THE BOULDER CANYON PROJECT and HOOVER DAM: Some of its Impacts on the Engineering Profession

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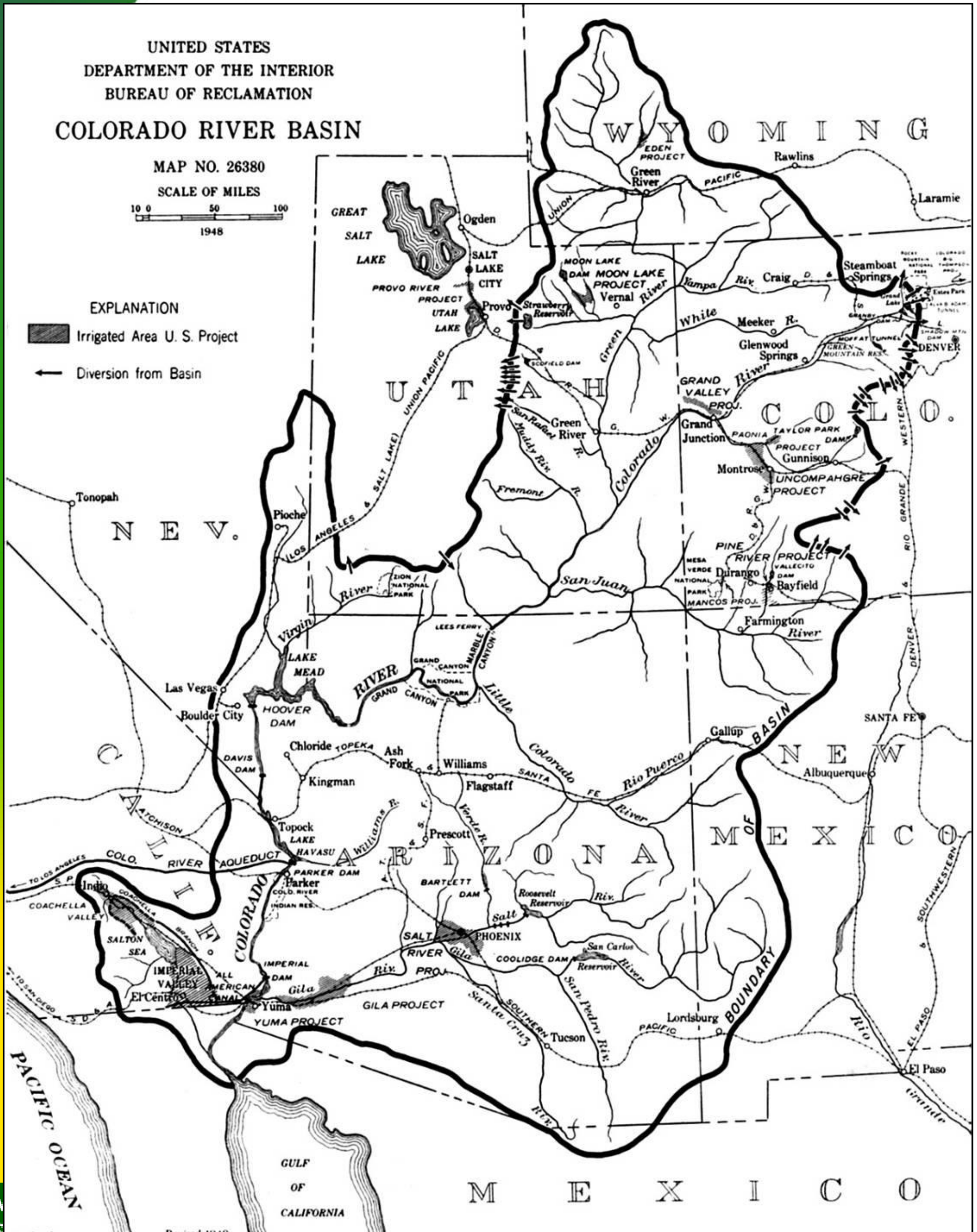
for the conference on

The Fate and Future of the Colorado River

sponsored by

Huntington-USC Institute on California and the West

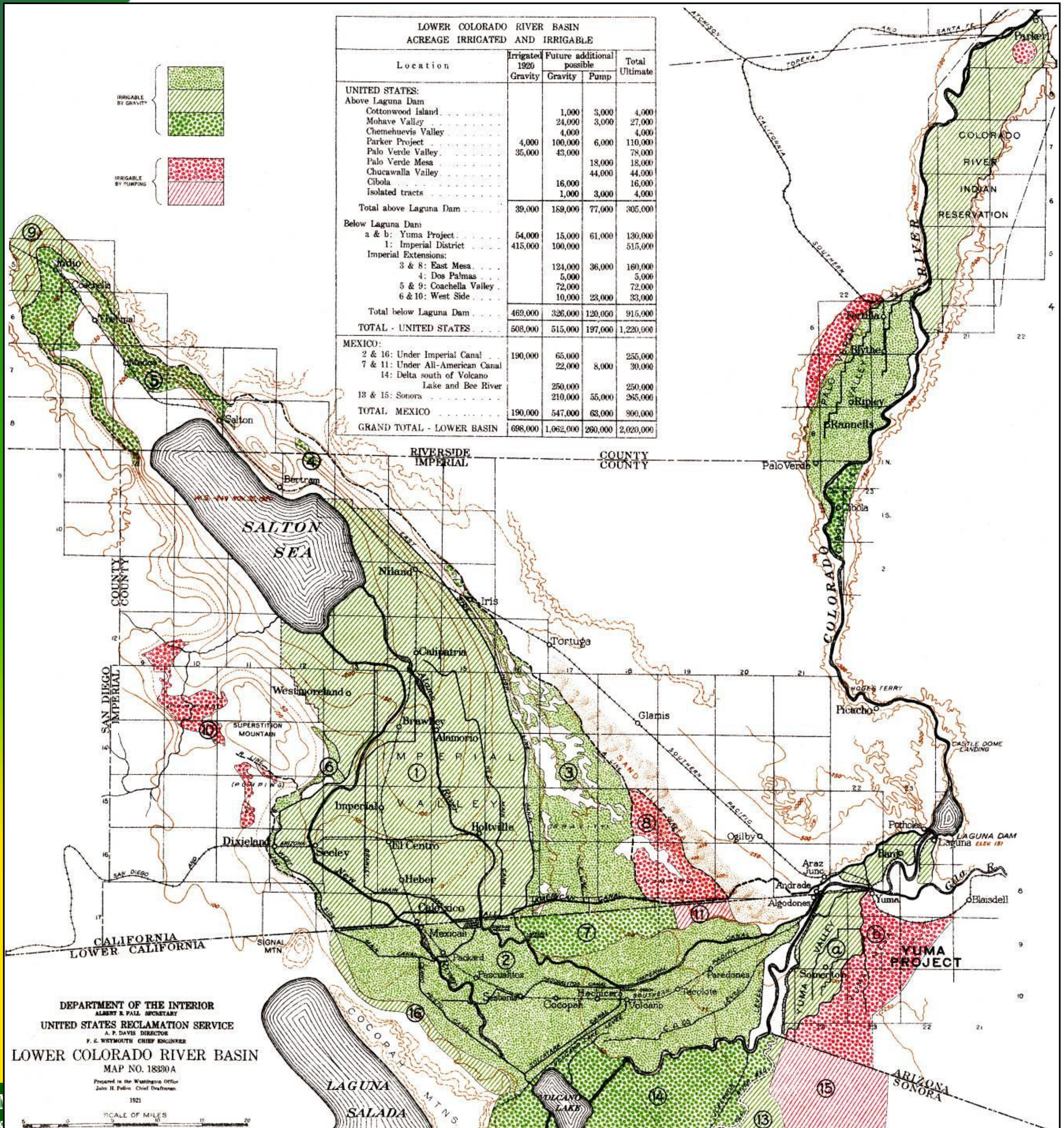
Water Education Foundation



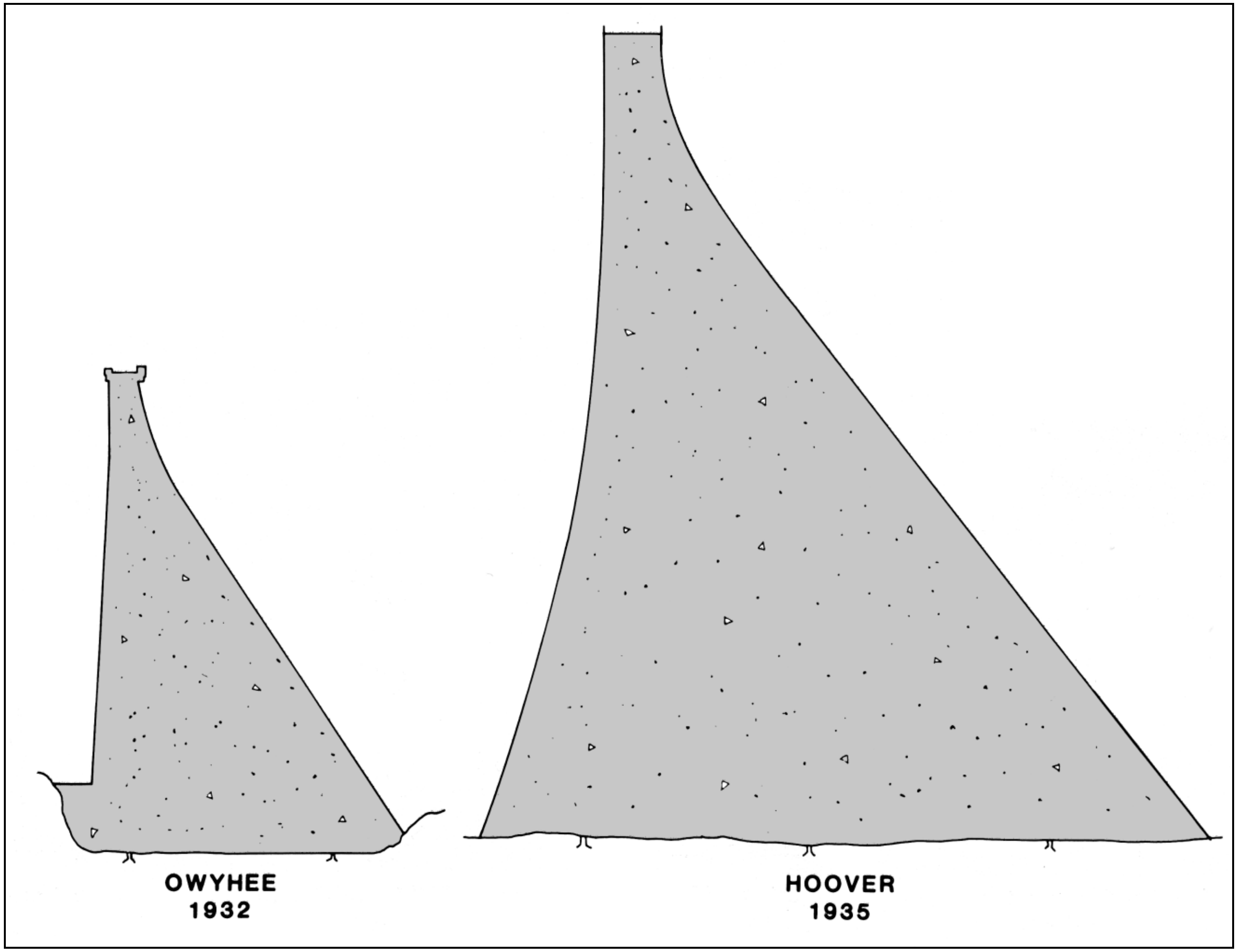
COLORADO RIVER BASIN

- Total watershed area of 246,000 square miles
- Shared by 7 states
- Only river in North America that flows through arid valleys

The Goal:



- **1.5 year supply of then entire Colorado River**
- **To Irrigate:**
- **Palo Verde Valley**
- **Yuma Valley**
- **Imperial Valley**
- **Coachella Valley**



- Unprecedented size: Hoover Dam was almost twice as tall as the highest dam in the world, Owyhee, slated for completion in 1932!
- Owyhee Dam was designed by the same BurRec design team, led by Jack Savage.

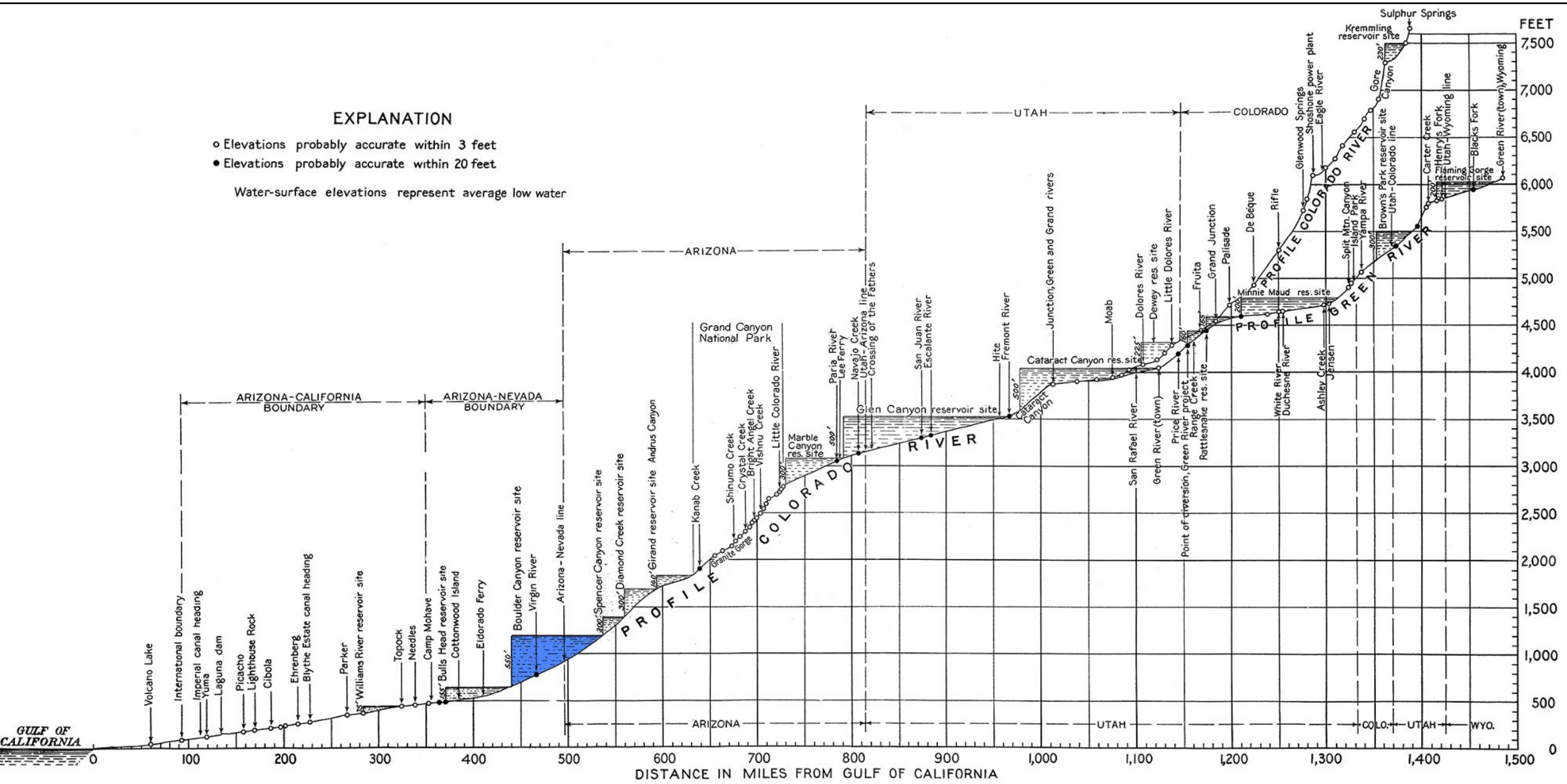
Boulder Canyon Project:

- With a budget of $165 million, it would be the largest federal contract ever awarded up to that time
- It would require more concrete (4.5 million cubic yards) than ALL previous Bureau of Reclamation projects, combined (4.4 mcy)
- No single contractor was capable of doing the work

The Colorado is America's most fickle river

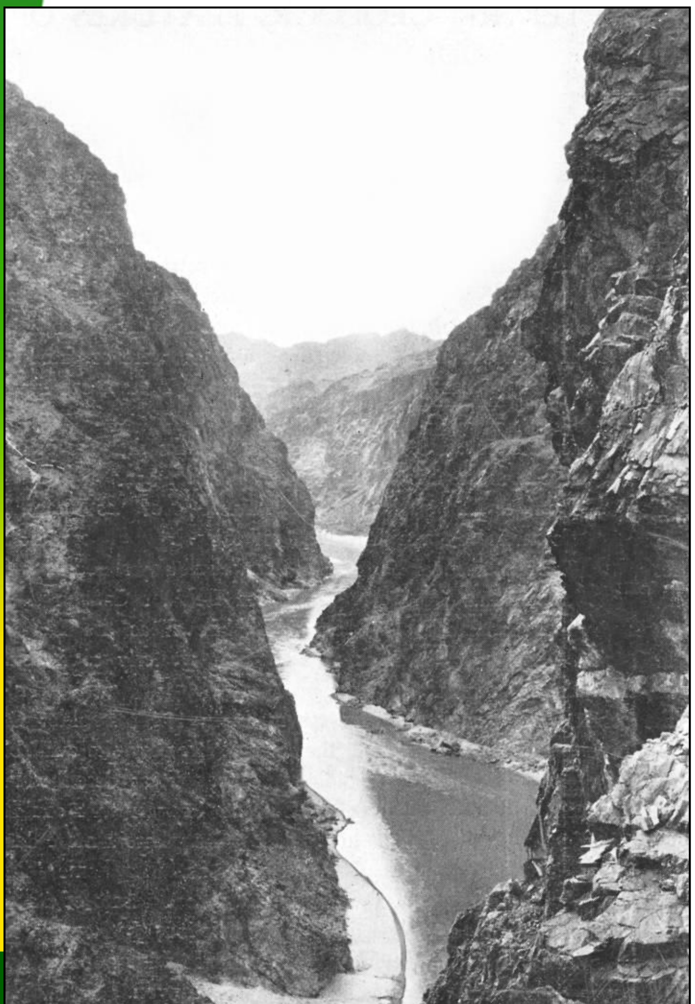
- Named *Rio Colorado* by Spanish because of red color of highly turbid flow of the Little Colorado
- At that time thought to have the 5th highest silt load of any river in the world
- Maximum flows of 384,000 cfs at Topock in 1884; and ~400,000+ in 1857(?)
- Minimum observed flows of ~500 (Jan 1912) to 1,000 cfs (Aug 1934)
- High-low flow ratio of between 400:1 and 800:1

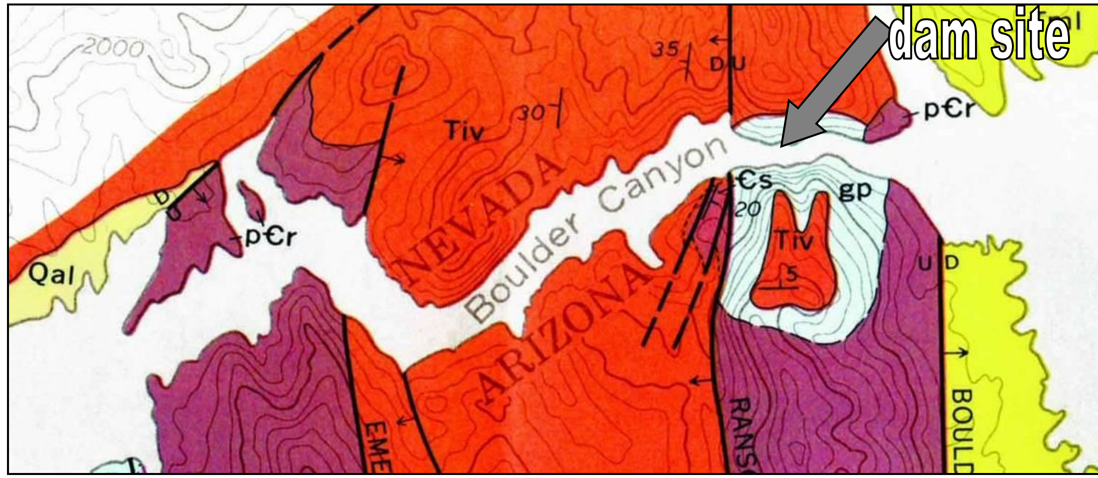
WHY WAS IT CALLED THE BOULDER CANYON PROJECT?

