large irregular blocks, which are gradually rounded on the edges by the weather. Where erosion is active near the water level the granite is carved into curving surfaces and irregular potholes and is more or less smoothly polished. Such features are developed only in the most resistant rocks, and their occurrence here indicates the hardness of the granite. In all respects the walls of the canyon here are admirably fitted for dam construction.

The granite is capped on both sides of the gorge by the Tapeats sandstone, a coarse, hard, gritty formation which is also resistant to erosion. Above the massive lower Tapeats sandstone are softer rocks that weather back, forming a bench. This topographic feature is important in planning parts of a development program.

On the right side of the gorge nearly opposite Spencer Canyon is a patch of basaltic lava that rests on a sort of shelf about 100 feet above the river. The granite on which the lava lies forms a nearly vertical cliff rising sheer from the river's edge, and this cliff is continued with very little break by the lava to a height of 150 feet. The lava is apparently a remnant of extensive flows which at one time descended along the bottom of the canyon from the volcanic eruptions of the Uinkaret Plateau. As it is the only rock of the sort in this section of the canyon, it is a rather striking and convenient marker by which to locate one of the worst rapids on Colorado River—that just below the mouth of Spencer Canyon, which is designated Lava Cliff Rapids. As the basalt is all above the dam site, it does not enter into consideration of construction problems except as regards its availability for use as concrete aggregate. It is sufficiently hard and dense for that purpose and can be broken fairly readily, especially along the rather closely spaced columnar joints. There is not enough of the lava rock, however, to furnish all the material needed for aggregate.

As shown in the topographic map and cross section of the Spencer Canyon dam site (Pl. LIX), the steep-sided projecting mass that lies between the lower part of Spencer Canyon and the main river gorge is partly cut off from the canyon walls behind it by a steep-sided gully joining Spencer Canyon about 1,000 feet above the river and by an ill-defined hollow in the left wall of the main gorge just below the cliff that furnishes the left abutment at the dam site. The lower Tapeats sandstone, which caps this rounded spur, is cut off from the continuation of the formation beyond this depression. The topography and especially the alinement of the ravine on the Spencer Canyon side with the depression on the main gorge side suggest a major fracture or fault. The depression here affords topographic conditions for a spillway site. No displacement of the Tapeats sandstone was observed, and accordingly it appears that the erosion features noted have been guided by weakness resulting from pre-Cambrian faulting, or by major jointing or other structural weakness of undetermined origin, or it may be that the position of the small erosion depression is fortuitous. Detailed examination should be made here in advance of spillway construction, and, if needed, provision can be made readily to guard against unduly rapid erosion in the spillway. Even though this spillway site should prove to be somewhat less resistant to erosion than the main mass of the granite walls, the probability of unsafe erosion at or below the spillway is believed to be extremely small.

In the cliffs above the rim of the inner gorge, only a few hundred feet distant, are unlimited quantities of limestone and dolomite, suitable for use in concrete construction. This limestone or any part of the granite near by can be used for plums. The nearest available sand is obtainable by crushing portions of the Tapeats sandstone, just above the granite. This sand is medium to coarse and subangular, and, though hard, it can be crushed without too great difficulty.

Different beds in the formation vary in coarseness and hardness, softer sandstones occurring in the middle and upper parts. Because of the entire lack of suitable shale, it is not feasible to manufacture Portland cement in the vicinity of the dam site, notwithstanding the presence of abundant limestone (Redwall) of sufficient purity.

Lower Granite Gorge between Spencer Canyon and Salt Creek.—Below Spencer Canyon the rocks of the Lower Granite Gorge are almost exclusively granitic. They are massive and in general show very little gneissoid banding. Irregular joints that traverse the granite in various directions define the large and small blocks that are loosened by weathering and control the main details of surface conformation within the gorge. In places the granite is deeply stained to a red-brown color, and rounded rock surfaces project through a scanty mantle of the débris produced by disintegration. Elsewhere abrupt cliffs and steep slopes of bare hard rock ascend from the water level to the overlying cliff of Tapeats sandstone, which to the west becomes very gradually lower. At the mouth of a large tributary canyon entering from the left (southwest) at mile 252, the head of the Boulder Canyon reservoir survey of 1921, Colorado River turns rather abruptly northward, and thence it follows for some 3 miles the line of a fault that lifts the rocks on the west side of the displacement about 200 feet above the corresponding rocks on the east. This fault extends up the canyon of Salt Creek, which enters at mile 255.5. This tributary has the apparently anomalous course of due south into a main stream that flows north.

