GEOLOGIC ASSESSMENTS OF THE LAKE MEAD AREA FOR THE BOULDER CANYON PROJECT 1921-31

J. David Rogers, Ph.D., P.E., P.G.

for Session 227

Recent Advances in Engineering Geology

Annual Meeting
Geological Society of America

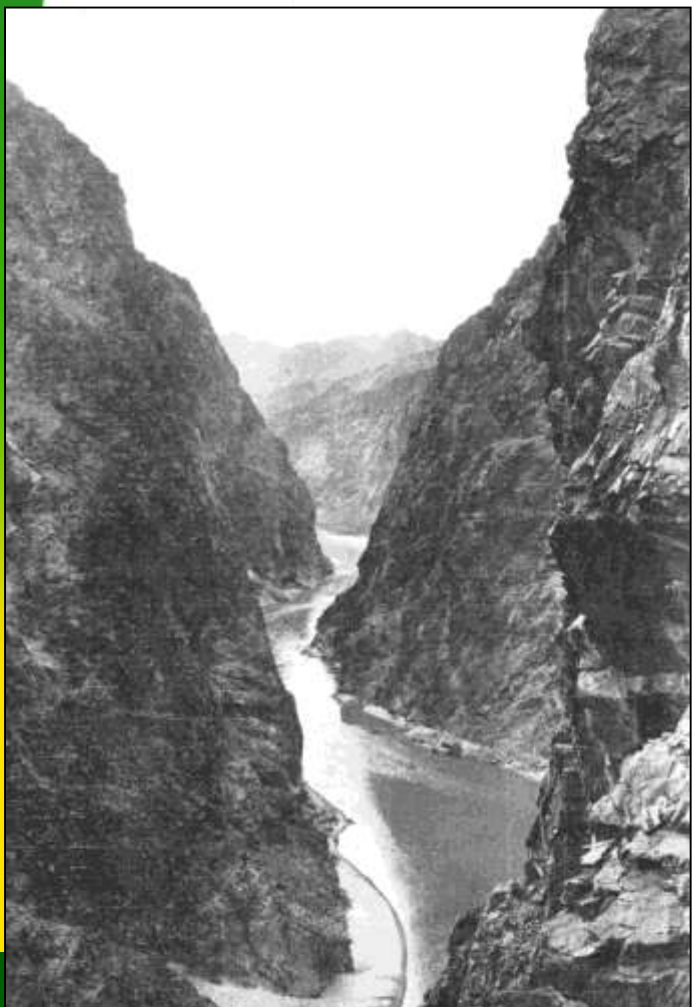
Denver, Colorado

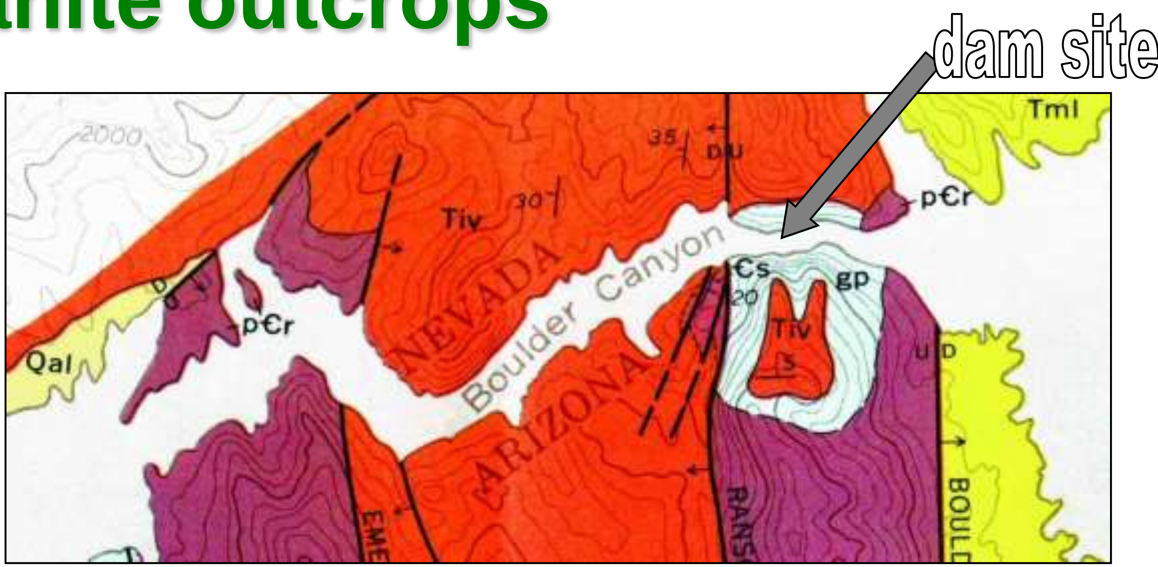
November 3, 2010

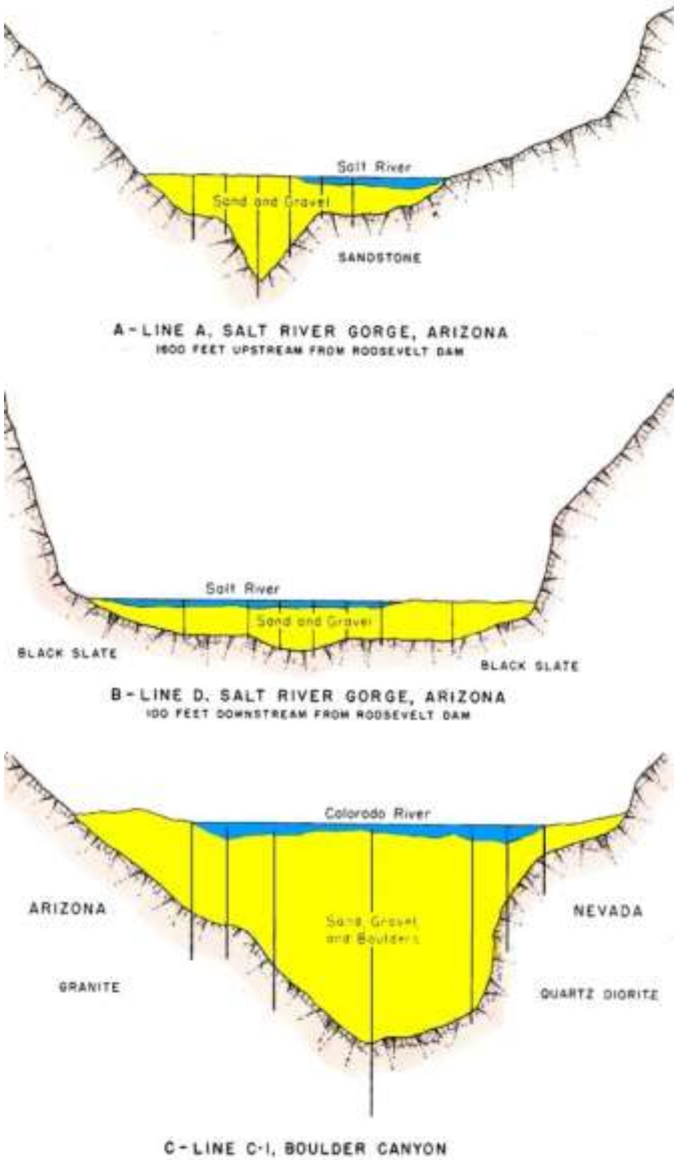
The Geological Society of America

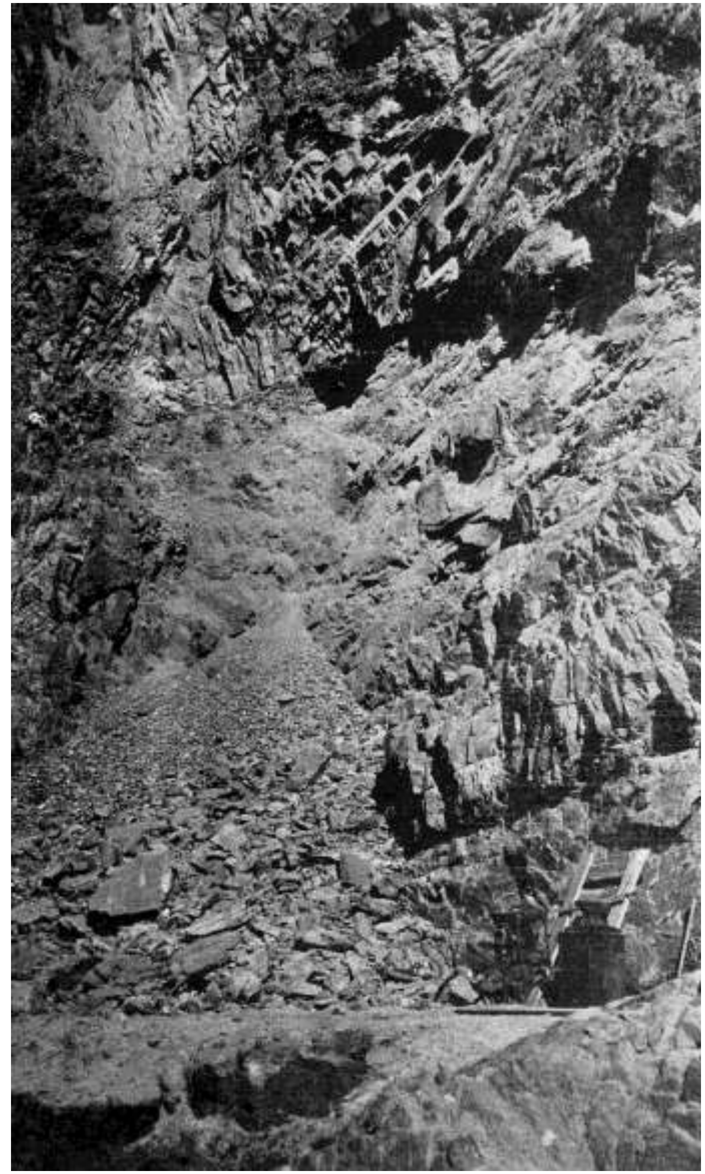
Missouri S&T University of Science & Technology

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



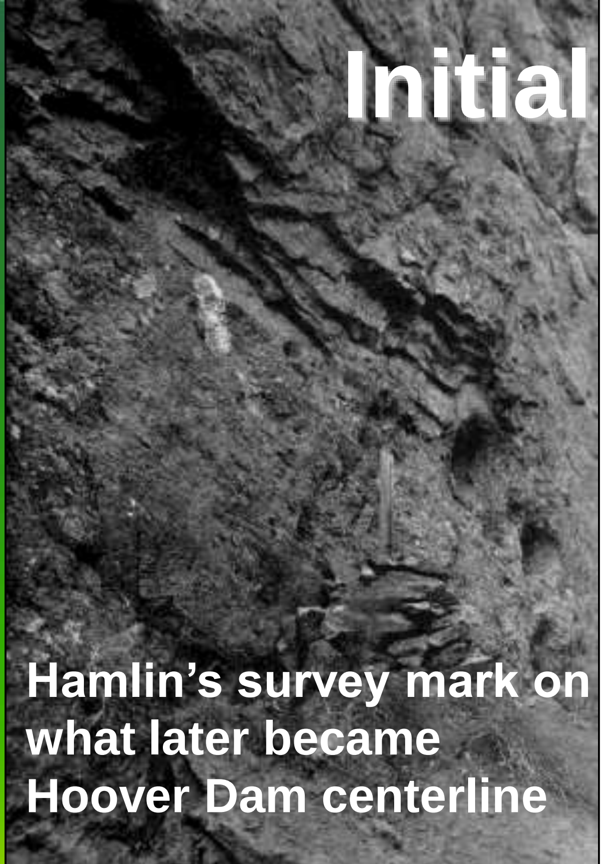






- **Channel cross section through Boulder Canyon site (lower left), compared with earlier Reclamation projects. Right image shows fractured nature of the granite**

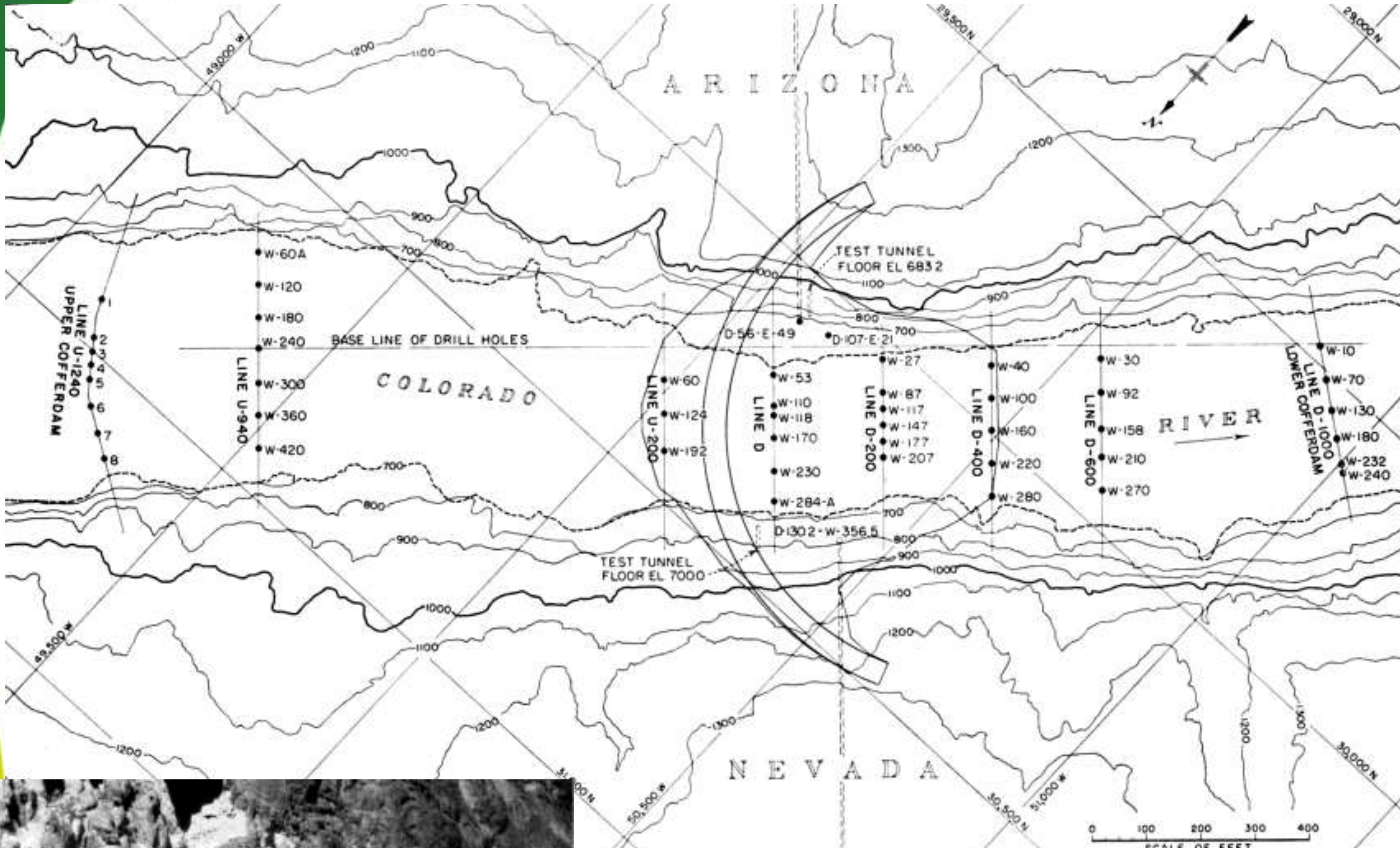
Initial Surveys in Black Canyon

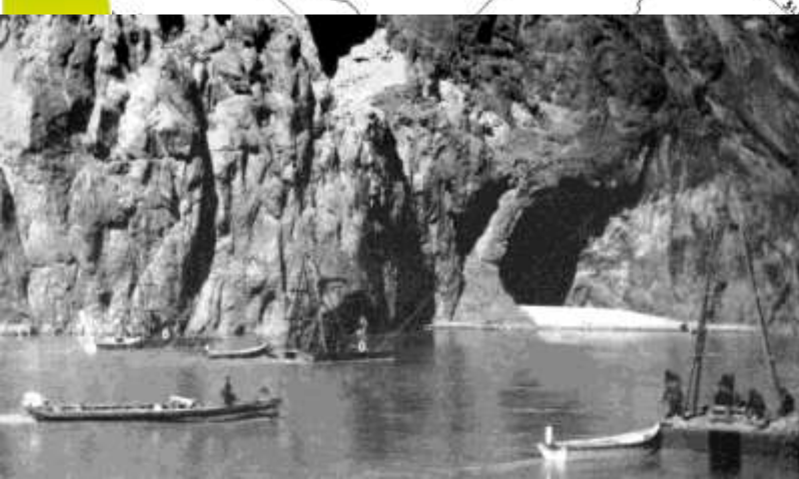


Hamlin's survey mark on what later became Hoover Dam centerline

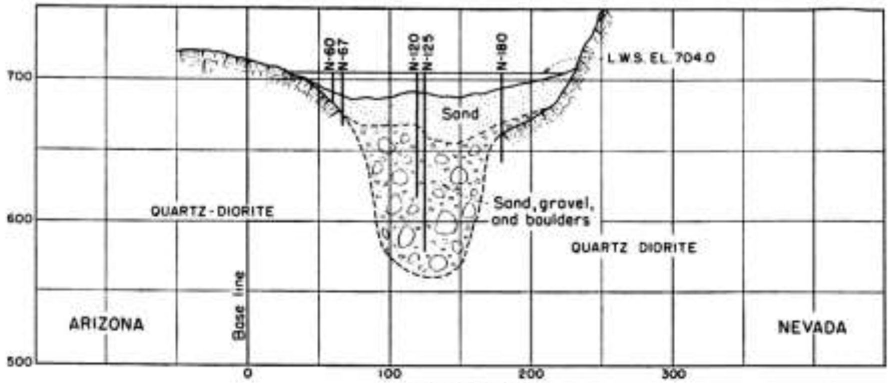
Engineer-geologist Homer Hamlin made the first survey of upper Black Canyon dam sites in the spring of 1920; marking the axis of the site that was eventually chosen, 8-1/2 years later

The characterization of the Hoover Dam site focused principally on the channel fill.