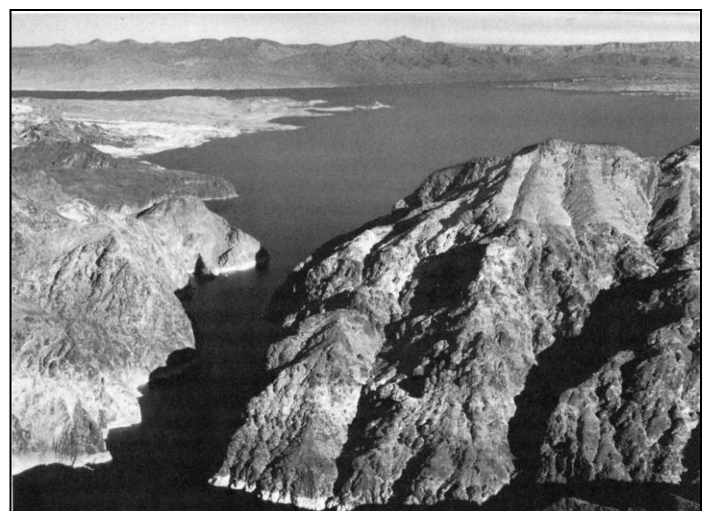


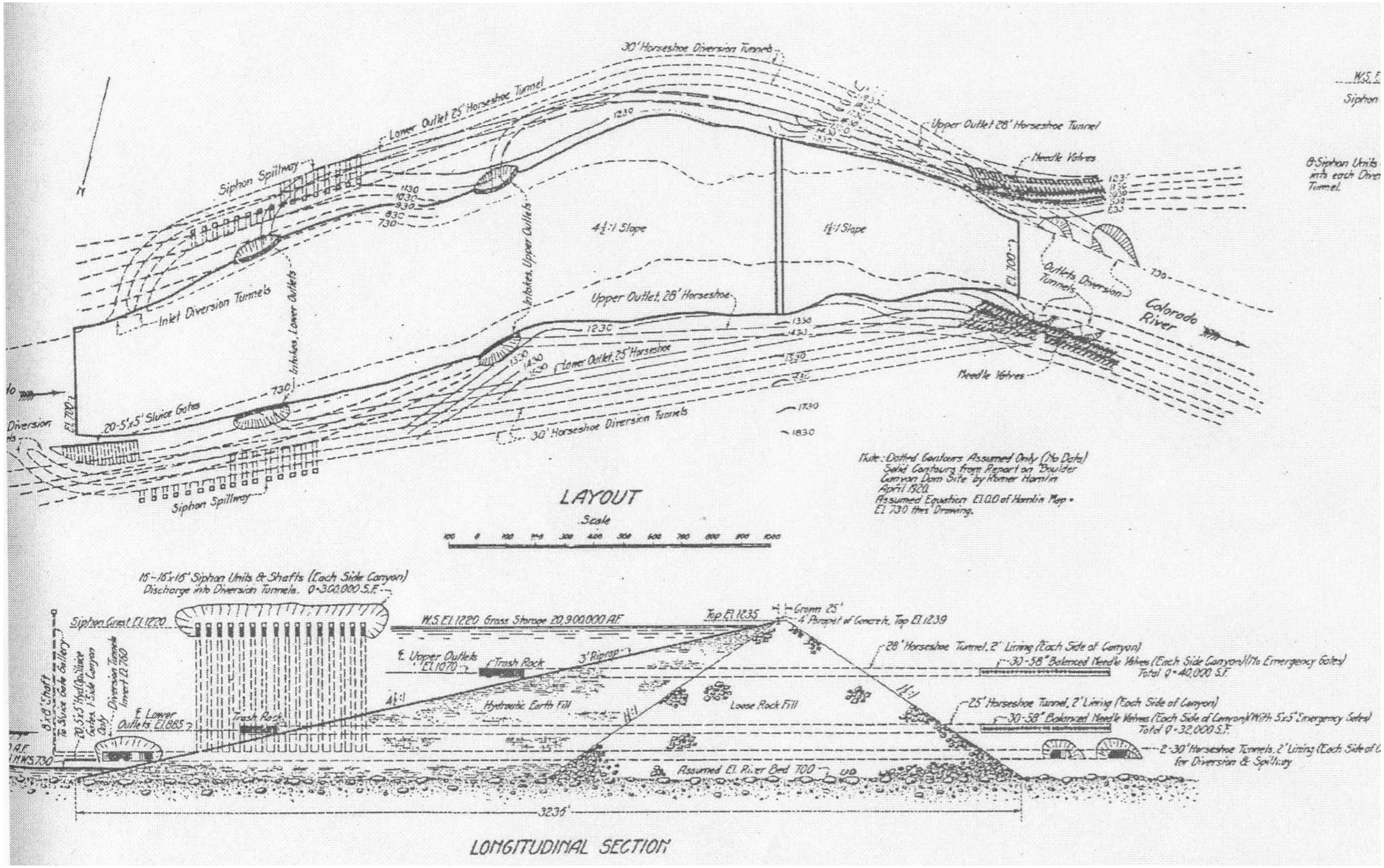
- **Colorado River profile from the 1922 Fall-Davis report, which envisioned a scheme for flood control and storage of the river's erratic flows for irrigation. The kingpin structure of the Lower Basin was at Boulder Canyon, with a pool elevation of >1150 ft.**

Initial studies focused on the head of Boulder Canyon, with a narrow gorge & granite outcrops

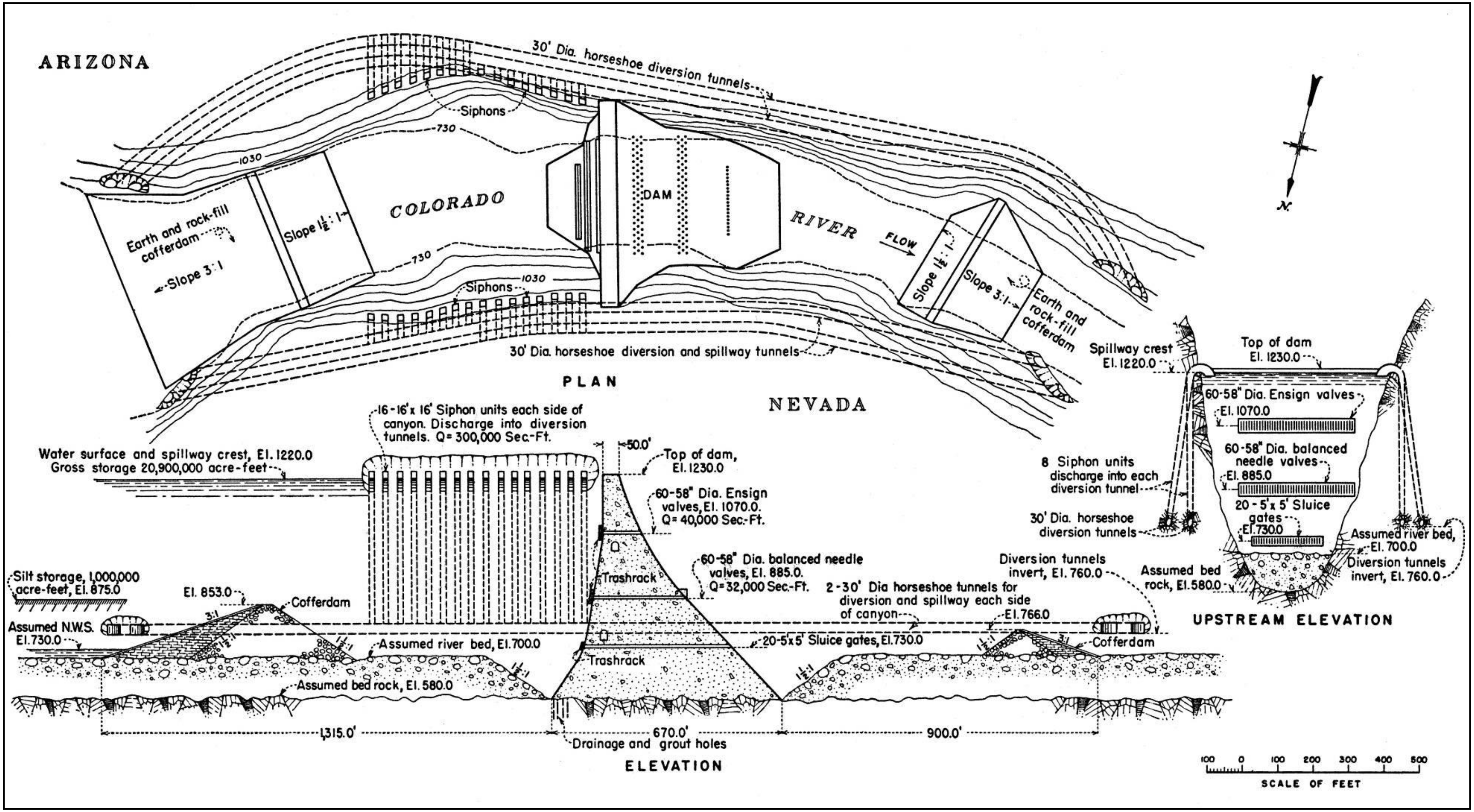




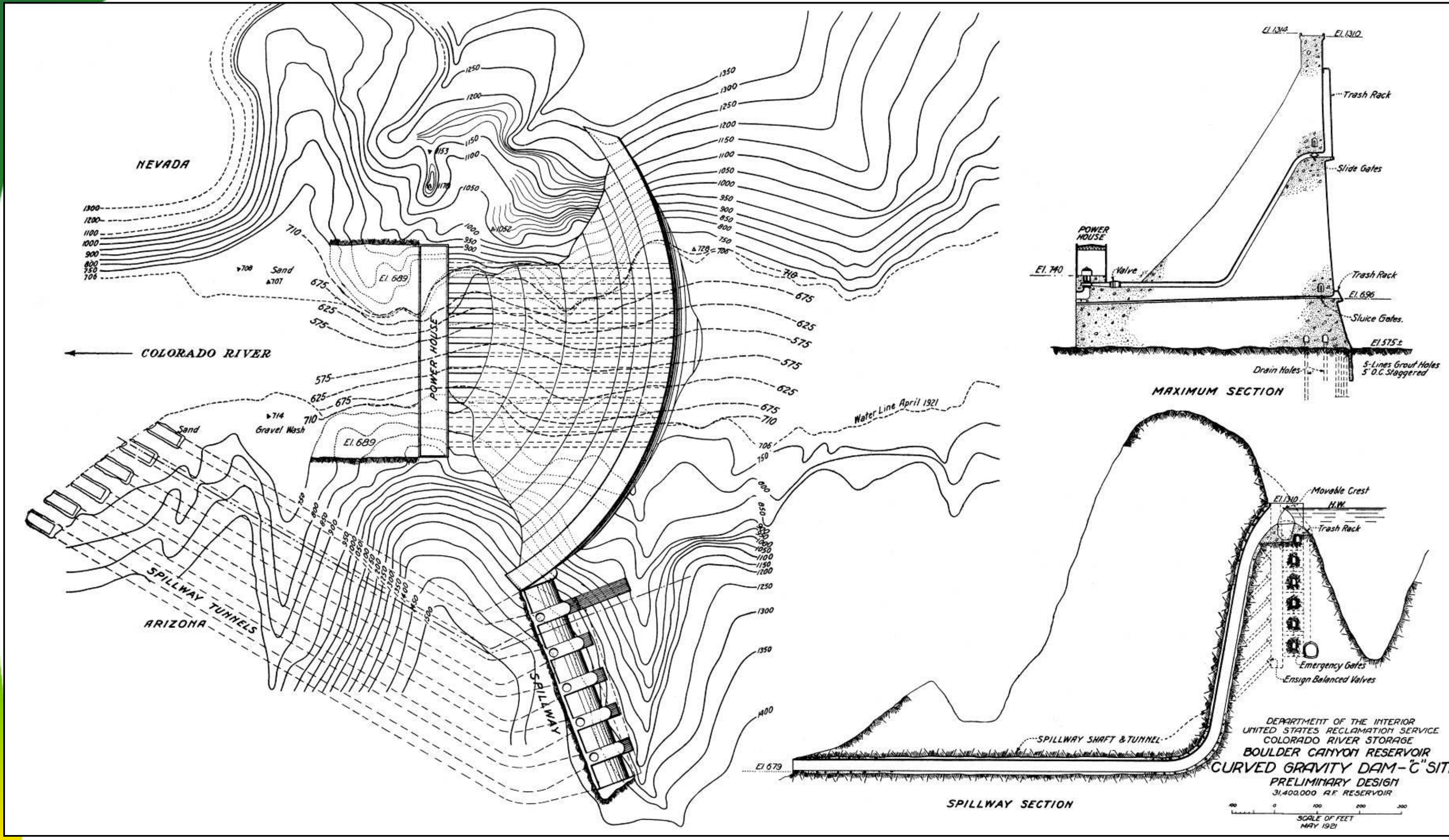




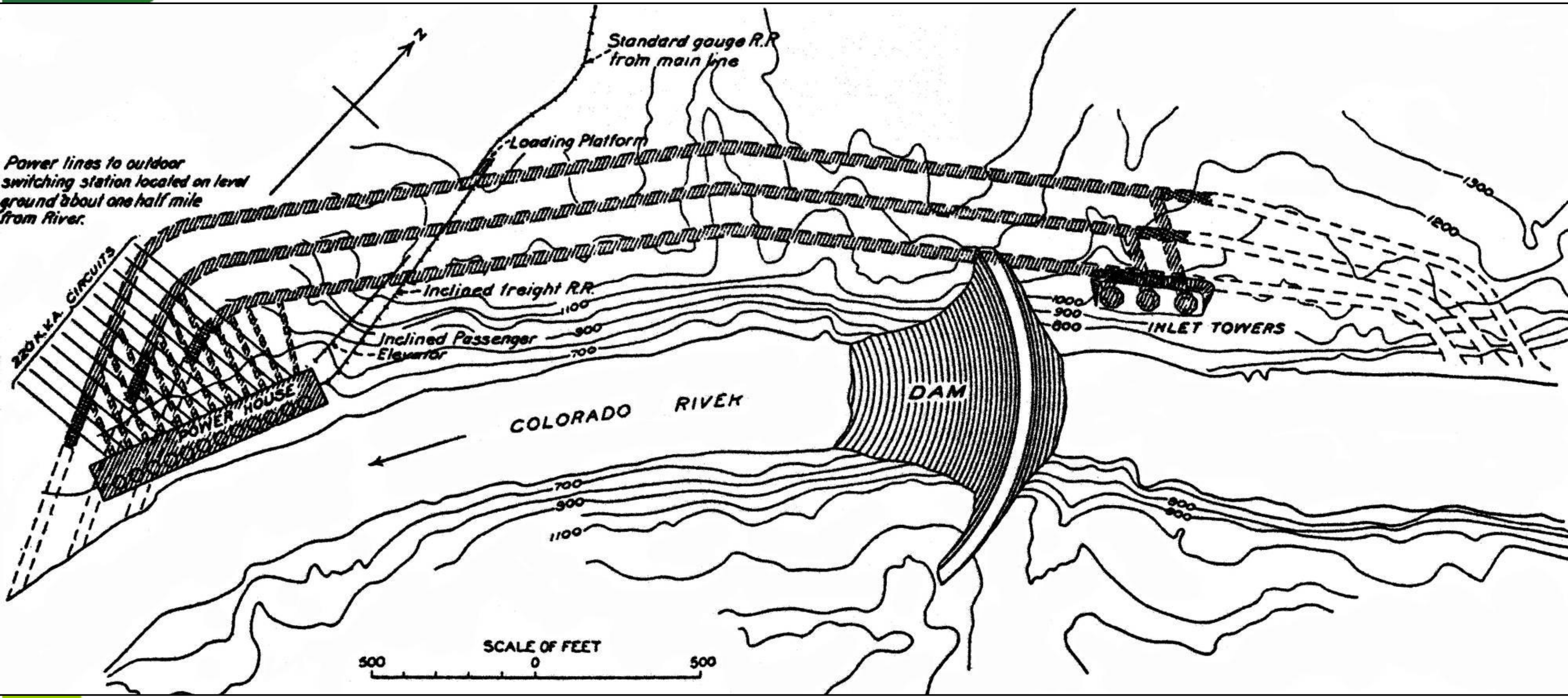
- **The original design for Boulder Dam in early 1920 envisioned an earth-rock embankment rising 535 feet above the existing river bed. . Note the asymmetric layout. This obviated the need for excavating the channel gravels**



This shows the alternative 1920 design for a concrete gravity dam at the Boulder Canyon site. It would have been 650 feet high, to extend through an additional 120 ft of river gravels.

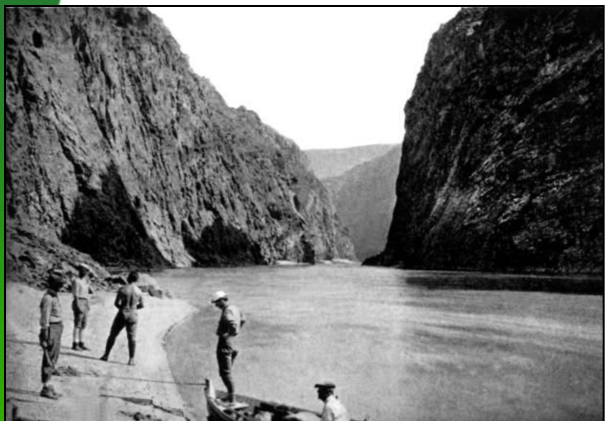


- **By 1922 the Boulder Dam design had morphed into a 735 ft high arched concrete gravity dam, employing six massive spillway tunnels**



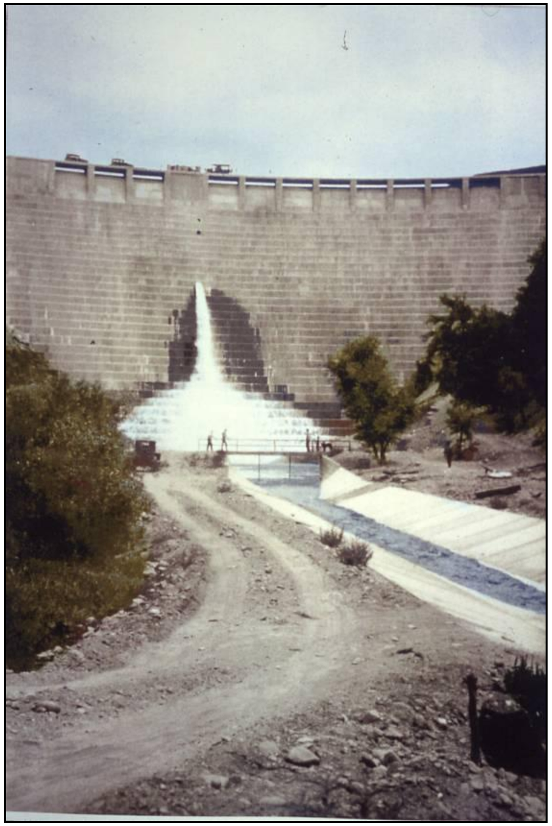
- **In 1928 the Bureau of Reclamation amended their design of Boulder Dam to include hydroelectric power generation, with the general layout shown here.**
- **This was the design concept presented to the 70th Congress in the proposed Boulder Canyon Project Act.**

Surveys in Black Canyon



Former Los Angeles City Engineer Homer Hamlin made the first survey of the upper Black Canyon dam sites in the spring of 1920; marking the axis of the site that was eventually chosen, 8-1/2 years later

THE COLORADO RIVER BOARD

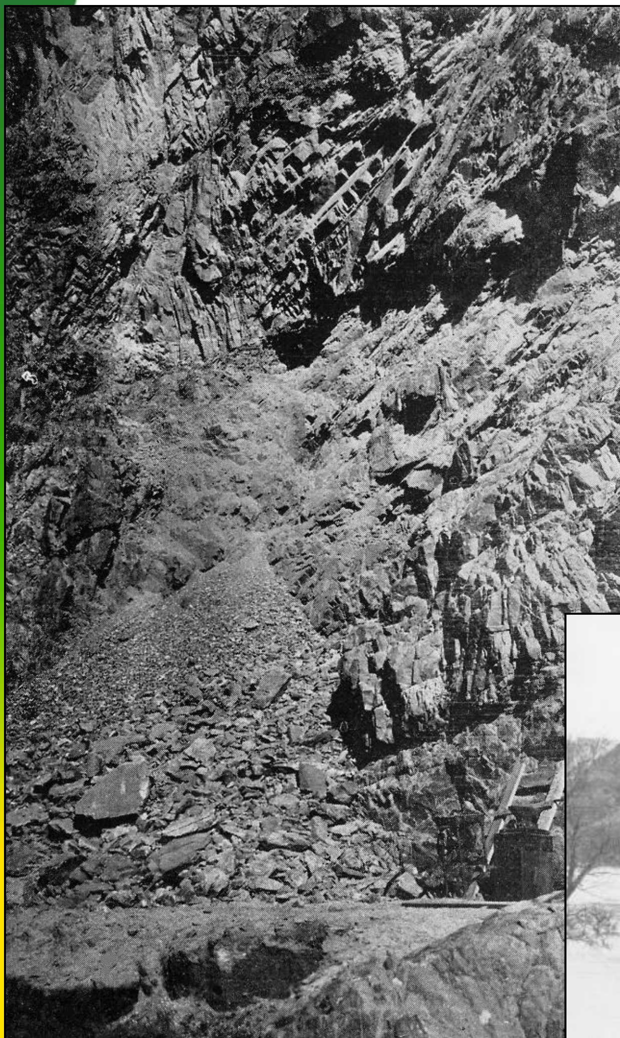


- The untimely failure of the St. Francis Dam north of Los Angeles in March 1928 killed at least 432 people
- Public outcry and concern following the failure of a brand new concrete gravity-arch dam constructed by the same people pushing for passage of the Boulder Canyon Project prompted the appointment of an independent panel of experts to review the Bureau of Reclamation's plans for the Boulder Canyon Project and advise Congress on its feasibility and practicality.

Colorado River Board May 1928

Left to right: MGEN William L. Sibert (Chair), Elwood Mead (advisor), and included geologists Warren J. Mead and Charles P. Berkey (Secretary) and engineers Daniel W. Mead and Robert Ridgway.

The CRB investigates the dam sites



The Board's geologists raised a number of concerns that had not been addressed previously.

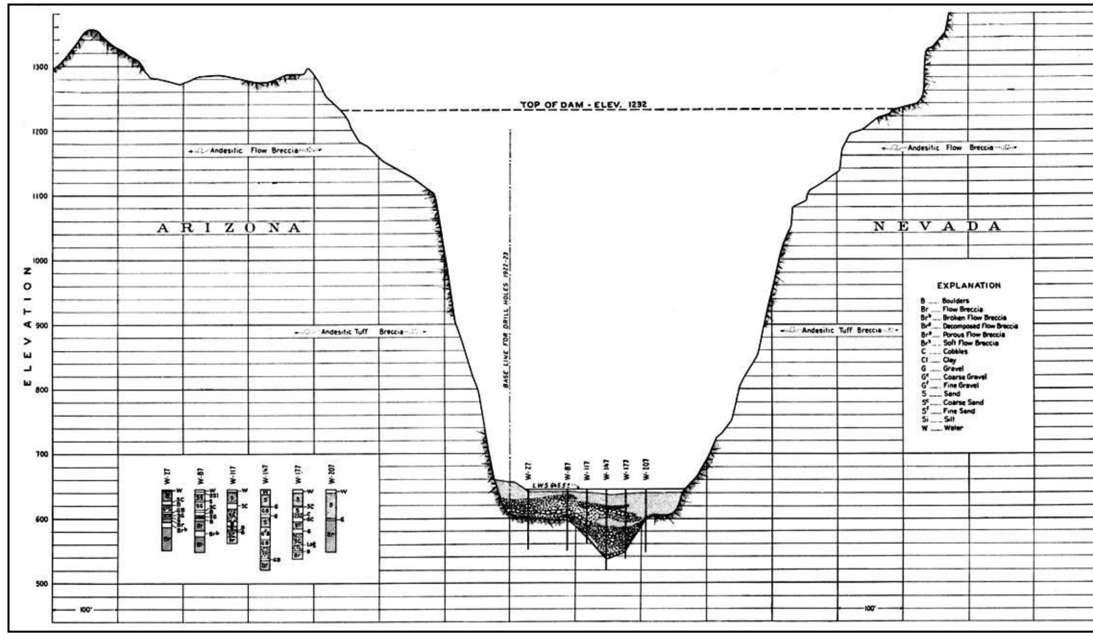
REVIEW OF PLANS AND ESTIMATES

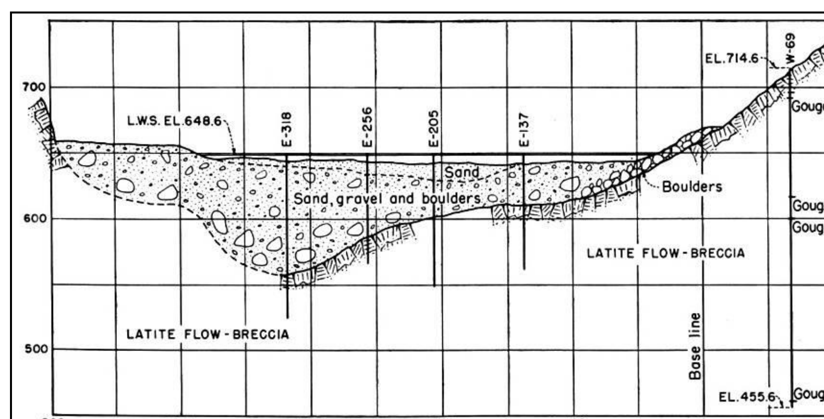
The Dam and Incidental Works

The Board is of the opinion that it is feasible from an engineering standpoint to build a dam across the Colorado River at Black Canyon that will safely impound water to an elevation of 550 feet above low water. The cost, however, will be greater than that contemplated in the project authorized in H. R. 5773.