Devils Slide dam site.—Massive hard pink to red granite of fine to medium grain forms the lower 370 feet of the steep-sided inner gorge of the Grand Canyon just below the mouth of Salt Creek (Pls. LII, *A*, and LI). That the rock has the strength requisite for the foundation and abutments of a high dam is shown by the narrow, steep cross section of the gorge, as well as by examination of typical parts of the granite. The massiveness of the granite and the absence of numerous joints indicate the absence of danger of seepage. Above the granite, considerably higher than the proposed crest of a dam, lies the Tapeats sandstone, which forms a cliff with an average height of about 130 feet. Here, as elsewhere in the canyon, this formation is massive, hard, and resistant, being almost a quartzite.

Along the broad saddle in the divide between the lower part of the canyon of Salt Creek and the main river gorge the granite is somewhat decomposed. Excavation to provide a spillway at a somewhat lower elevation would reveal fresh granite, but although the width of the saddle and the breadth of the divide would satisfactorily accommodate with little erosion a large overflow, it might be desirable to face the spillway with concrete.

The fault that is followed by Salt Creek and by Colorado River above the mouth of the creek affects conditions at the dam site in no way except to influence the erosion that has developed the favorable spillway conditions. The fault is entirely above the dam and spillway sites and can not produce leakage or affect the stability of construction at the site.

Materials for construction are close at hand and can be obtained without difficulty. They are the same in kind and in relation to the site as at Diamond Creek.

Grand Canyon from Salt Creek to Grand Wash Cliffs.—Below Salt Creek the Lower Granite Gorge is somewhat deeper than it is a few miles upstream, because of the uplift of the rocks west of the Devils Slide fault. The rocks consist mainly of massive red granite, essentially uniform in character for several miles. It weathers in steep craggy slopes or forms precipitous cliffs, which, as elsewhere, are surmounted by the nearly vertical wall of Tapeats sandstone. The westward inclination of the stratified rocks overlying the granite gradually reduces the depth of the Lower Granite Gorge. At mile 257, about 4 miles below Salt Creek, the river crosses a zone of faulting which drops the base of the Tapeats within about 100 feet of the river. On the left side of the Colorado here and at many places farther downstream there are large accumulations of travertine. Near mile 260 the red granite disappears beneath the river, and the Tapeats sandstone forms abrupt cliffs on each side. Here are found remnants of basalt not far above the river. For a few miles below mile 260 the river surface coincides almost exactly with the gently sloping contact between the Tapeats and underlying crystalline rocks. Consequently there are alternating stretches where 2 or 3 feet of granite appears above the water and stretches where the Tapeats extends to the river level. Beyond mile 266 the bottom of the Grand Canyon is carved in the Tapeats sandstone, but as the westward dip of the rocks continues, the lower, cliff-forming portion of the Tapeats disappears beneath the river. The relatively weak upper portion of the Tapeats and the soft Bright Angel shale, which overlies it, produce a moderately open, wide-bottomed canyon.

A north-south fault near mile 275 with approximately 250 feet upthrow on the west and another fault near mile 276.5 lift the base of the Tapeats over 100 feet above the river, exposing at the base of the canyon walls the upper part of the Archean granite. About 1½ miles downstream the main Grand Wash fault is reached, along which the rocks have been dropped several thousand feet on the west. Tertiary and Quaternary gravel and other relatively recent deposits lie west of the fault. The Grand Canyon ends where the river emerges from the plateau, the western edge of which, determined by the great fault that cuts off the granite in the river, is known as the Grand Wash Cliffs. To the west and south of these cliffs the river flows through a very different country.