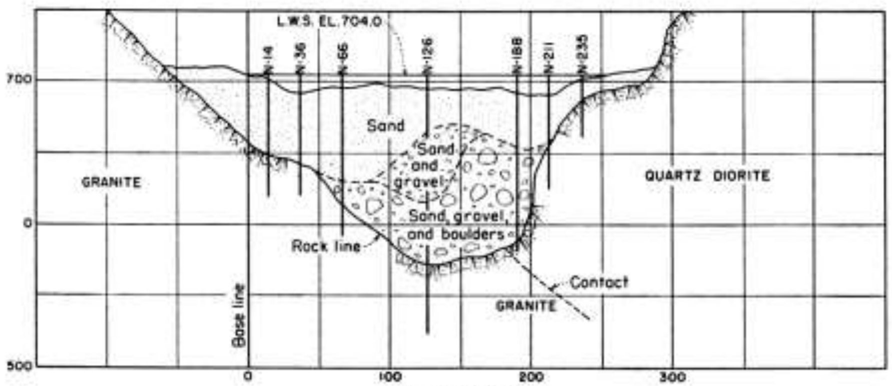




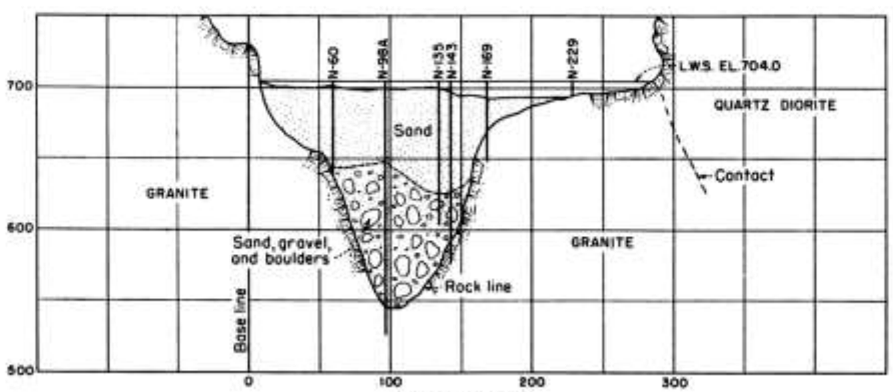
Only 22 borings were advanced in the Colorado River channel beneath the proposed dam, along the four lines shown above.



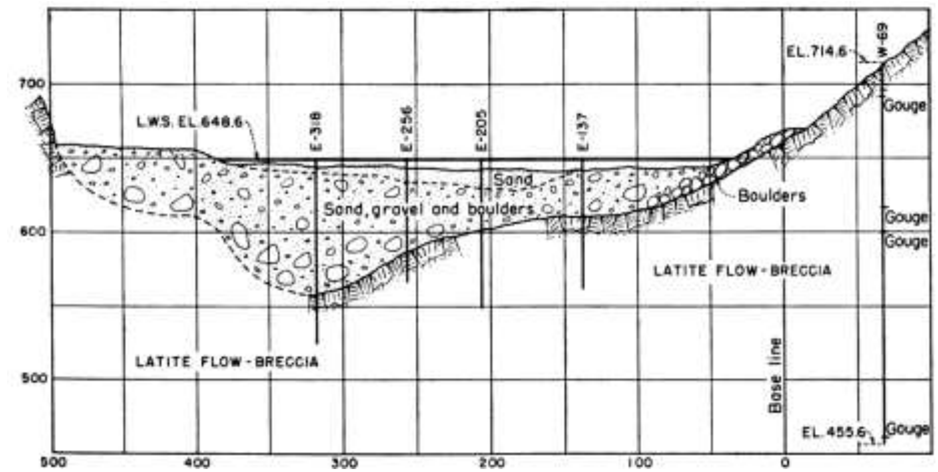
A. LINE U-200



B. LINE C-1



C. LINE D-200



The primary focus of the engineering assessments were to ascertain the depth and character of the channel fill over the bedrock.

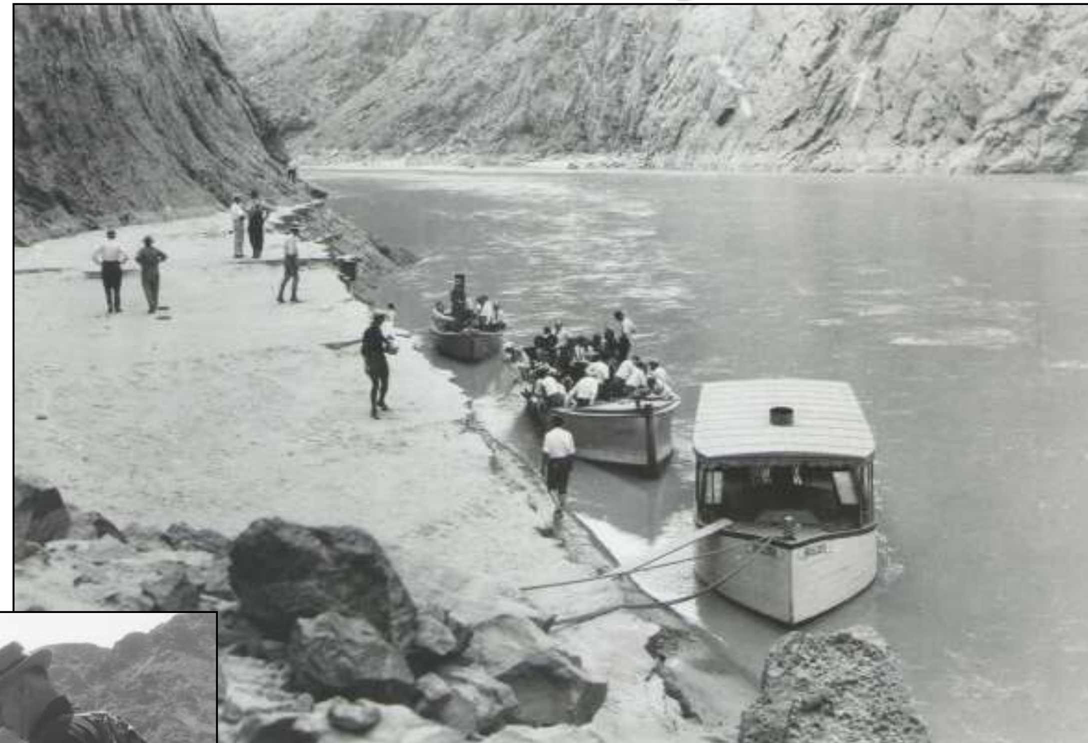
One boring was drilled to a depth of 545 feet below low water level.

Before construction began, the Black Canyon site was assumed to have less channel fill than the sites in Boulder Canyon.

Colorado River Board appointed by Congress in May 1928, after failure of the St. Francis Dam near Los Angeles

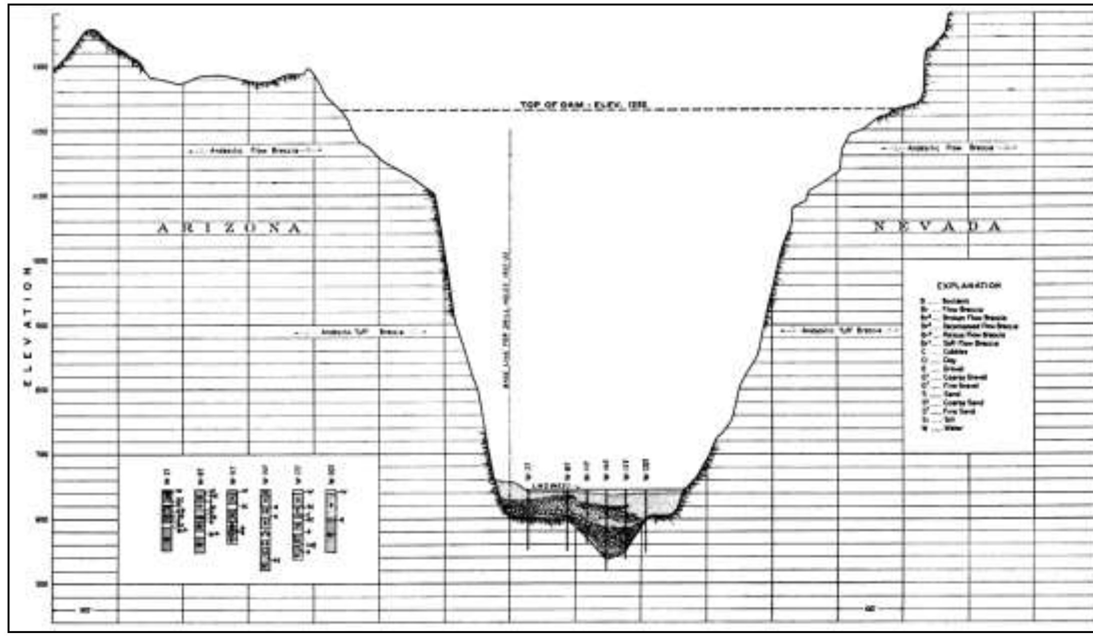
Left to right: MGEN William L. Sibert (Chair), Elwood Mead (advisor), and included geologists Warren J. Mead and Charles P. Berkey (Secretary) and engineers Daniel W. Mead and Robert Ridgway.

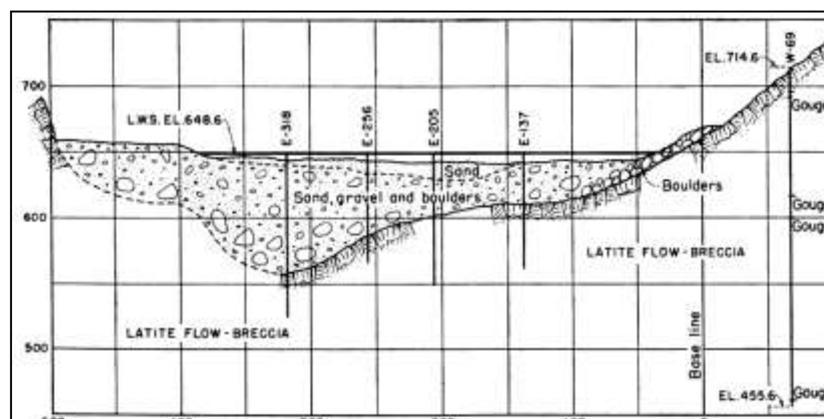
The Colorado River Board reviewed six dam sites in Boulder and Black Canyons

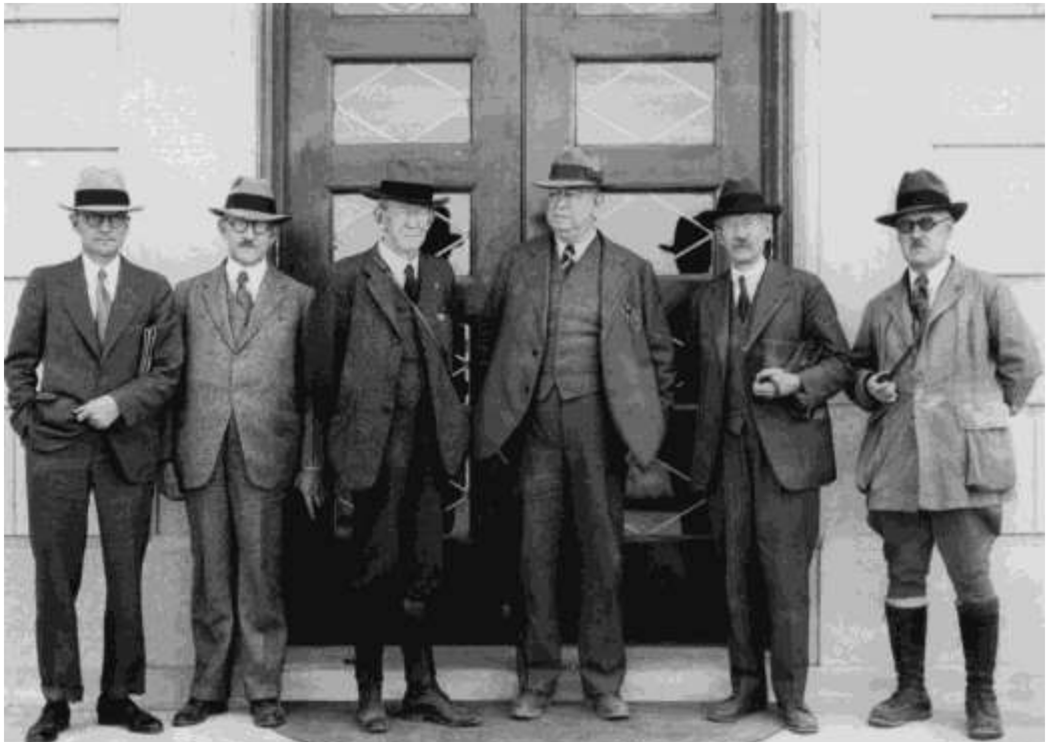


The Board's geologists raised a number of concerns that had not been addressed previously.

Colorado River Board recommends the upper Black Canyon site in December 1928

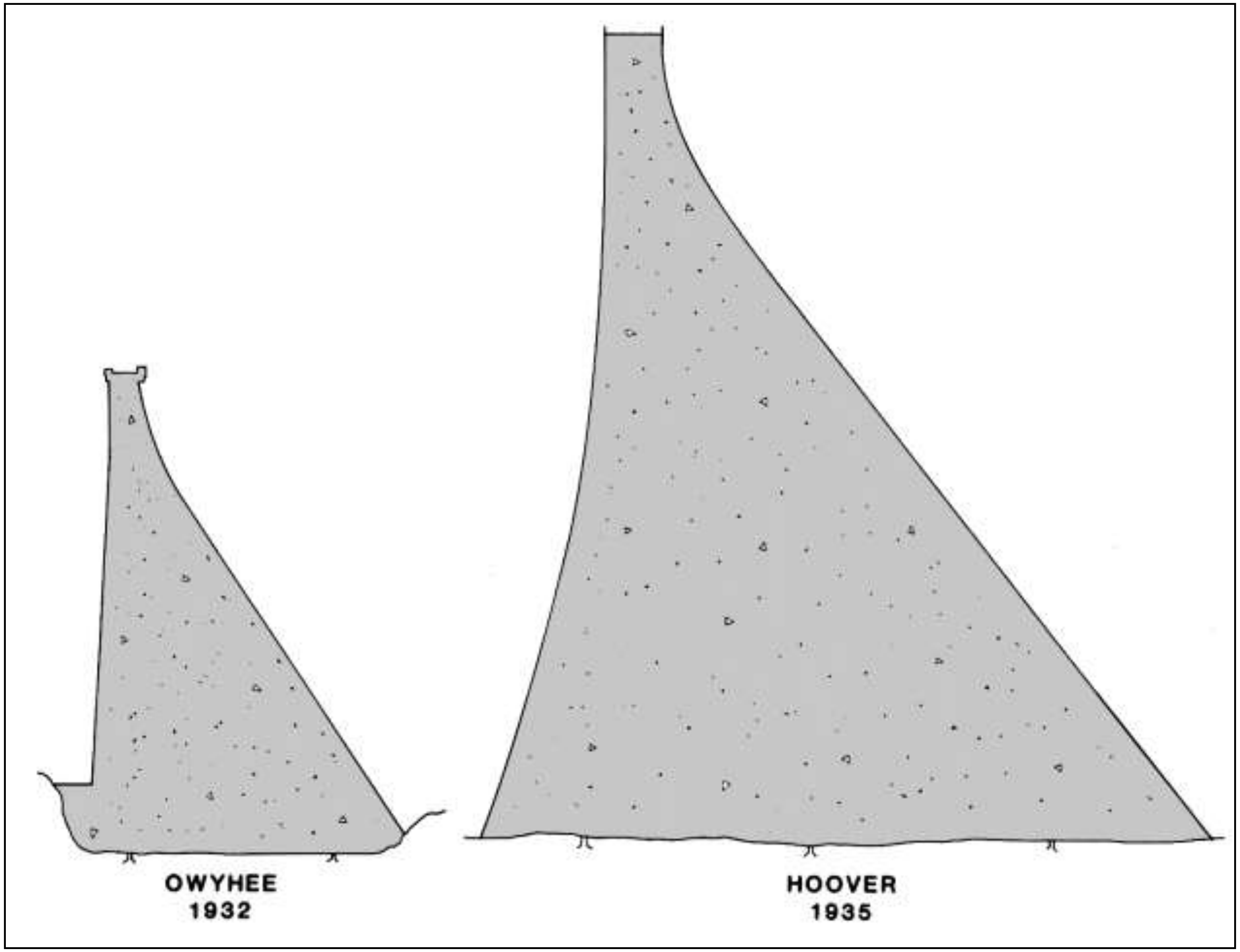




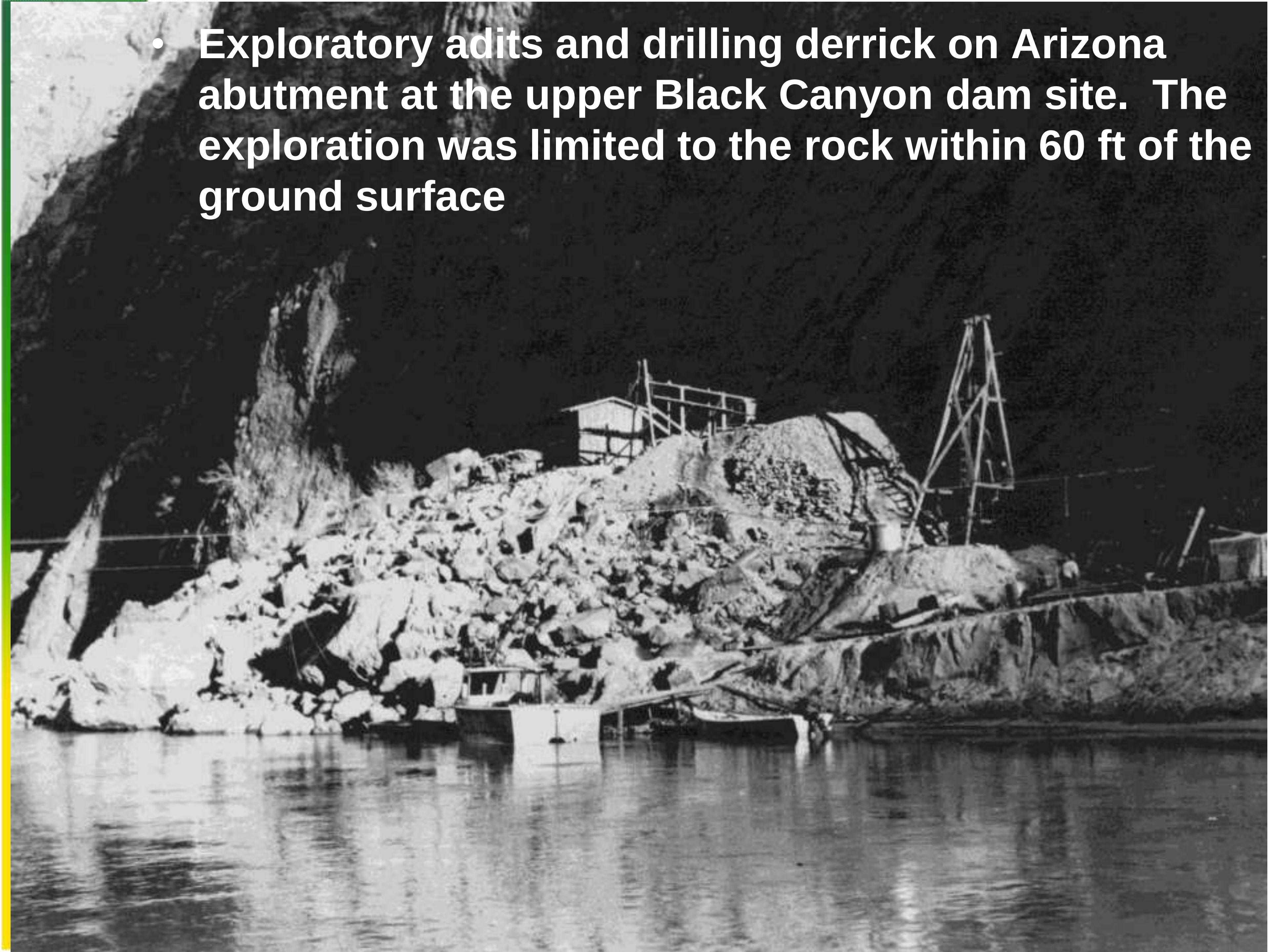


Colorado River Board re-convenes in Boulder City

- In their initial report of Dec 2, 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.