The proposed dam would be by far the highest yet constructed and would impound 26,000,000 acre feet of water. If it should fail, the flood created would probably destroy Needles, Topock, Parker, Blythe, Yuma, and permanently destroy the levees of the Imperial District, creating a channel into Salton Sea which would probably be so deep that it would be impracticable to reestablish the Colorado River in its normal course. To avoid such possibilities the proposed dam should be constructed on conservative if not ultra-conservative lines.

Colorado River Board chose the Black Canyon site in Nov 1928

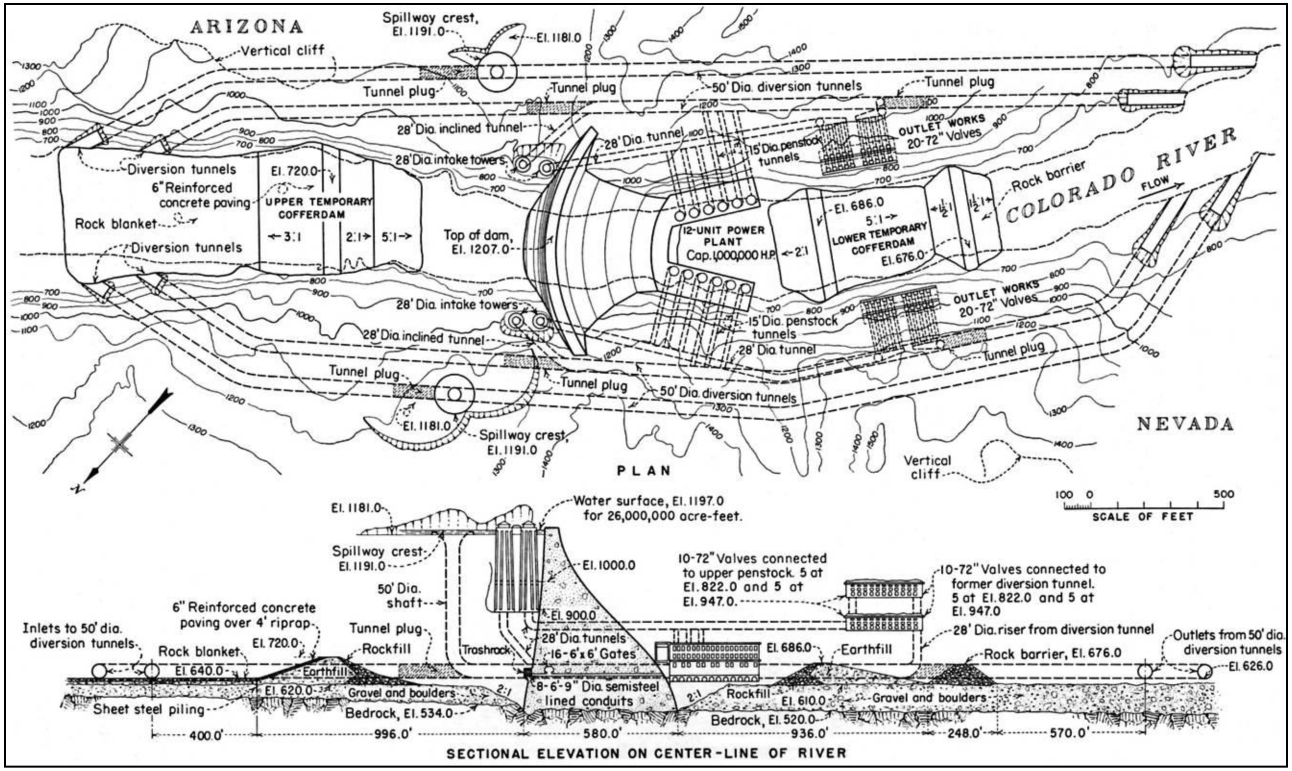


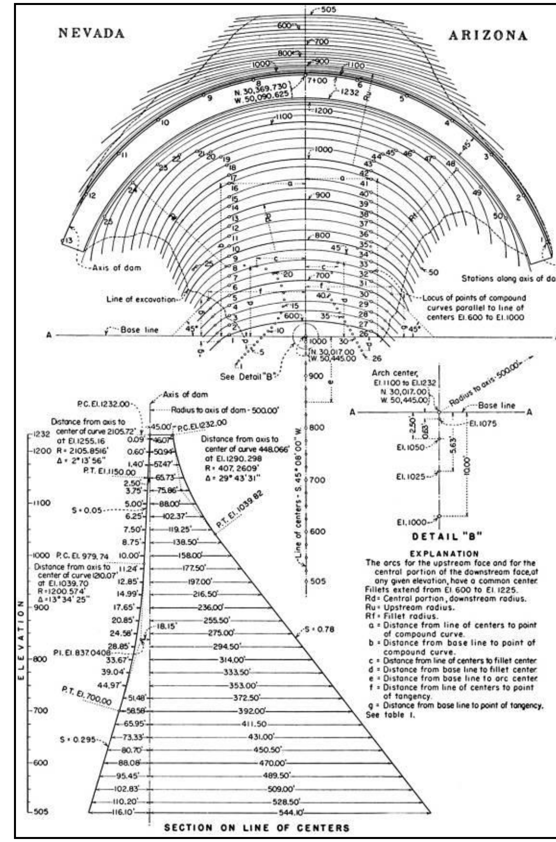


In November 1928, the CRB recommends design changes:

- Reduce foundation contact pressure from 40 tons per square foot (tsf) to 30 tsf;
- Increase capacity of river bypass diversion tunnels from 100,000 cfs to at least 200,000 cfs (25 yr flood);
- Limited depth of water behind upper cofferdam to no more than 55 ft (El 700 ft)
- Increase spillway capacity from 110,000 cfs to > 160,000 cfs;
- Increase volume of flood storage to 9.5 million ac-ft of the total capacity of 30.5 million ac-ft (or 31%);
- All-American Canal can be built north of the Mexican border; and
- Electricity generated by dam could be absorbed by the expanding market of greater Los Angeles.

In April 1930 the decision is made to raise the dam 25 feet to increase flood storage





- Dam crest elevation raised to 1232 ft; dam height now ~730 ft. 30,500,00 ac-ft capacity with 9,500,000 ac-ft flood storage (actually 32,547,000 ac-ft)
- Curvature tightened from crest radius of 740 ft to 505 ft

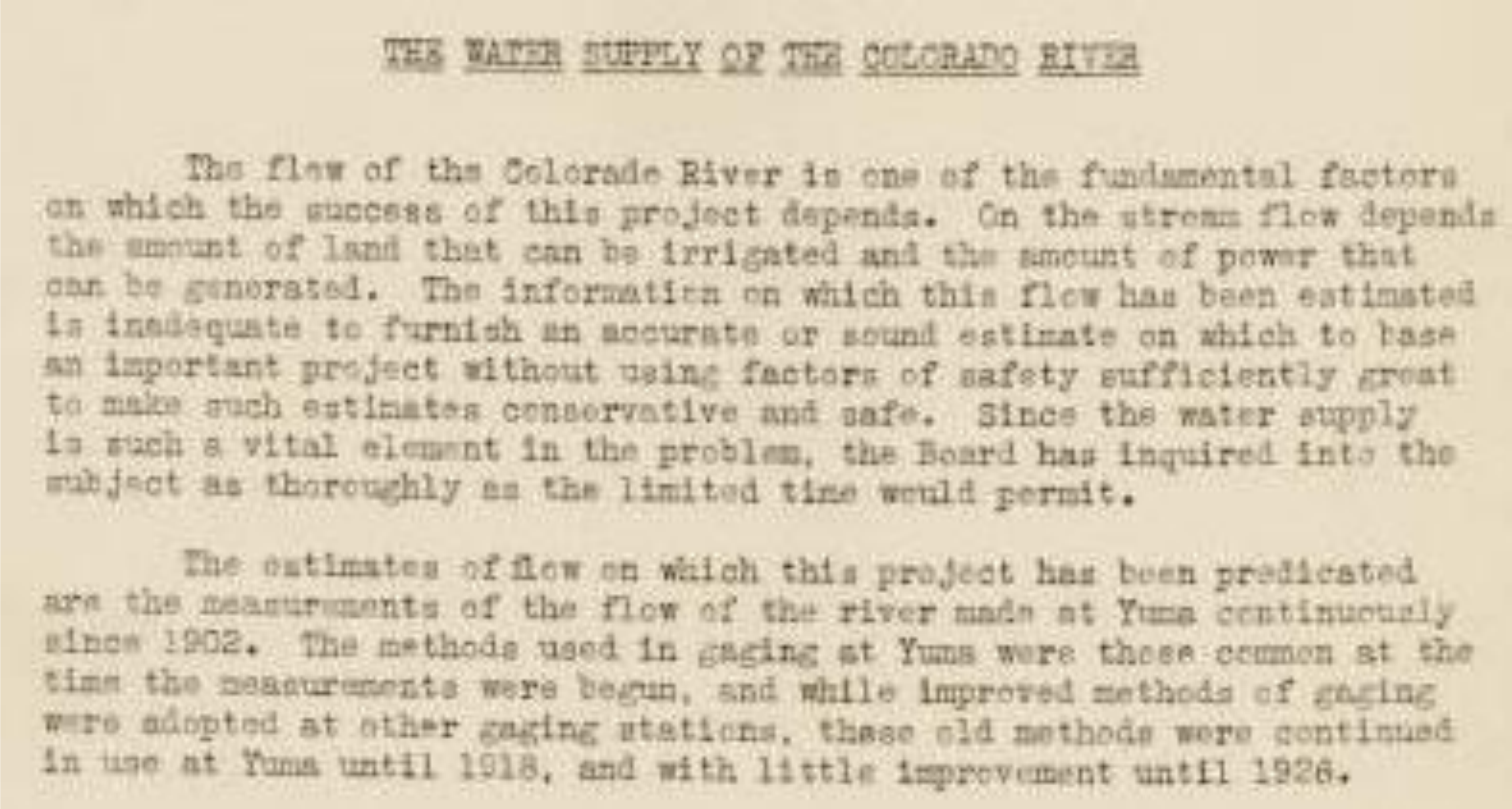
FLOOD HYDROLOGY OF THE COLORADO RIVER

PAUCITY OF HYDROLOGY INPUT

- 1) 26 yr flow volumes at Yuma (312 miles downstream of Hoover Dam). (flow heights recorded at Yuma since 1878, but no velocity measurements until 1902)
  2) 6 yr flow volumes at Lee's Ferry, AZ after 1922 (346.6 miles upstream)
  3) 5 yr flow volumes at Bright Angel, AZ (in Grand Canyon) after 1923 (260 miles upstream)
  4) 5 yr flow volumes at Topock, AZ after 1923 (111 miles downstream)

How much flow data is sufficient to design engineering structures?

- Within natural systems there exist considerable uncertainties, due to many variables
- For instance, in record rain storms of Jan 1997, the Feather River watershed recorded 48“ equivalent precipitation and runoff, because of coincident snowmelt. Two watershed south, the total was just 15.5“
- In order to accurately estimate the 100-yr recurrence flood, we would need 1000 years of records
- In the case of Hoover Dam, BurRec had less than 10 years of reliable flow records, a ridiculously low figure to be sizing such a colossal project



THE WATER SUPPLY OF THE COLORADO RIVER

The flow of the Colorado River is one of the fundamental factors on which the success of this project depends. On the stream flow depends the amount of land that can be irrigated and the amount of power that can be generated. The information on which this flow has been estimated is inadequate to furnish an accurate or sound estimate on which to base an important project without using factors of safety sufficiently great to make such estimates conservative and safe. Since the water supply is such a vital element in the problem, the Board has inquired into the subject as thoroughly as the limited time would permit.

The estimates of flow on which this project has been predicated are the measurements of the flow of the river made at Yuma continuously since 1902. The methods used in gaging at Yuma were those common at the time the measurements were begun, and while improved methods of gaging were adopted at other gaging stations, these old methods were continued in use at Yuma until 1918, and with little improvement until 1926.

- ***"The information on which this flow has been estimated is inadequate to furnish an accurate or sound estimate on which to base an important project without using factors of safety sufficiently great to make such estimate conservative and safe."***

The information desired was the flow for each year at Black Canyon brought down to present conditions. To calculate this required that to each year's flow, estimated as above, should be added the amount of water used for irrigation that year, after which the amount of water used for irrigation at the present time was deducted. Neither of these quantities was known and they had to be estimated. These estimates were based on the assumption that the net use or "consumptive use" of water per annum was 1½ acre feet per acre irrigated. This is as good an approximation as can be made. The amount of irrigation from year to year was calculated on the basis of the census returns for 1902, 1909 and 1919.

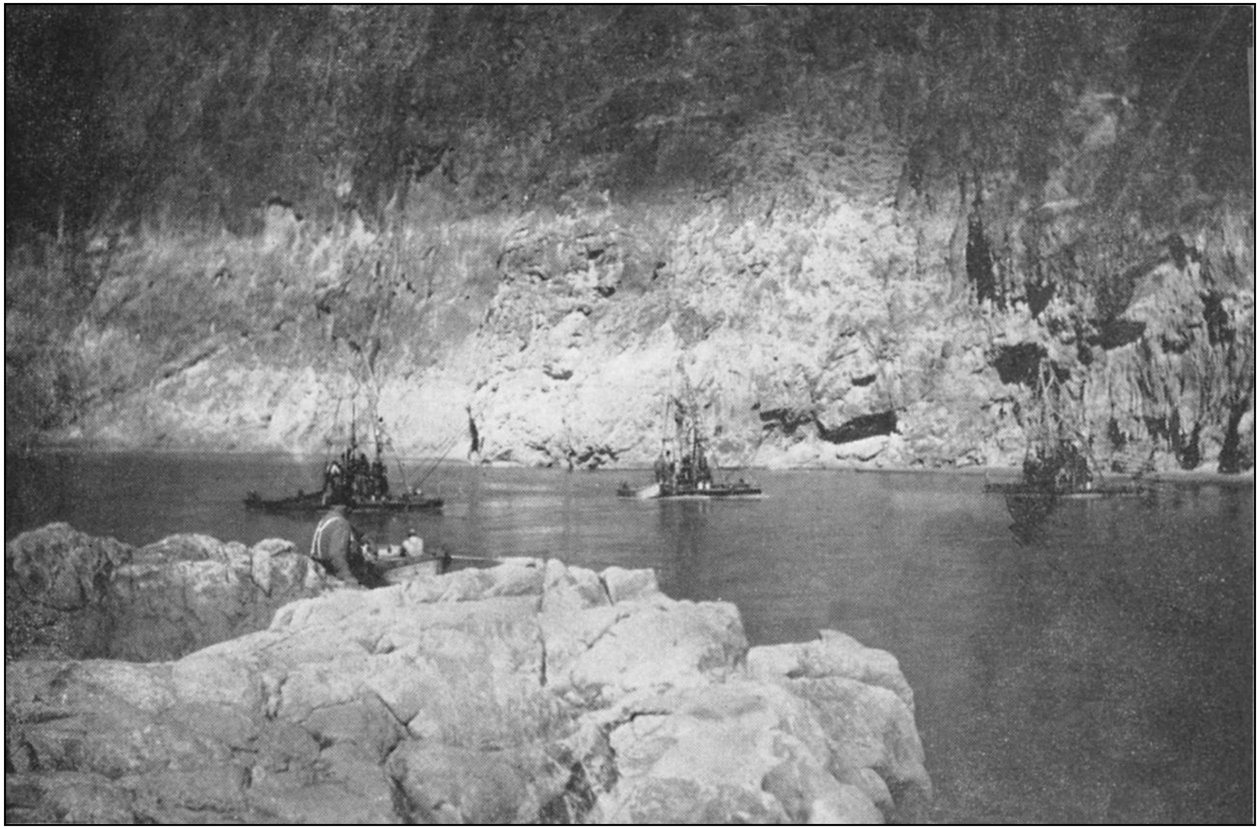
In consequence of these methods the net results arrived at in the original estimates for the flow at Black Canyon are exceedingly uncertain, and in the opinion of the Board are too high.

- ***The Colorado River Board zeroed in on the problems with using Yuma gage readings between 1902-22***
- ***BurRec used these data to estimate a flow volume of 16,200,000 ac-ft at the dam site***
- ***USGS estimated a average annual flow of just 13,600,000 ac-ft for the period 1878-1922, a much longer, and more reliable, sampling***

In this connection the estimates of Mr. Herman Stabler should be noted. His estimates made from the long record of gage heights and the measured flows at Yuma, were based on the assumption that the measurements at Yuma were correct. If the Yuma flows were corrected and reduced, Mr. Stabler's estimate would also be reduced. Since the Board finds that the Yuma gagings for the period 1902-1922 are at least 10 per cent too high, Mr. Stabler's estimate based on these gagings should be correspondingly reduced. Thus modified, his estimate for the average flow of the period 1887-1904 of 10,420,000 acre feet is reduced to 9,360,000 acre feet.

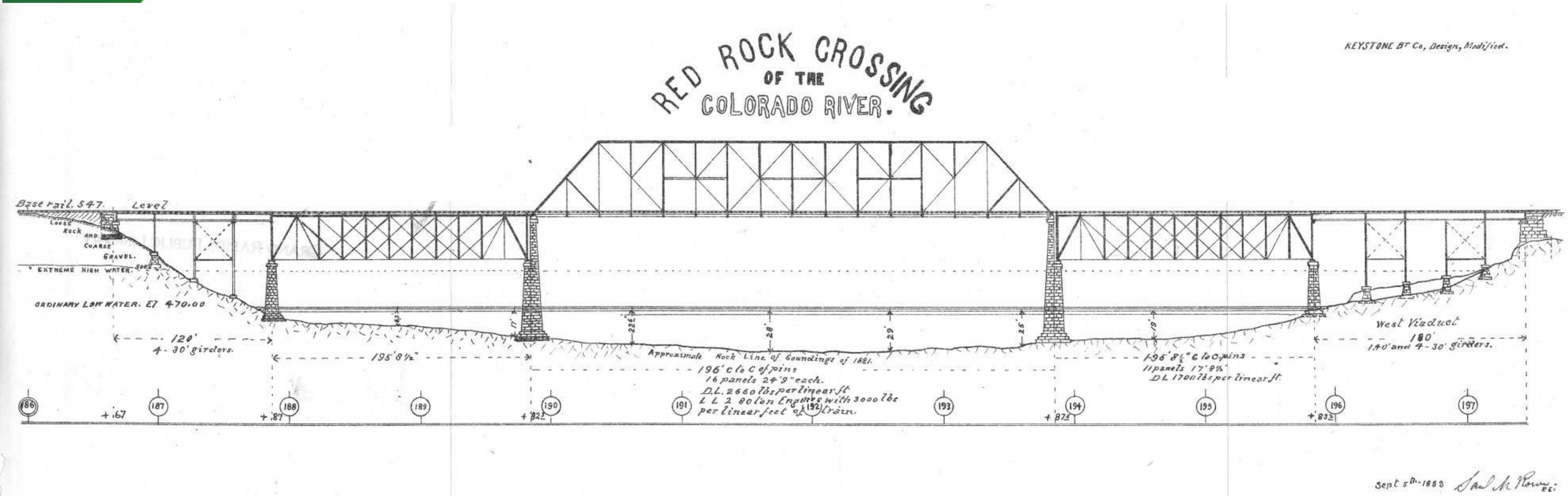
One of the most important facts shown by these estimates is the existence of a long dry period in the Colorado River flow prior to 1906. This low period is clearly shown by an inspection of the Yuma gage heights for that period. Further investigation of this matter has convinced this Board that the flows of the Colorado River as determined by the gagings from 1906 to 1927 are materially higher than the flow for the preceding 20 years, and that a long period of equally low flows must be expected to recur at any time.