Pierces Ferry dam site.—For about a mile upstream from the great fault that separates the Colorado Plateau country on the east from the Basin and Range country on the west, the river flows in a fairly narrow but not deep canyon carved in Archean granite. Only a little more than 100 feet of the granite is exposed in most parts of this gorge, the crystalline rocks being unconformably overlain by the Tapeats sandstone, which forms a more or less precipitous cliff above the granite.

At the Pierces Ferry dam site, mile 277.3 (Pls. LXII and LXI, *B*), the rocks in the bed of Colorado River and for a little more than 100 feet on each bank consist of rather coarse grained hard reddish granite, which is massive and in the main unbroken by abundant joints. In strength and in resistance to leakage this rock is as satisfactory as in most of the other sites in the granite gorges of the Grand Canyon already described. In places the granite is smoothly polished by the action of the water, in much the same manner as the more resistant crystalline rocks upstream. The flow of the river in this section is quiet. There is very little opportunity for the deposition of sand or gravel, and it is probable that most of the channel is fairly clean. From 1 to 2 miles above the site there are consolidated deposits of river gravel and extensive accumulations of travertine 100 to 200 feet above the present river level. The conditions observed indicate canyon excavation almost but not quite to the depth of the present canyon, followed by filling to the height of the present gravel remnants or beyond. Subsequently there has been excavation of this fill and erosion into bedrock. Continuous exposures of the crystalline rocks and the overlying stratified rocks along the present course of the stream indicate no possibility of leakage in the section above the dam. Although no evidence of a different former course of Colorado River was found in this section, it should be recognized that there is a possibility that a buried channel, filled with gravel and travertine, may extend from a point where the entire right bank of the river is covered by a great mass of travertine, a little more than a mile above the site, to some point below the place where the river now crosses the fault. This possibility is regarded as improbable, but in advance of actual construction geologic inquiry should be made on this point.

The upper parts of the walls of the gorge, which are composed of Tapeats sandstone, are more shattered and more porous than the underlying granite. In order to insure satisfactory abutments for the upper part of the dam, rising to the height of the sandstone, it will be necessary to excavate back a sufficient distance to reach fresh, comparatively unbroken sandstone. This rock is very hard, practically a quartzite, and except near the exposures, where it is broken by weathering, it is very massive and may be used with confidence as a part of the dam foundation.

The upper part of the Tapeats sandstone and the overlying Bright Angel shale are incompetent and have wasted away, leaving a wide bench above the cliff of the lower Tapeats sandstone.

Most of the materials required for construction are readily available in the vicinity of the dam site. Granite can be procured from the lower parts of the gorge but is rather too hard for cheap crushing. The overlying sandstone will yield moderately coarse and angular or subangular sand and pieces of larger dimensions. Limestone can be obtained at a distance of about a mile or less to the east, in the direction of the Grand Wash Cliffs. The dolomite beds in the Bright Angel shale can be most readily obtained. These beds are very massive here and make a prominent bench. There are extensive gravel deposits within a mile or two downstream, but most of the pebbles are throughly well rounded.

MOHAVE CANYON DAM SITE

Beginning just south of Topock, Ariz., where the Atchison, Topeka & Santa Fe Railway crosses Colorado River, the river has carved through the Mohave Mountains a narrow, steep-sided canyon, the rock walls of which are in some places several hundred feet high. This section of the river, which is called Mohave Canyon, is about 10 miles long. The course of the canyon is fairly straight in a direction slightly east of south. The dam site here described is in the upper part of this canyon, a short distance south of the rugged axial portion of the mountain that is locally named The Needles (Pls. XI, *A*, and XII).

The field work on which the report on this dam site is based is a brief reconnaissance which was made in company with Herman Stabler and E. C. La Rue, hydraulic engineers, on October 20, 1923. In the short time available an examination was made of the topography and the rock formations along the road from Topock and of the geology of the dam and spillway sites. Travel by boat on the river, proceeding southward to Needles, and by automobile to the dam site permitted observation of the area that will be flooded to make the reservoir north of the dam.

