BANK STORAGE

LAKE POWELL

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BANK STORAGE--LAKE POWELL

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Introduction

During the first 2 years of filling of Lake Powell behind Glen Canyon Dam, it was evident that a considerable amount of the storage water was being absorbed by the sandstone which forms the reservoir walls. If this continued at the rate of the first 2 years, more water would be required to fill this space than had been anticipated during the planning stages. Since information on this type of bank storage is largely lacking, a study was made to determine the quantity of water that could reasonably be expected to be retained as bank storage. This paper presents the results of these studies.

Bank storage is defined as water which enters the reservoir foundation after filling begins. It is experienced at all reservoirs and usually fills the voids within 2 or 3 miles of the reservoir. The amount of bank storage is not subject to exact determinations. Partial recovery of the storage can be accomplished by lowering the reservoir sufficiently to reverse the hydraulic gradient.

Glen Canyon Statistical Data

Glen Canyon Dam is located on the Colorado River in Arizona about 15 miles upstream from Lees Ferry. It was authorized by the Colorado River Storage Project Act (Public Law 485, 84th Congress, 2nd Session) in 1956. Construction was initiated that year on the diversion tunnels, and the dam was finished in 1964. Storage was started in March 1963, but low runoff resulted in storage of only 2.9 million acre-feet by the end of 1963. The reservoir rose to elevation 3,414 feet in January 1964 and remained there until March 1964. Releases to meet downstream requirements lowered the reservoir to elevation 3,394 feet by May 1964. The gates were then closed, and the reservoir rose to minimum power head at elevation 3,490 feet (surface content 6.1 million acre-feet) in August 1964. The reservoir was held generally at this elevation until the spring runoff of 1965 which allowed both heavy downstream releases to Lake Mead and storage in Lake Powell to elevation 3,531 feet (surface content 8.5 million acre-feet) by July 31, 1965. The lake reached elevation 3,581.18 feet (surface content 12.3 million acre-feet) by July 21, 1969.

When full, Lake Powell will extend 186 miles up the Colorado River from Glen Canyon Dam and about 71 miles up the San Juan River from its

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confluence with the Colorado River. Major storage basins are located in the Warm Creek-Last Chance Creek area, the Halls Creek-Bullfrog Creek area, and the Hite area. Much of the remainder of the reservoir is buried in long, deep canyons or narrow tributaries. The meanders and storage areas result in an exceptionally long shoreline.

Reservoir statistics are as follows:

At normal water surface level	
Elevation (feet)	3,700
Content (acre-feet)	27,000,000
Area (acres)	161,390
Shoreline (miles)	1,900
Drainage area (sq.miles)	107,700

Principal gaging stations used in studies relating to water supply and bank storage are as follows:

Gaging Station	Drainage Area (sq.miles)
Colorado River at Lees Ferry	107,900
Colorado River near Cisco, Utah	24,100
Green River at Green River, Utah	40,600
San Juan River near Bluff, Utah	23,000
San Rafael River near Green River, Utah	1,690
Dirty Devil River near Hite, Utah	4,360

Reservoir Geology

The Lake Powell basin is located entirely within the Colorado Plateau province. Most of the area consists of flat to gently folded sedimentary formations ranging in age from upper Paleozoic through Cretaceous. Formations of both marine and continental deposition are present within the reservoir basin, but continental sediments, especially sandstone of aeolian deposition, predominate.

Stratigraphy

The formations exposed within the reservoir basin are described briefly on the two columnar sections, Figures 1 and 2. The Paleozoic formations which occur upstream from Hite are described in Figure 1, taken from Geological Survey Bulletin 951 (Baker, 1946). Rock units of similar age and characteristics downstream from Hite are described in Figure 2, taken from Geological Survey Bulletin 1137 (Phoenix, 1963). Formations older than the Kayenta and younger than the Chinle are included in the Moenave formation in Figure 2 and correlate with the Wingate sandstone of Figure 1. In general, the nomenclature and descriptions in Figure 1 apply to the reservoir area. A complete and recent presentation of the geology is shown on Geologic Map of Utah, southeast quarter (Stokes and Hintze, 1964).

Detailed descriptions of the Navajo sandstone and Chinle formation follow. Both are critically important with respect to bank storage.

Navajo Sandstone.--Because of its physical characteristics and widespread occurrence throughout the reservoir basin, the Navajo sandstone is the most important formation involved with bank storage. It extends upstream from Glen Canyon Dam almost continuously for 108 miles along the Colorado River and about 6 miles along the San Juan River. It is 1,200 to 1,800 feet thick and has been incised an average of 500 feet by the Colorado River to form the walls of Glen Canyon. It will not come in contact with reservoir water in the upstream areas of either the San Juan or Colorado River because it has either been eroded away or if present is above elevation 3,700 feet.

As seen in outcrops and hand specimens, the rock is red to pink, uniformly graded, very well sorted, medium to very fine grained, poorly cemented sandstone. It is predominantly massive but displays remarkable large-scale crossbedding typical of aeolian origin. It is friable and porous but contains only small pore spaces. Consequently it is absorptive due to capillarity but is not highly permeable. It is remarkably uniform and homogeneous over wide areas, and nearly identical samples can be obtained from areas separated by as much as 400 miles.

Microscopic examination shows that the sandstone particles are composed mostly of rounded to subrounded, pitted grains of quartz, minor feldspar and chalcedony, and traces of other minerals. The grains are cemented at points of contact by secondary quartz, opal, and chalcedony. Within crossbedded zones thin laminations occur which are well cemented by quartz or calcite. Small amounts of mica, hematite, and clay partially fill some of the intergranular pore spaces.

Grain and pore sizes on a large number of thin sections from rock at Glen Canyon Dam were determined at Bureau of Reclamation laboratories. These tests gave the following results:

	Millimeters
Grain diameter	
Maximum	0.73
Minimum	.04
Average	.17
Pore diameter	
Maximum	.46
Minimum	.00
Average	.03

Porosity in percent by volume of 53 samples tested from Navajo sandstone at Glen Canyon Dam ranged from 22.8 to 26.5, averaging 24.7.

Permeability tests of the Navajo sandstone were conducted by the Bureau of Reclamation on laboratory samples and in 6-inch diameter drill holes at the dam site. Tap water was used in the laboratory, and settled river water was used at the dam site. Forty-one laboratory tests showed an average of 221 feet per year. Twenty tests in 6-inch drill holes showed an average of 64 feet per year. During the field tests the permeability rate diminished with time. Attempts to grout the foundation rock during construction, utilizing either water-cement grout or silicate gel chemical grout, met with little or no success. The grouting agents penetrated the pore spaces for only a short distance.

Chinle Formation.--The Chinle formation is important to bank storage and water-holding capabilities of the reservoir because of its stratigraphic position beneath the Navajo sandstone, its structural relationship to the reservoir basin, and its impervious nature. It underlies the downstream two-thirds of the reservoir at an average of 400 feet below the bottom of the Navajo sandstone and occurs throughout much of the San Juan arm of the reservoir.

The Chinle formation is generally divided into three or four members; however, the thick Petrified Forest member is of most significance here. It is multicolored (shades of green, blue, and red), soft, poorly cemented bentonitic mudstone, claystone, and shale containing thin lenses of limestone, conglomerate, and sandstone. The member varies in thickness up to about 625 feet (Figures 1 and 2).

Because of its thickness and impervious character and because it forms a structural basin which encloses much of the reservoir, the Chinle formation creates "a gasket" which effectively "seals" the downstream portion of the reservoir.

Structure

Formations throughout the area have been uplifted and broadly folded so the reservoir basin is divided into four major structural units, discussed below.

Echo Monocline & Kaiparowits Syncline.--The downstream limit of the Kaiparowits Syncline is defined by the north-northwest trending Echo Monocline, a continuous major structure which extends a number of miles north and south of the Colorado River at Lees Ferry. At the monoclinal axis the formations dip upstream about 20°, gradually flatten, and gently undulate throughout the Kaiparowits Syncline.

Circle Cliffs Anticline.--The formations reverse direction and increase the steepness of dip as the axis of the Circle Cliffs Anticline is approached, there defining the upstream limits of the Kaiparowits Syncline. The reservoir walls, for about 60 river miles within this area, are almost entirely composed of Navajo sandstone. The Circle Cliffs Anticline brings older rocks, including the Chinle shale, to the surface for a few river miles.