- ***The CRB then made their own estimates of the average annual flow, based on the available data. They concluded that for the period 1887-1904 the average flow was only 9,360,000 ac-ft….***

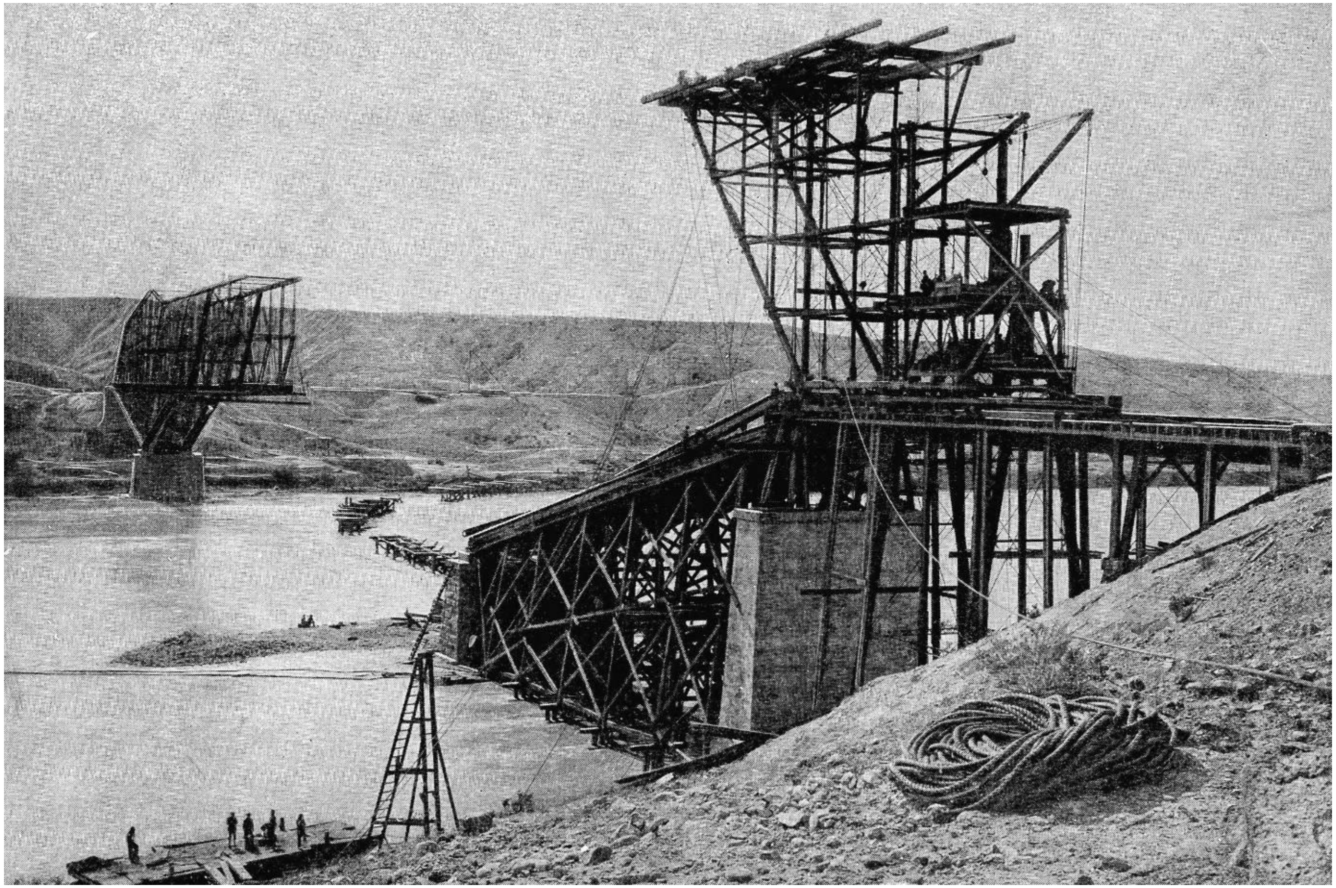


BurRec engineers observing high water marks 80 feet above low water level at the head of Boulder Canyon (shown above) and about 40 feet above low water at the mouth of Boulder Canyon.

- The recent flood history of the Colorado River is recorded at Topock, 10 miles south of Needles. Six bridges have been constructed here since 1889



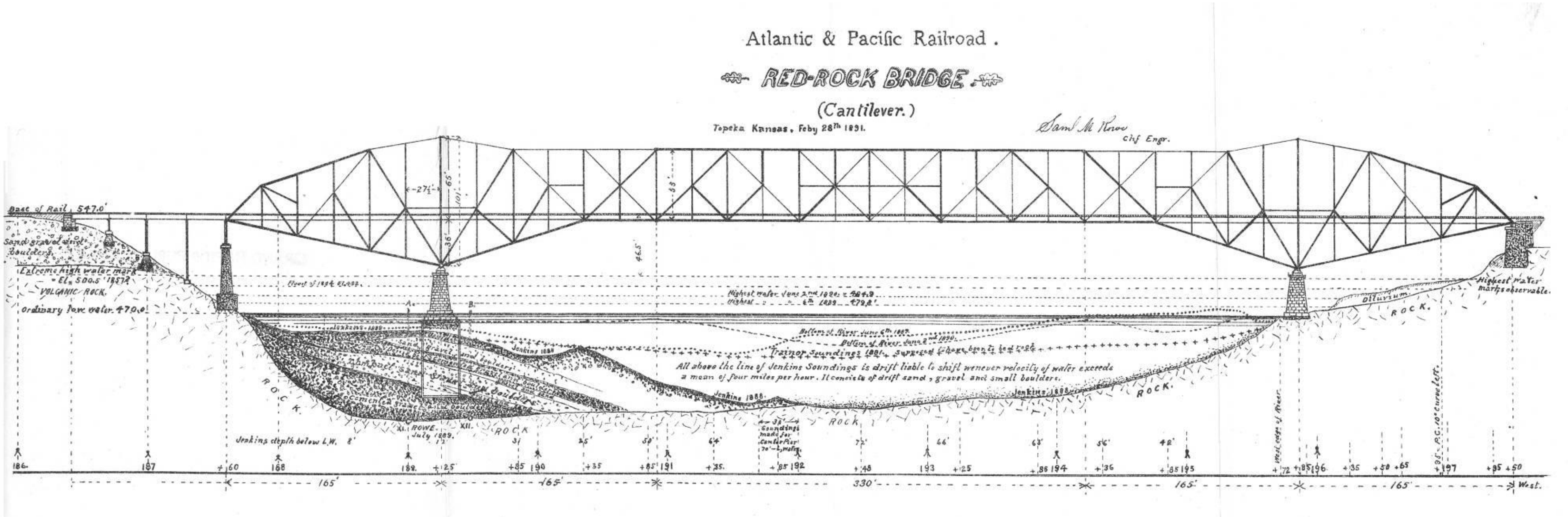
- **This shows the original Red Rock Crossing over the Colorado River, designed by the Atlantic & Pacific Railroad in 1888, based upon soundings made by Wm Trainor of the the Southern Pacific in 1881. The maximum depth to “bedrock” was believed to be about 40 feet below low water.**



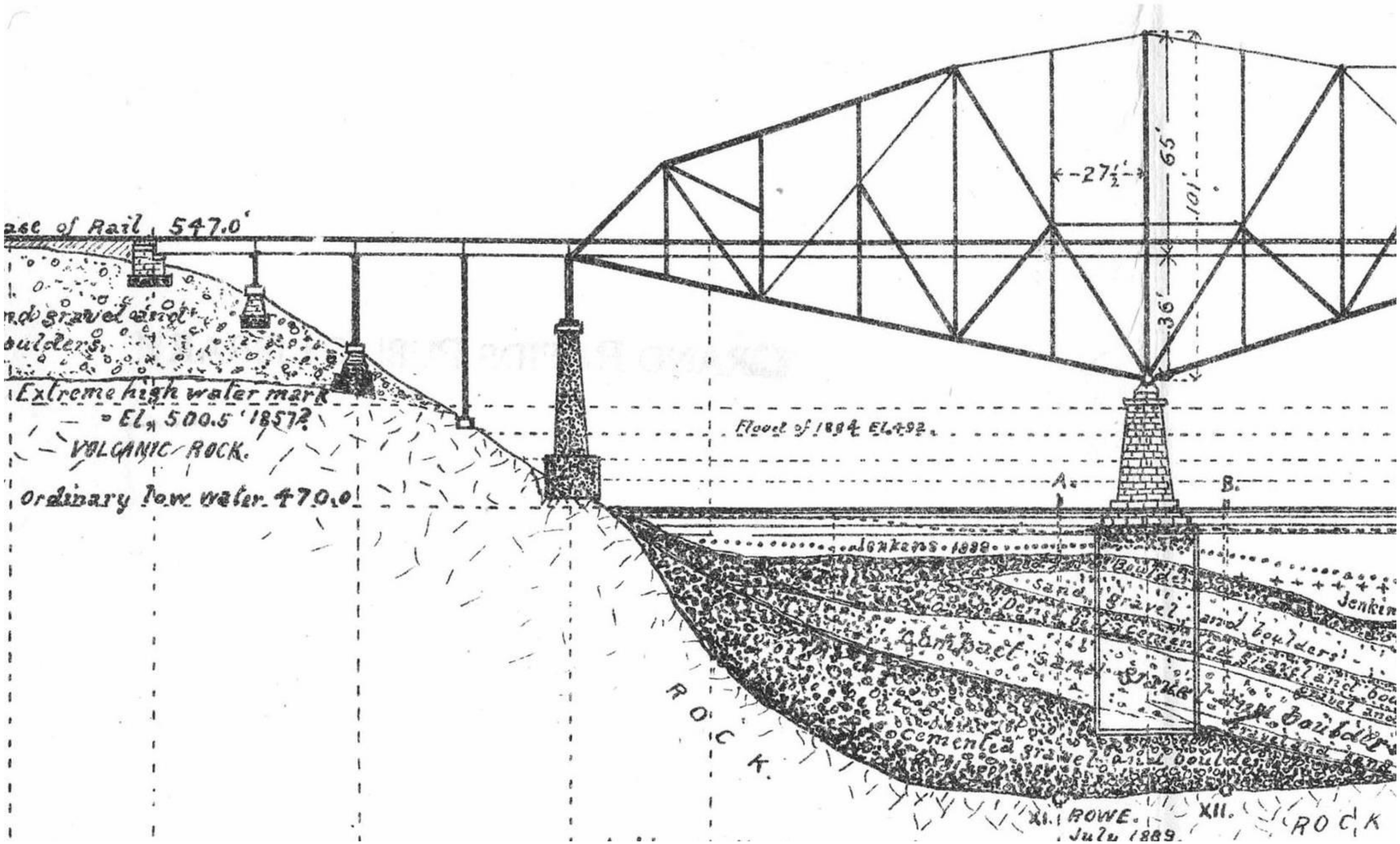
- **When the railroad made new soundings at the bridge site in 1888, following the 1884 floods that destroyed their bridge at Needles, they soon discovered that the river bed was now 80 feet deep! This necessitated a major design change.**

The Colossal Flood of 1884

- Heavy rains in Jan-Feb 1884 destroyed every railroad bridge between Santa Fe, NM and Santa Barbara, CA
- During the flooding at Needles, W.A. Drake, Chief Engineer of the Atlantic & Pacific Railroad, made a number of important measurements
- Max flow of 384,000 cfs at Topock, almost double that of the "record" 1902 flood, recorded at Yuma
- 7,900,000 cubic yards of sediment moved in 24 hours (concentration 1.56 grains per cubic inch of water)
- River silt deposited by the flood had a dry density of 59.95 pcf



- **The railroad was forced to build the longest cantilever span bridge in the United States, so the caissons could be constructed above the low water surface.**
- **They ran into lots of surprises on the Arizona side, and this footing could not be founded on the bedrock**

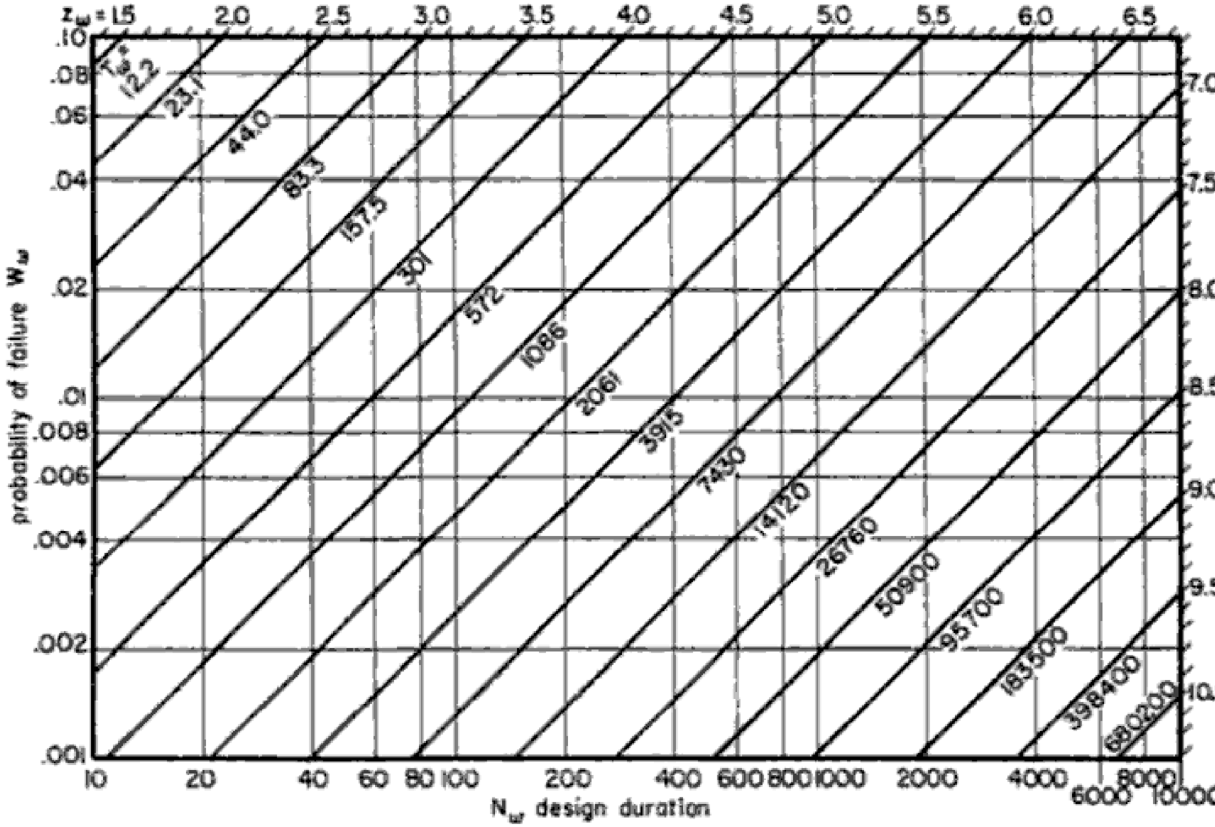


- **Of particular consternation is the "extreme high water mark, recorded at an elevation of 500.5 ft, five feet higher than that of the record 1884 flood. This was labeled 1857? Nobody knows for sure…**

PROBABLE FREQUENCY OF FLOOD DISCHARGES AT BLACK CANYON	
Discharge, Second-Feet	Frequency With Which Discharge May be Equaled or Exceeded
130,000	Once in 5 years
160,000	Once in 10 years
190,000	Once in 20 years
230,000	Once in 50 years
260,000	Once in 100 years

At that time (1930) the general assumption employed by most designers was to build dams strong enough to withstand *double the largest flood that ever been observed*. The highest recorded flow BurRec had was 200,000 cfs at Yuma in 1902, so that's what they used

BurRec concluded recurrences of 320,000 cfs every 500 years and 450,000 cfs every 10,000 years



Graph 6.3.2. Design Flood for Given Risk

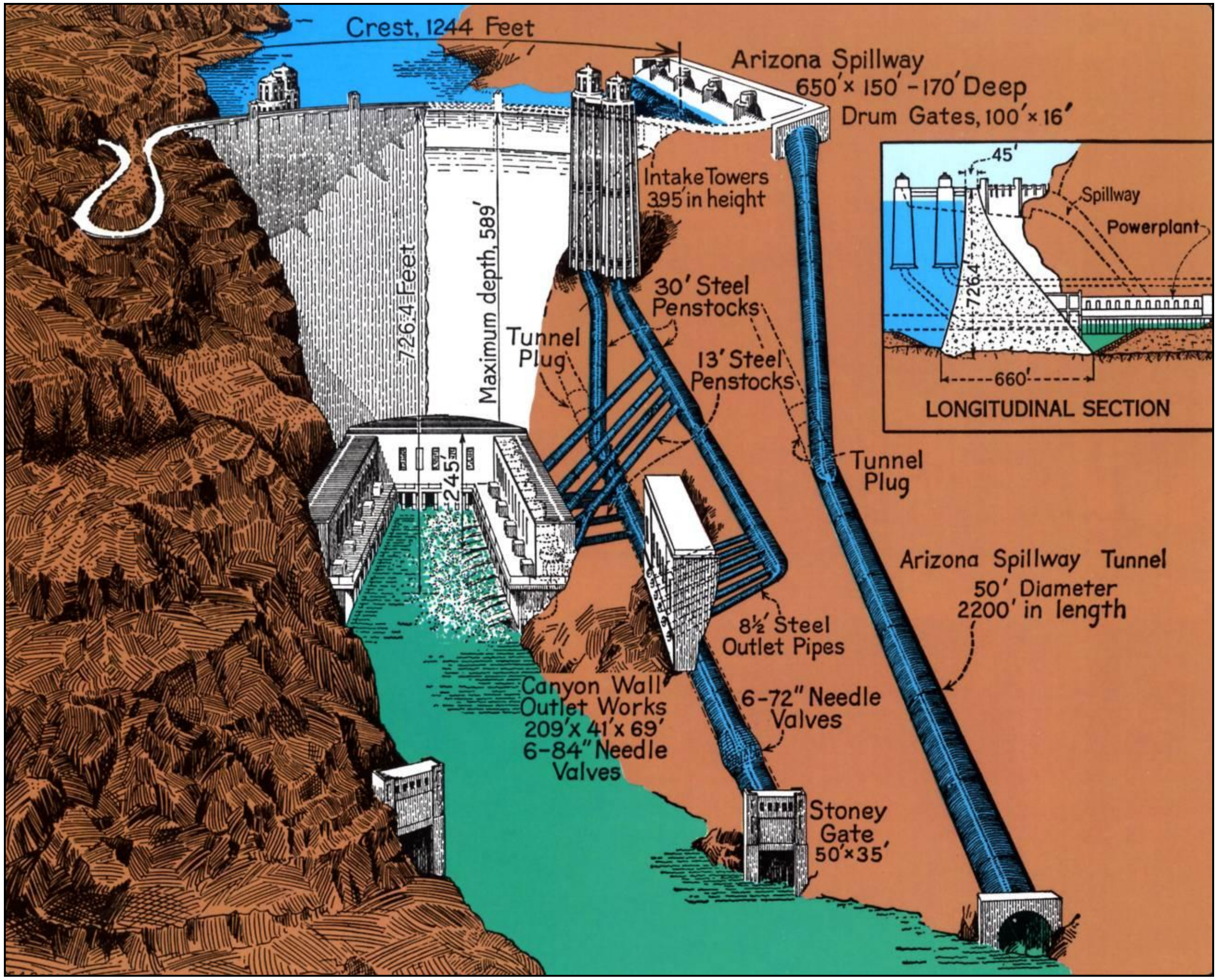
- **This is Gumbal's table, published in 1941. BurRec used this to justify their estimates, 15 years later. Yuma gage flows for 1878-1929 (49 yrs) with x_o = 100,000 cfs; std deviation 45.9; $2x_N$ = 400 z_w = 6.5**
- **They estimated the Design flood using $x_w = 2x_N$ = 400,000 cfs, which is predicted to occur once every 3,950 years**

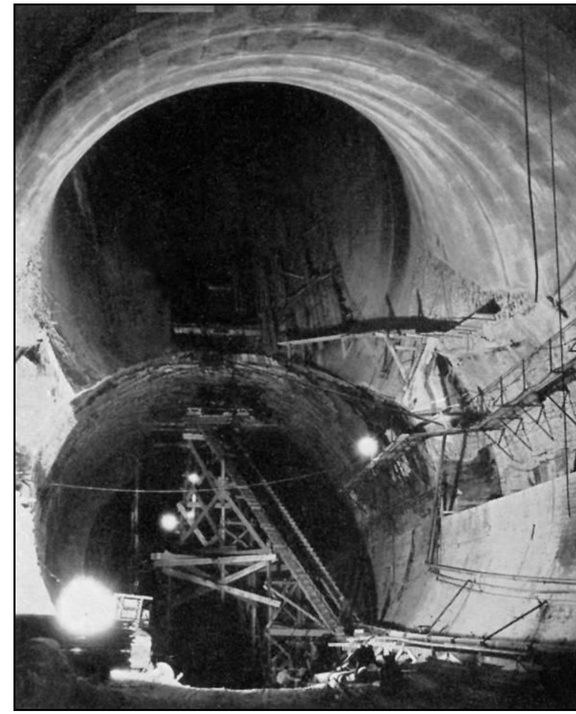
Aggregate Spillage Capacity

- The two side channel spillways were designed to accommodate 400,000 cfs
- The canyon wall outlet works could discharge an additional 48,000 cfs;
- The tunnel plug outlet works could discharge up to 43,200 cfs;
- The powerhouse turbines were assumed to pass 28,800 cfs (50,000 cfs today)
- Total as-built spillage was 520,000 cfs
- Total spillage at present is 493,200 cfs

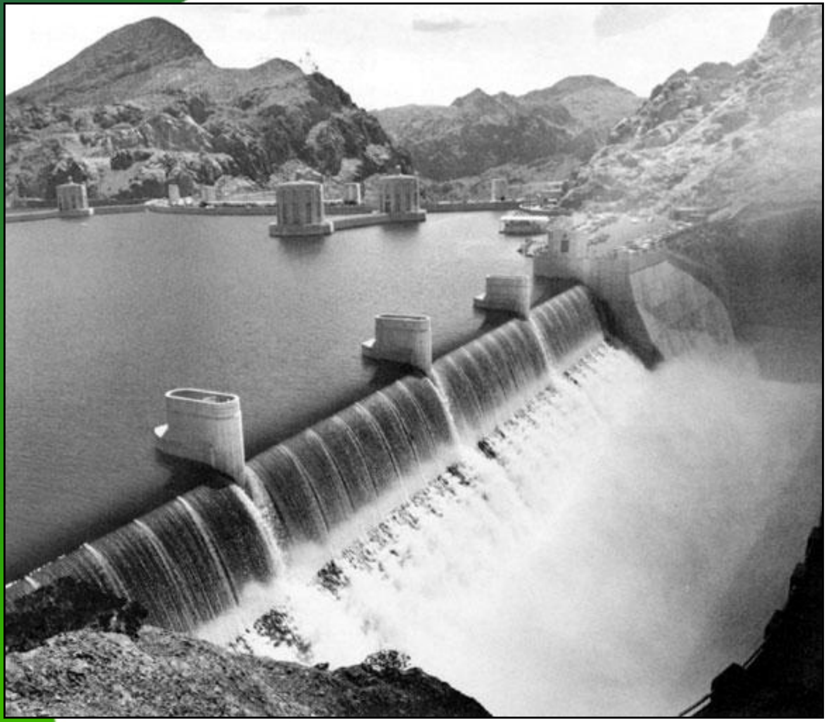
CAVITATION OF THE SPILLWAYS
Test Flows of 1941
Flood of 1983