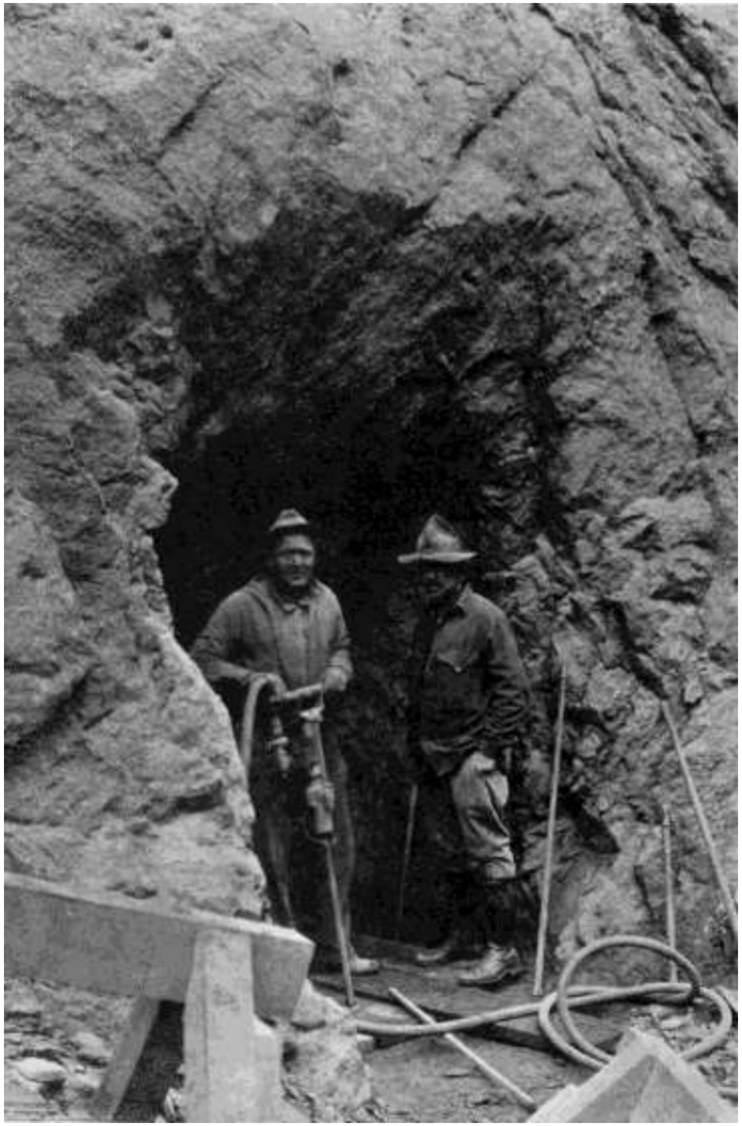


- **Unprecedented size:** **Hoover Dam would be almost *twice as tall* as the highest dam in the world, Owyhee Dam, slated for completion in 1932!**
- **Owyhee Dam was conceived by the same Reclamation design team, led by Jack Savage.**

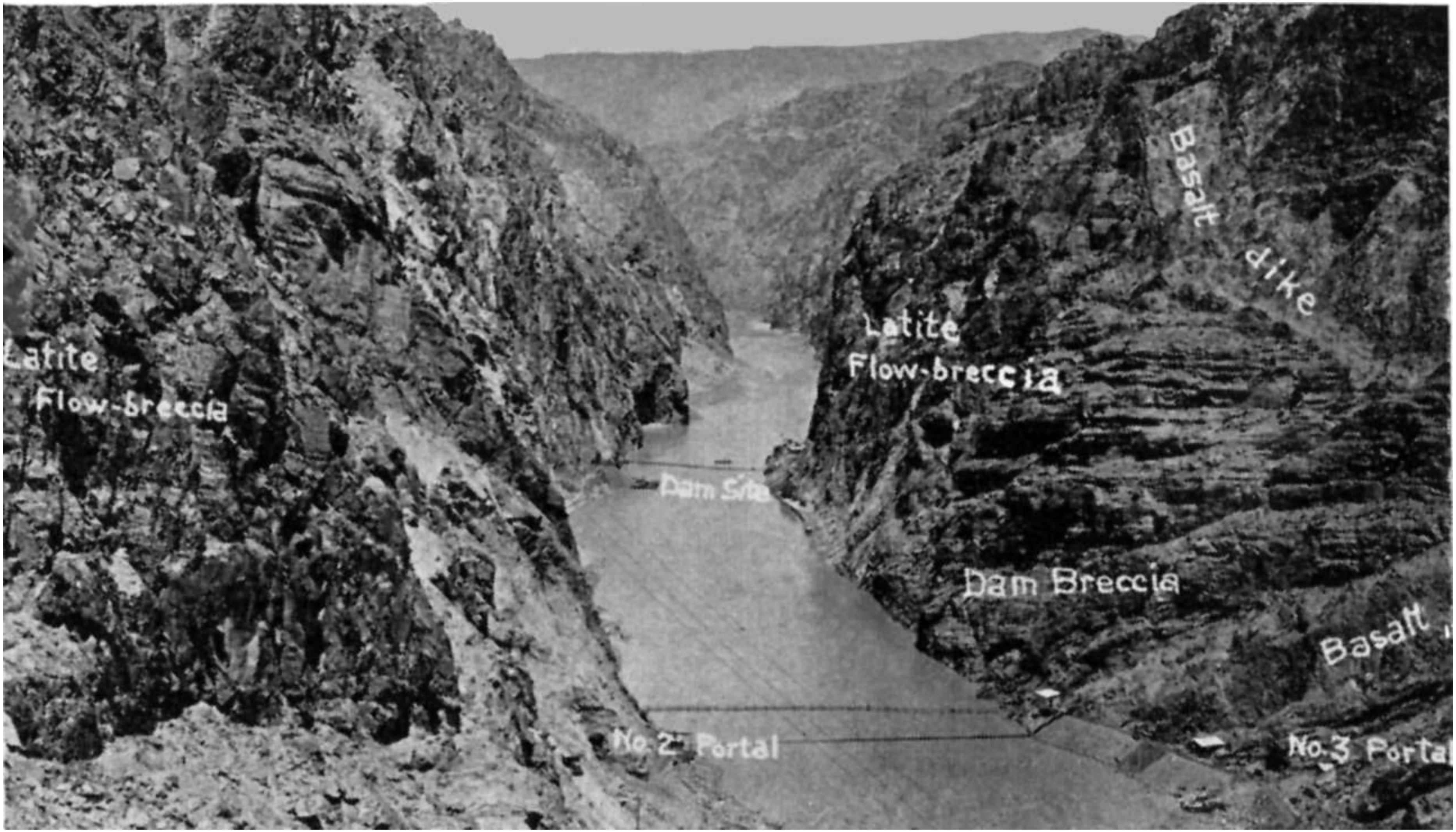


• Exploratory adits and drilling derrick on Arizona abutment at the upper Black Canyon dam site. The exploration was limited to the rock within 60 ft of the ground surface

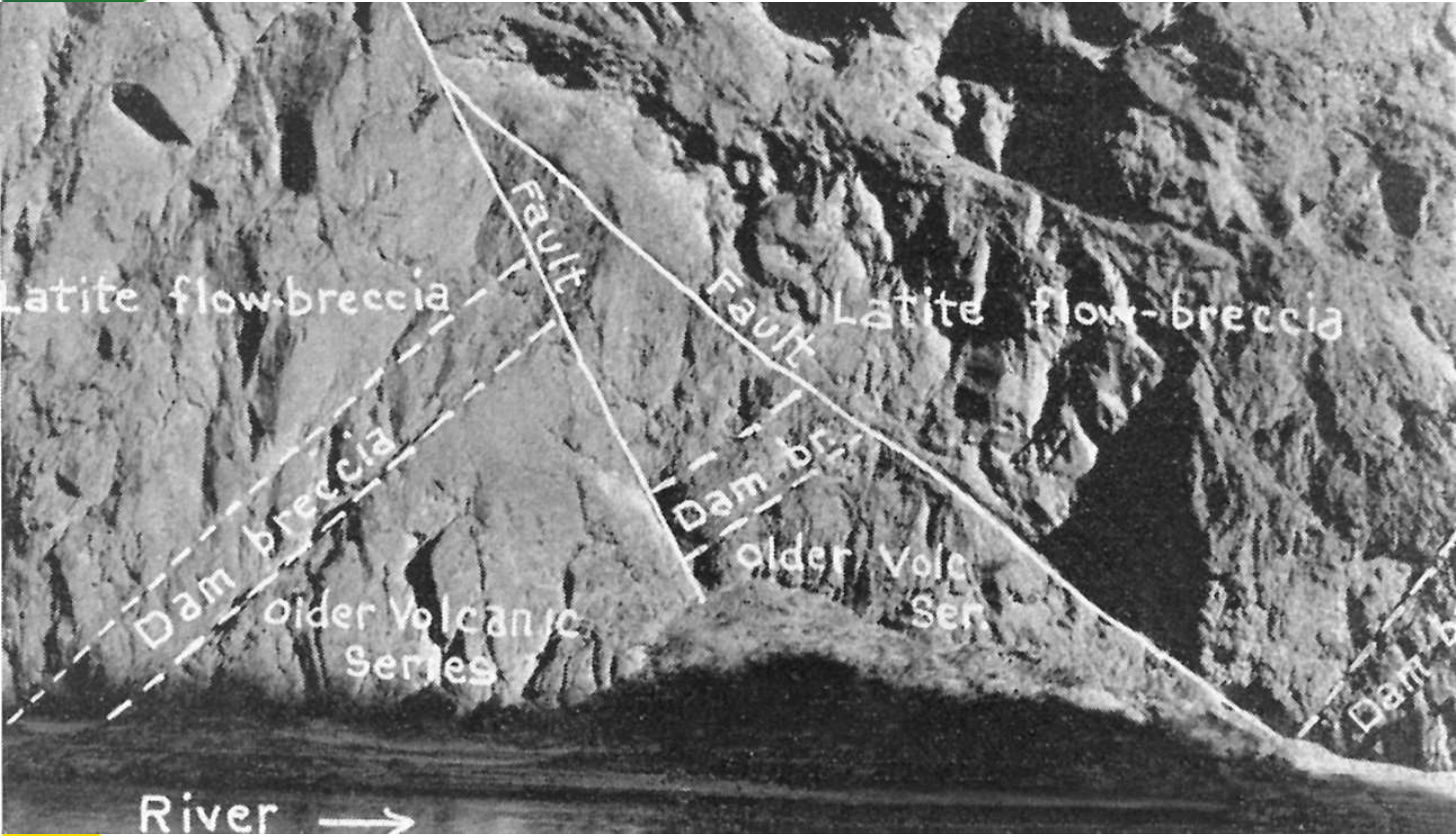
6-inch cores were extracted from the abutments for unconfined compression tests



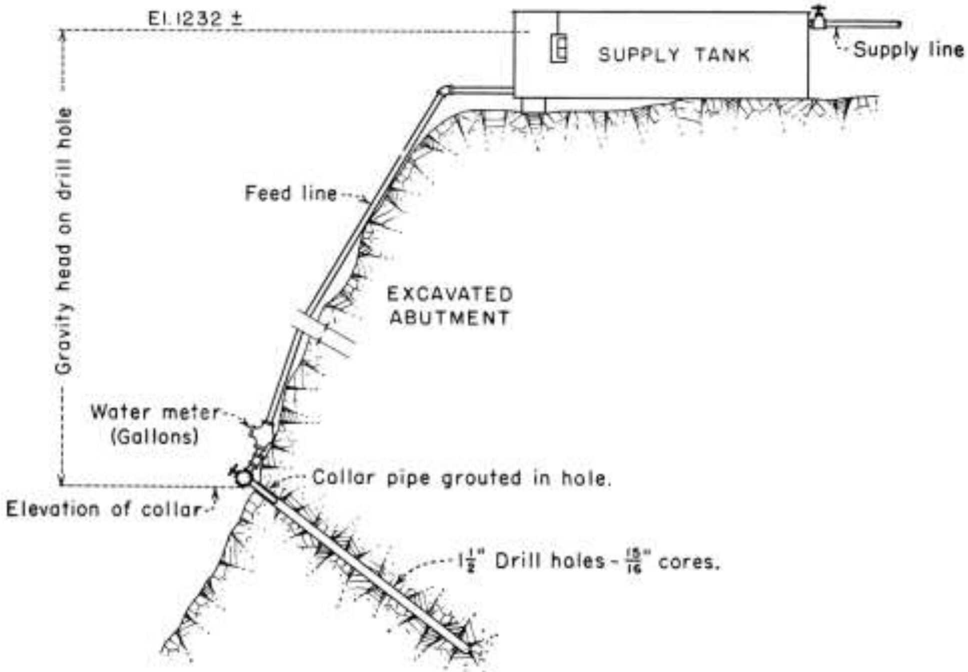
Portal of exploratory adit on Arizona abutment, at elevation 683 ft



View of Hoover Dam site looking upstream, annotated with geology. Note basalt dike at right, on Arizona abutment. These dikes perturbed both abutments.



Normal faults mapped near base of the left (Arizona) abutment.

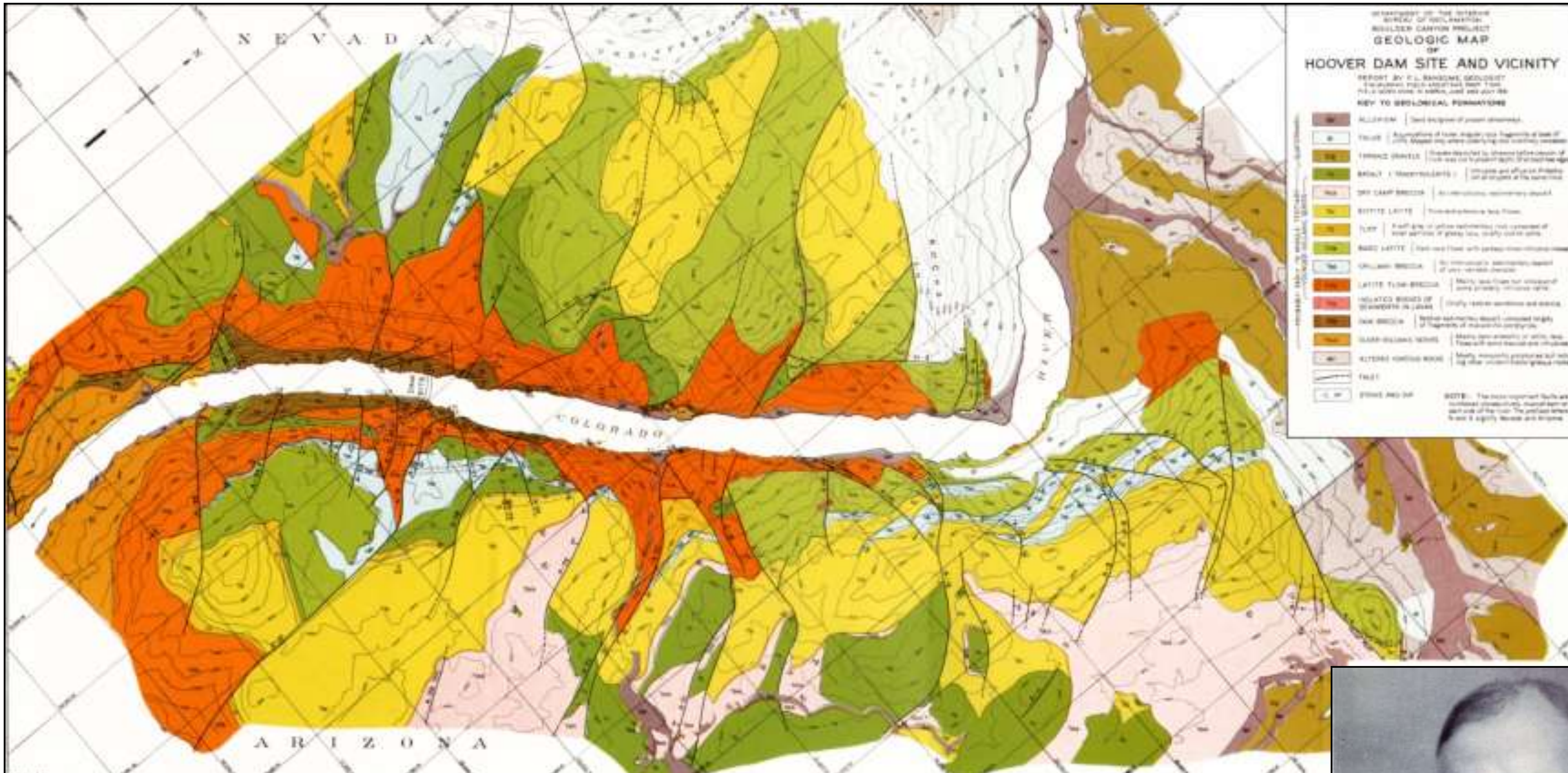


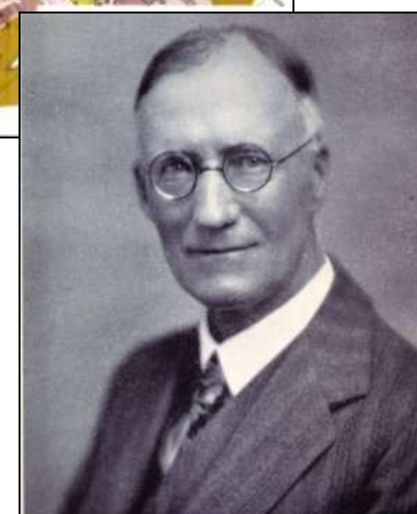
The crude percolation tests employed a gravity-feed reservoir that was conveyed to drill holes through sealed pipes.