Henry Mountains Syncline.--The downstream limits of the Henry Mountains Syncline is defined by the axis of the Circle Cliffs Anticline. From the axis the rocks dip upstream and gently to the north, away from the river, but flatten out and reverse dip as the river approaches the broad axis of the Monument Anticline. For about 40 river miles the reservoir walls are again predominantly Navajo sandstone.

Monument Anticline to Head of Lake Powell.--The upstream limit of the Henry Mountains Syncline is gradual and difficult to define but is designated at 108 river miles above Glen Canyon Dam. Upstream from this point the Monument Anticline has brought Paleozoic formations to river level, and the reservoir walls are composed of more impervious and less porous formations than the Navajo sandstone.

Ground Water

Ground Water Levels

A number of wells have been drilled near the lower end of Lake Powell. Wells OW 1, 2, 5, 8, 9, and 10 were drilled by the contractor for use during construction. Wells OW 101, 102, 103, 104, and 105 were drilled by the Bureau of Reclamation in 1965 for observation purposes. Three privately owned wells were drilled for potential domestic uses but have not been used. Other wells have been drilled for the Navajo Indians. The contractor wells have been observed since storage began on a monthly or biweekly interval. The Bureau wells have been observed since completion in 1965. Pertinent data on the wells are shown on Table 1 and Figures 3, 5, 6, and 7.

It has been proved conclusively by observation of wells that the pre-Lake Powell water table was a normal ground water condition which roughly paralleled the surface topography and rose uniformly from the river to elevations well above normal water surface of Lake Powell within roughly 10 miles of the reservoir.

Yield of Wells

Study of the location, surface elevation, ground water elevations, and yield of a number of pertinent wells shows that the wells fall into two categories which display extremely divergent characteristics. One group of wells drilled by the contractor in the Wahweap area (Wells OW 5, 8, 9, and 10, inclusive) yielded an average of 1,000 gallons per minute from the Navajo sandstone at depths of roughly 700 feet. These wells all had original ground water elevations which corresponded closely to elevations along the adjacent Wahweap channel, or about 200 feet above river level at the dam site. The rise in water levels in these wells during partial filling of Lake Powell to elevation 3,531 shows that they reflect rather rapidly the changes in water surface elevation of the reservoir. By contrast, another group of wells, including OW 1 and 2 and Bureau observation wells OW 103 and 105, display strongly contrasting characteristics. Yields from these wells are very low (20 to 30 gallons per minute), and they reflect the rise in reservoir water very slowly. Relative information is given in detail on Table 1 and Figure 3.

Data on numerous wells are presented in Geohydrologic Data in the Navajo and Hopi Indian Reservations (Davis, 1963). These data show that the low-yield wells near the dam site are representative of wells found throughout the area whereas the high-yield wells are exceptional. The high-yield wells are located along the axis of the Kaiparowits Syncline. Downstream from Wahweap Creek the formations dip upstream 15 to 20° within the Echo Cliffs Monocline. Near Wahweap Creek the attitude of bedding changes rapidly to a downstream dip, creating a flexure in bedrock. The thick, homogeneous Navajo sandstone displays very little tensile strength; consequently, adjustment to folding results in vertical fractures which parallel the trend of folding. These fractures become increasingly open at depths along the axis of the syncline. Drilling records of the high-yield wells show that production was greatest within areas of fracturing generally encountered below 700 feet. These fractures trend roughly parallel to Wahweap Creek and intercept the reservoir basin in the general area of the Wahweap Creek-Colorado River confluence. These geologic conditions allow reservoir water into the joint system which is reflected rapidly in the wells. It is evident that data obtained from these wells are not representative of the rate at which water is entering the Navajo sandstone. A more realistic condition is presented in wells OW 1, 2, and 105.

Formations in the reservoir basin other than Navajo sandstone have very low porosity and do not absorb significant quantities of water. Small amounts of water enter sand dunes and talus along the water's edge but are regarded as inconsequential.

Any seepage passing around the dam and into the river above Lee Ferry can be observed. Since the path of percolation is shortest adjacent to the dam, this is the area where the first water should appear. To date inspection has shown no ground water or seepage is returning to the river between the dam and Lees Ferry. Considering the volume of surface storage in Lake Powell and the rate of discharge from the reservoir, seepage through the abutments from the reservoir will be insignificant in the future. The steep ground water gradient between the reservoir and some of the adjacent wells and the slow rate at which these wells respond to fluctuations in reservoir water surface are indications of the very slow rate at which water will pass through the rock from the reservoir.

Measurement of Bank Storage

Bank Storage to Date

Inflow-outflow studies have been made to estimate probable bank storage since the beginning of surface storage in Lake Powell in March 1963. Bank storage was determined as the residual water unaccounted for after consideration of inflow to the basin as measured by three gages on the Green River, Colorado River, and San Juan River; inflow adjusted for ungaged areas based on correlation with past records; outflow as measured by the Lees Ferry gage; evaporation determined from tables developed from adjusted pan records at three locations in the vicinity of the reservoir basin; and changes in reservoir content.

Measurements of bank storage based on inflow-outflow studies are subject to inherent errors such as measurements of flow, estimates of evaporation, errors in capacity tables for Lake Powell, and variations in the unmeasured inflow, especially during high runoff months. Perhaps the greatest of these are variations in unmeasured inflow and evaporation due to wind and temperature. Flow records are rated as good to excellent. The area-capacity table is based upon high order topography obtained by photogrammetry. The topography was produced at a scale of 1 inch to 400 feet, and the contour interval of 10 feet was based upon an extensive network of high order controls established by the Coast and Geodetic Survey and the Geological Survey.

Estimates of bank storage based on inflow-outflow studies are as follows:

Period	Res. elev. at end of period (feet)	Bank storage increase for period (acre-feet)	Bank storage cumulative total (acre-feet)
3/1 - 12/31/63	3,410	579,000	579,000
1/1 - 12/31/64	3,492	1,185,000	1,764,000
1/1 - 12/31/65	3,535	1,023,000	2,787,000
1/1 - 12/31/66	3,521	716,000	3,503,000
1/1 - 12/31/67	3,527	537,000	4,040,000
1/1 - 12/31/68	3,539	552,000	4,592,000
1/1 - 6/30/69	3,580	-4,000	4,588,000

Total Anticipated Bank Storage

Estimates were made of the total anticipated bank storage in Lake Powell from consideration of the original position of the ground water, void space in the Navajo sandstone, and anticipated slope of ground water from the reservoir into the rock.

Of the factors considered in computing the volume of void space which may be filled with reservoir water, the length of time required to fill the pore space is the least predictable. The porosity and position of the original ground water level are roughly known, but the time required for stabilization of the gradient from the reservoir into the bank is not known.

The amount of pore space as determined in the laboratory from 53 samples is 24.7 percent. This was on an oven-dry basis, so allowance must be made for residual moisture in the rock, for entrapped air, and local perched water table areas. An arbitrary figure of 20 percent for pore space was used but is probably high.

The volume of the triangular-shaped wedge of rock and reservoir (see Figure 4) between river level and elevation 3,700 feet (normal water surface) was calculated and the reservoir capacity was subtracted. The gradient of the original water table was measured in several wells near the lower end of the basin. (Three wells ranged from .012 to .013--average .0125.) Here the elevation was low and annual precipitation was very low. Near the Rainbow Bridge large springs were used and a figure of .032 selected. The ground water here is doubtless affected by higher elevations on each side of the river and higher annual precipitation.

Since the porous formations are in contact with the reservoir only in the lower 60 air miles,1/ the volume of rock was computed on end areas at 5-mile intervals. In one interval between river mile 90 and 102, the Navajo formation rises above high water level so this section was excluded. The total volume of porous rock and water (ACD X L, Figure 4) below 3,700 feet and between the dam and river mile 134 is 86,800,000 acre-feet.

In time, the water from the reservoir will extend outward into the porous rock and will assume a gradient which varies with the permeability of the rock. The flattest pre-reservoir gradient measured in wells was .0125, so this figure was used in the computations. This gradient will require many years to reach equilibrium, possibly over 100 years. For instance, Wells OW 1 and OW 2 west of the dam both have gradients of .075 after 5 years of observation. Well OW 105 has a gradient of .032 after 5 years and the reservoir half encircles it. This indicates that it will be a long time before the balance between friction in the aquifer equals the head in the reservoir and the outward movement ceases.

The area between AEF (Figure 4) is unsaturated by either reservoir water or ground water. This was subtracted from the volume of rock. Over the centuries the ground water may eventually fill this, but it should not affect the reservoir.