World's Largest Spillways

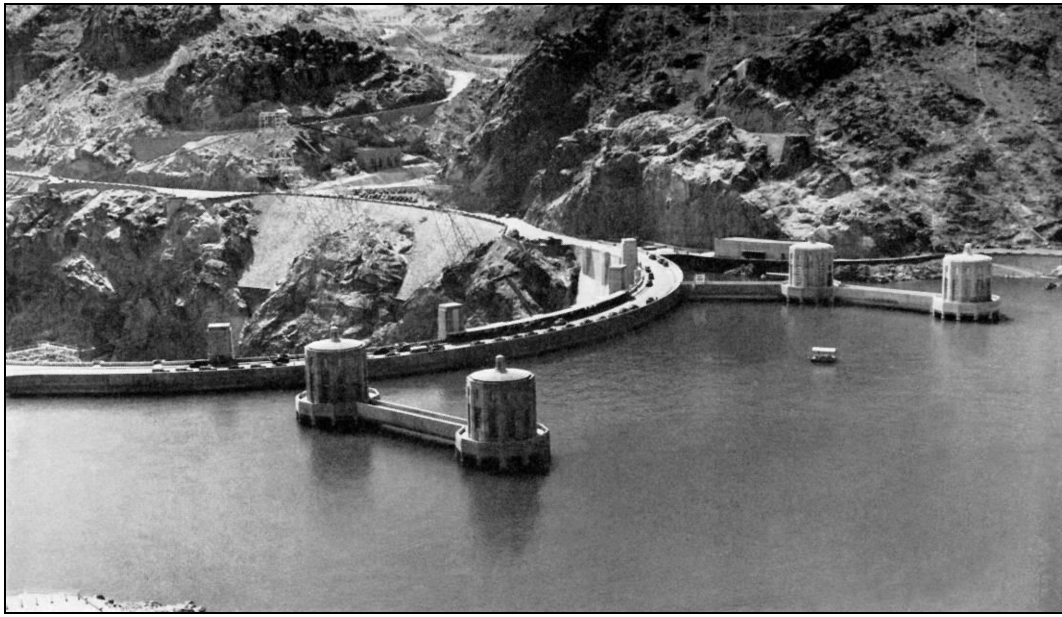




The outer bypass tunnels were connected to enormous side channel spillways; giving the dam an aggregate spillage capacity of 520,000 cfs

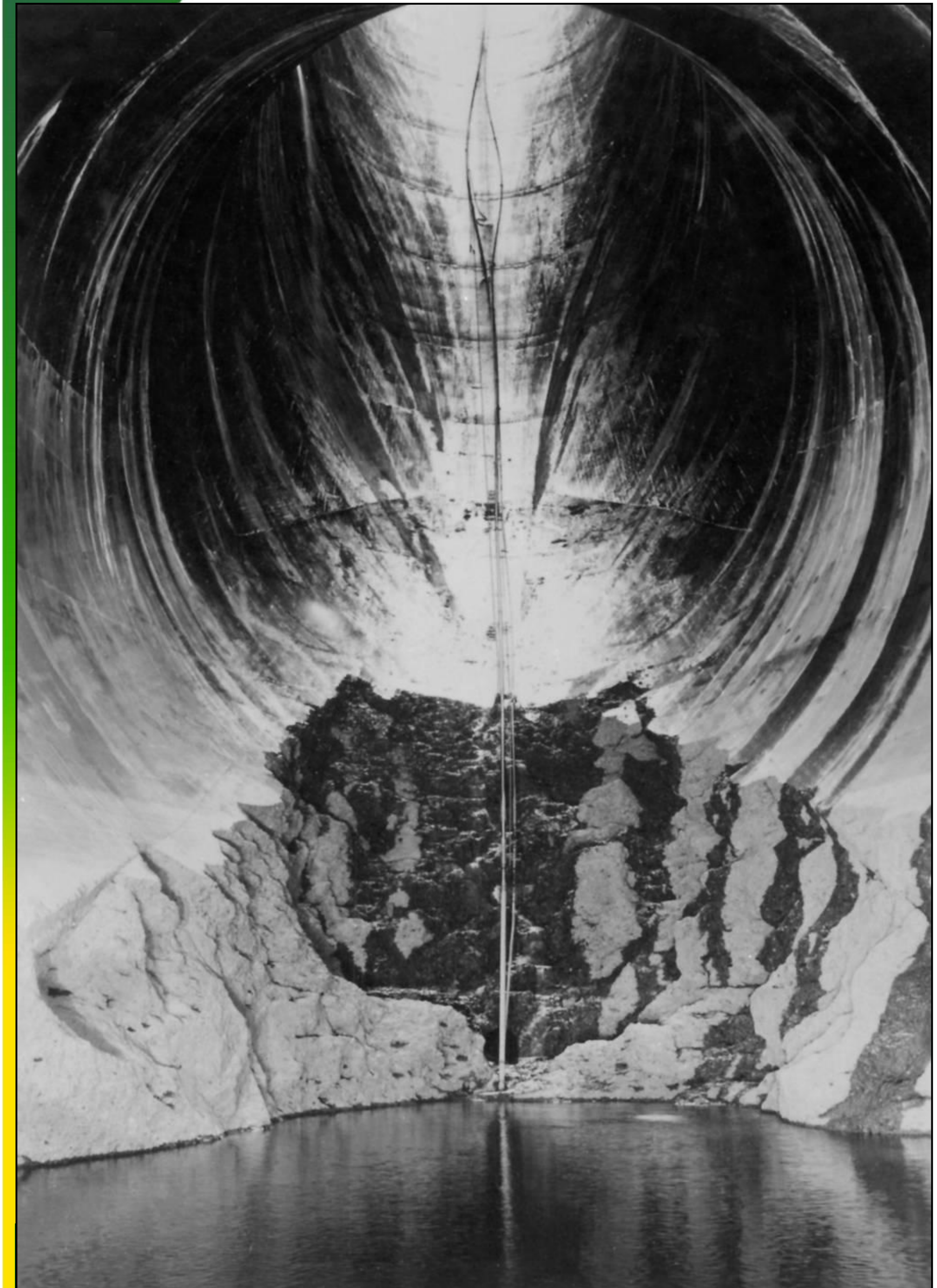


Spillway test August-October 1941



Lake Mead topped out in August 1941

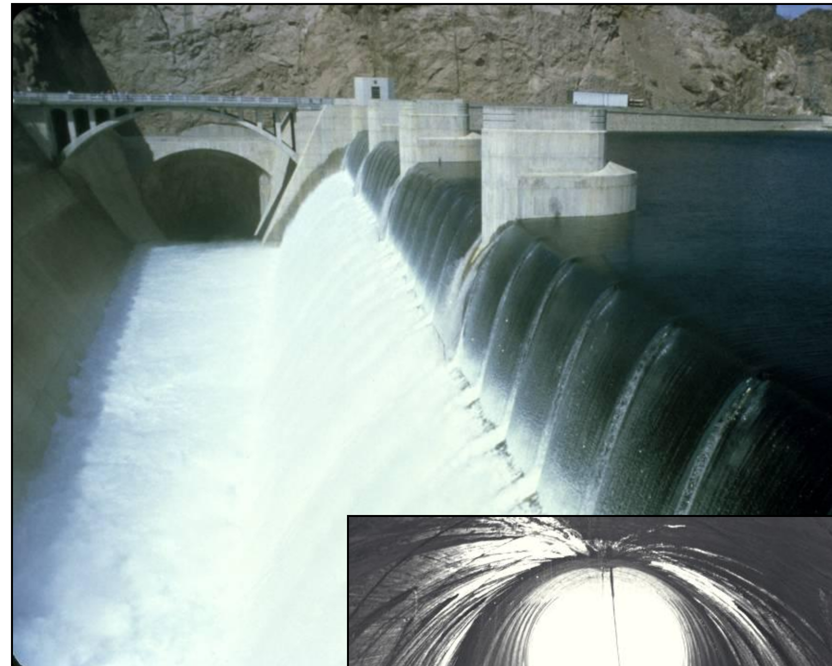
BurRec designers wanted confirmation on the design assumptions they had employed and the dam was fully instrumented. So, as downstream water demands allowed, Lake Mead was brought to maximum pool level and the spillways were tested between August and October 1941

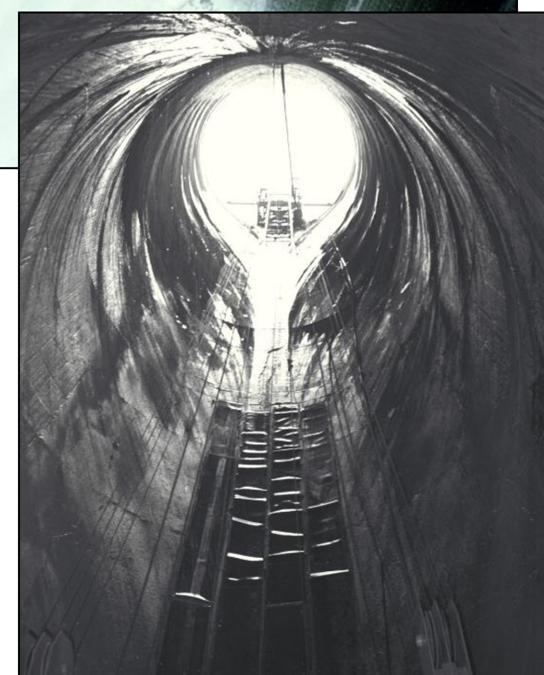


Cavitation Damage in 1941

- BurRec engineers were surprised to discover that the spillways experienced severe cavitation
- They wrongly ascribed this to a ½ inch variance in alignment of the tunnel lining

Spillway Cavitation in 1983





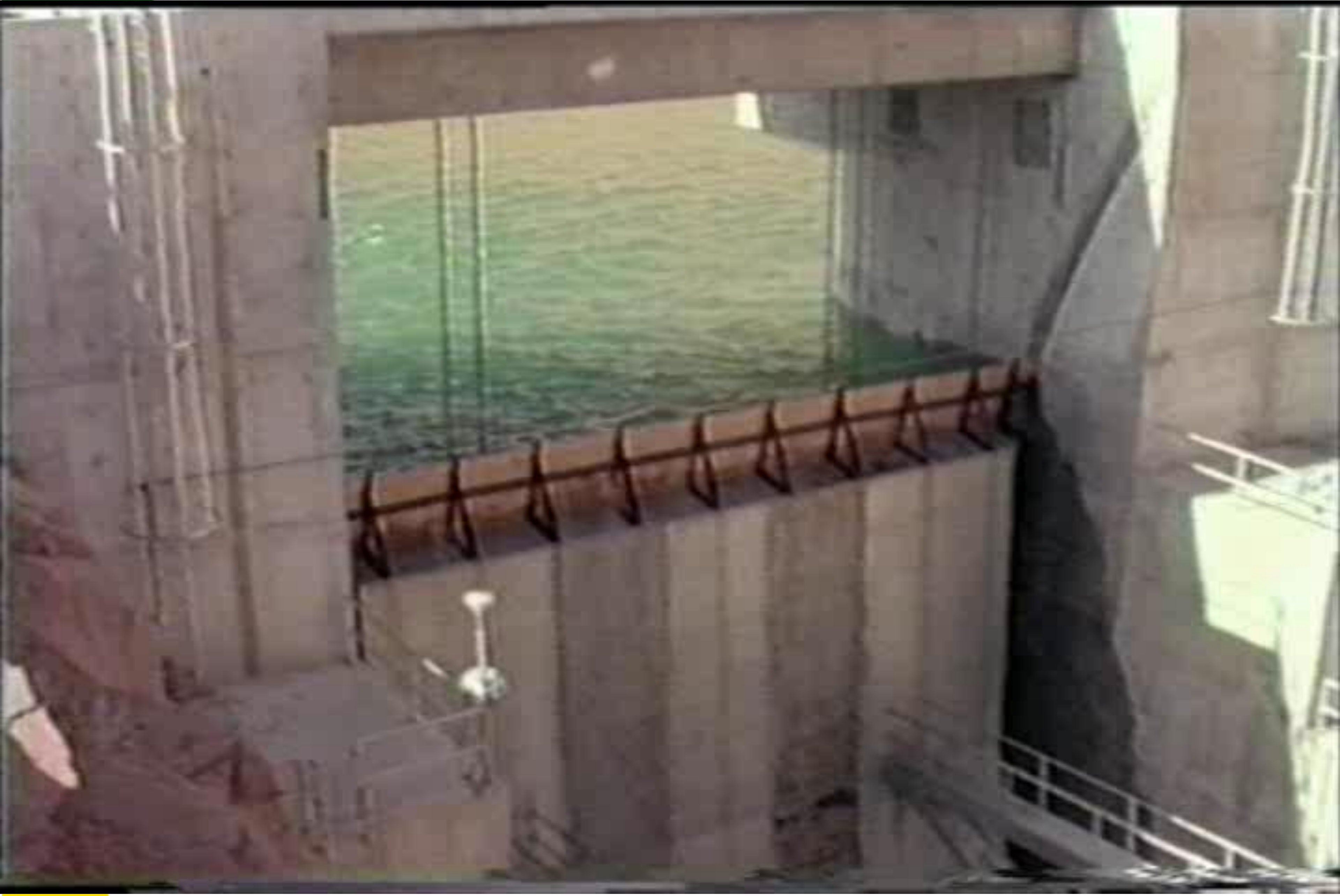
The spillways were next used in 1983 because of excessive runoff and a flawed computer program that was supposed to model runoff in the upper Colorado Basin. As in 1941, excessive cavitation damage occurred at the heel transition with the old bypass tunnel. BurRec undertook an emergency retrofit of aeration slots in the spillway tunnels at Hoover and Glen Canyon Dams later that year.

Glen Canyon Dam-1983

- Glen Canyon had insufficient flood storage in 1983 to handle the unusually high inflows of 90,000 cfs
- They were forced to install flashboards on their radial gates because spillway cavitation curtailed their use

Missouri University of Science and Technology

MISSOURI S&T



FRONTISPIECE.–Glen Canyon Dam. Left Spillway Tunnel Sept. 1983. The “big hole” in the spillway invert was 11 meters deep. Photo C557-400-690NA

- **The spillway transitions at Glen Canyon Dam experienced up to 32 vertical feet of erosion, through the reinforced concrete tunnel plugs and into the Navajo Sandstone**

- **Hoover Dam discharging from both spillways during the 1983 flood**

- **Davis Dam spilling during the 1983 flood**

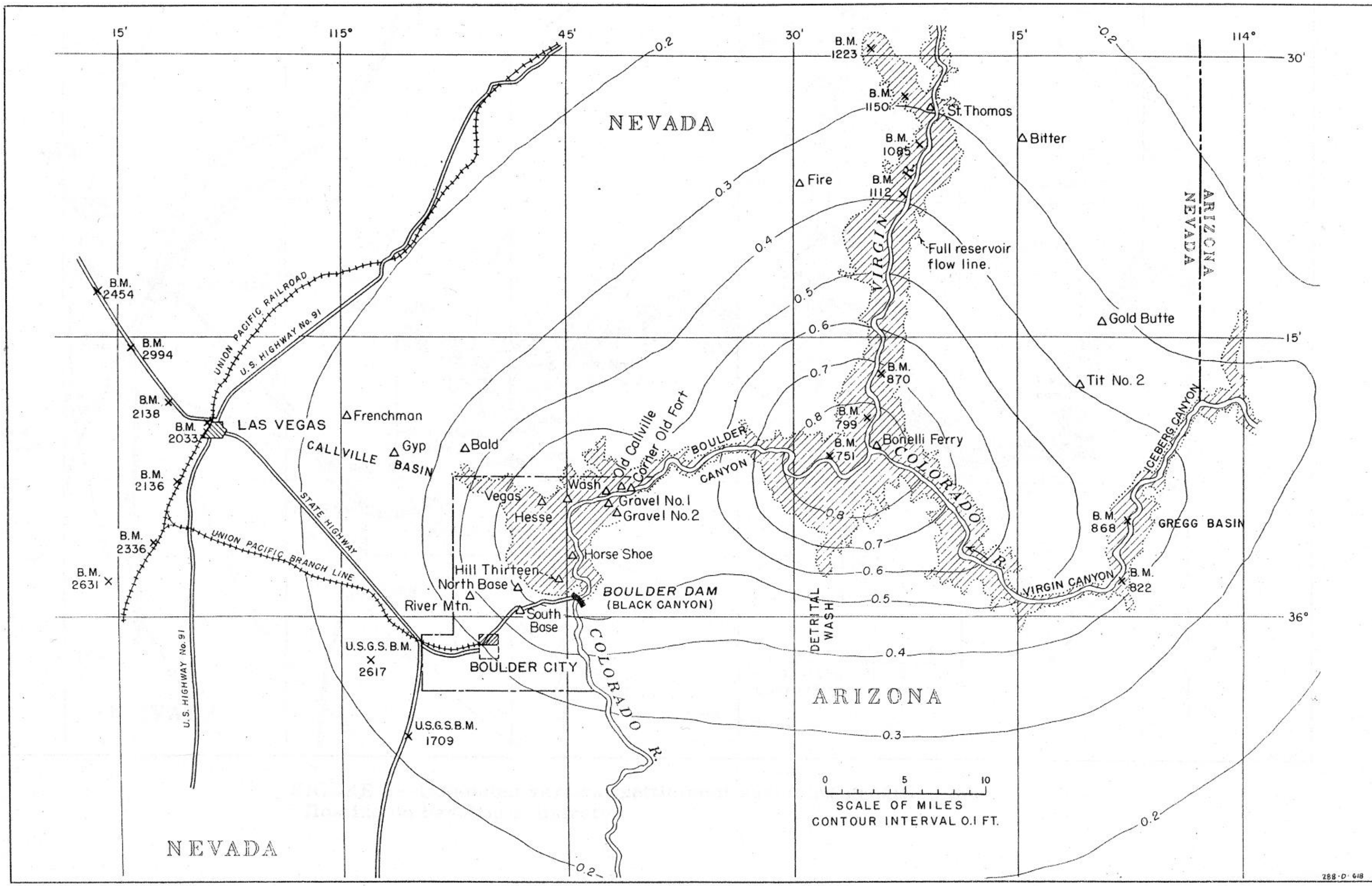
- **Parker Dam spilling in the 1983 flood**

- **Flooding in 1983 at Buckskin Point and Redrock Canyon, just downstream of Parker**

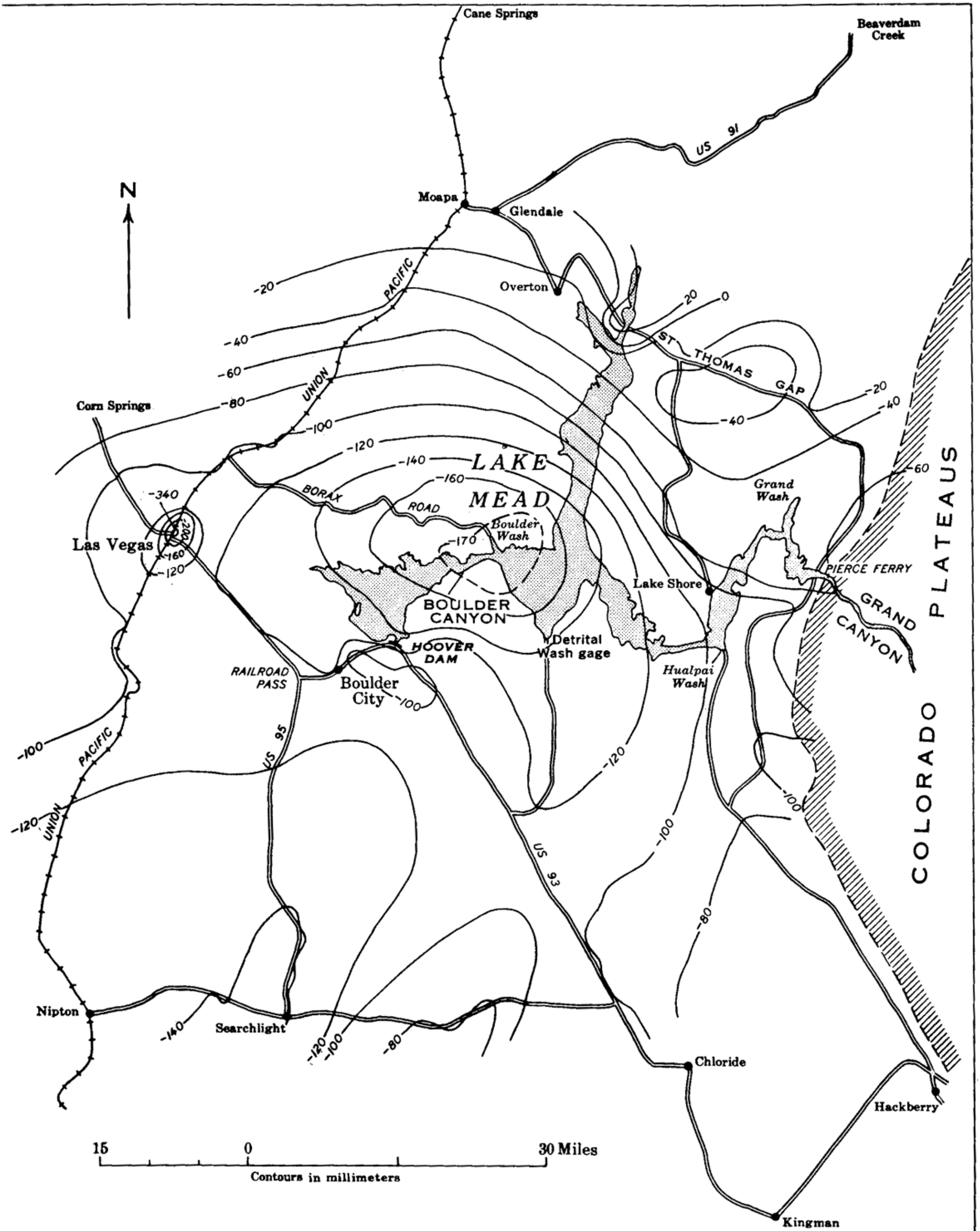
- **Flooding of the Palo Verde Valley in 1983 near Parker, Arizona**