These could not replicate pore pressures induced by 500 to 800 feet of head.

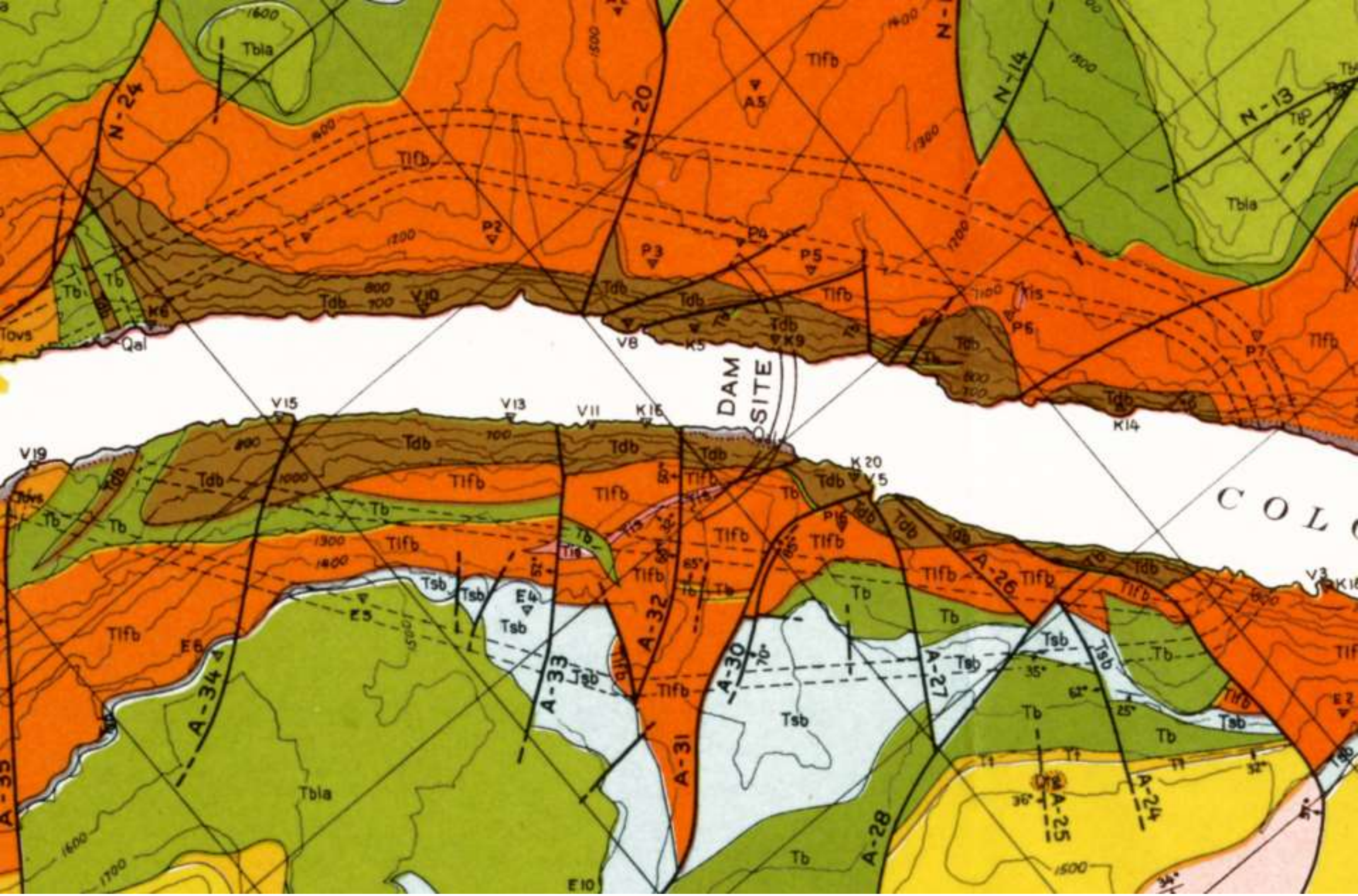
The latite breccia was characterized by locally intense fractures, especially along faults and shear zones. These inclined faults also crisscrossed one another.

Leslie Ransome mapped the dam site

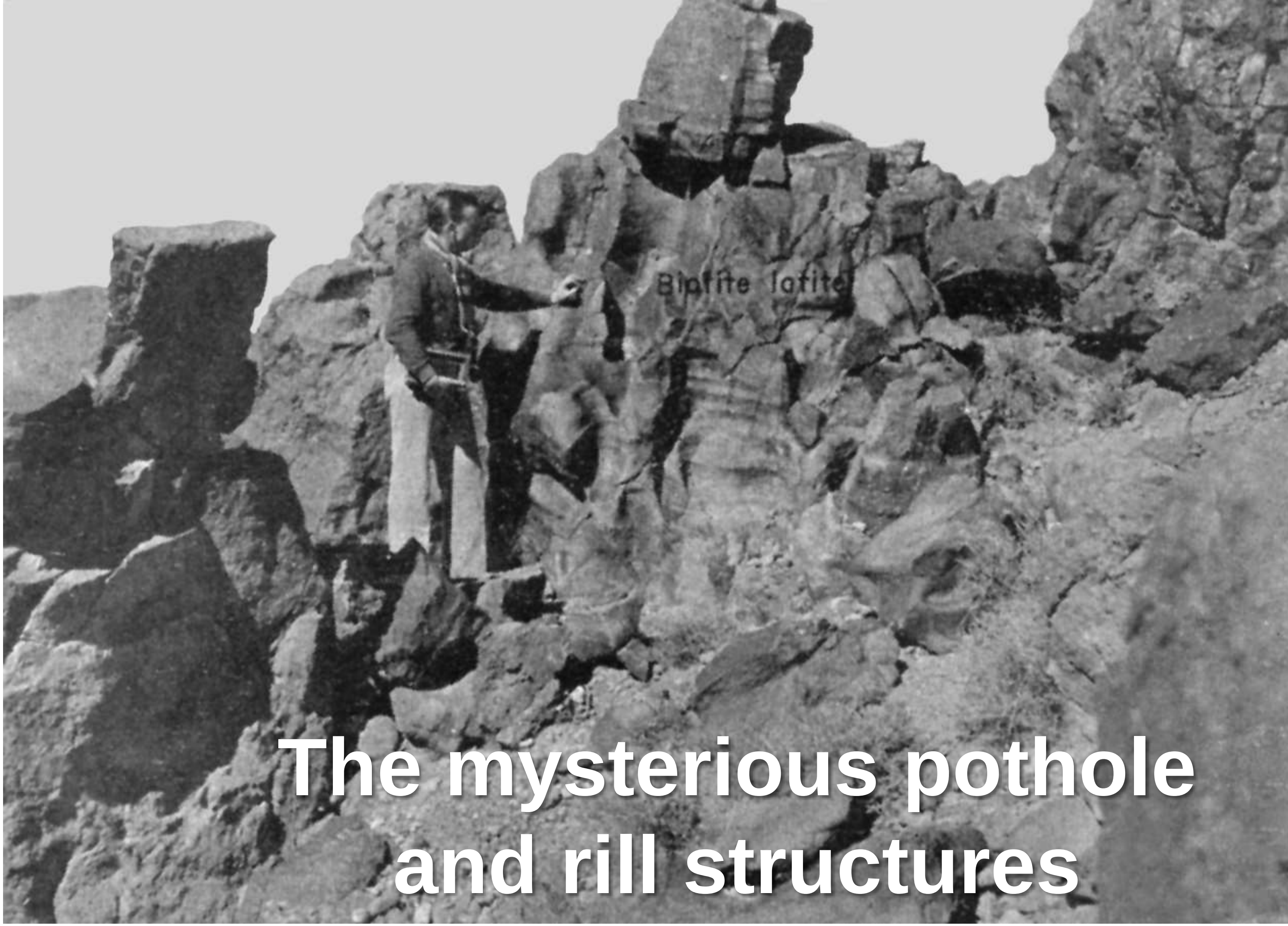




The dam was founded on the dam breccia, a dense reddish unit composed of fragments of monzonitic porphery; covered by a latite flow breccia. The deepest boring encountered dam breccia to a depth of 545 feet below river level.

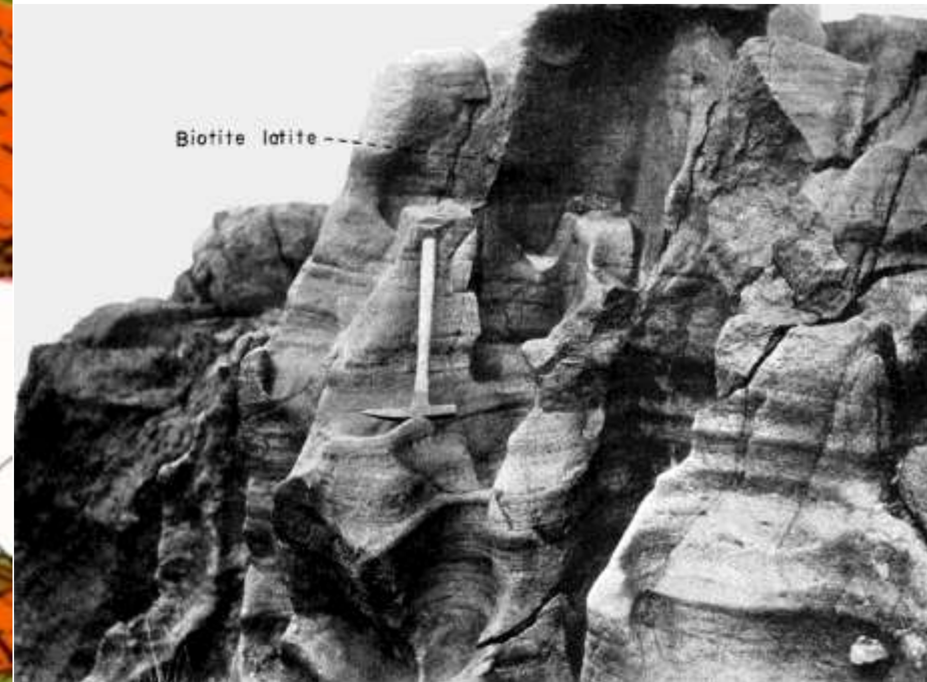


Ransome's geologic map controlled the position of the dam's axis, to wedge the dam in between the two prominent faults mapped on the right abutment



The mysterious pothole and rill structures

- **Ransome discovered a series of pothole and rill structures more than 900 ft above the channel bed**



Ransome mapped the potholes as Quaternary terraces deposits (Qtg), shown here (blue arrow). These perched river-laid gravels and sands reach a thickness of 90 ft. Later work by the USGS revealed that this bedrock paleochannel is ~100 ft deep, and only 82 ft wide, incised a few meters below a low-relief erosional surface. This intermediate channel lies about 660 ft below the pre-river topographic surface, recorded by interior-basin fill including the Fortification Hill basalt flow (5-6 Ma).

Excavation of Inner Gorge in Colorado River channel beneath the dam.

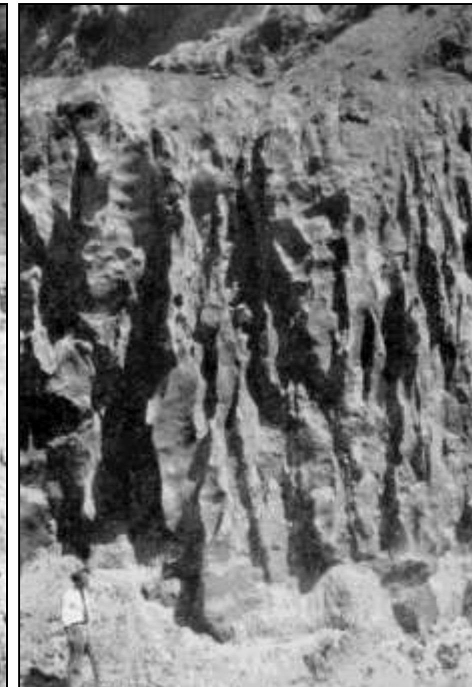
The contractor encounters all sorts of surprises

A total of 6 million yards of bedrock and alluvial material was excavated at the dam site.

A sawn 2 x 6 plank was found in the river bed buried 50 feet beneath the low water surface! Geologists suggested that it was deposited from a debris flow in Callville Wash during the high water of 1922.

Cleaning out the inner gorge

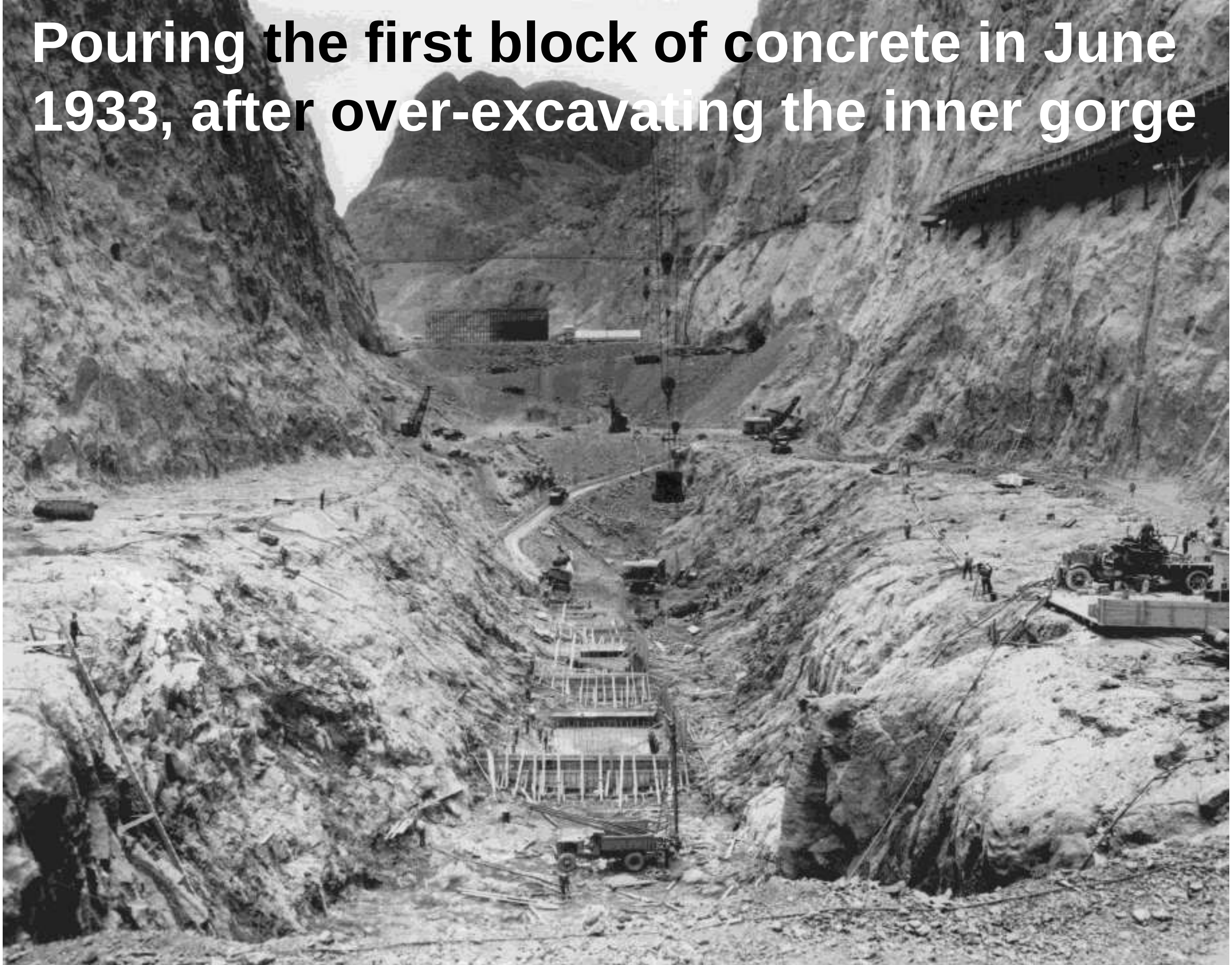
Note overhanging pothole structures



Uneven flute structures, note man for scale (lower left)

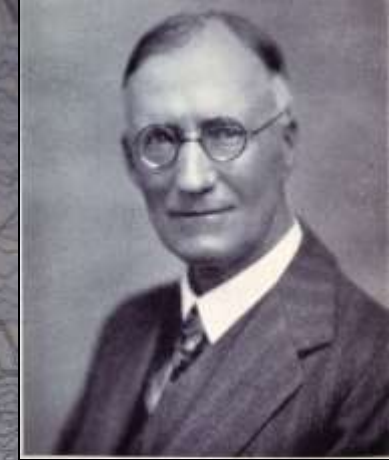
About 2 million cubic yards of material was excavated out of the river channel beneath the dam, revealing an incised inner gorge with fluting and boulders up to 12 feet across.