Calculations

$\frac{\overline{BD}}{\text{slope}} = \overline{AB} =$	Where $\overline{BD}$ is the depth of a full reservoir below 3,700 where the cross section is measured. The slope varies from .0125 to .032.
$\frac{\overline{AB} \times \overline{BD} \times 2}{2} =$	Area of unsaturated rock and reservoir, pre-Lake Powell.
$\text{Area } \frac{(ACD) \times L}{43560} =$	Volume in acre-feet of rock and reservoir (86,800,000) where L is distance in feet from dam to limit of porous strata in contact with reservoir. (This is 60 miles straight line or to river mile 134 on USGS river sheets.)

1/ The upper limit of the porous formations is river mile 134 at the mouth of Smith Creek.

86,800,000		
Less 23,200,000	=	Volume of reservoir in contact with vol. of porous rock (from capacity studies).
63,600,000 AF	=	Vol. of porous rock (AED X 2 X L).
63,600,000		
Less 37,500,000	=	Volume not filled (AEF X 2 X L).
26,100,000	=	Volume filled by reservoir (FED X 2 X L).
26,100,000 X 20%		(Void space) = 5,220,000 acre-feet which is volume of water admitted into the bank with time and a full reservoir.
Add 780,000	=	Estimate of bank storage in the upper end of the reservoir (above river mile 134 where formations are impervious but contain normal joints, talus, and unsaturated sediments found in any reservoir). This is 3% of the total capacity of the reservoir.
5,220,000		
6,000,000		

The calculations show a total of 6,000,000 acre-feet of water as eventual bank storage in the sandstone. This estimate is probably on the high side since the reservoir is likely to remain at elevation 3,700 feet for only short periods.

Summary and Conclusions

It has been proved conclusively that the pre-Lake Powell ground water surface was normal and rose above the normal water surface level of the lake within about 10 miles from the river. There is no possible path for ground water to leave the basin except around the dam and back into the river above Lees Ferry.

The rate at which reservoir water moves through unfractured Navajo sandstone cannot be determined precisely but is slow and will diminish with time. The rate of movement through fracture zones is much faster but is representative of only small, isolated areas.

The ultimate volume of bank storage cannot be determined precisely but is estimated at about 6,000,000 acre-feet. It will be somewhat less than the volume available from saturating all rock adjacent to the reservoir beneath a newly established ground water surface which slopes away from the river at about 66 feet per mile or .0125 (pre-Lake Powell ground water gradient). It is obvious that the future rate of bank storage will fluctuate with the rate of surface storage and will diminish to an insignificant amount a few months after the reservoir surface becomes stable.

The determination of bank storage based on inflow-outflow data is subject to several inherent errors, the greatest of which are the fluctuation in unmeasured flow, especially during periods of high runoff, and perhaps evaporation due to wind and temperature.

The observation of wells and collection of other data are continuing. This information will be available for future analyses. Ground water data from additional observation wells located at strategic points near the reservoir would be helpful in refining the bank storage figures.

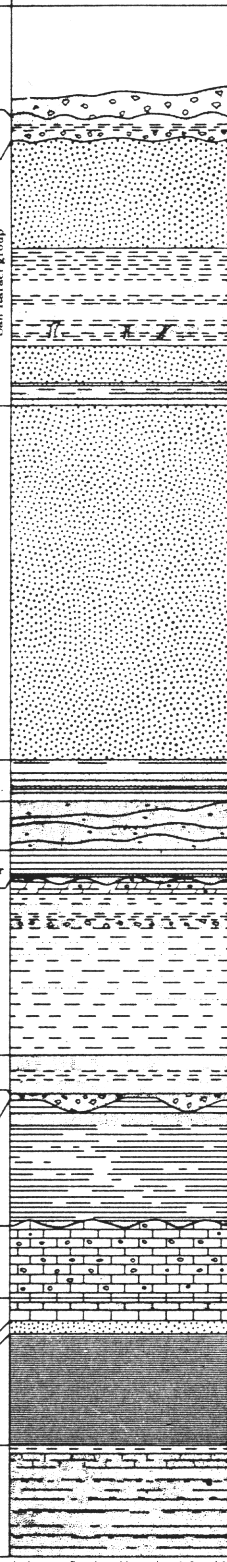
System	Series		Formation	Section	Thickness (feet)	Character of rocks
CRETACEOUS	Upper Cretaceous		Mancos shale		800+	Steel-gray marine shale with a few thin beds of buff to brown sandstone.
			Dakota (?) sandstone		0-40	Yellowish-brown conglomeratic sandstone with chert pebbles as much as 1 inch or more in maximum diameter and with abundant silicified wood; contains some yellow sandy clay and carbonaceous shale.
JURASSIC	Upper Jurassic		Morrison formation (Salt Wash sandstone member)		590-637	Upper part consists of well-banded variegated shale with a few siliceous conglomeratic sandstone beds containing varicolored chert pebbles; Salt Wash sandstone member constitutes approximately lower third of formation and consists of irregularly bedded gray sandstone interbedded with red mudstone and with a thick bed of gypsum at the base.
		San Rafael group	Summerville formation		96-205	Thin regularly bedded red-brown more or less earthy sandstone and shale with some veins and beds of gypsum.
			Curtis formation		34-235	Greenish-gray to brown fine- to coarse-grained sandstone and greenish-gray to red shale; contains locally geodes lined with celestite crystals and nodules and beds of light-gray to flesh-colored gypsum.
			Entrada sandstone		405-460	Silty red sandstone with a few ledge-forming beds of buff to gray sandstone in the western part; grades eastward into massive cross-bedded red to buff sandstone.
			Carmel formation		85-230	Brown to gray fossiliferous sandy limestone and limy sandstone at the base, overlain by interbedded red to gray silty sandstone and shale; abundant gypsum near the San Raphael Swell; grades eastward into interbedded silty red sandstone and shale.
JURASSIC (?)		Glen Canyon group	Navajo sandstone		420-552	Massive cross-bedded buff to gray sandstone with a few thin lenses of sandy limestone.
			Kayenta formation		270-294	Irregularly bedded fine- to coarse-grained red to gray thin-bedded to massive, in part cross-bedded, sandstone, locally conglomeratic, with some red, gray, and green shale.
			Wingate sandstone		270-323	Massive cross-bedded buff to brownish-red medium-grained sandstone, which weathers into cliffs characterized by vertical joints.
TRIASSIC	Upper Triassic		Chinle formation		265-455	Variegated shale with some interbedded red to gray sandstone, conglomerate, and a few beds of sandy limestone; contains fossil wood.
			Shinarump conglomerate		0-135	Gray medium- to coarse-grained cross-bedded and irregularly bedded sandstone with lenses and streaks of conglomerate containing pebbles of quartzite, limestone, and clay pellets and with interbedded gray shale; contains fossil wood.
	Lower Triassic		Moenkopi formation (Sinbad limestone member)		326-684	Thin and regularly bedded red-brown and greenish-gray siltstone with thin beds of ripple-marked gray to red-brown sandstone with the Sinbad limestone member in the lower part on the San Rafael Swell; locally thick parts of the formation are greenish gray.
PERMIAN		Cutler formation	Unnamed upper unit		0-60	Coarse- to fine-grained red to purplish-brown micaceous sandstone and siltstone similar in lithology to Organ Rock tongue.
			White Rim sandstone member		0-230	Massive cross-bedded tan to light-gray, medium- to coarse-grained sandstone.
			Organ Rock tongue		117-870	Red siltstone, silty more or less arkosic sandstone, and sandy shale, weathering into fluted surfaces.
			Cedar Mesa sandstone member		747	Light-gray to tan friable, fine- to coarse-grained thick-bedded and cross-bedded sandstone, which grades northward into red shale, siltstone, and arkosic sandstone.
			Rico formation		575	Interbedded gray to reddish-purple fine- to coarse-grained sandstone, red to purplish shale and siltstone, and gray to greenish-gray fossiliferous limestone.
CARBONIFEROUS	Pennsylvanian		Hermosa formation		913+	Massive to thin-bedded light- to dark-gray dense to coarsely crystalline cherty, fossiliferous limestone interbedded with gray to brown massive to thin-bedded sandstone, with a few thin beds of gray to red shale.
			Paradox formation		?	Crops out as small gypsum plugs shown by drilled wells to contain salt and anhydrite with interbedded black and brown shale and some limestone.

ROCKS EXPOSED IN THE REGION EXCLUSIVE OF THE CARBONIFEROUS AND PERMIAN ROCKS OF THE SAN RAFAEL SWELL.