- **Slight spilling at Imperial Dam during the 1983 flood**

CRUSTAL DEFLECTION AND RESERVOIR TRIGGERED SEISMICITY



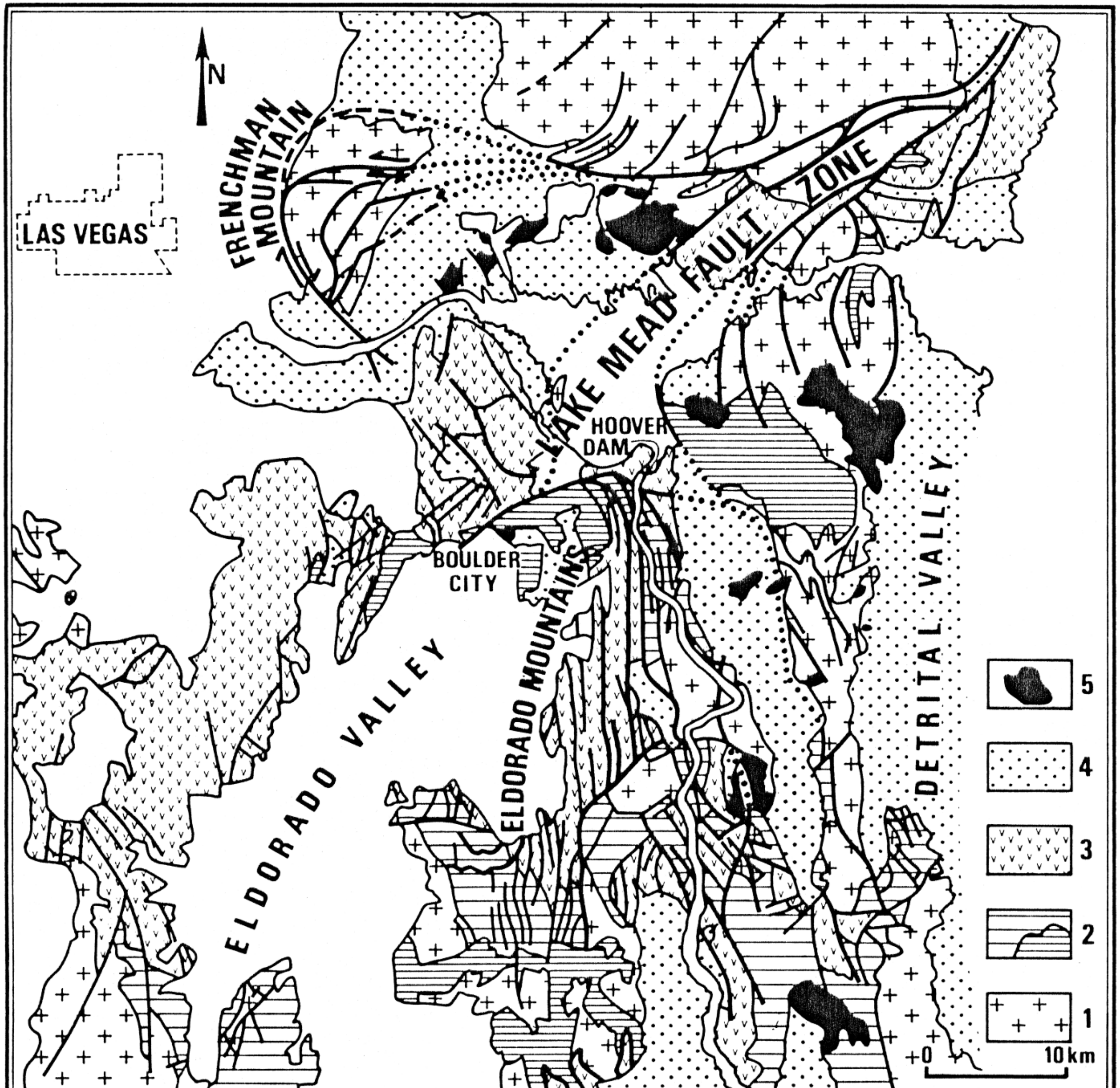
- **Predicted deflection of the Earth's crust by BurRec under weight of Lake Mead, assuming elastic deflection of a solid granite mass (CI=0.1 ft)**



- Three precise leveling surveys performed 1935, 1940-41, and 1949-50.
- The predicted deflections were up to 10 inches; actual deflections were about 7.5 inches, quite close to that predicted for an assumed mass of granite crust behaving elastically, under 41,500 million tons of water

Seismographs and strong motion sensors

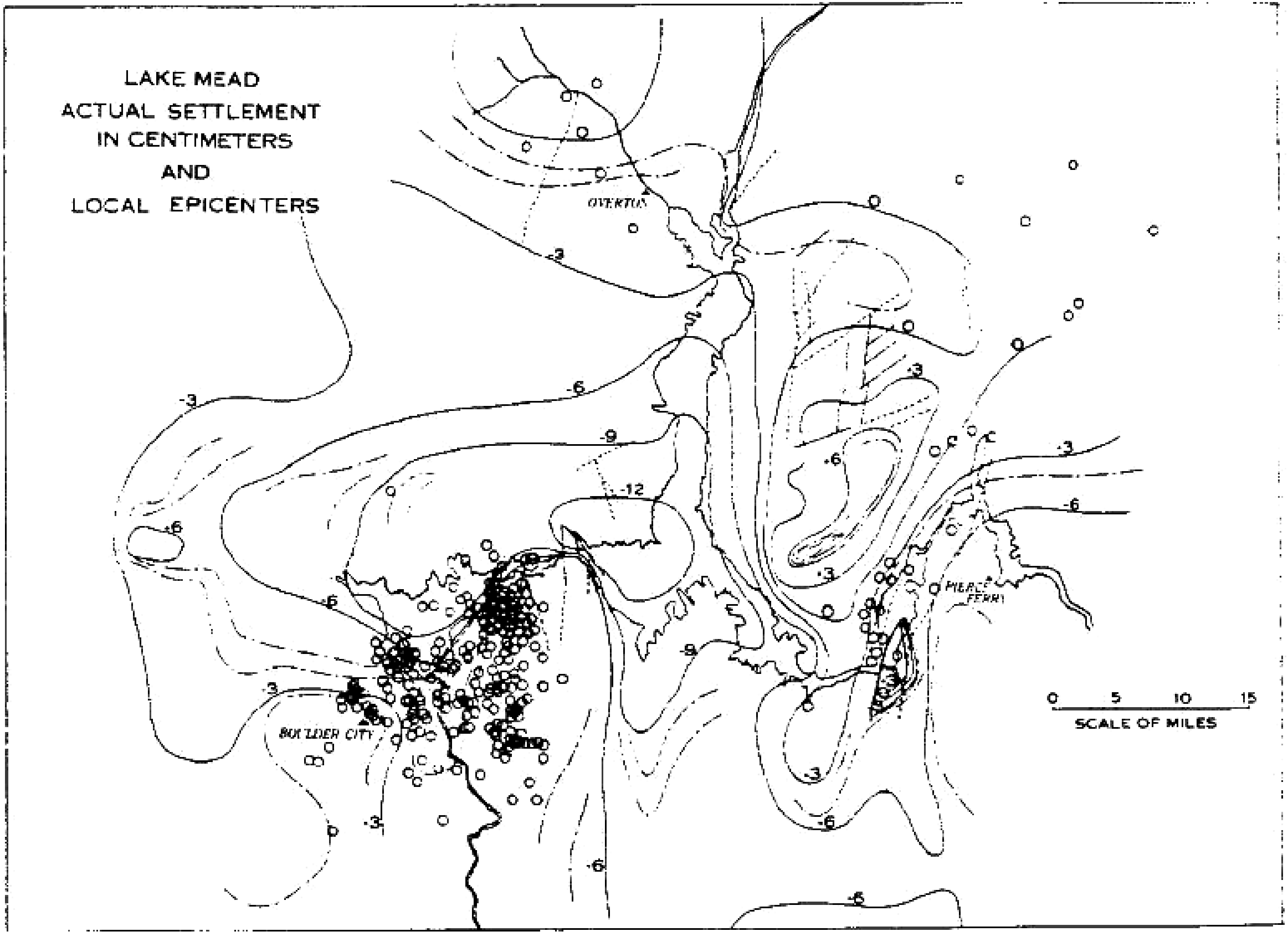
- In 1937 BurRec installed three strong motion accelographs in Hoover Dam
- 1938 Caltech loans seismograph placed at Boulder City
- 1940 Seismographs placed at Pierce Ferry and Overton; allows accurate locating and focal mechanisms of local quakes



Simplified geologic map of the Lake Mead

The area is pervasively sheared by more than 500 mapped faults

Map from Angelier, Colletta, and Anderson, GSA Bulletin (March 1985)

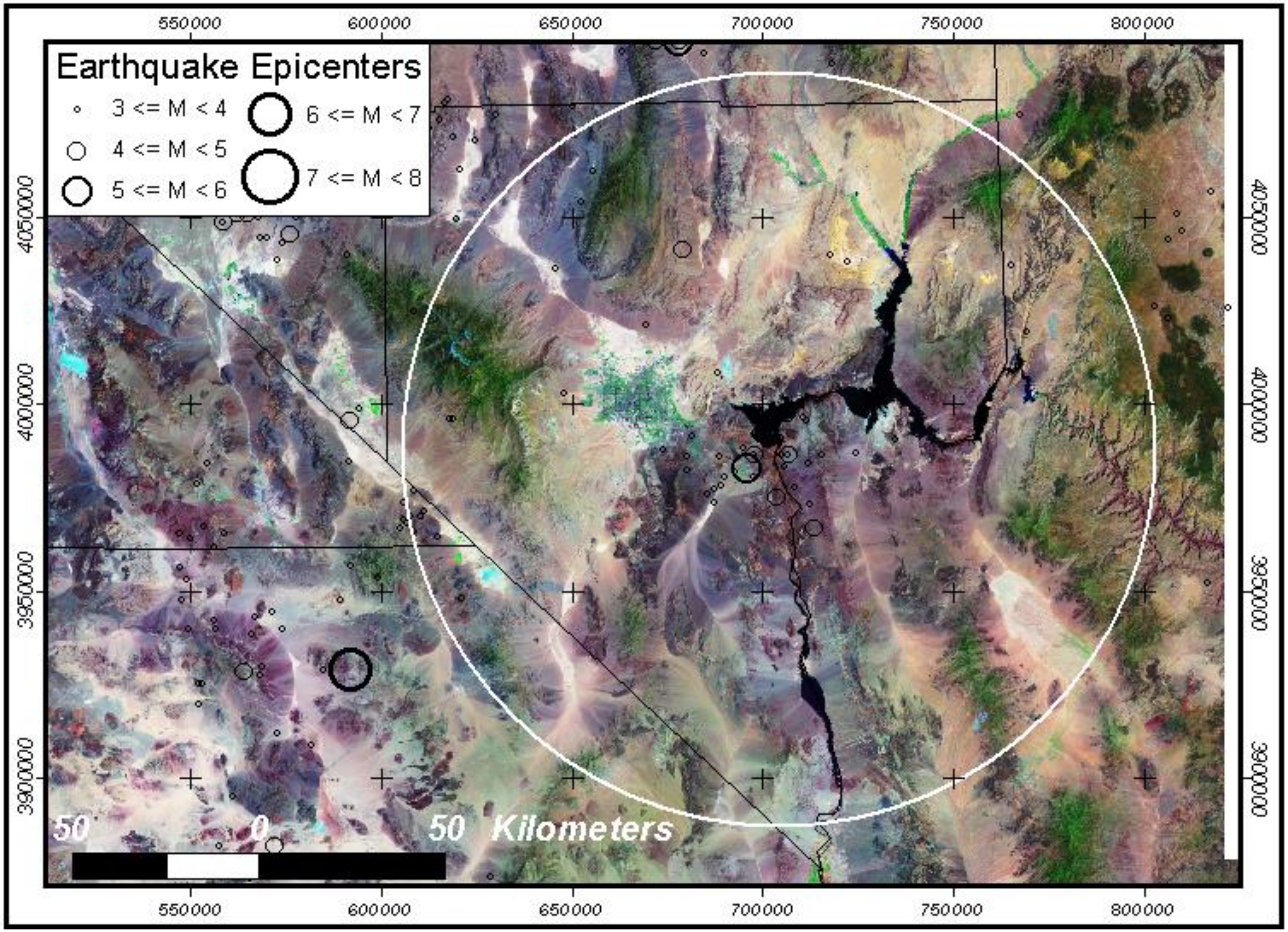


- **First earthquakes in Sept 1936, when reservoir depth reached 300 ft. These increased in magnitude as the reservoir filled, reaching M4**

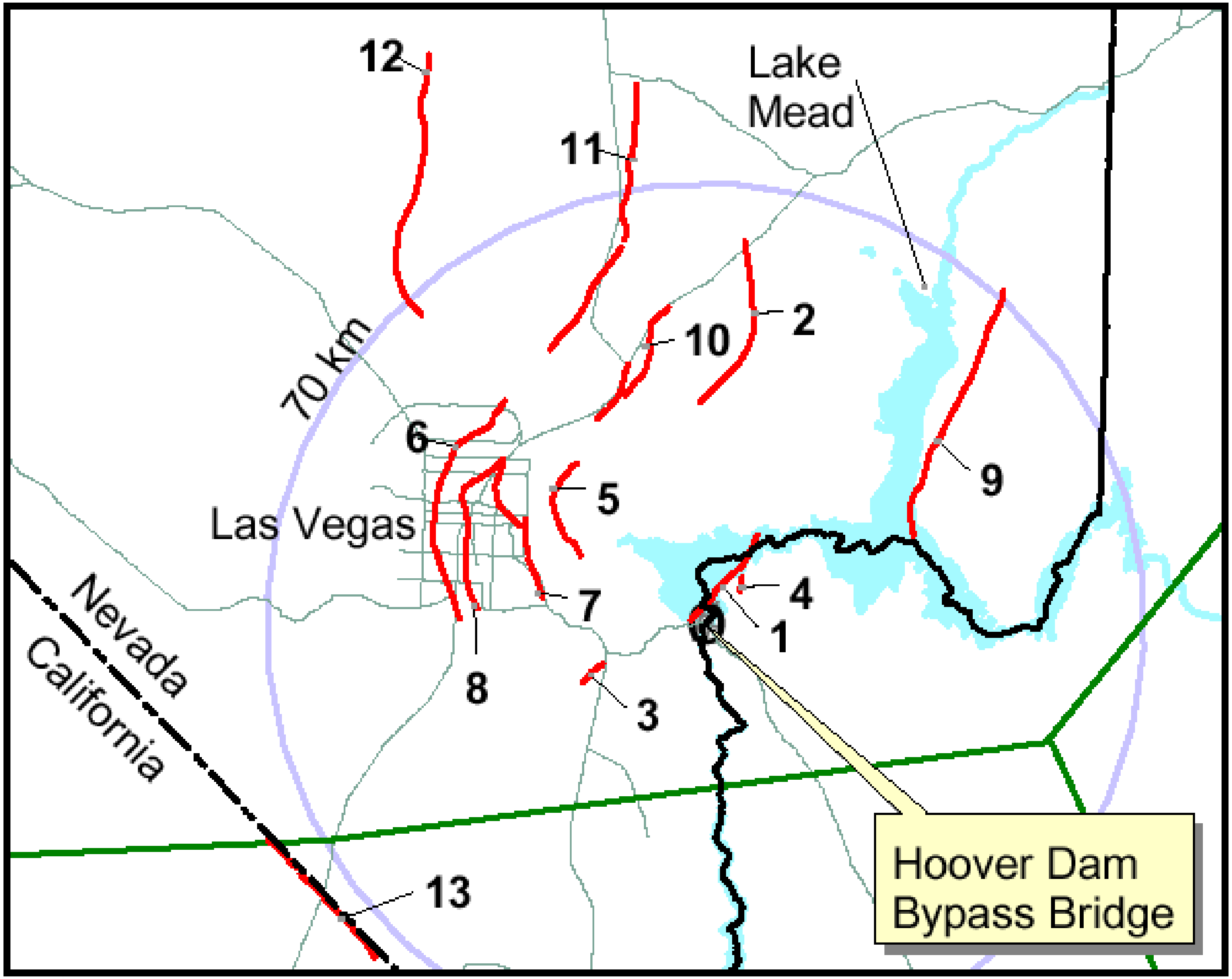
Reservoir Triggered Seismicity

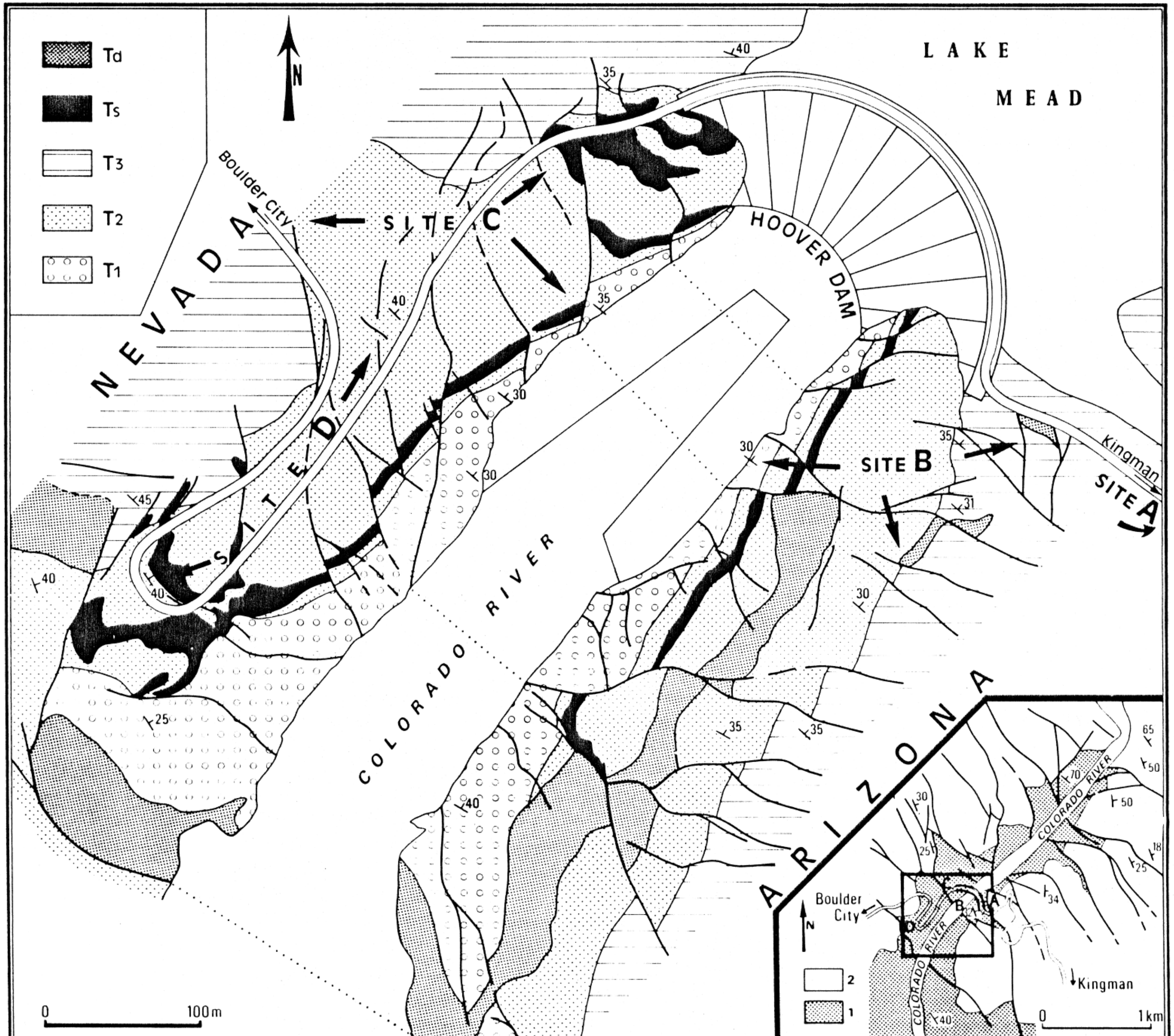
- **Seismic activity at Hoover Dam slowed considerably after first 10 years (1935-45)**
- **Quakes tend to correlate with rapid increases and decreases in lake levels, most notably in 1963-65, when lake level dropped.**
- **Since 1966 all quakes $< M 4$**
- **Hoover Dam designed for a = 0.10g. Largest acceleration recorded to date is 0.034g**
- **Most cases of reservoir triggered seismicity exceeding maximum historical earthquake was later determined to be on faults that had not previously been recognized, or their seismic potential ignored because of historic inactivity (USCOLD, 1997)**