Pouring the first block of concrete in June 1933, after over-excavating the inner gorge



Side Channel Spillways

- **The two side channel spillways were monstrous excavations, each capable of converying 200,000 cfs discharge**



Ransome's field map showing the bedrock geology exposed in the area of the proposed Arizona side-channel spillway in March 1931

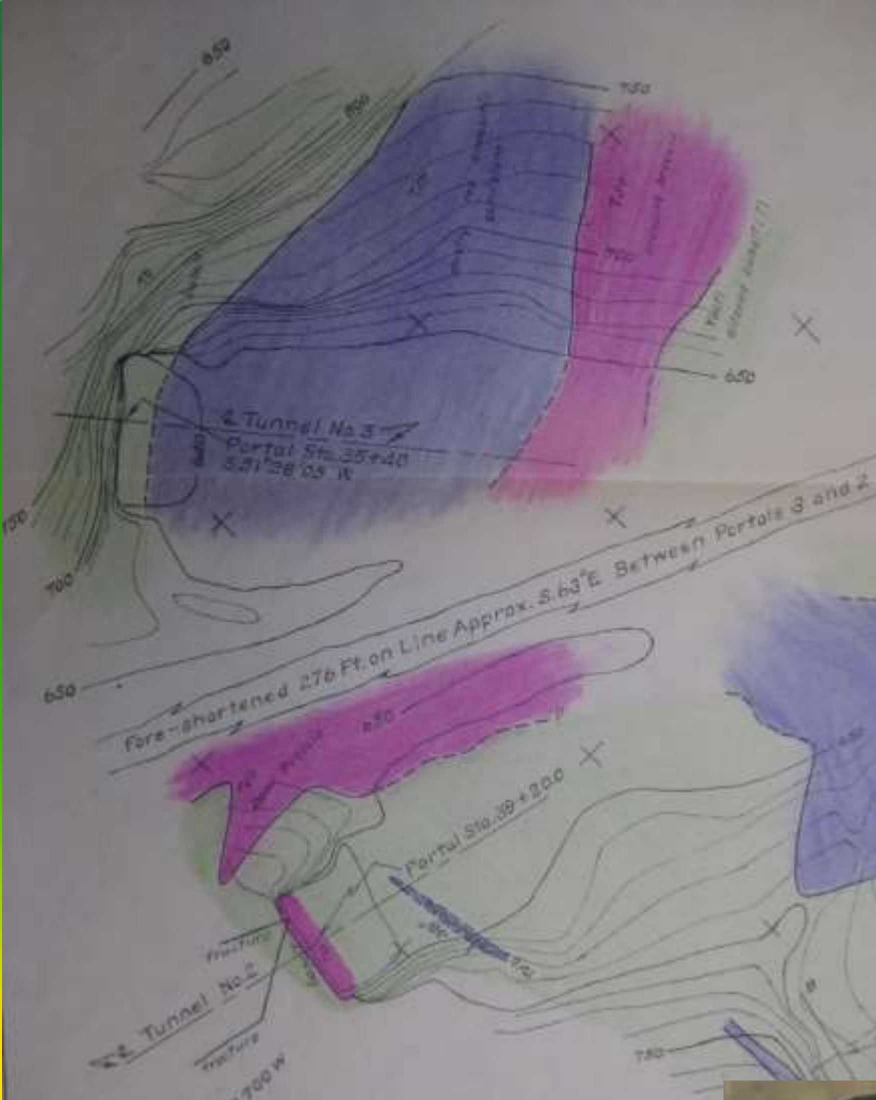
Ransome was pressed into service in the winter of 1931 making repeated trips to the expanding site to map the geology as it was exposed. He was soon overwhelmed, and Frank Nickell, one of his former students, was hired by Reclamation to provide full-time mapping.

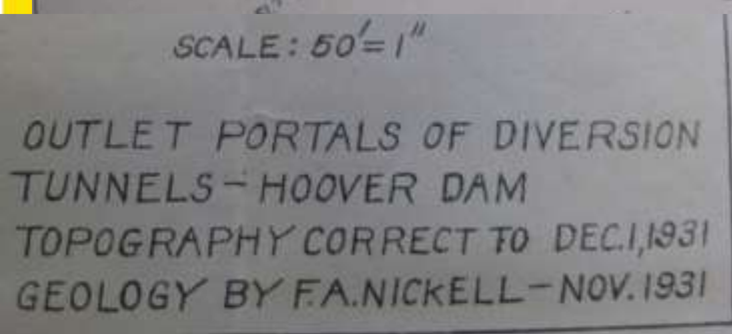
Reclamation hires their first geologist-1931

Frank Nickell

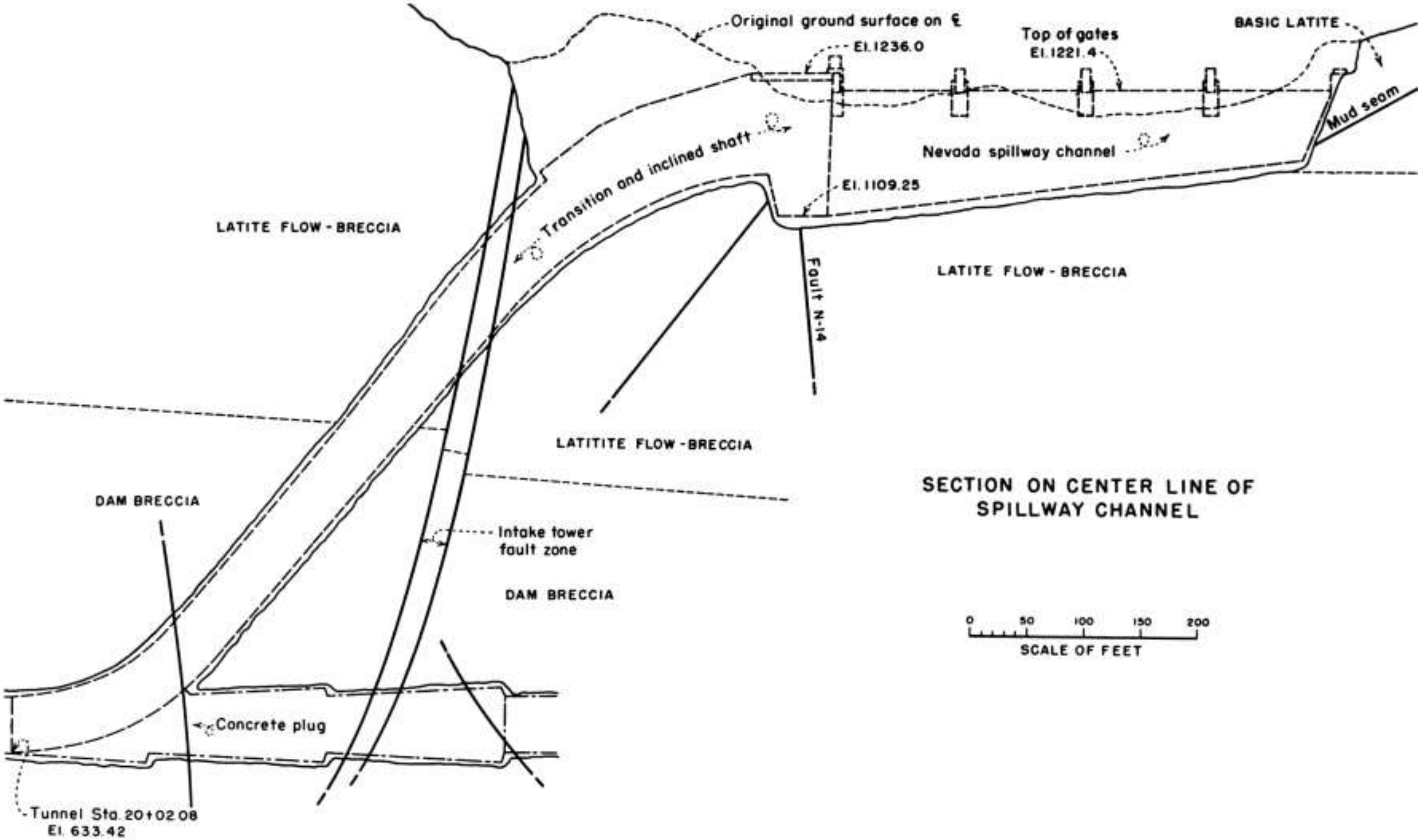
- In the fall of 1931 the Bureau of Reclamation hired Dr. Frank A. Nickell, a Caltech graduate with an undergraduate degree in civil engineering and MS and PhD degrees in geology. He was the first of three full-time geologists to work at Hoover Dam
- The Corps of Engineers hired E.B. Burwell, Jr. as their first engineering geologist in 1931

- In 1933 the Tennessee Valley Authority hired their first engineering geologist
- In 1934 the California Division of Water Resources was established, hiring a staff of five engineering geologists

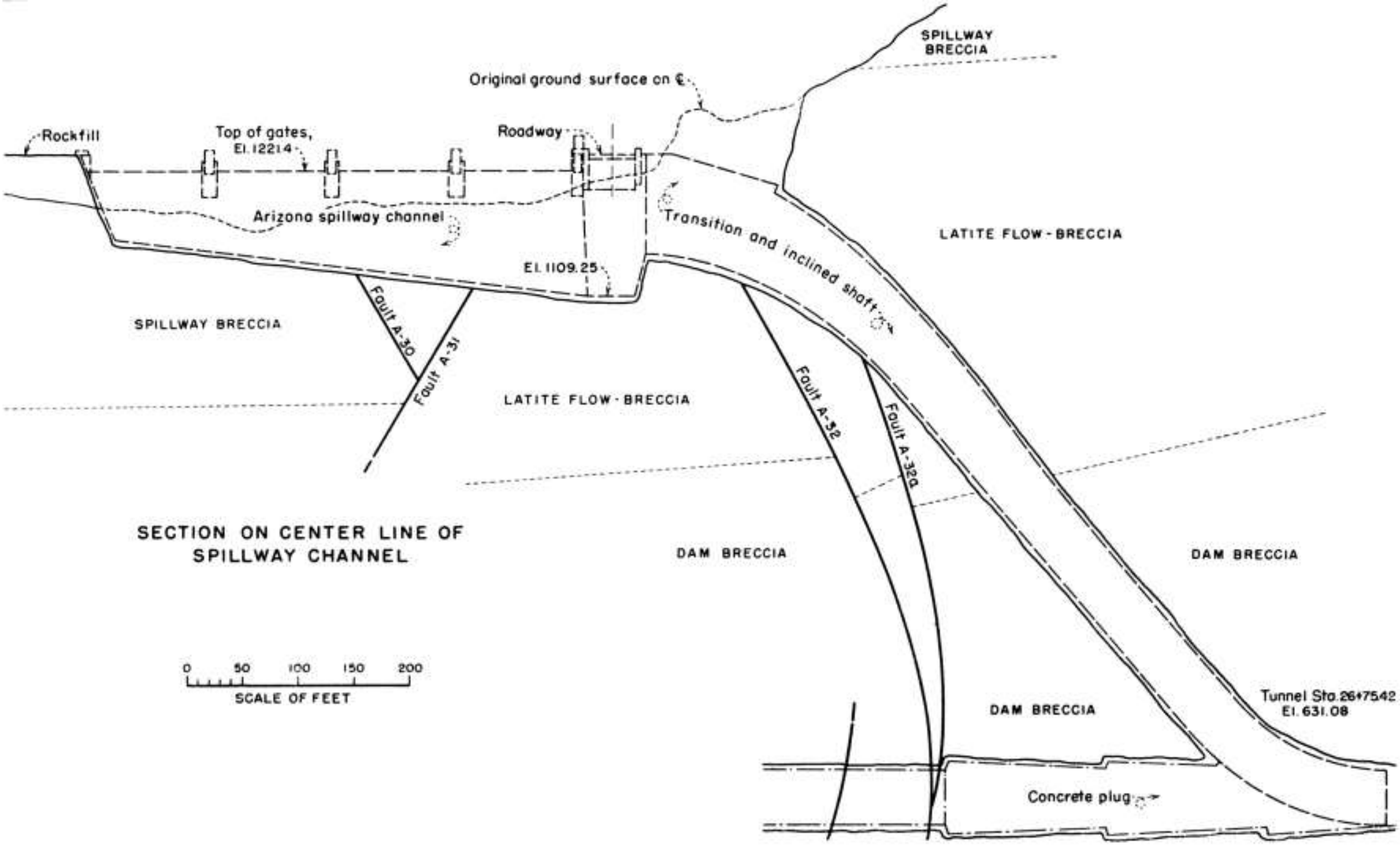




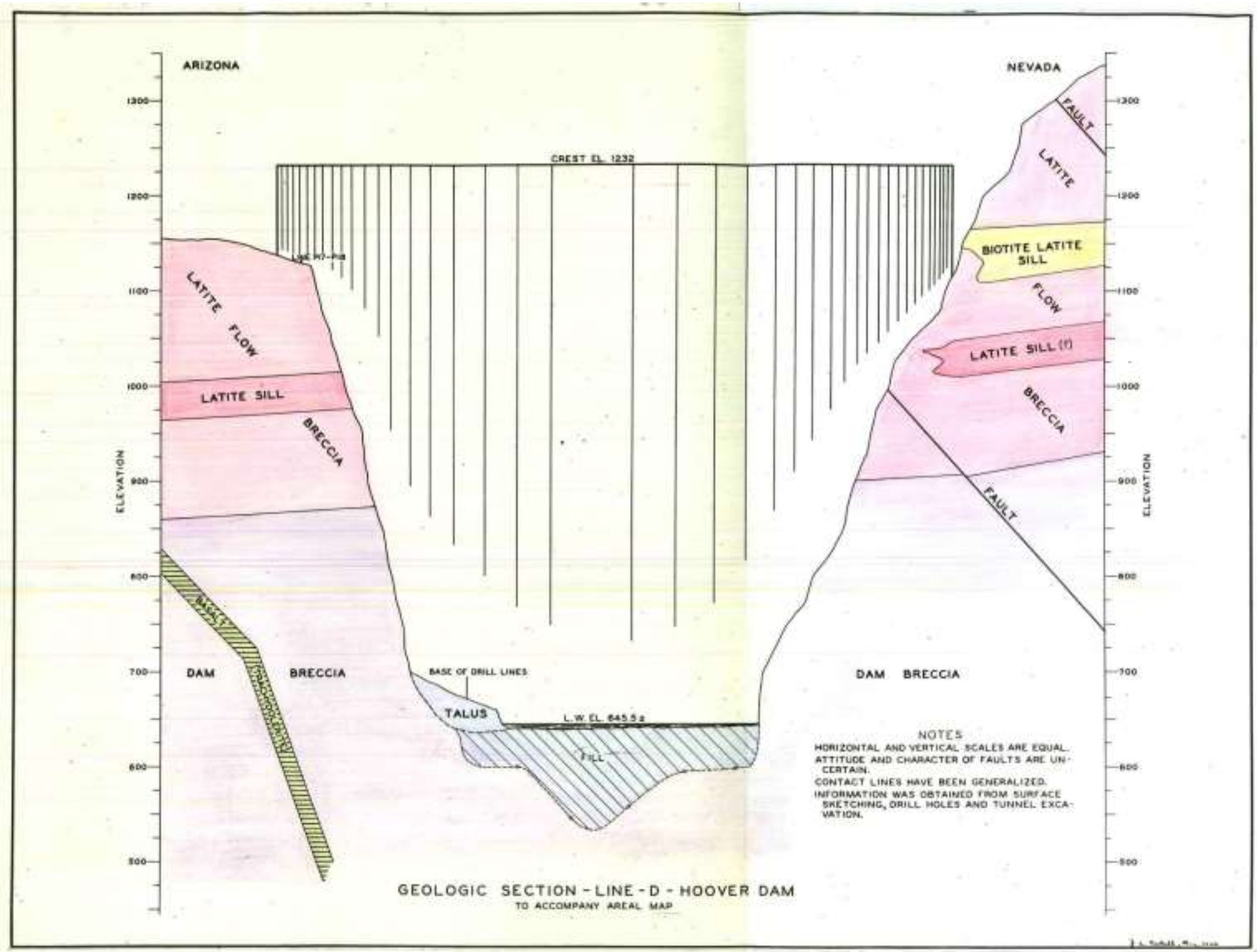
- **Frank Nickell mapped the geology exposed in the numerous excavations as they were being advanced throughout 1931-32**



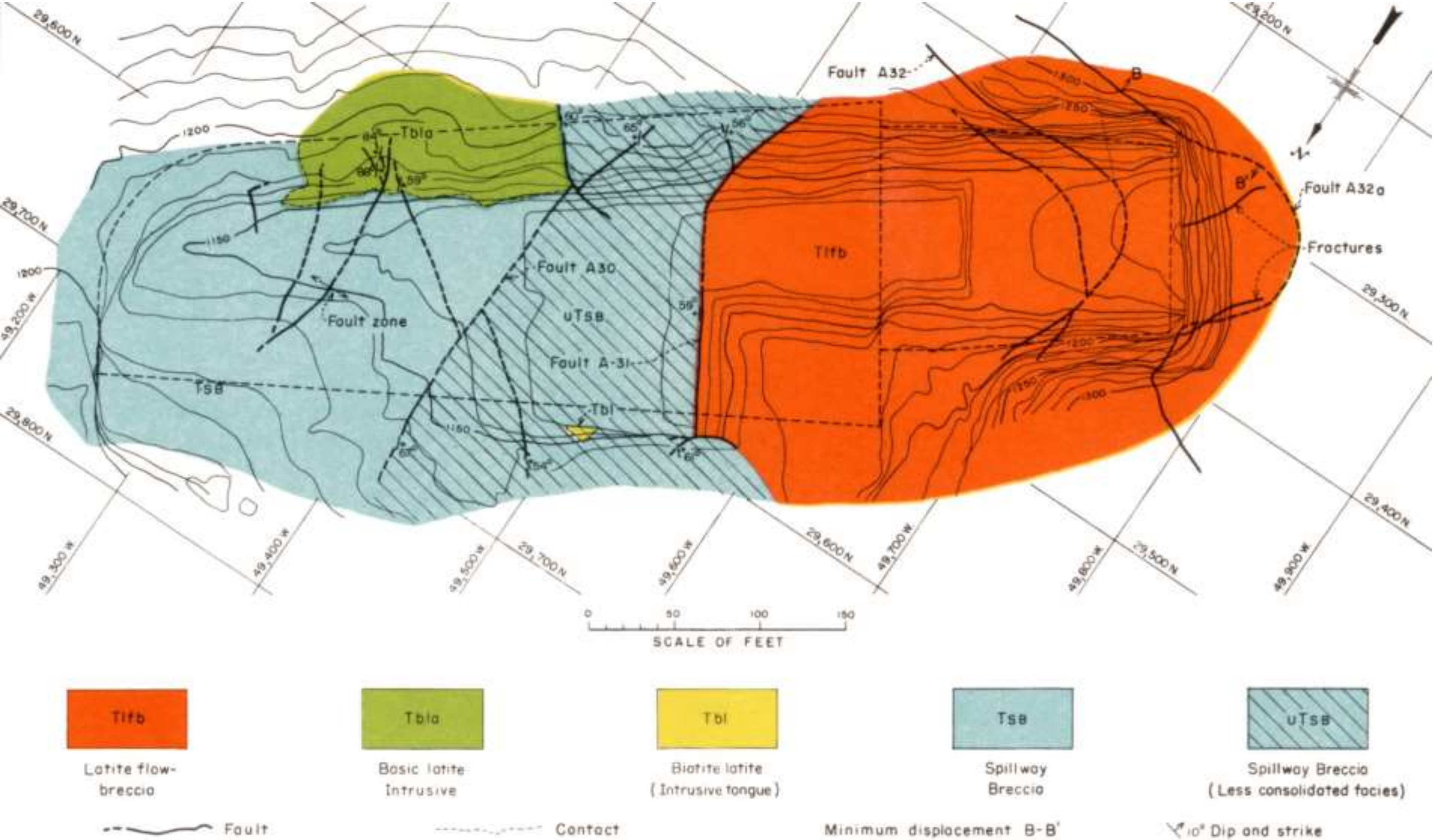
- **Nickell mapped numerous faults exposed in Nevada Spillway excavations. Note "mud seam" at upper right. The spillway shaft experienced significant seepage after the reservoir filled, along brecciated zones adjacent to faults.**