System	Series	Formation	Section	Thickness (feet)	Character of rocks
PERMIAN		Kaibab limestone		0-102	Light-gray to brown cherty fossiliferous limestone, commonly sandy.
		Coconino sandstone		685	Massive cross-bedded light-gray to buff sandstone with irregular patches of red, medium- to coarse-grained sandstone.
CARBONIFEROUS	Pennsylvanian	Hermosa (?) formation		432+	Interbedded gray to tan sandstone and gray to pink more or less cherty limestone; exposed in Straight Wash Canyon.

CARBONIFEROUS AND PERMIAN ROCKS EXPOSED IN THE SAN RAFAEL SWELL.

GENERALIZED COLUMNAR SECTION OF THE ROCKS EXPOSED IN THE GREEN RIVER DESERT-CATARACT CANYON REGION, UTAH.

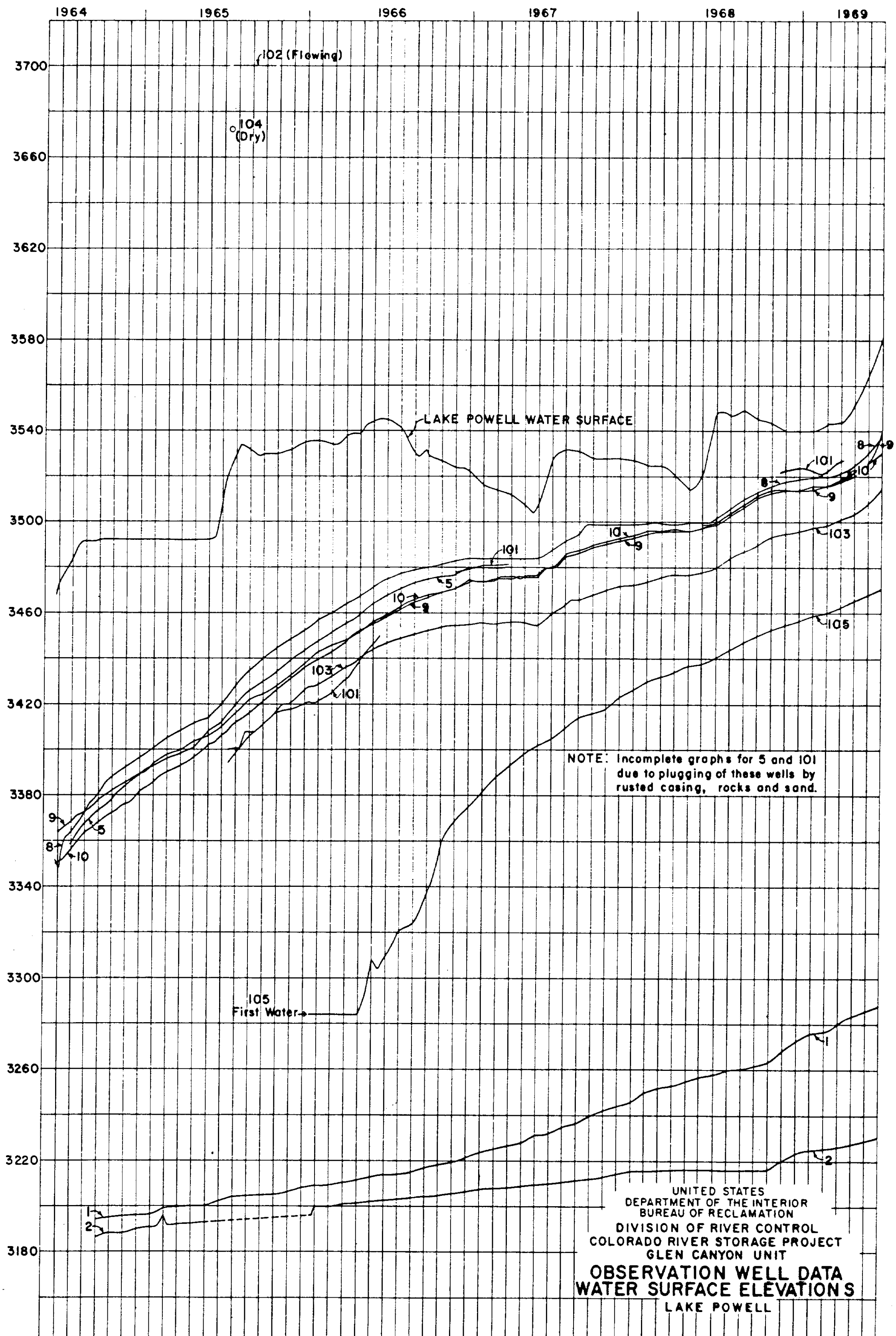


Age	Group	Formation	Thickness (feet)	Description	Land forms
Quaternary				Terrace gravel, landslide, alluvial fan, and talus debris; windblown sand and stream gravel.	Benches, lobate tongues, cones, dunes, and valley bottoms.
Upper Cretaceous		Dakota sandstone	100±	Conglomerate and coarse-grained sandstone overlain by ripple-bedded sandstone and laminated siltstone.	Ledges and short slopes.
Upper Jurassic	San Rafael group	Entrada sandstone	650	Massive pale-gray medium- to fine-grained crossbedded sandstone.	Bluffs
Middle and Upper Jurassic	San Rafael group	Carmel formation	401	Mudstone; red sandstone interstratified with siltstone; slump deformed red-brown siltstone and pale-brown sandstone.	Ledges and short slopes.
Middle and Upper Jurassic	San Rafael group; Glen Canyon group	Thousand Pockets tongue	0-228	Massive pale-yellow medium- to fine-grained crossbedded sandstone.	Broad slopes
Middle and Upper Jurassic	San Rafael group; Glen Canyon group	Judd Hollow tongue	0-32	Evenly bedded dark-brown to pale-gray medium- to fine-grained sandstone and siltstone.	Ledges
Jurassic and Jurassic(?)	Glen Canyon group	Navajo sandstone	1675-1857	Massive gray- to red-brown crossbedded sandstone with a few lenses of dark-brown chert.	Nipples, buttes, and sheer cliffs.
Jurassic(?)	Glen Canyon group	Kayenta formation	120-200	Massive even-bedded pale-red-brown sandstone	Benches and ledges.
Triassic(?)	Glen Canyon group	Moenave formation: Springdale sandstone member	180-223	Massive dark-colored sandstone	Cliffs
Triassic(?)	Glen Canyon group	Moenave formation: Dinosaur Canyon sandstone member	90-220	Even-bedded reddish-orange sandstone and siltstone	Ledges and steep slopes.
Late Triassic		Chinle formation: Owl Rock and Petrified Forest members, undifferentiated	825	Owl Rock member: cherty limestone, limestone conglomerate, sandstone, and mudstone; 150-200 ft thick. Petrified Forest member: bentonitic mudstone and claystone colored shades of green, blue, and red, overlain by reddish silty mudstone and pebble conglomerate in thin lenses; all about 625 ft thick.	Smooth rounded slopes.
Late Triassic		Chinle formation: Sandstone-mudstone unit	175±	Lenticular pale-gray arkosic sandstone, varicolored mudstone.	Ledges
Late Triassic		Chinle formation: Shinarump member	0-150	Lenticular pale-brown conglomerate sandstone	Benches and ledges.
Early and Middle(?) Triassic		Moenkopi formation	320-469	Thin-bedded gypsiferous pale-red- to dark-brown mudstone, siltstone and silty limestone, with pale-brown sandstone as marker bed near top of formation.	Concave slopes
Permian	Aubrey group	Kaibab limestone	244-320	Massive light-gray sandy and cherty limestone	Cliffs
Permian	Aubrey group	Toroweap formation	120±	Interbedded sandstone; mudstone and cherty limestone.	Cliffs
Permian	Aubrey group	Coconino sandstone	50-60	Massive light-yellow-gray crossbedded sandstone	Cliffs
Permian	Aubrey group	Hermit shale	520±	Thin-bedded brownish-red siltstone and shale	Steep slopes
Permian and Pennsylvanian	Aubrey group	Supai formation	500+	Light-colored medium- to fine-grained sandstone interstratified with laminated red-brown siltstone and shale.	Ledges and cliffs.

[1] Thickness of stratigraphic units in this table apply only to the area shown by the geologic map. Stratigraphic sections 1, 2, and 6 have been measured outside the map area, and the thickness of the formations described at these places may be more or less than those in this plate.