Historic Quake Epicenters

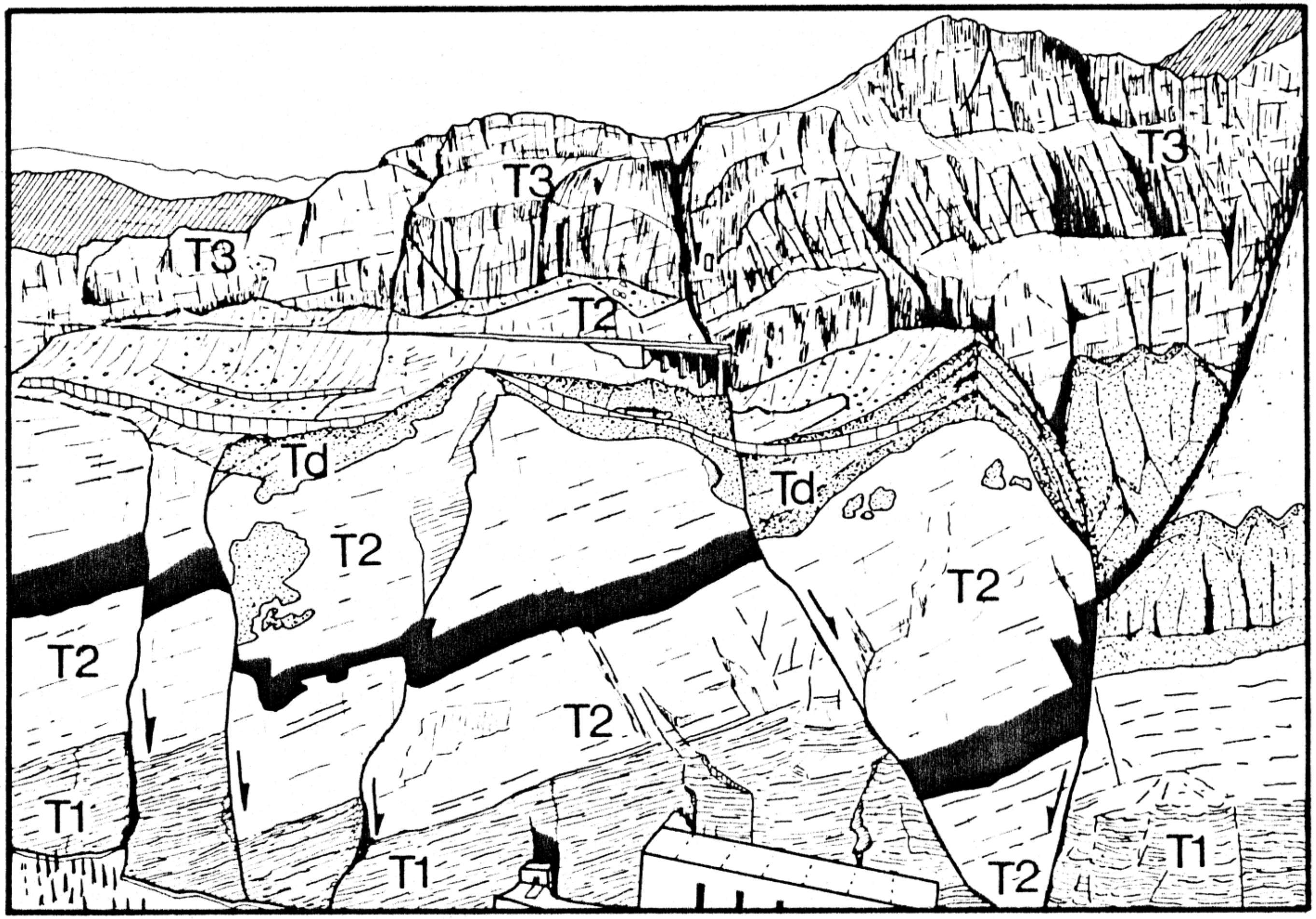


Active Quaternary Faults



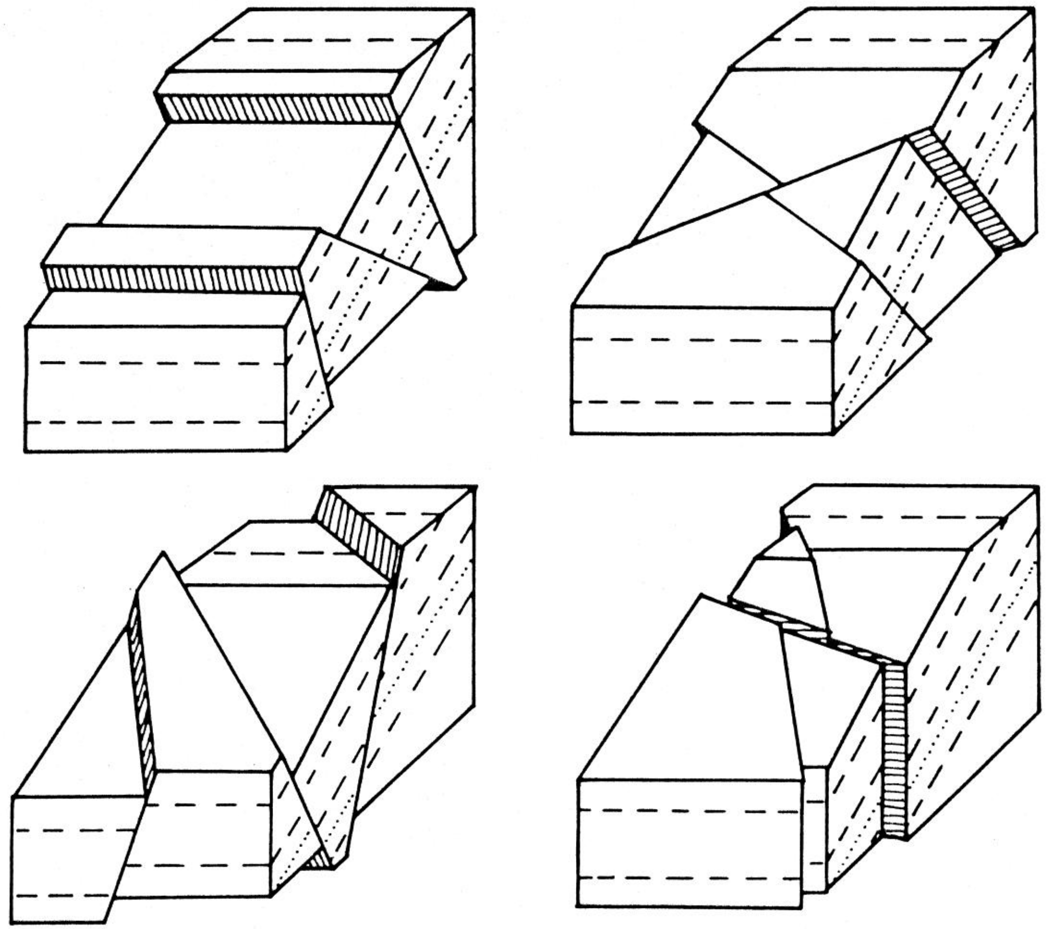


- **Detailed geologic map of exposed faults and volcanic units downstream of Hoover Dam**

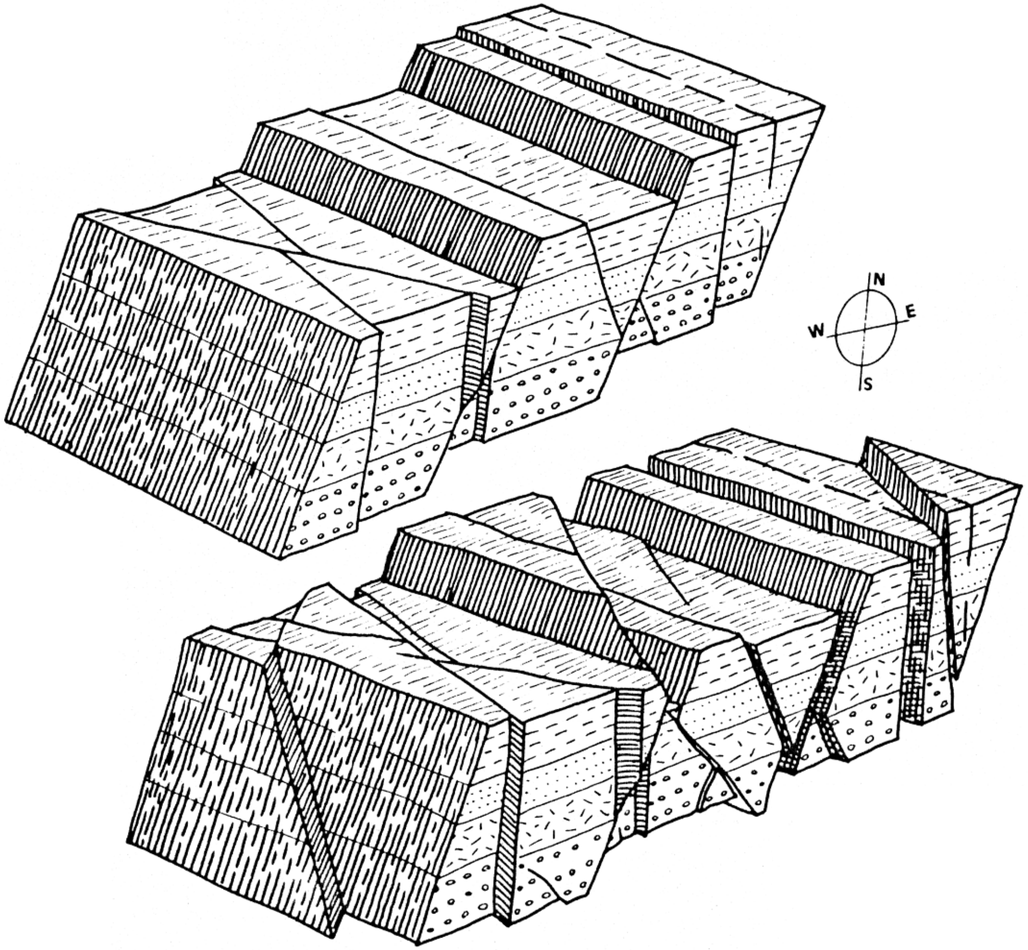


- **Sketch of geologic units exposed on Arizona abutment, just downstream of the dam. Note offset of dark colored sill. The faulted blocks are tilted 30 degrees to the northeast.**

Missouri University of Science and Technology



- **Four basic types of conjugate fault sets exposed at Hoover Dam, relative to tilt of flow foliation (from Angelier et al., 1985). Upper left shows early normal faults; upper right is early strike-slip faults; lower left late normal faults; and lower right is late strike-slip faults.**

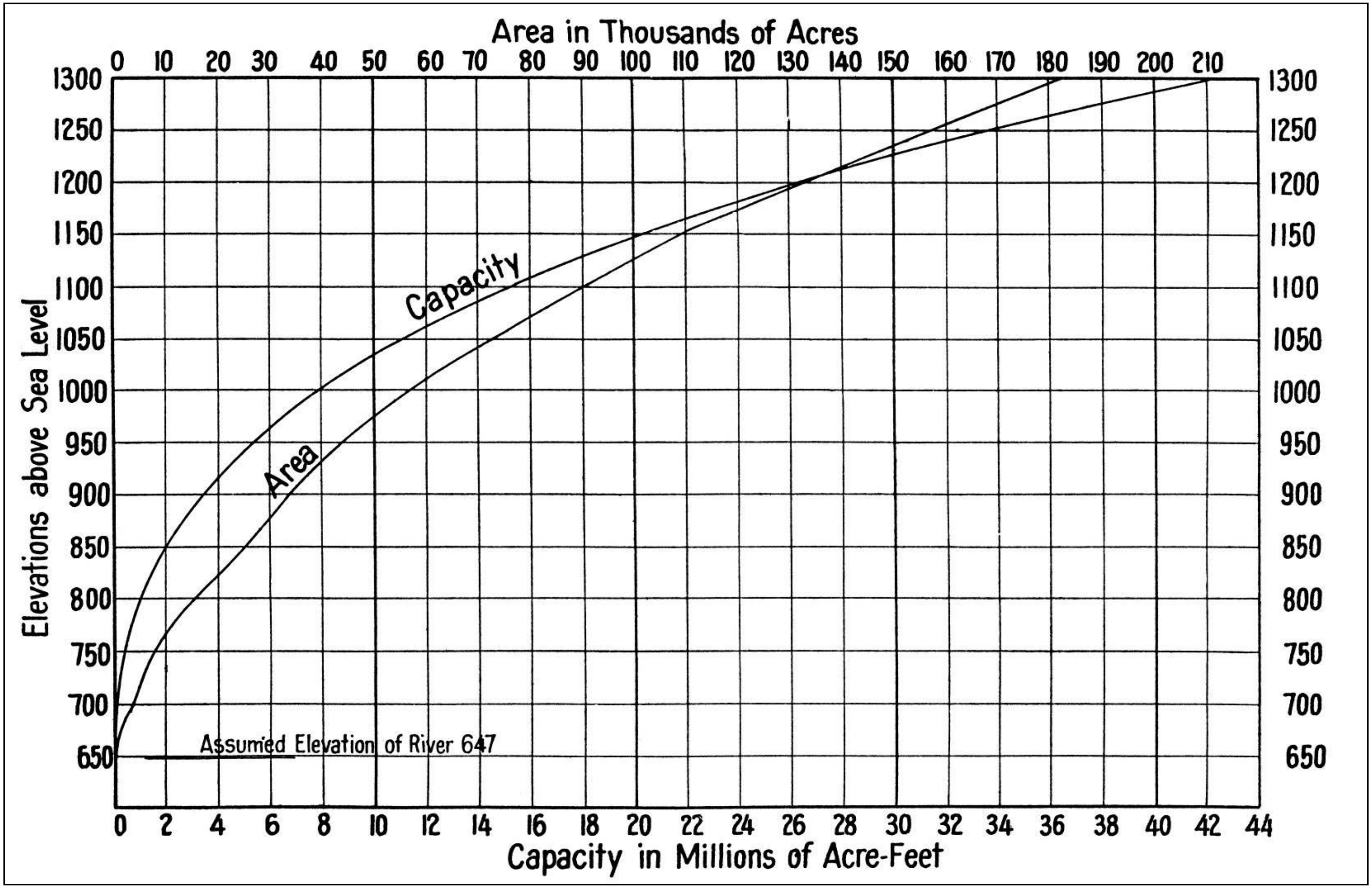


- **Block diagrams from Angelier et al (1985) illustrating tectonic evolution of the dam site. Upper diagram shows the main tilting stage, typified by NE-SW extension; lower diagram shows the principal post-tilt stage, typified by WNW-ESE extension**.

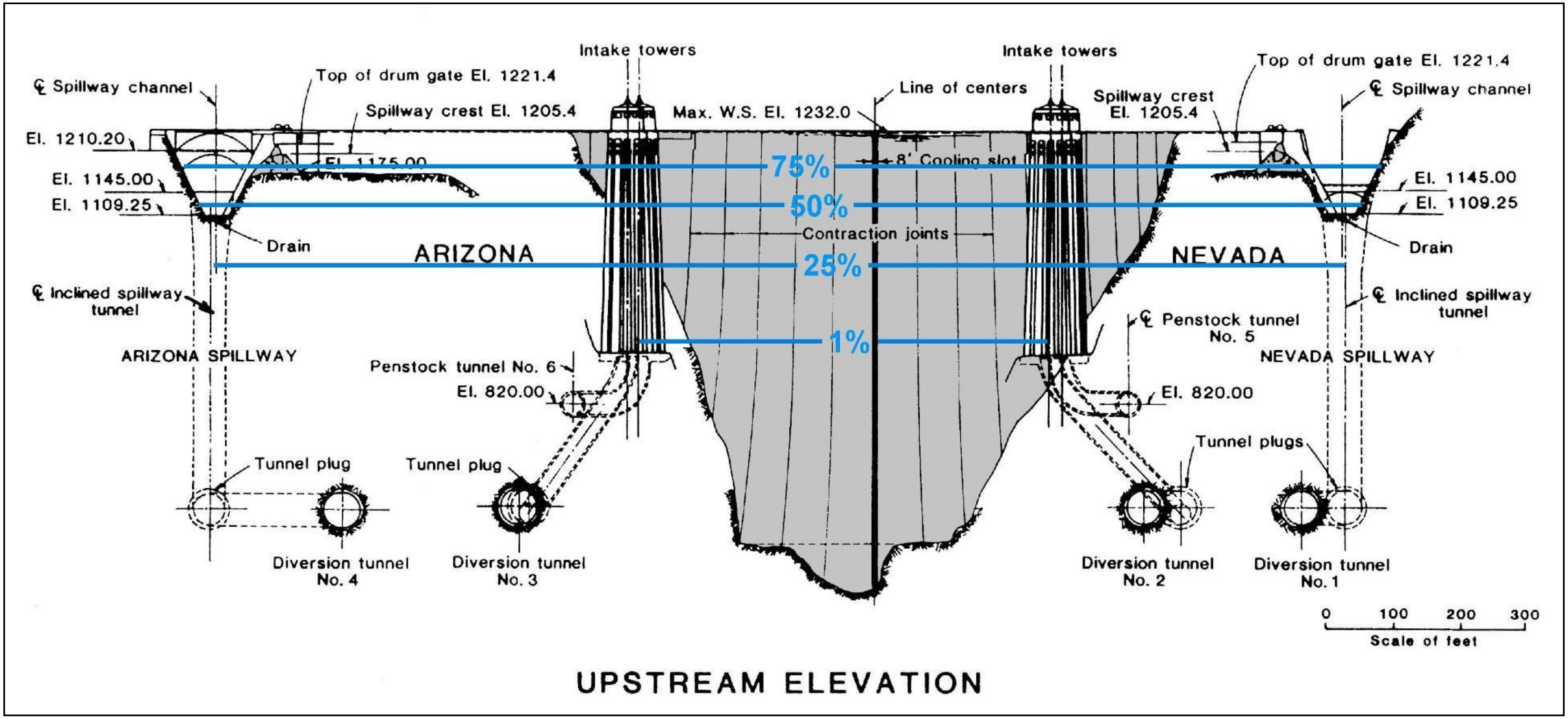
Something to ponder….

- There are 26 mapped faults cutting the abutments of Hoover Dam
- All of these faults are less than 4 Ma
- None of these faults have been precisely dated, to determine their state-of-activity or recurrence frequency
- The dam was designed for minimal seismic loading, using a pseudo static coefficient of 0.1g horizontal acceleration
- If constructed today, these issues would have to be addressed in much greater depth

LAKE MEAD SEDIMENTATION STUDIES



- **The 1935 area-capacity curves for Lake Mead predicted storage of 32,547,000 acre-feet, at a maximum reservoir pool of 1230 ft. Of that, 9.5 million ac-ft were originally reserved for flood storage.**



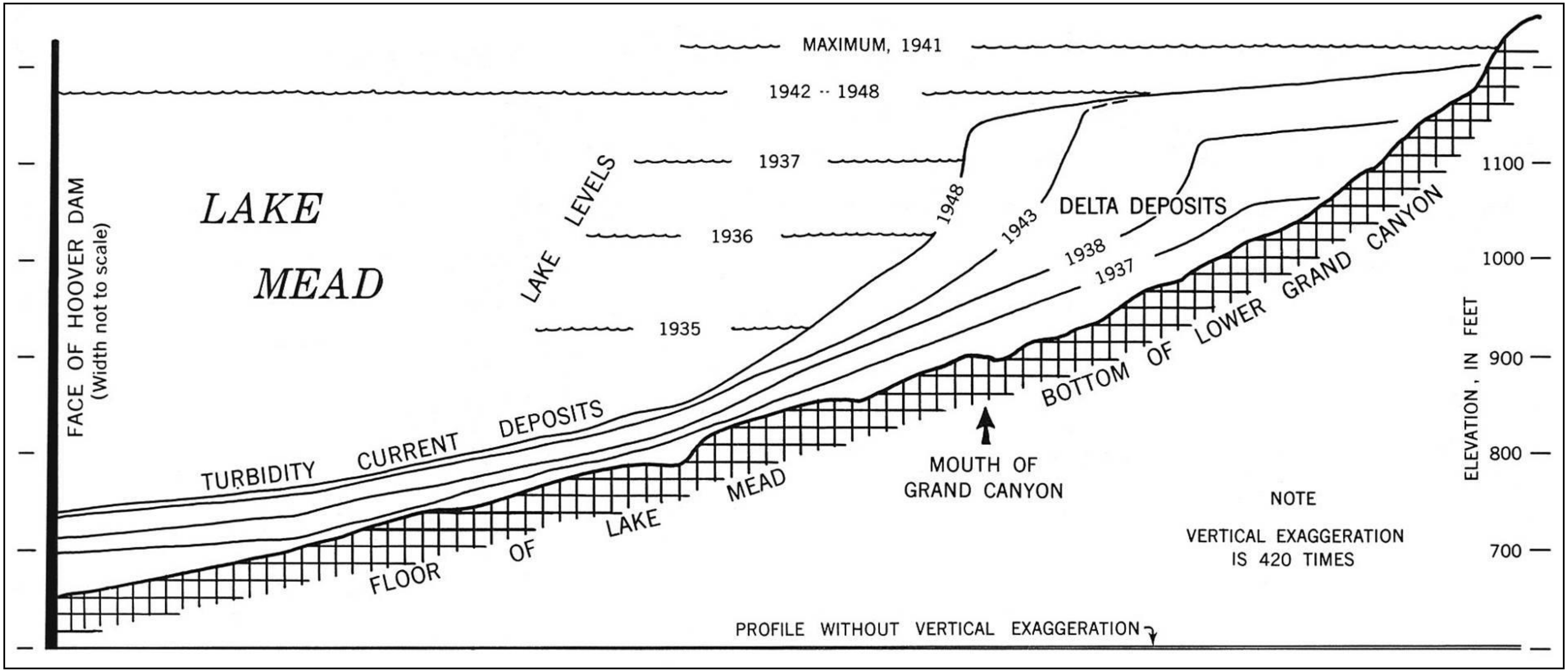
- **The storage capacity of Lake Mead increases dramatically in the uppermost elevations of the dam. Note how the lower half of the dam only retains 1% of the reservoir's water!**

Monitoring

- Filling began in Feb 1935
- BurRec monitored sedimentation closely
- Up to 230 feet of sediment was deposited in upper reaches of the new reservoir

- Dispersion plays a significant role in the sediment budgets for the San Juan and Little Colorado Rivers, which supply most of the sediment

The Expanding Delta

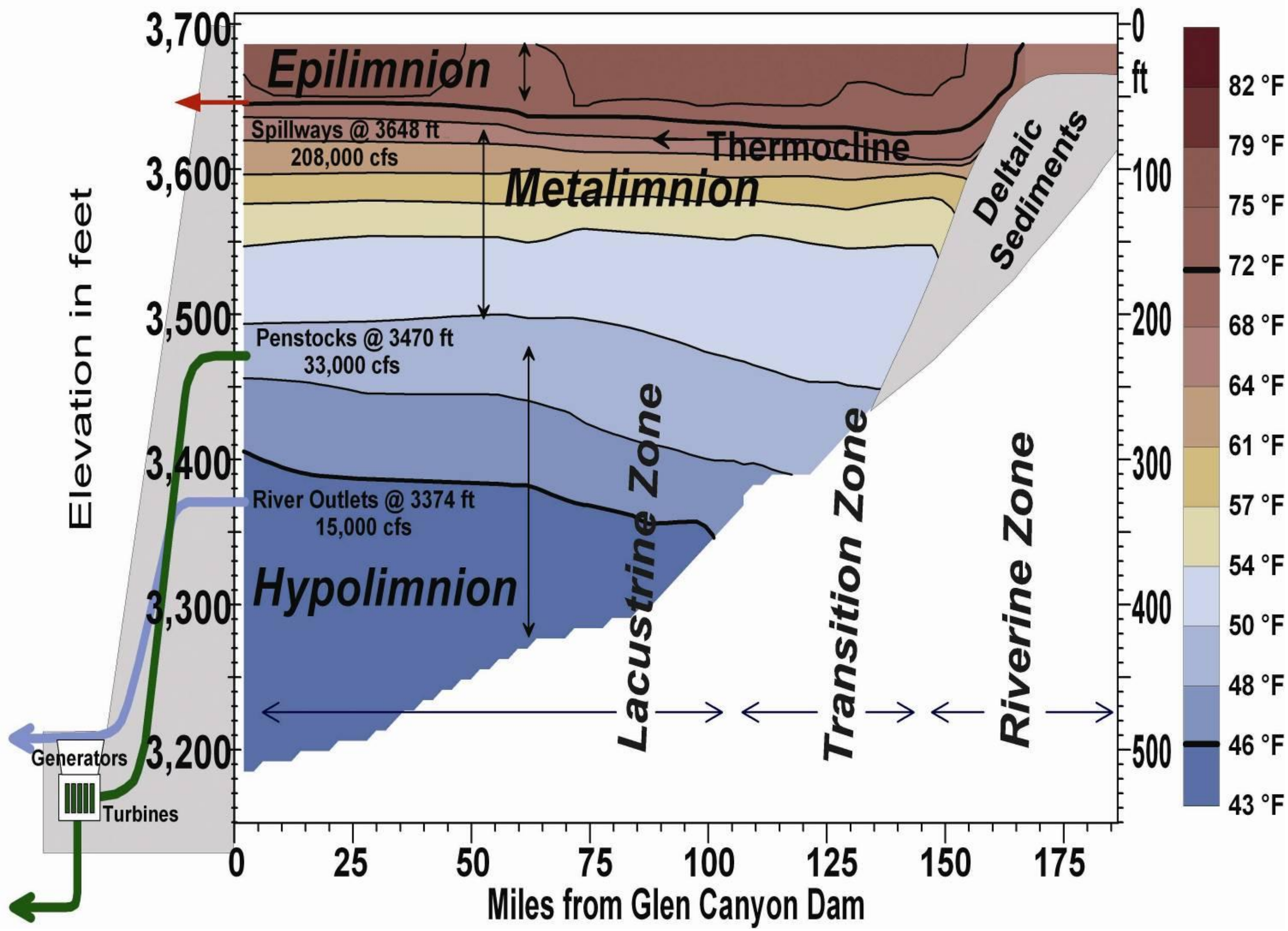


The big surprise was turbidity current deposits filling the deeper basins, all the way to the dam face.