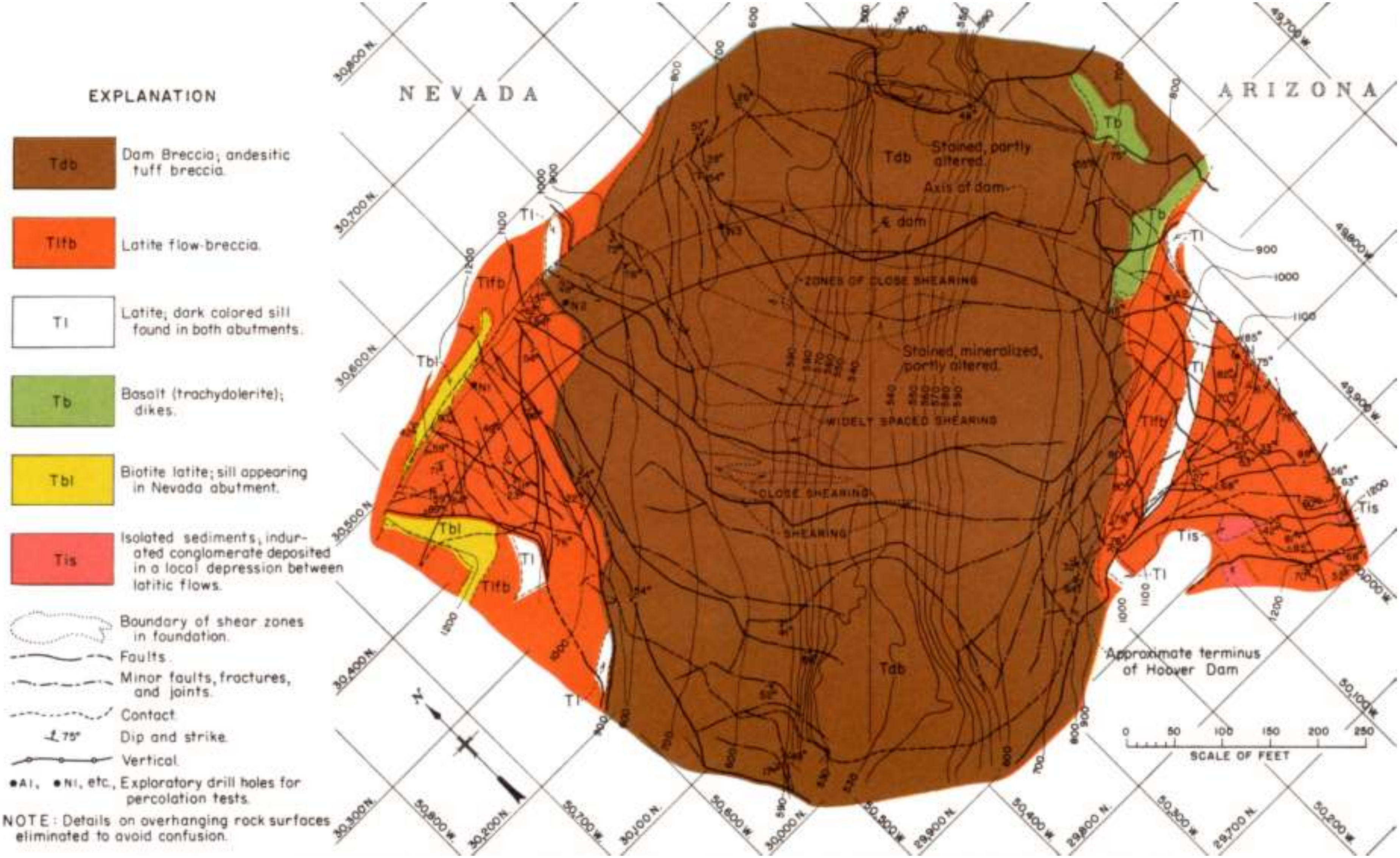
- **Section through the Arizona Spillway excavations, showing the contacts and apparent dip of the principal faults encountered.**



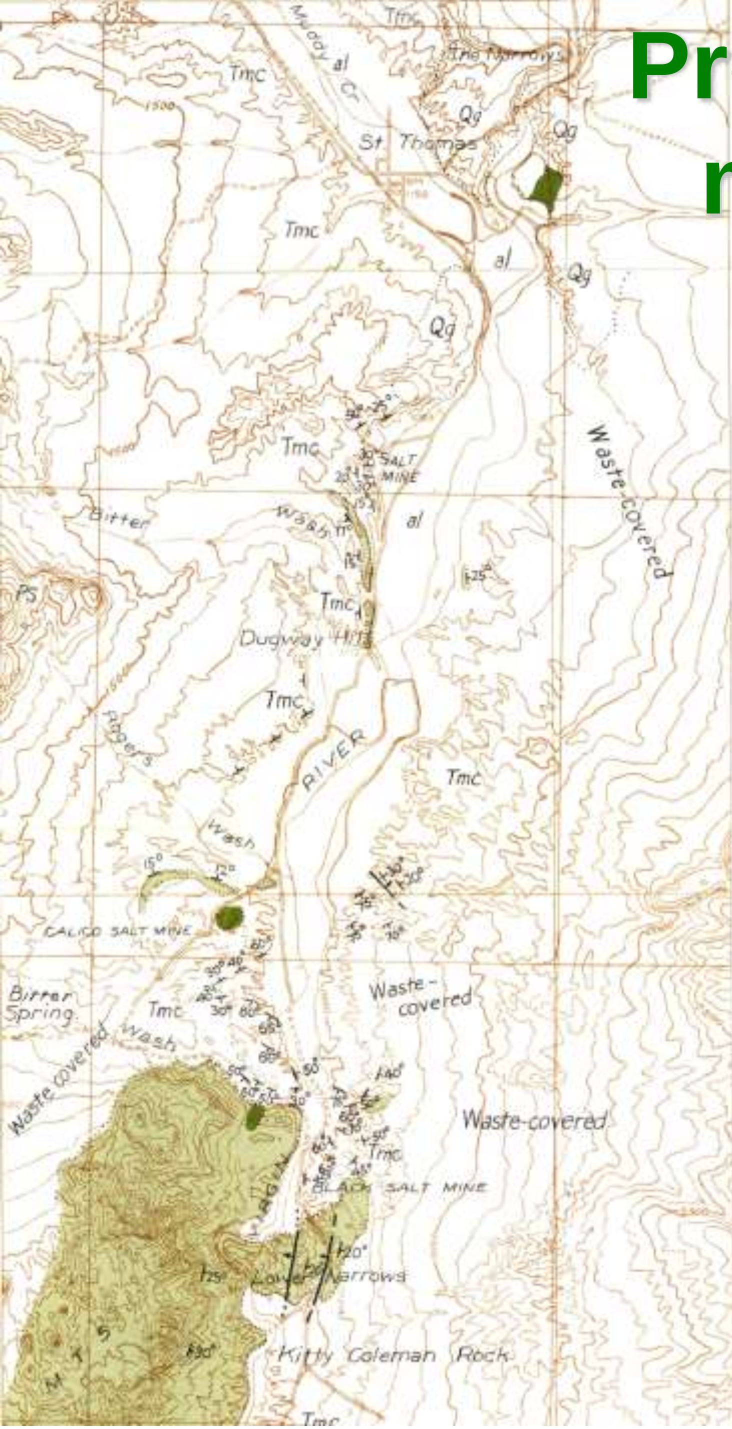
- **Nickell's Geologic Section along Line D, beneath the center of the dam's downstream face, looking downstream**



- **Geologic map of the Arizona Spillway excavation. Faults were designated with alphanumeric nomenclature, @ to AZ or NV side of the canyon.**



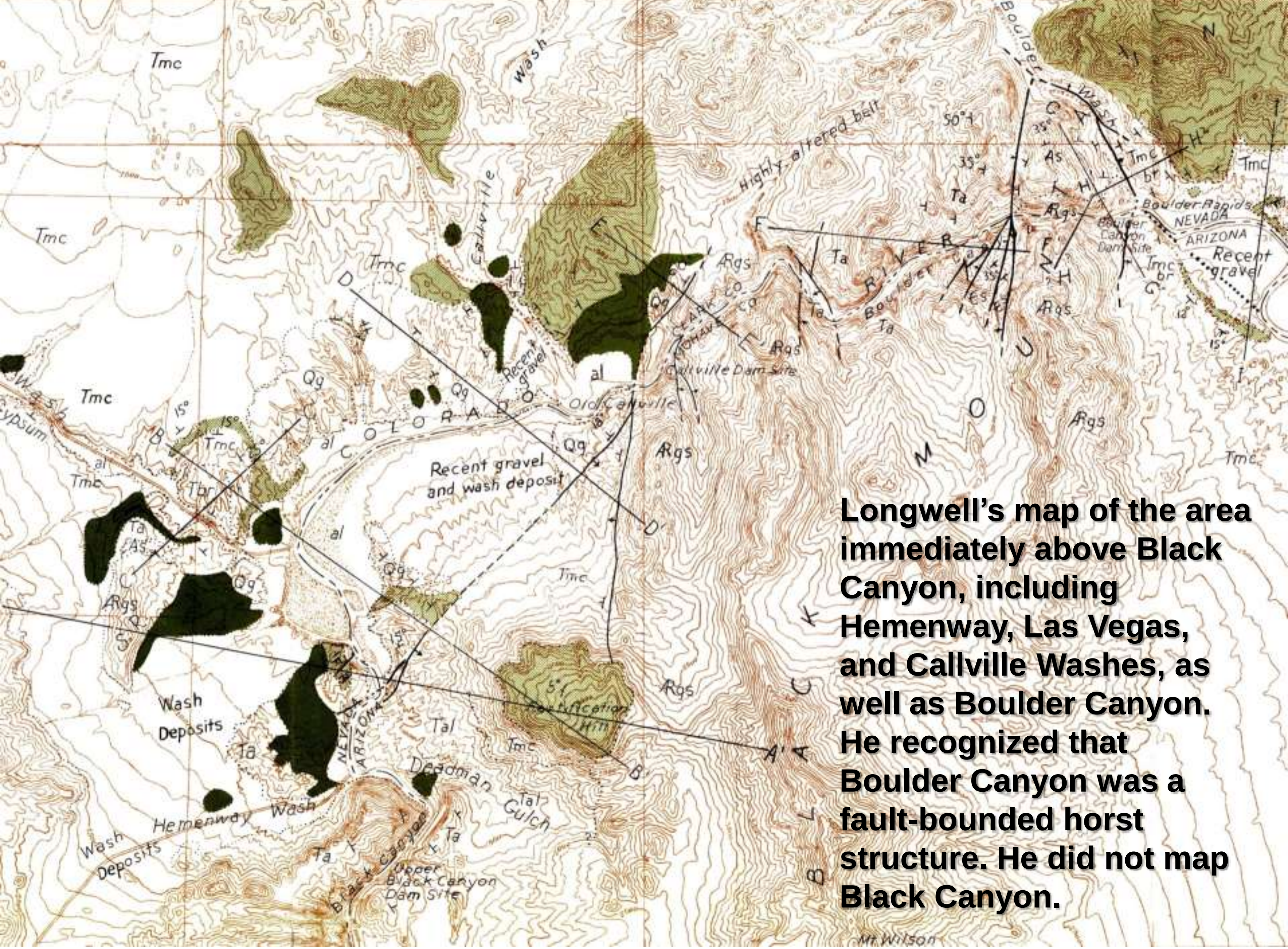
- **The geology of the dam base was mapped after excavation of the channel gravels. Note faults and adjacent zones of intense shearing.**



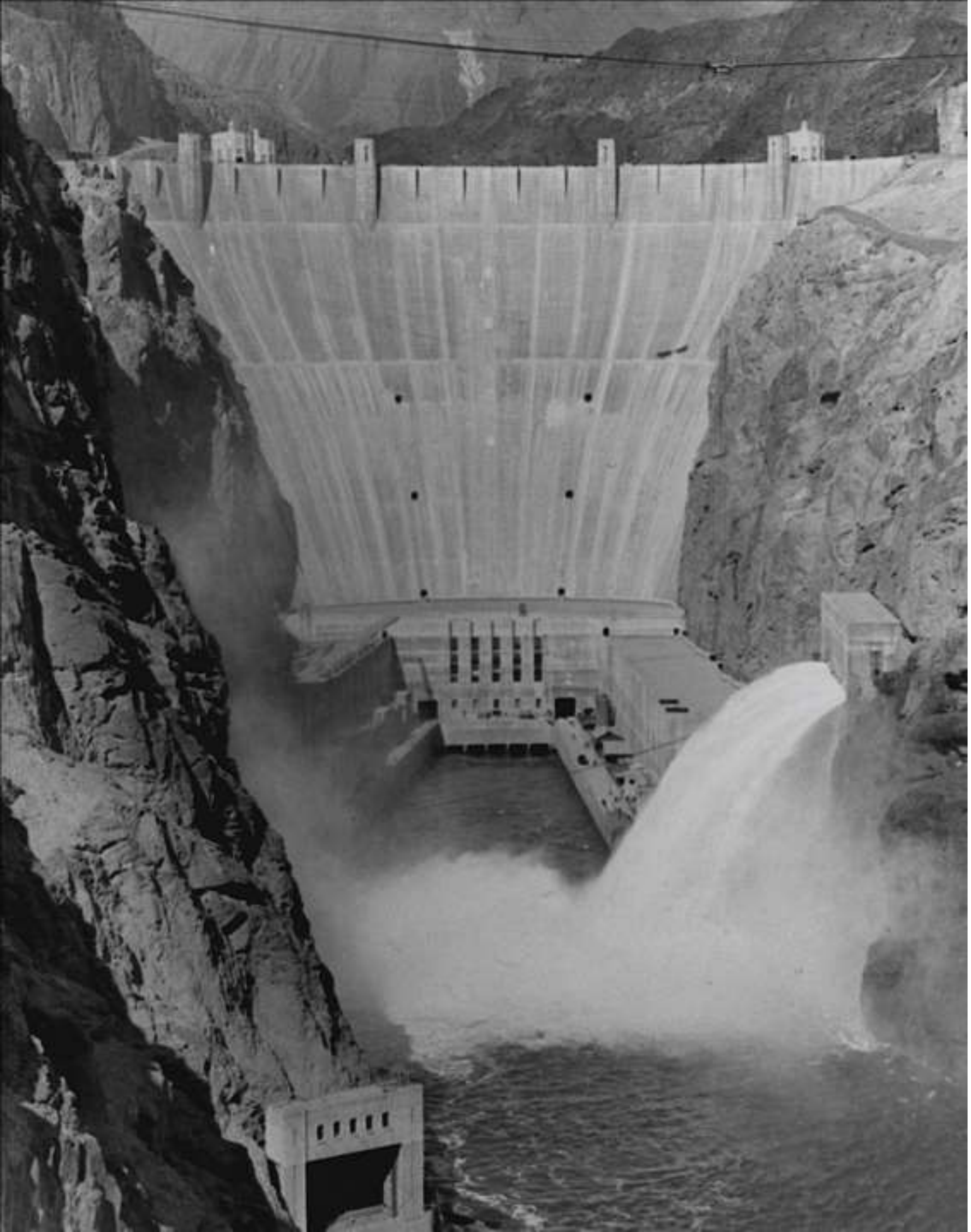
Professor Chester Longwell mapped the reservoir area

Numerous salt mines dotted the lower Virgin River Valley

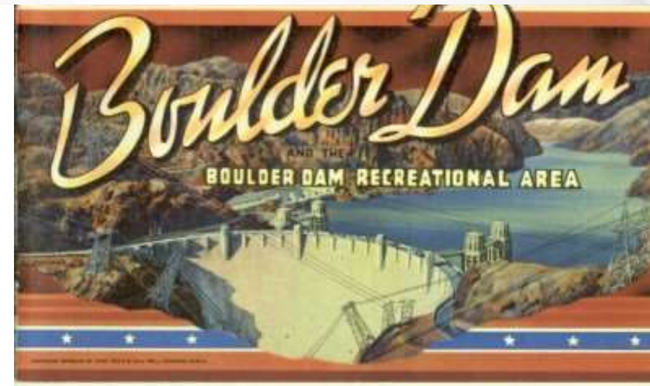
- **The Colorado River Board felt that the geology of the reservoir area should be mapped in detail before impoundment.**



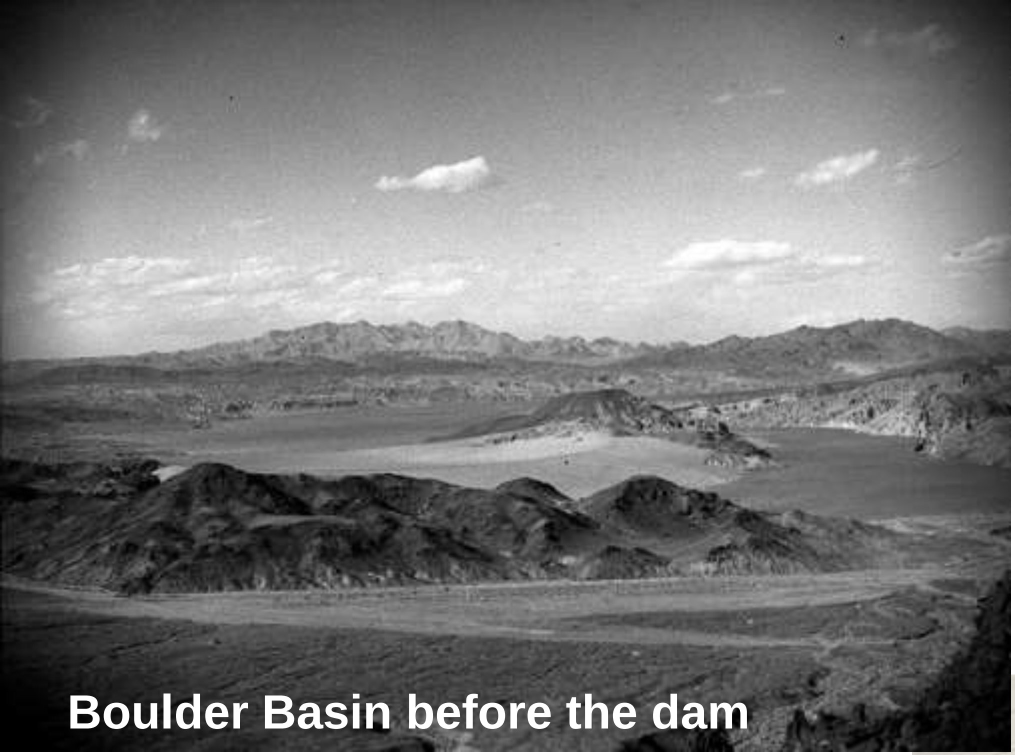
Longwell's map of the area immediately above Black Canyon, including Hemenway, Las Vegas, and Callville Washes, as well as Boulder Canyon. He recognized that Boulder Canyon was a fault-bounded horst structure. He did not map Black Canyon.