GENERALIZED COLUMNAR SECTION OF ROCKS EXPOSED IN THE LEES FERRY AREA, COCONINO COUNTY, ARIZONA

680610 O - 63 (In pocket)

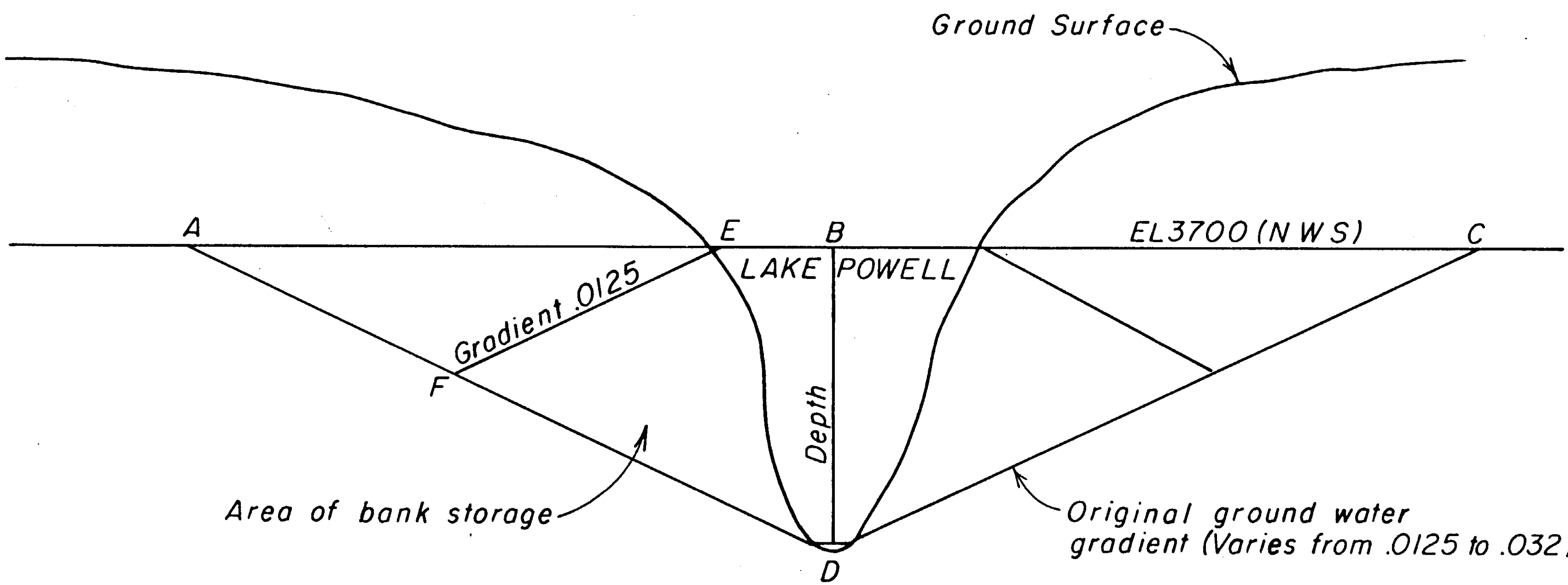


1964
1965
1966
1967
1968
1969
3700
3660
3620
3580
3540
3500
3460
3420
3380
3340
3300
3260
3220
3180
3140
102 (Flowing)
104 (Dry)
LAKE POWELL WATER SURFACE
101
103
105
105 First Water
NOTE: Incomplete graphs for 5 and 101 due to plugging of these wells by rusted casing, rocks and sand.
UNITED STATES
DEPARTMENT OF THE INTERIOR
BUREAU OF RECLAMATION
DIVISION OF RIVER CONTROL
COLORADO RIVER STORAGE PROJECT
GLEN CANYON UNIT
OBSERVATION WELL DATA
WATER SURFACE ELEVATIONS
LAKE POWELL

Figure 3

Fig. 4

LAKE POWELL
BANK STORAGE STUDY



SECTION OF END AREA USED IN CALCULATING
BANK STORAGE AT LAKE POWELL

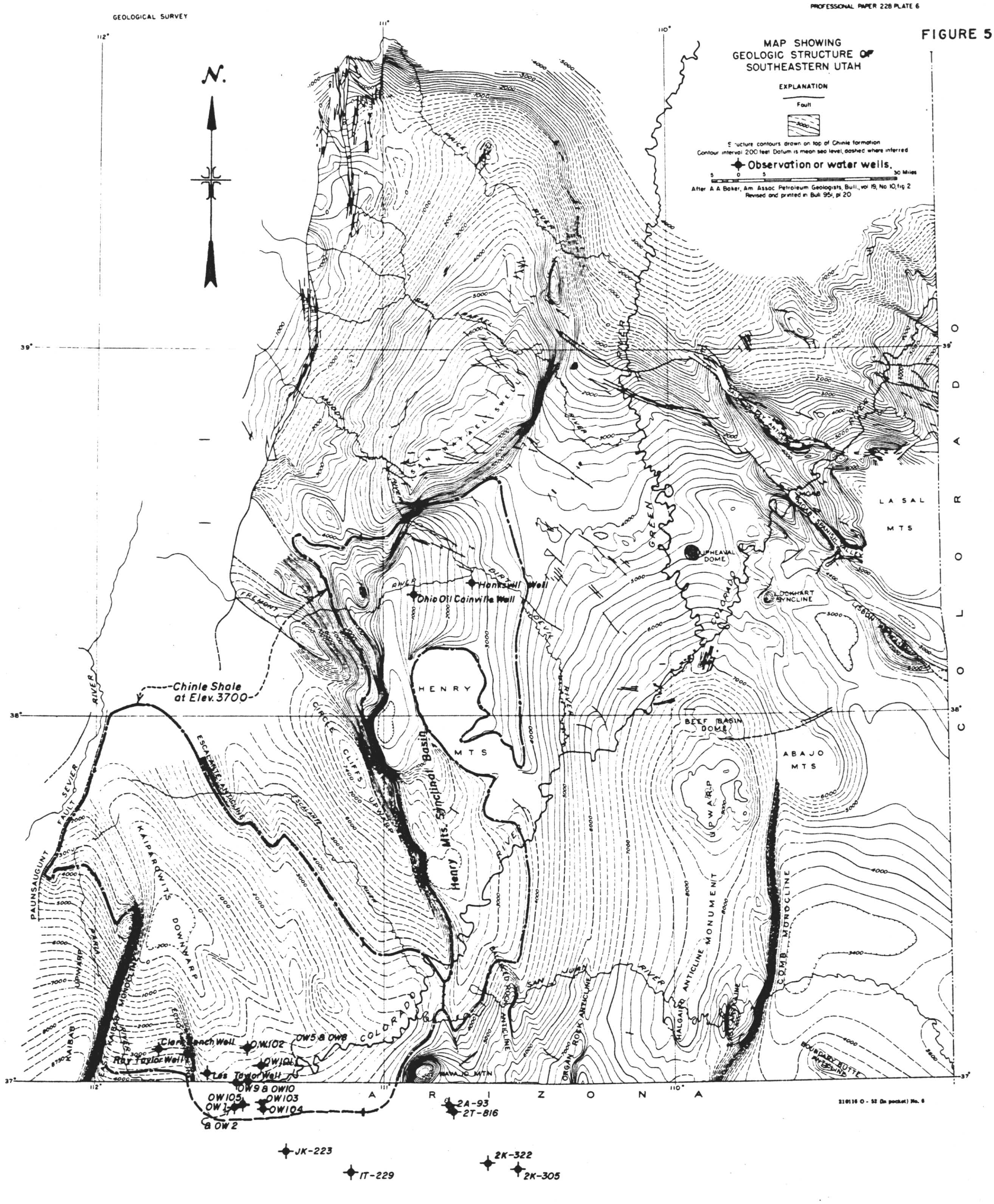


FIGURE 5

NOTES:

OW1 thru 10 contractor wells

OW101 thru 105 Bureau wells

1K--2K--IT--2T & 2A--Indian Wells

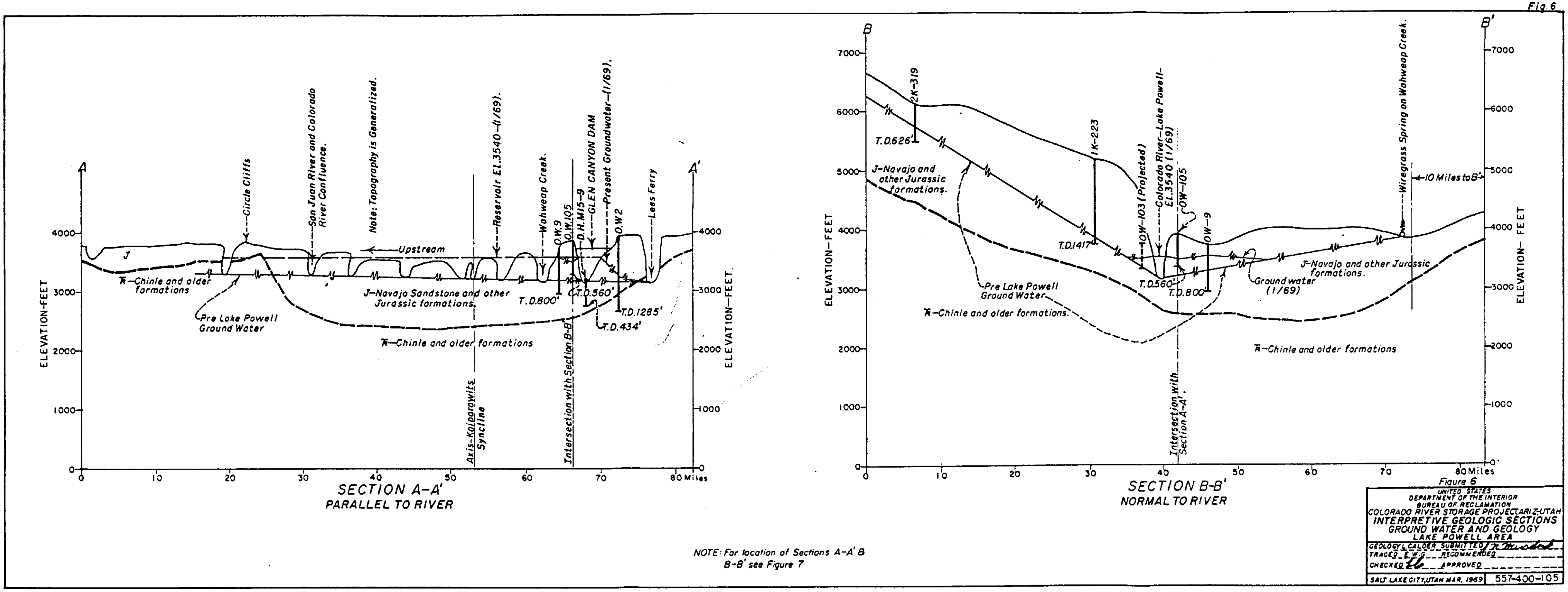
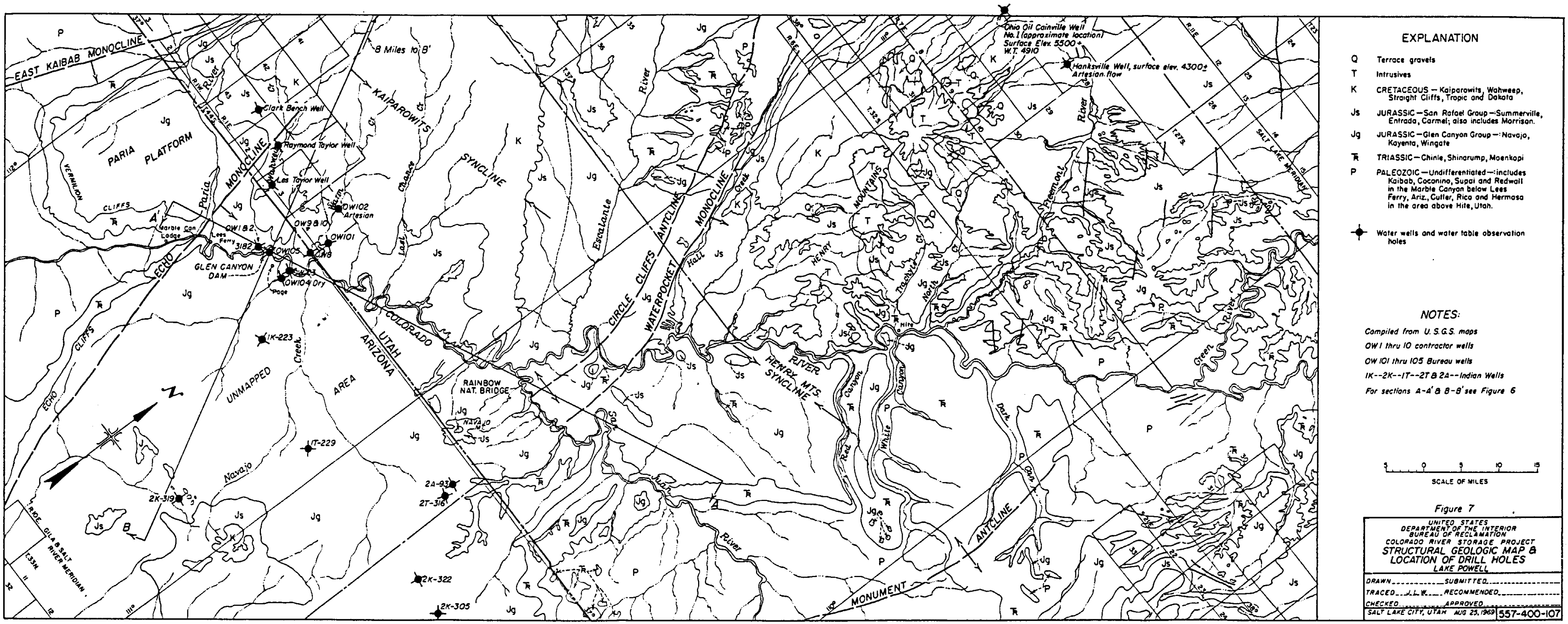


Fig. 6
SECTION A-A'
PARALLEL TO RIVER
Circle Cliffs
San Juan River and Colorado River Confluence.
Note: Topography is Generalized.
Reservoir El. 3540—(1/69).
Wahweap Creek.
O.W. 9
O.W. 105
D.H. M15-9
GLEN CANYON DAM
Present Groundwater—(1/69).
O.W. 2
Lees Ferry
Upstream
J
Ꞧ—Chinle and older formations
Pre Lake Powell Ground Water
J—Navajo Sandstone and other Jurassic formations.
T.D. 800'
C.T.D. 560'
T.D. 1285'
T.D. 434'
Ꞧ—Chinle and older formations
Axis-Kaiparowits Syncline
Intersection with Section B-B'
ELEVATION-FEET
80 Miles
SECTION B-B'
NORMAL TO RIVER
2K-319
T.D. 626'
J—Navajo and other Jurassic formations.
1K-223
T.D. 1417'
OW-103 (Projected)
Colorado River—Lake Powell—EL. 3540 (1/69)
OW-105
OW-9
T.D. 560'
T.D. 800'
Wiregrass Spring on Wahweap Creek.
10 Miles to B'
J—Navajo and other Jurassic formations.
Ground water (1/69)
Pre Lake Powell Ground Water
Ꞧ—Chinle and older formations.
Ꞧ—Chinle and older formations
Intersection with Section A-A'.
NOTE: For location of Sections A-A' & B-B' see Figure 7
Figure 6
UNITED STATES
DEPARTMENT OF THE INTERIOR
BUREAU OF RECLAMATION
COLORADO RIVER STORAGE PROJECT ARIZ.-UTAH
INTERPRETIVE GEOLOGIC SECTIONS
GROUND WATER AND GEOLOGY
LAKE POWELL AREA
GEOLOGY L. CALDER SUBMITTED
TRACED E.W.G. RECOMMENDED
CHECKED APPROVED
SALT LAKE CITY, UTAH MAR. 1969 557-400-105