The topography in the vicinity of the dam site and northward to Topock is rather rugged on a small scale, for a number of small dry washes with a maximum depth of about 100 feet cut across the land sloping down to the river. On the east side of the river, north of the dam site, many of these washes are carved in partly consolidated gravel and alluvial débris, but on the west side most of them are in solid massive rock.

The rocks that are exposed in the walls of the Mohave Canyon at the dam site consist of medium to coarse grained crystalline igneous rocks that have been altered, apparently by heated aqueous solutions. The general character of the rock is granitic, but the alteration makes it difficult to determine the precise megascopic classification of the rock. However, so far as the construction of a dam is concerned it is sufficient to indicate that the rock is massive and hard and, although somewhat minutely fractured on long-exposed surfaces, would undoubtedly in strength and resistance to leakage be very satisfactory for the foundation and abutments. The rocks that appear in the canyon wall extend back from the canyon several hundred feet eastward, as far as the small gullies that head at the saddle which might be used as a spillway. The rocks east of the saddle are softer, coarser grained, and more deeply disintegrated than the rocks near the canyon. Nevertheless, they are massive, and it is believed that excavation will reveal much stronger rock than is now exposed. All the evidence observed points to the conclusion that these rocks in the canyon and extending back uninterruptedly to the east and west are constituent parts of the igneous material of the Mohave Mountains and that there is no likelihood of seepage of any importance through these rocks. If the saddle east of the dam site should be used as an overflow spillway, some concrete lining may be necessary, as the rocks below and in the spillway would be cut away considerably more rapidly than an ordinary massive, resistant granite. This statement is based on the more or less disintegrated condition of the material at the surface and would doubtless require modification if it were possible to cut deep enough into the rock to reach fresh material, though it is believed that even the fresh rock is not as strong as ordinary fresh granite. The bedrock is traversed by numerous joints, which do not appear to have a definite arrangement. However, except near the surface, it does not seem that the rock is sufficiently fractured to make the possibility of leakage serious.

The reservoir which a dam at this site would create would be relatively large. For a dam with a crest 585 feet above sea level, or about 158 feet above river level, the water would be impounded for many miles upstream. On both sides of Mohave Valley, the broad flood plain of Colorado River, the waters would cover the lower parts of the long, gentle slopes leading up to the mountains. Mohave Valley and parts of the adjacent slopes are composed of sand and alluvial material brought down by the river. In addition, there are large quantities of rock waste which have been brought from the adjacent mountains, building up the slopes to the river. The area that would be included in the reservoir site was not examined in detail, but the more or less well-consolidated materials that form the slopes appear of themselves to offer very little possibility of leakage, even if the basin of Mohave Valley were not rimmed on practically all sides with massive igneous rock. Undoubtedly the solid rocks that appear at the surface in the mountains west and east of the river and extend across the course of the river in the Mohave Mountains lie beneath the materials that form the land-waste slopes and the flood plains of Mohave Valley.

At a point a few miles south of the dam site there is evidence of a gravel-filled channel of the river which has been abandoned in favor of a new course carved in the bedrock farther to the west, but there does not appear to be any outlet to the basin north of the dam site other than that which the river now occupies. In other words, if a dam is built at the site south of Topock, it is believed that this will effectually close the basin to the north, there being no possibility of seepage through unconsolidated materials at the same or lower levels at some point in the margin of the reservoir.

The conclusions derived from the reconnaissance examination outlined above should be checked by detailed observation in the vicinity of the dam site to determine the continuity of the massive igneous rocks that make up the Mohave Mountains and The Needles. A more detailed study of the reservoir basin north of the dam site would also be desirable, although there is very little likelihood of disadvantageous features in the geology of the reservoir site. Diamond core borings to determine the extent of the more fractured, less firm superficial zones, especially in the vicinity of the spillway site, should be undertaken in advance of actual construction.

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