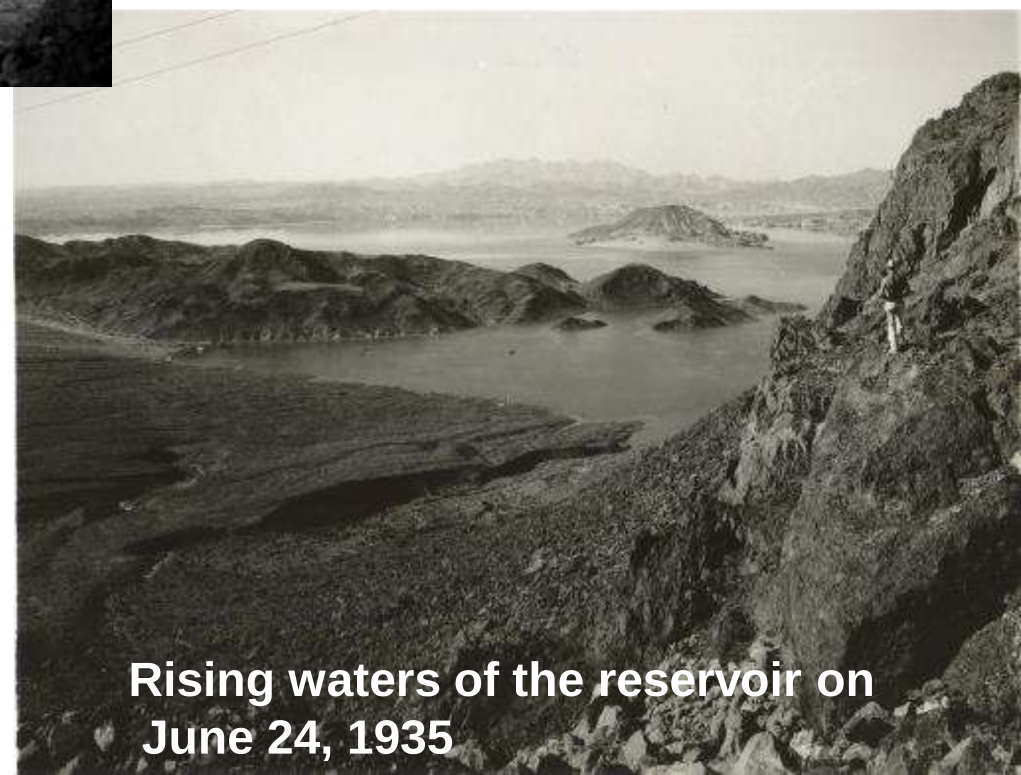
Dedication by Franklin Roosevelt on September 30, 1935



Rising Waters of Lake Mead

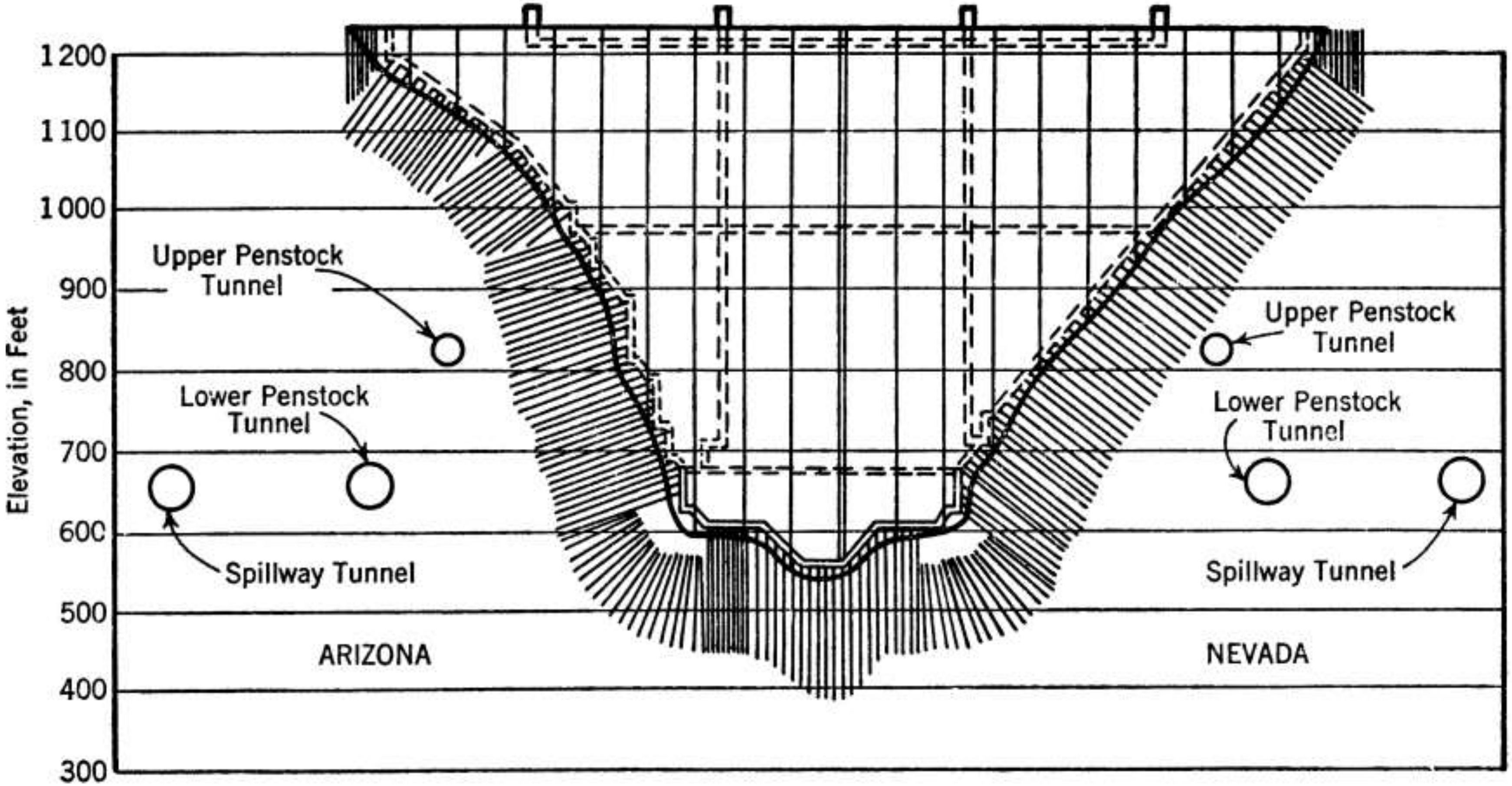

Boulder Basin before the dam

- **As the reservoir rose the hydrostatic pressure on the dam's foundation increased dramatically, from near zero to as much as 400 psi, forcing water through seemingly tight fissures…**

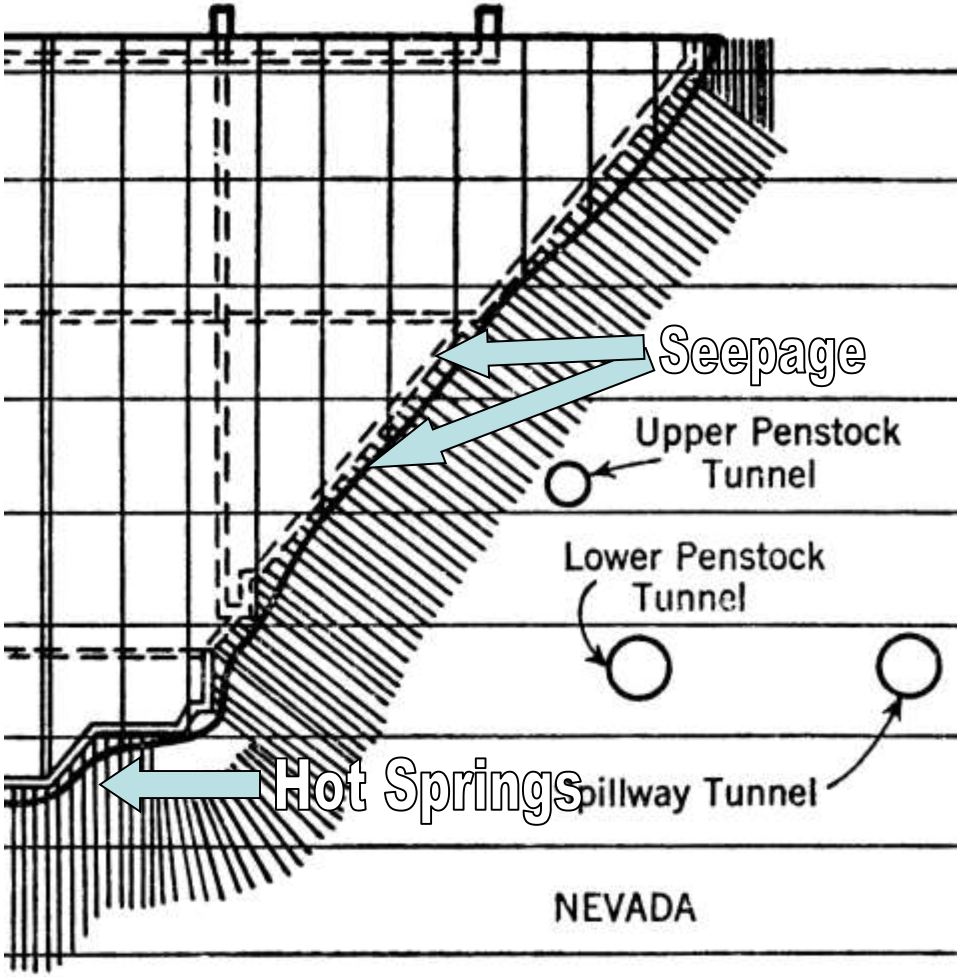

Rising waters of the reservoir on June 24, 1935

Original Grouting Program

- **Foundation grouting was carried out during construction along a *single line* of grout holes**
- **This shows grouting of fault A-31 in the Arizona abutment, which required 1300 bags of neat cement grout**

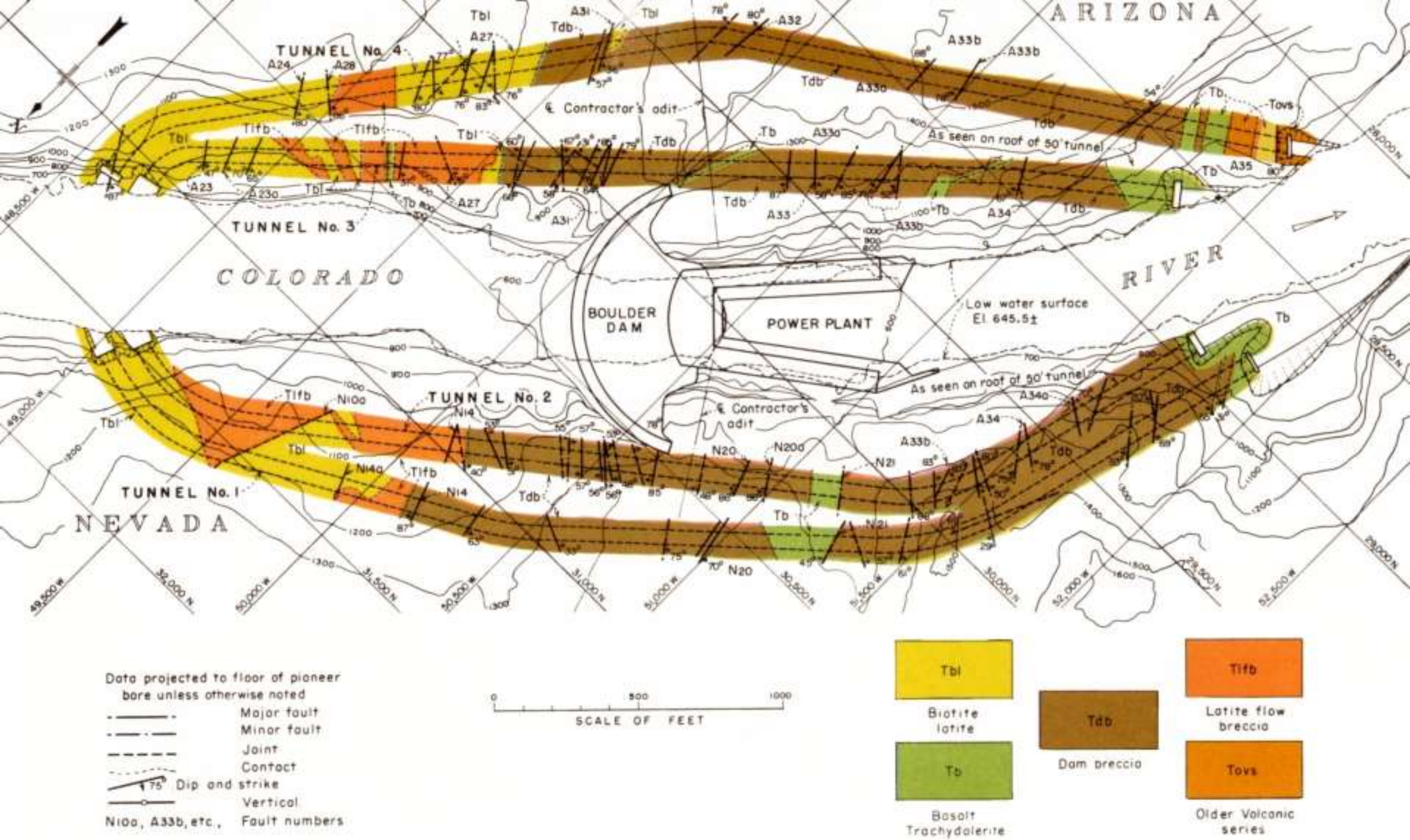


- **Profile of dam centerline showing the pattern of original grout curtain. Note the ratio of dam height to depth of the curtain.**
- **Of the 393 grout holes, 54 (14%) were abandoned because of loss of circulation. This should have been a clue that they could expect future problems in these shattered zones.**



- **On the Nevada abutment between elevations 840 and 940, several gout holes penetrated two distinct minor faults, and four holes had to be abandoned, because excessive grout take and leaks.**
- **When the reservoir reached 1100 feet elevation, the faults daylighted in the right abutment, and water began entering the fault zone**
- **At this time the abutment drains in the Nevada side began discharging cool water.**

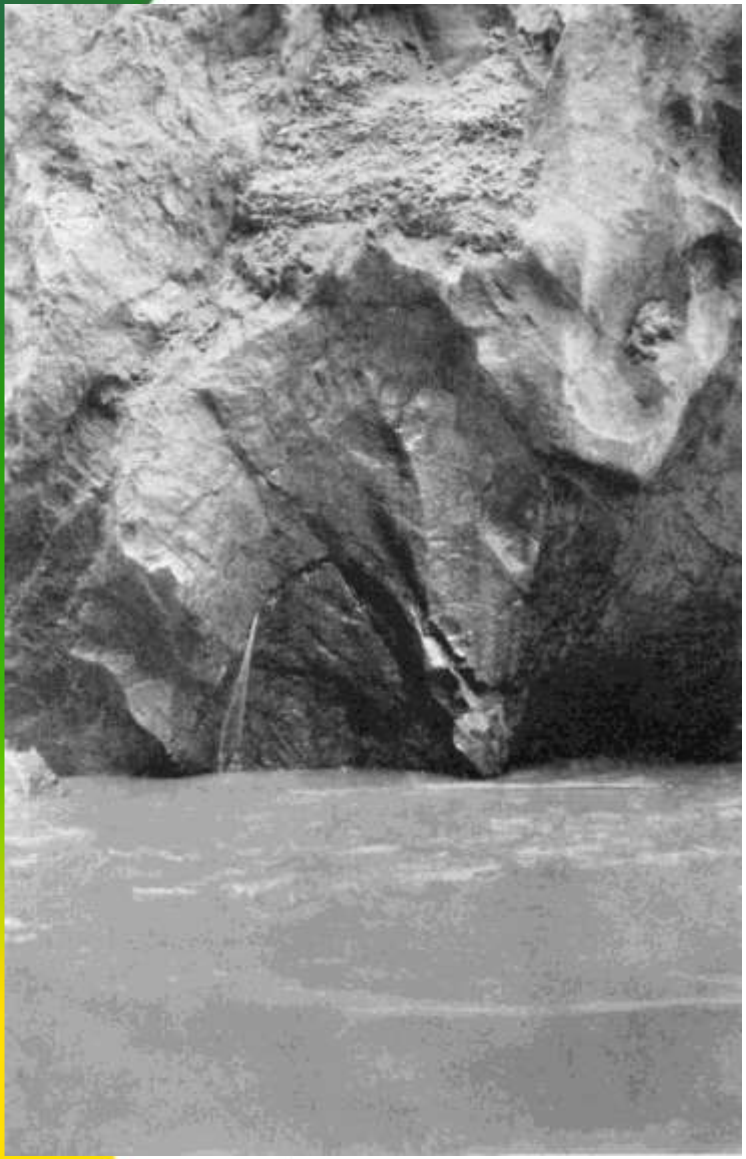
- **Warm water from the natural hot springs was collected along the right abutment drainage gallery near elevation 555, emanating from several "shattered zones." During the original construction, grouting of this area was ineffective due to *premature set* of the cement grout, because of the high water temperatures.**



- **Geology encountered in the four river diversion tunnels. Note the number of mapped faults.**