EXPLANATION
Q Terrace gravels
T Intrusives
K CRETACEOUS — Kaiparowits, Wahweep, Straight Cliffs, Tropic and Dakota
Js JURASSIC — San Rafael Group — Summerville, Entrada, Carmel; also includes Morrison.
Jg JURASSIC — Glen Canyon Group — Navajo, Kayenta, Wingate
TRIASSIC — Chinle, Shinarump, Moenkopi
P PALEOZOIC — Undifferentiated — includes Kaibab, Coconino, Supai and Redwall in the Marble Canyon below Lees Ferry, Ariz., Cutler, Rico and Hermosa in the area above Hite, Utah.
Water wells and water table observation holes
NOTES:
Compiled from U.S.G.S. maps
OW 1 thru 10 contractor wells
OW 101 thru 105 Bureau wells
1K--2K--1T--2T & 2A--Indian Wells
For sections A-A' & B-B' see Figure 6
SCALE OF MILES
UNITED STATES
DEPARTMENT OF THE INTERIOR
BUREAU OF RECLAMATION
COLORADO RIVER STORAGE PROJECT
STRUCTURAL GEOLOGIC MAP & LOCATION OF DRILL HOLES
LAKE POWELL
DRAWN
SUBMITTED
TRACED J.L.W.
RECOMMENDED
CHECKED
APPROVED
SALT LAKE CITY, UTAH AUG 25, 1969
557-400-107
EAST KAIBAB MONOCLINE
PARIA PLATFORM
VERMILION CLIFFS
ECHO CLIFFS
KAIPAROWITS SYNCLINE
8 Miles to B'
Clark Bench Well
Raymond Taylor Well
Les Taylor Well
OW102 Artesian
OW101
OW 9 & 10
OW 1 & 2
GLEN CANYON DAM
OW104 Dry
Page
Lees Ferry
Marble Can. Lodge
UNMAPPED AREA
UTAH
ARIZONA
COLORADO
1K-223
1T-229
2A-93
2T-316
2K-322
2K-305
2K-319
RAINBOW NAT. BRIDGE
Navajo
Escalante
CIRCLE CLIFFS ANTICLINE
WATERPOCKET MONOCLINE
HENRY MTS. SYNCLINE
HENRY MOUNTAINS
MONUMENT ANTICLINE
Ohio Oil Cainville Well No. 1 (approximate location) Surface Elev. 5500± W.T. 4910
Hanksville Well, surface elev. 4300± Artesian flow
SALT LAKE MERIDIAN
GILA & SALT RIVER MERIDIAN
Fremont River
Green River
Dirty Devil
Hite
Figure 7

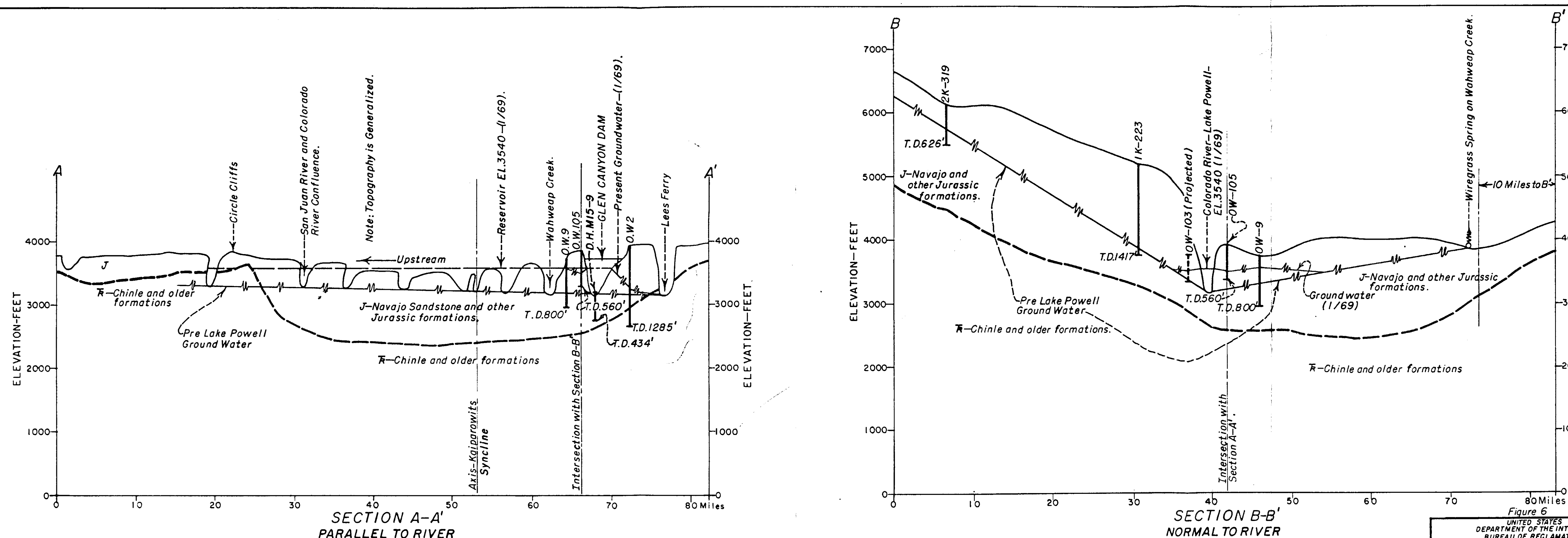
17

Table 1
Summary of
Observation and water well data
Lake Powell Area

Well No.	Location data and/or coordinates (Arizona) North	East	Surface elevation	Original water elevation and date	Water elevation 7/65	11/65	1/66	1/67	1/68	1/69	4/69	Yield (g.p.m.)	Total depth	Aquifer
					Contractor wells									
OW 1	2,160,385	622,744	3917	3182(1/58)	3203	3206	3208	3221	3247	3274	3280	30	910	Navajo
OW 2	2,158,892	622,053	3982	3182(7/57)	3160	3090	3083	3207	3226	3224	3226	34	1,285	Navajo
OW 5	2,181,788	623,697	3742	3319(1/58)	3419	3437	3445	3479				1,000	625	Fractured Navajo
OW 8	2,181,560	624,576	3735	3313(1/59)	3428	3447	3454	3484		3519	3522	1,200	655	Fractured Navajo
OW 9	2,185,607	618,714	3723	3315(1958)	3415	3432	3440	3473	3494	3515	3518	1,350	800	Fractured Navajo
OW 10	2,184,610	620,900	3734	3327(1958)	3412	3429	3437	3473	3495	3515	3519	1,000±		Fractured Navajo
					Bureau of Reclamation Wells									
OW 101	137,221(Utah)	2,023,759 (Utah)	3705	3401(4/65)	3401	3419	3422	3479	N.M.	3524	3526		350	Entrada and Carmel
OW 102	SW¼NW¼ sec. 3, T. 43 S., R. 4 E.		3701	3701(4/65)	3701	3701							598	Entrada
OW 103	2,166,158	645,871	3756	3394(7/65)	3394	3418	3428	3455	3474	3497	3501		450	Navajo
OW 104	2,158,975	648,464	3971	Dry 3675(6/65)	Dry 3675	Dry 3623							350	Navajo
OW 105	2,162,862(Ariz.)	629,965 (Ariz.)	3829	Dry 3283(7/65)	Dry 3283	Dry 3282	3284	3375	3453	3457	3463		560	Navajo
					Privately Owned Wells									
Les Taylor	SW¼SE¼ sec. 32, T. 43 S., R. 3 E.		3985	3693(5/64)	3720	3720								Entrada and Carmel
Ray Taylor	SW¼SW¼ sec. 11, T. 43 S., R. 2 E.		4129	3900	3900	3900								Entrada and Carmel
Clark Bench	SE¼SE¼ sec. 2, T. 43 S., R. 1 E.		4500	4300±	4300±								550	Carmel and Navajo
					Navajo Indian Wells East of Lake Powell									
IK-223	Locations not available for these wells.		5188	3820(3/54)								Very low	1,417	Navajo
IT-229			5650	4537(5/55)								Very low	1,248	Navajo
2K-305			7380	6723(1/54)								1-2	804	Navajo
2K-322			7300	6660(6/56)								1-2	742	Navajo
2A-93			6140	5517(2/53)								1-2	733	Wingate
2T-316			6320	5561(8/54)								1-2	858	Wingate
2K-319			6100	5715(8/54)								2-3	626	Navajo

Elevation of Lake Powell water surface--3492± (6/65), 3531±(11/65), 3536±(1/12/66), 3527±(1/3/68), 3539±(1/1/69), 3544(4/1/69), and 3581(7/21/69).