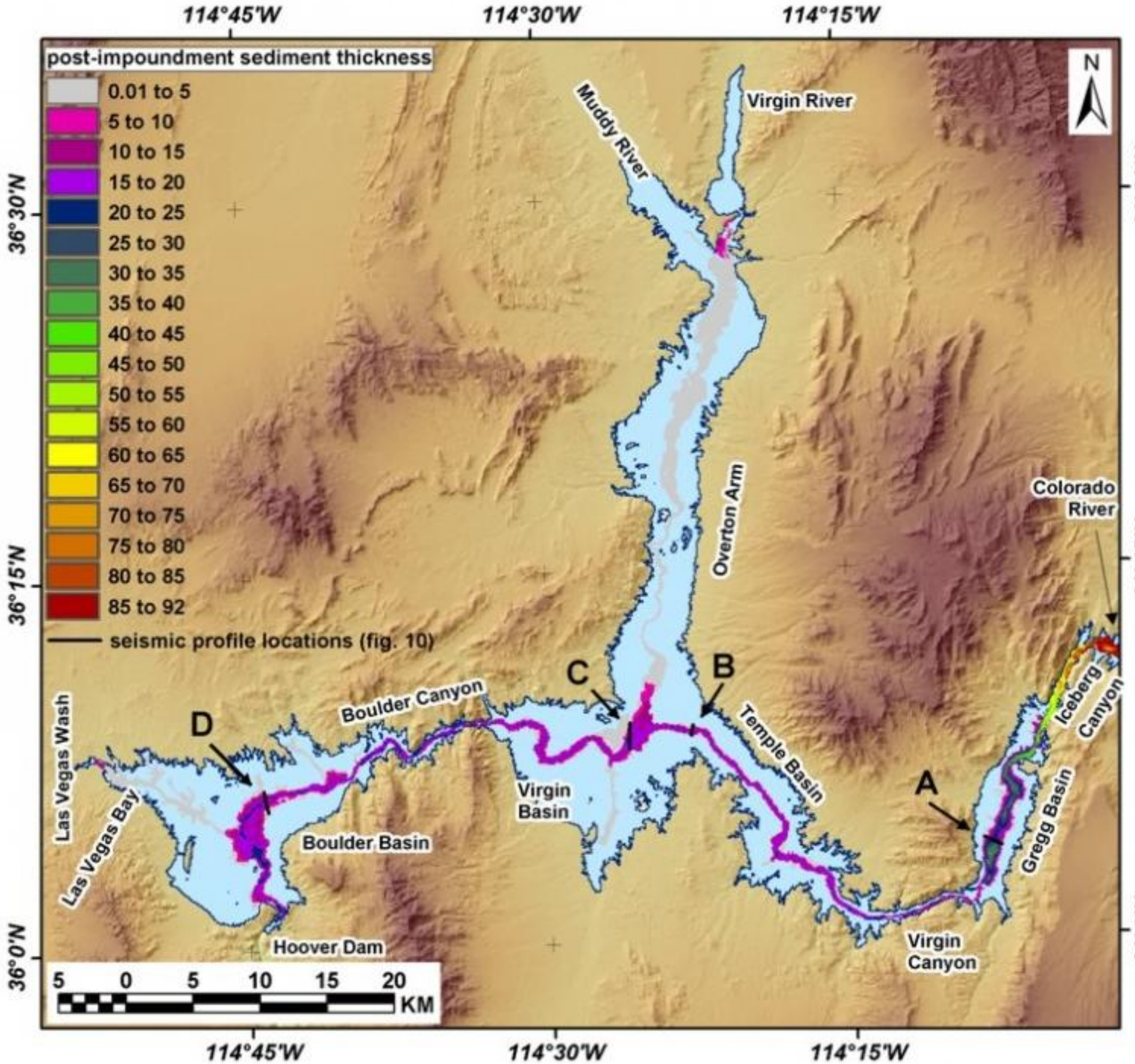
Unusually high temperatures developed in the lower 100 feet of the dam's upstream face, due to biologic reduction of nutrient rich silts brought 115 miles across the sinuous course of the old river channel by these density currents. Caltech scientists did some of the investigative work.

Reservoir Density Stratification

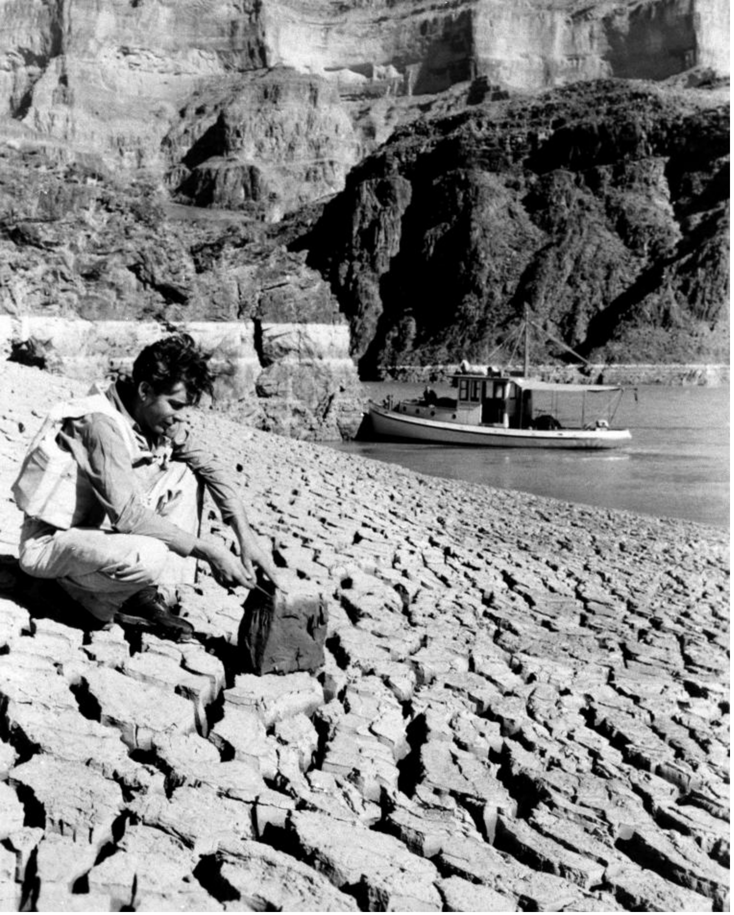
- Example of Glen Canyon Dam
- 3 Discharge structures
- Reservoir stratified by density
- Longitudinal zonation



Data from Bill Vernieu of USGS, Flagstaff



- **Distribution of sediment in Lake Mead, from Twitchell (2003)**



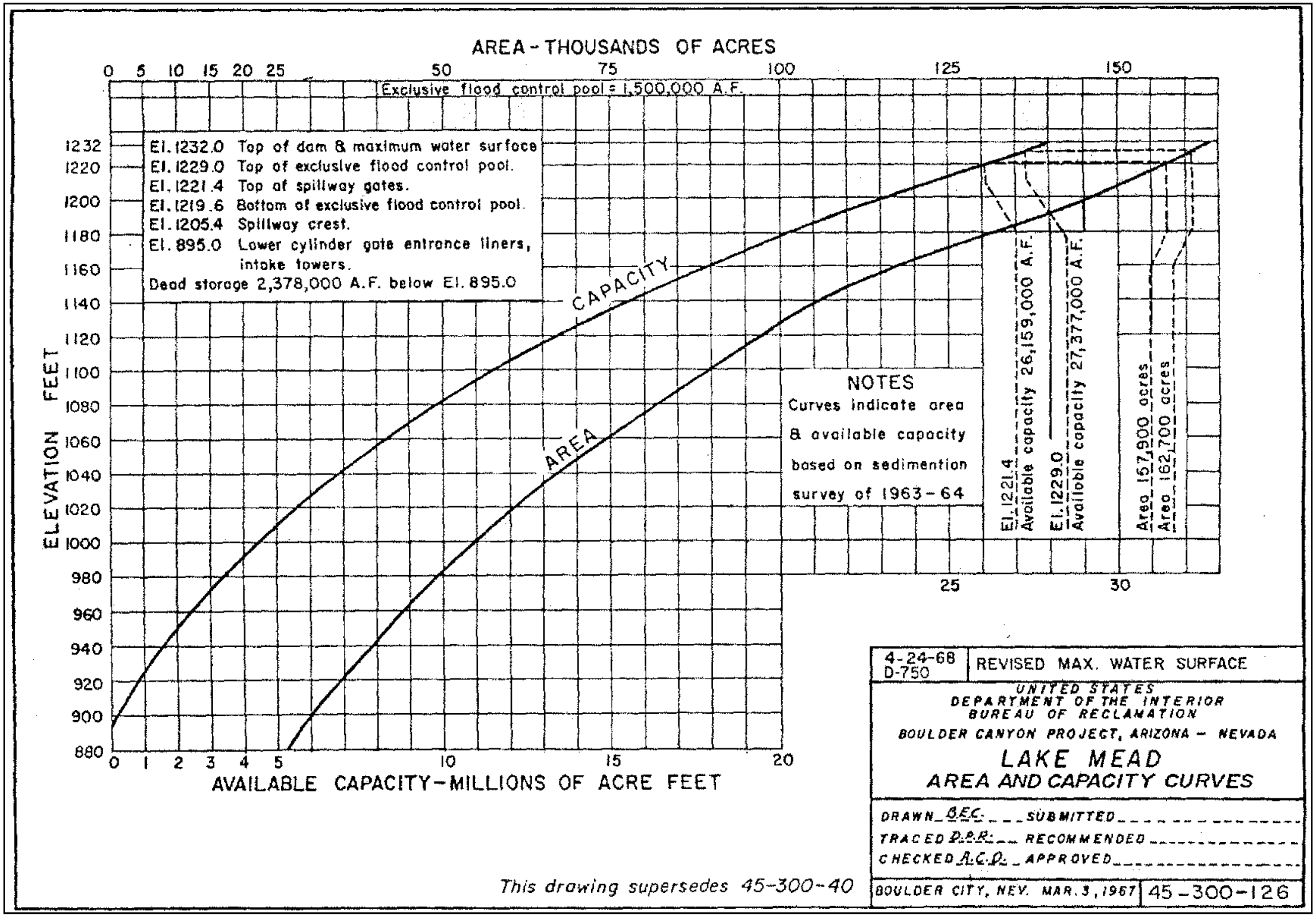
Rate of Sediment Accumulation and Predicted Project Life

- **Between 1935-1948 1,426,000 ac-ft of sedimentation. At that rate the reservoir would be filled with sediment in 296 years**

- **From 1935-1963, 2,631,228 ac-ft of sediment accumulated (15% drop in avg rate of accumulation), predicted reservoir life of 346 years.**

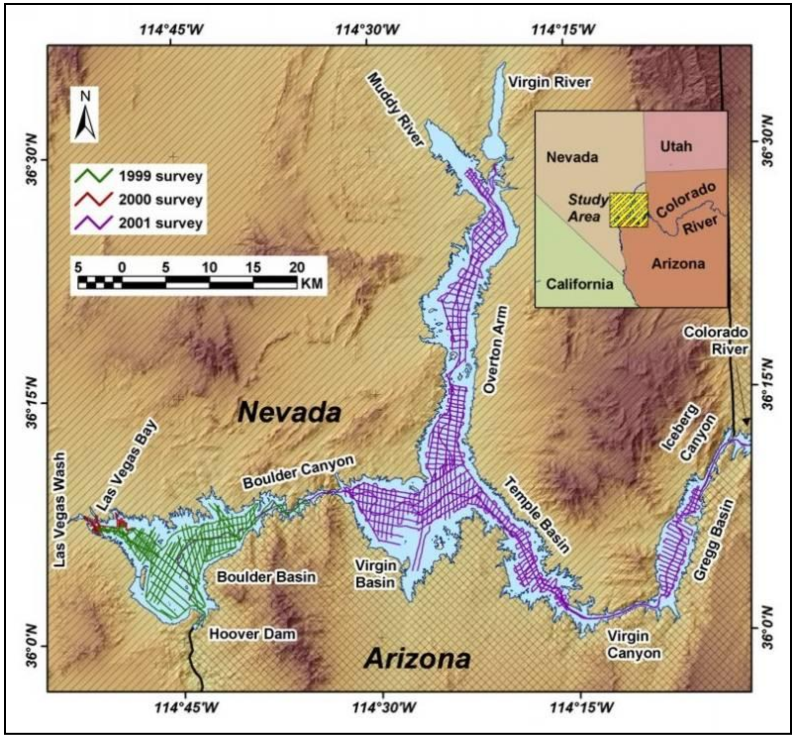
- **From 1963-2001 (after Glen Canyon built) only 301,434 ac-ft of sedimentation. This extrapolates to a predicted life of 2,750 years**

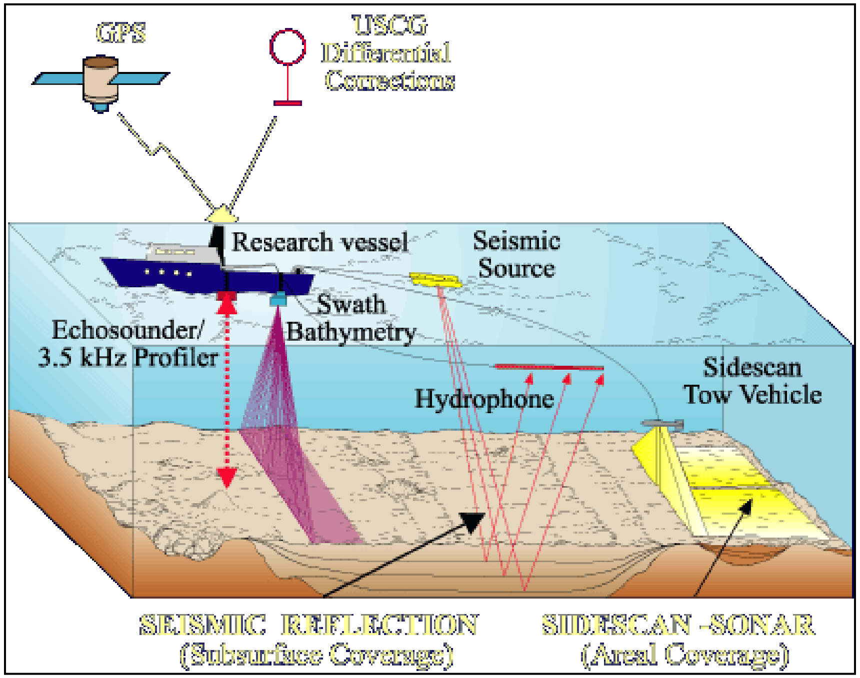
Hoover Dam had a design life of just 150 years before Lake Mead was expected to silt up, absent any upstream dams. About 50% more silt entered the lake than passed Lee's Ferry (360 miles upstream). Much of this emanates from the Little Colorado River Basin and the beaches being eroded in Grand Canyon.



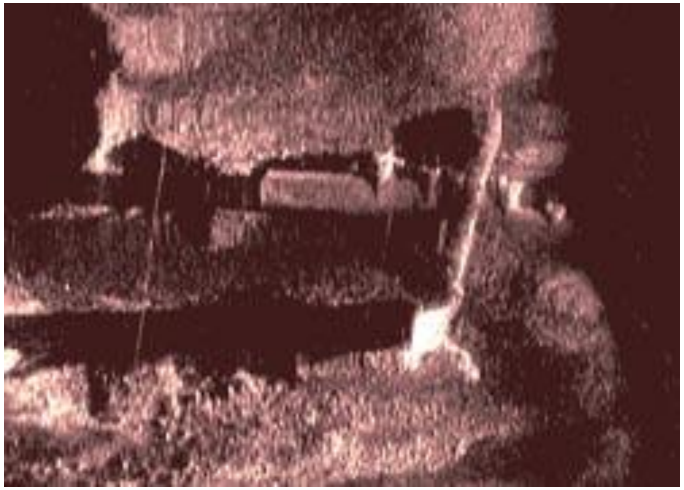
- **BurRec's revised area-capacity curves after the 1963 surveys, when Glen Canyon Dam cam on line. About 8.1% of the reservoir's stoarge capacity had been lost.**

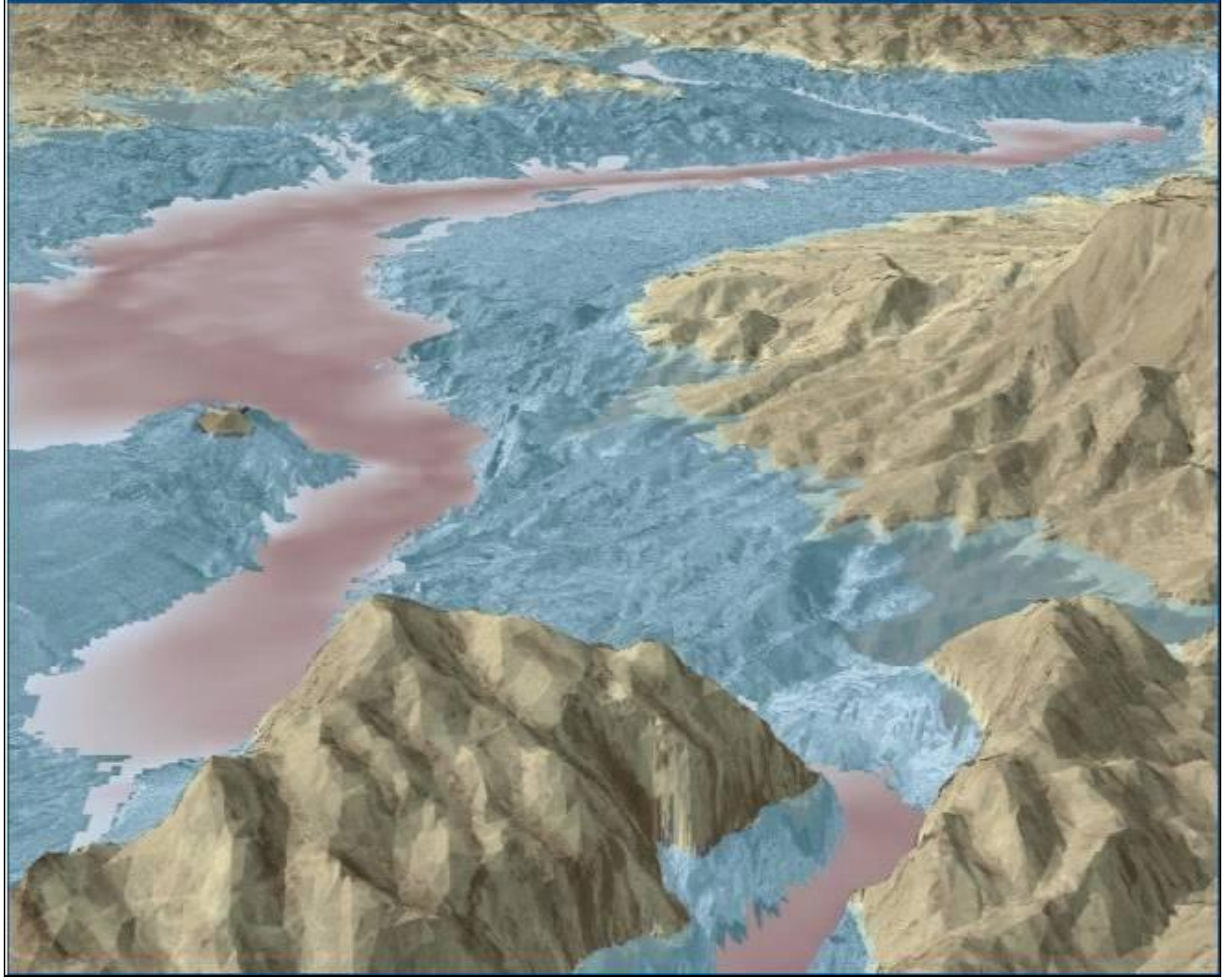
Recent Lake Mead sediment surveys





The channel thalweg and deep basins of Lake Mead are being infilled with silt coming out of the Grand Canyon. Only about 0.9% storage loss has been realized since Glen Canyon Dam began storing flows in 1963. Sonar image at right is B-29 bomber in Overton Arm.





- **Oblique Digital Elevation Model of sedimentation in Boulder Basin, as imaged in 1999. About 100 feet of sediment have accumulated against the upstream face of Hoover Dam.**

CONCLUSIONS

- Hoover Dam was significant because so it generated an unprecedented level of scientific information, which became the benchmark for subsequent projects
- We still don't have a good understanding of the basin's hydrology; only 85 years of reliable flow data
- The various unforeseen impacts of aging will continue to emerge, as will various environmental consequences
- The role of climate change needs to be considered in a rational way and monitored across a wide area for the foreseeable future

Special thanks to:

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