Fig. 6



SECTION A–A'
PARALLEL TO RIVER

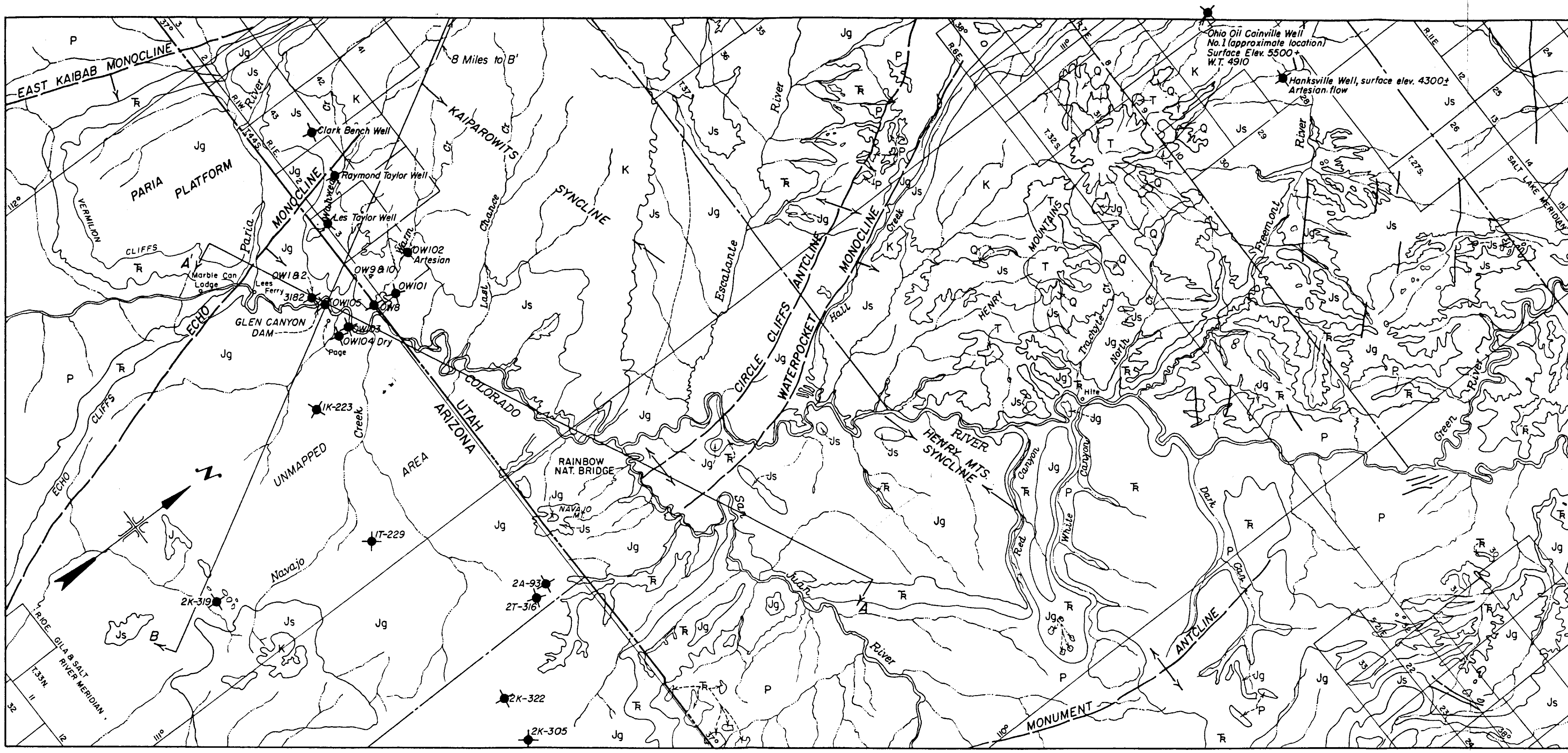
SECTION B-B'
NORMAL TO RIVER

Figure 6

NOTE: For location of Sections A–A' & B-B' see Figure 7

UNITED STATES
DEPARTMENT OF THE INTERIOR
BUREAU OF RECLAMATION
COLORADO RIVER STORAGE PROJECT ARIZ.-UTAH
INTERPRETIVE GEOLOGIC SECTIONS
GROUND WATER AND GEOLOGY
LAKE POWELL AREA

GEOLOGY L.CALDER SUBMITTED
TRACED E.W.G. RECOMMENDED
CHECKED APPROVED
SALT LAKE CITY, UTAH MAR. 1969 557-400-105



EXPLANATION

Q	Terrace gravels
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Compiled from U.S.G.S. maps

OW1 thru 10 contractor wells

OW 101 thru 105 Bureau wells

1K--2K--1T--2T & 2A--Indian Wells

For sections A-A' & B-B' see Figure 6

5 0 5 10 15

SCALE OF MILES

Figure 7

UNITED STATES
DEPARTMENT OF THE INTERIOR
BUREAU OF RECLAMATION
COLORADO RIVER STORAGE PROJECT

STRUCTURAL GEOLOGIC MAP & LOCATION OF DRILL HOLES

LAKE POWELL

DRAWN............SUBMITTED............
TRACED....J.L.W.....RECOMMENDED............
CHECKED............APPROVED............
SALT LAKE CITY, UTAH AUG 25, 1969 557-400-107

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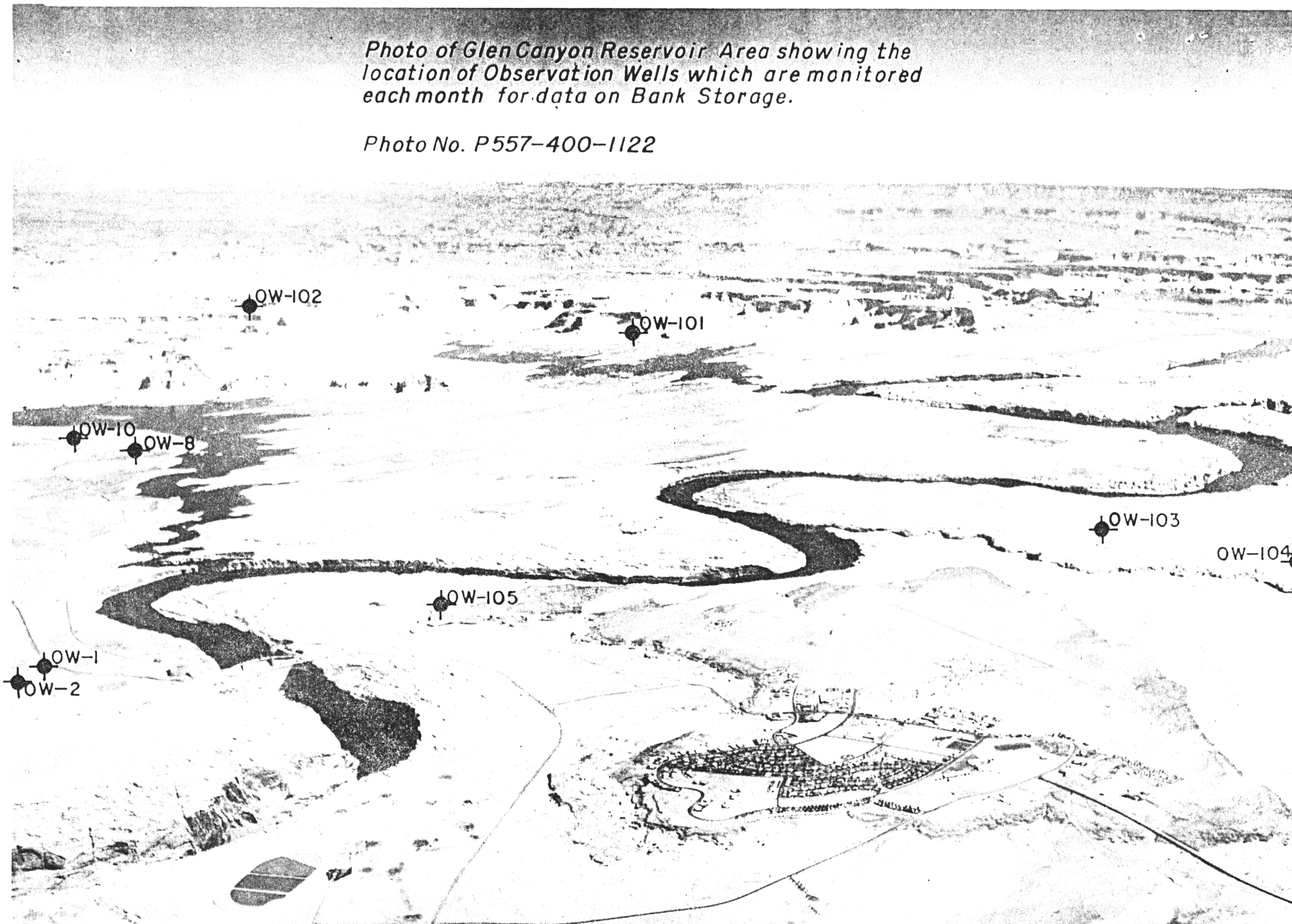

Photo of Glen Canyon Reservoir Area showing the location of Observation Wells which are monitored each month for data on Bank Storage.

Photo No. P557-400-1122

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