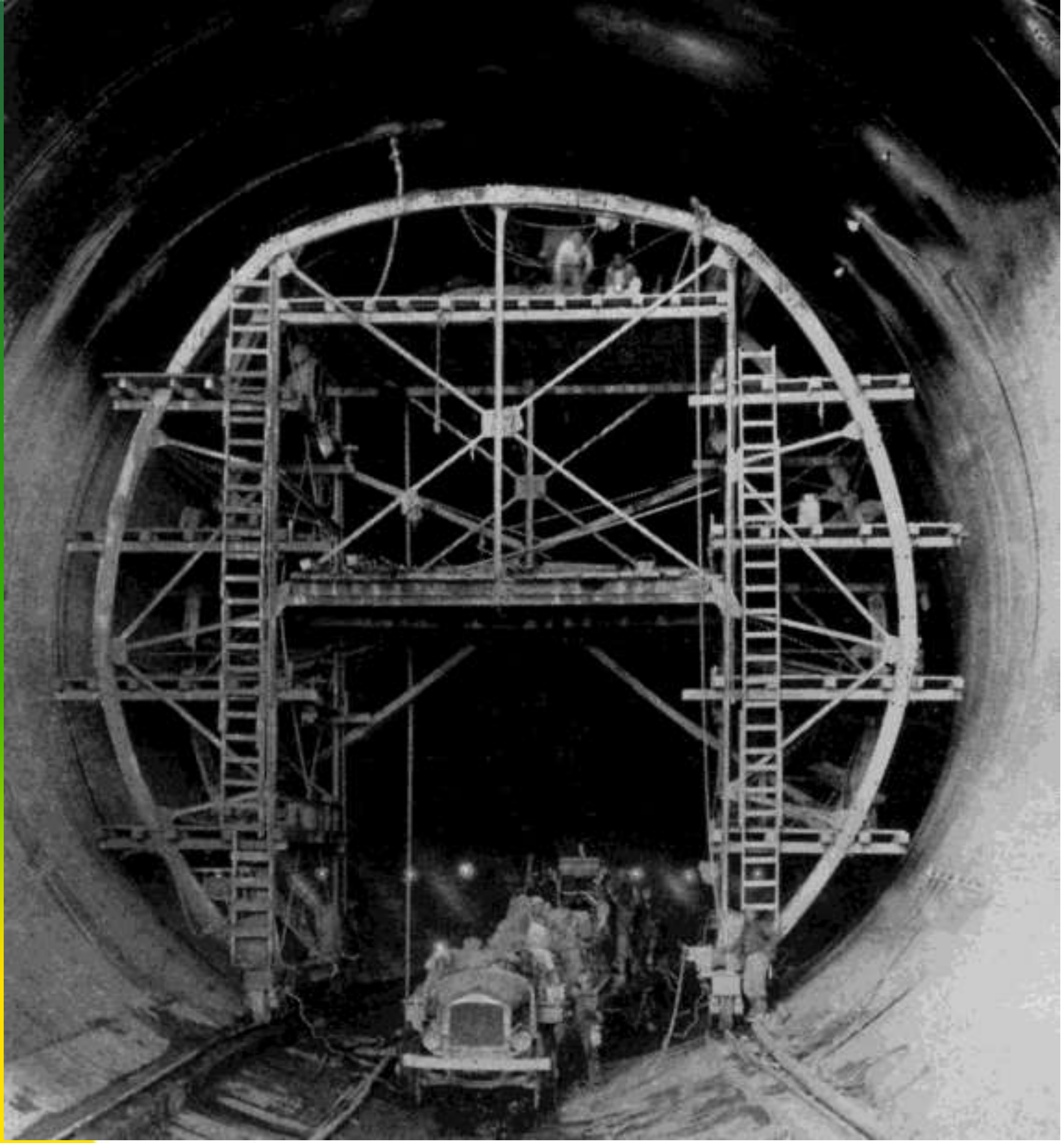
Missouri University of Science and Technology

Alkaline water also accelerated corrosion of the lower penstock feeder



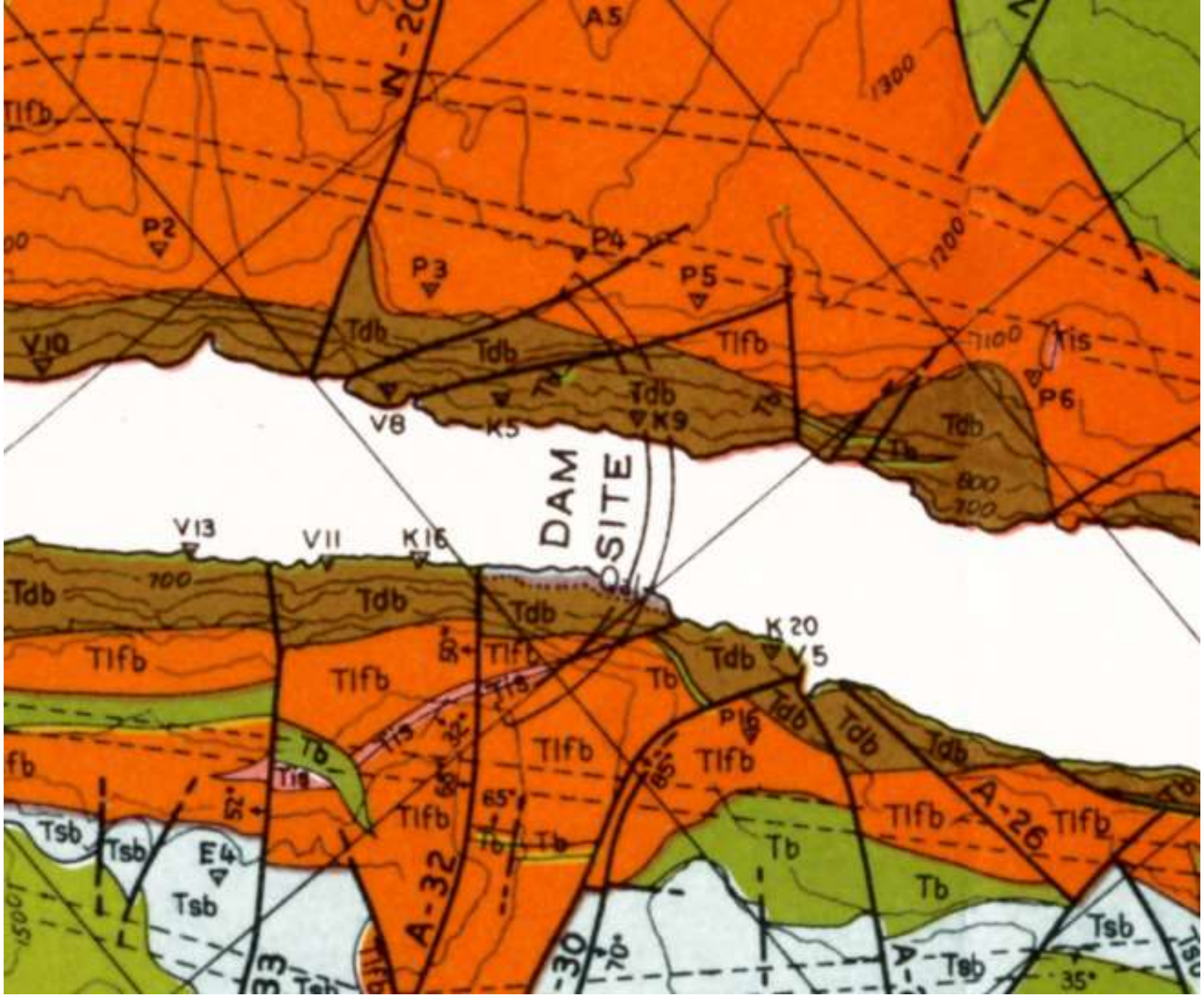
Hot springs on Nevada abutment

- **Hot alkaline water began seeping through the concrete liner of the inboard 56 ft diameter Nevada diversion tunnel, spilling onto the 30 ft diameter steel penstock feeder, causing accelerated corrosion**



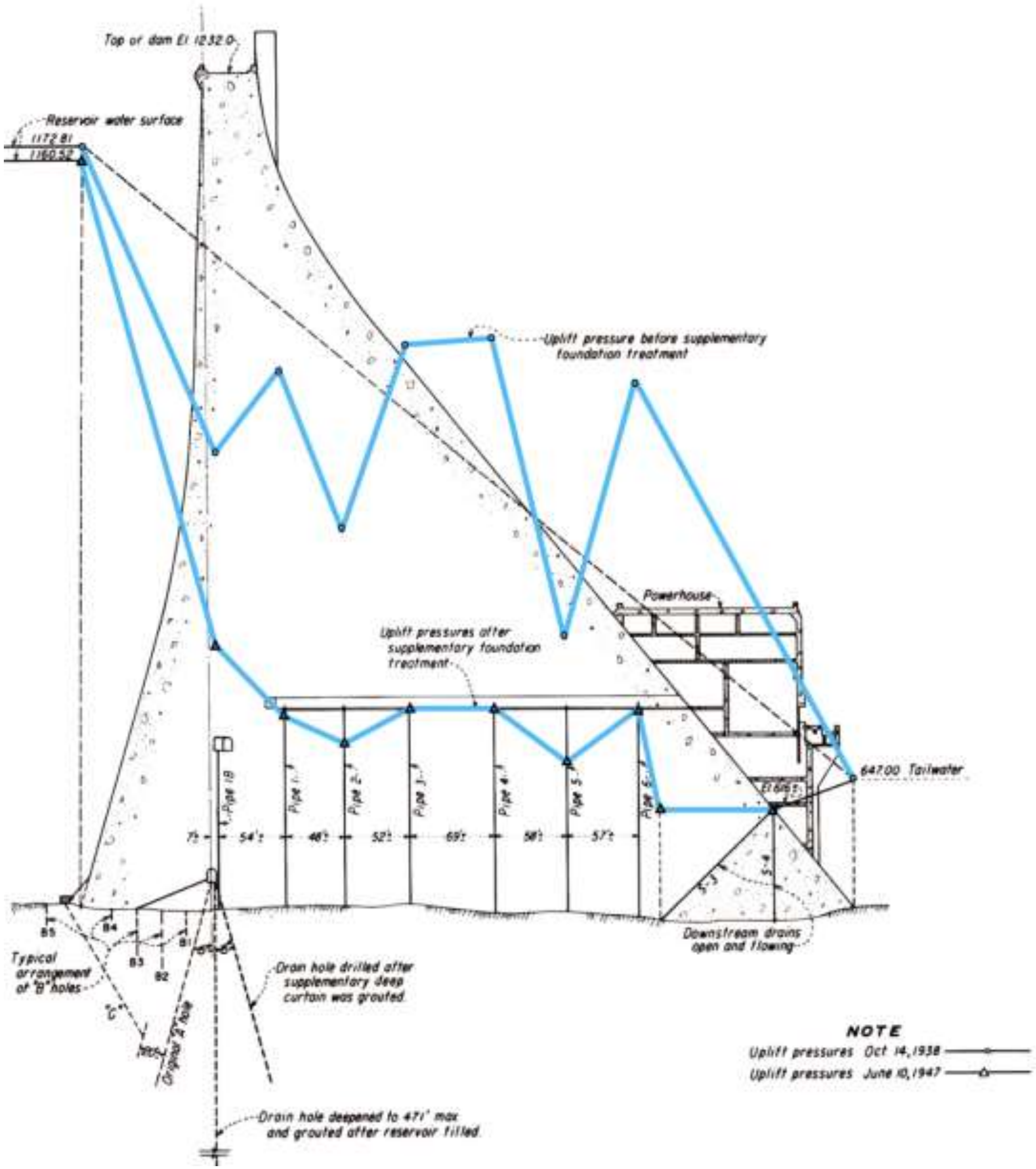
Grout drilling jumbo used in diversion tunnels

- The rock around the massive 56 foot diameter diversion tunnels was grouted after tunnel lining
- The lining of the inboard Nevada penstock started leaking as the reservoir filled



- **Excessive seepage also manifested itself along two fault strands through the right abutment when the reservoir reached elevation 1100 feet, 132 feet below crest.**

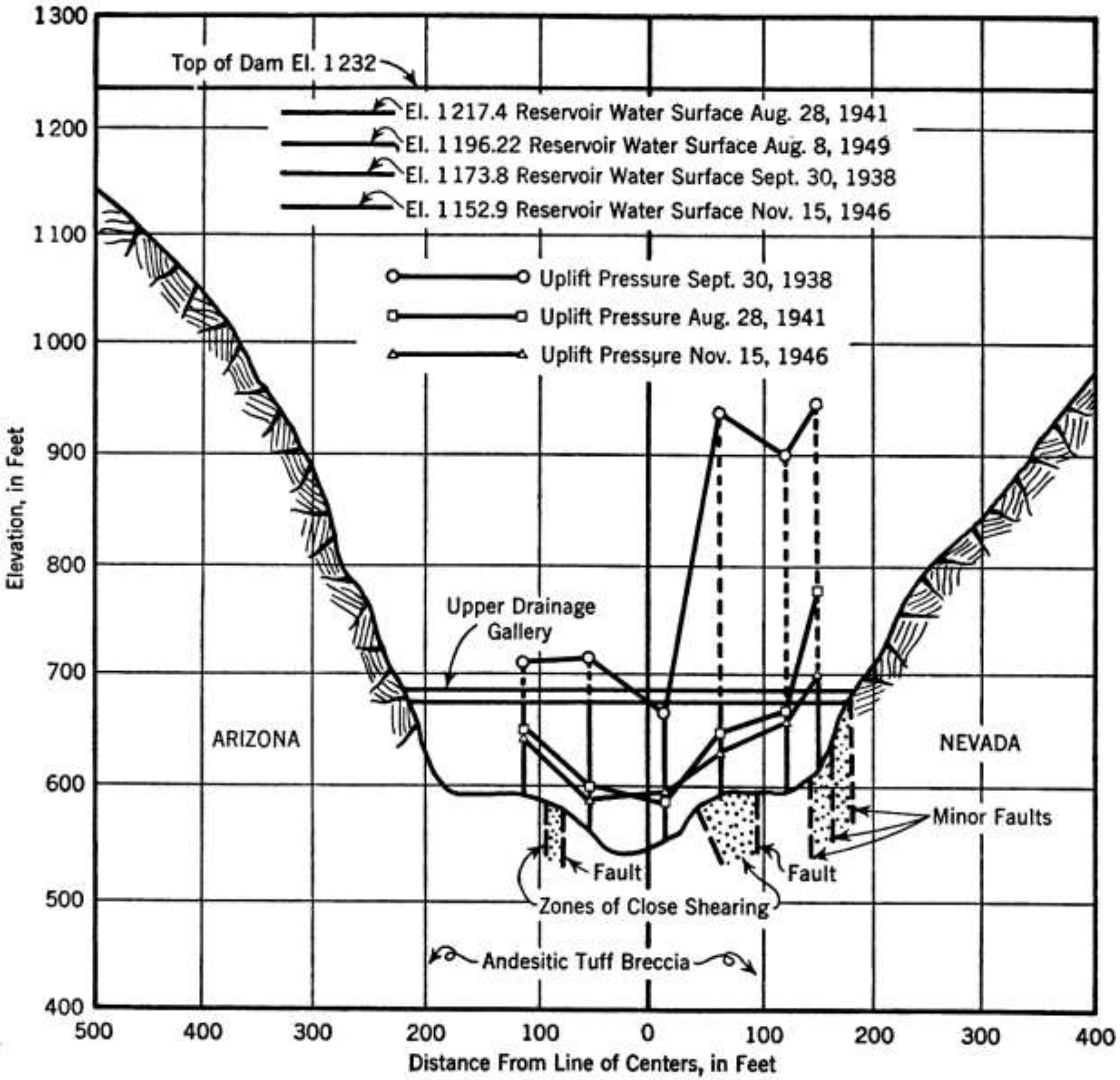
Failure of the Grout Curtain



By the second year of operation (June 1937) seepage problems arose.

Abnormally high uplift pressures developed beneath the center of the dam

Seepage began overwhelming the lower galleries, and poured out of the canyon wall above the Nevada Powerhouse

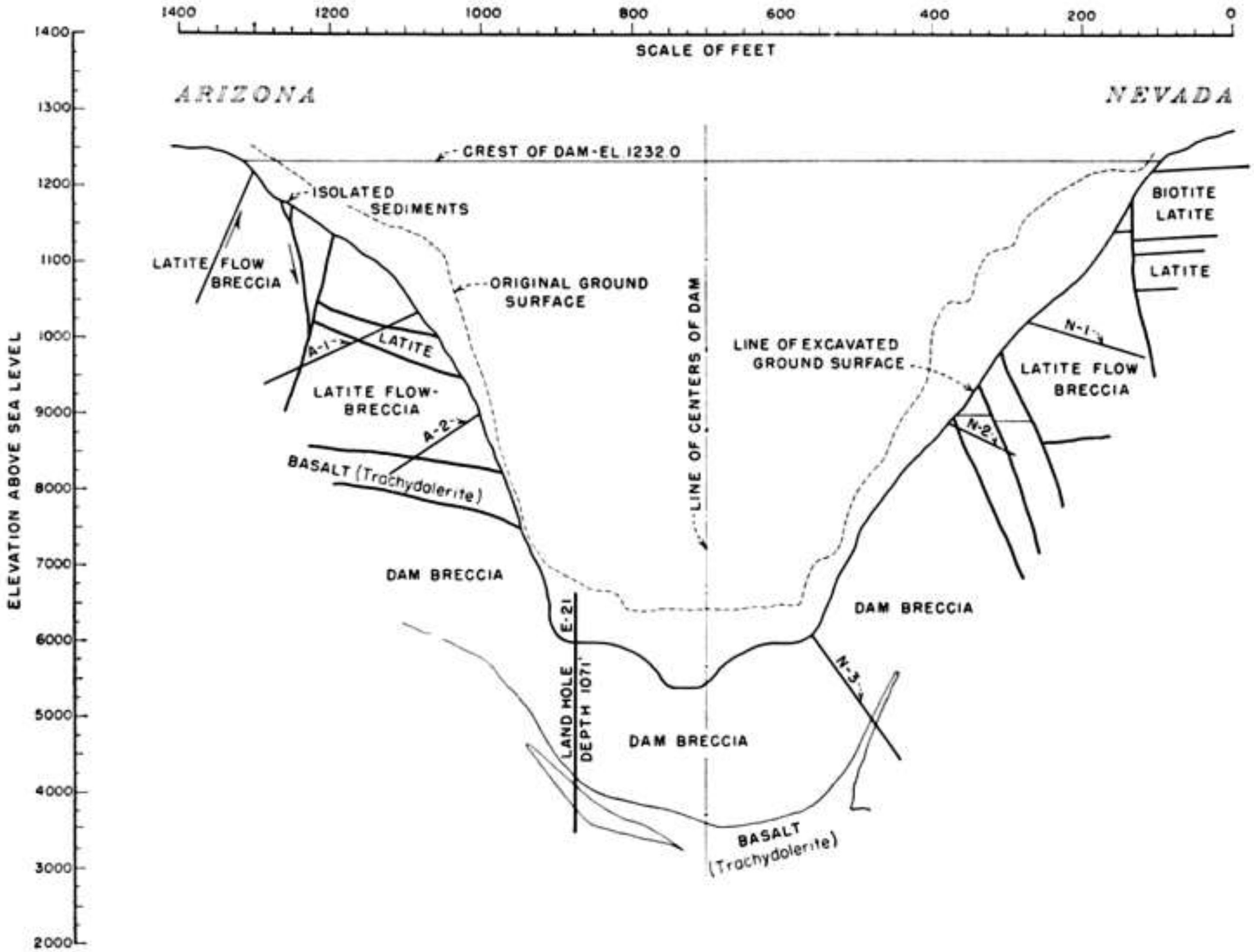


Uplift pressure gradients measured along centerline of upper drainage gallery.

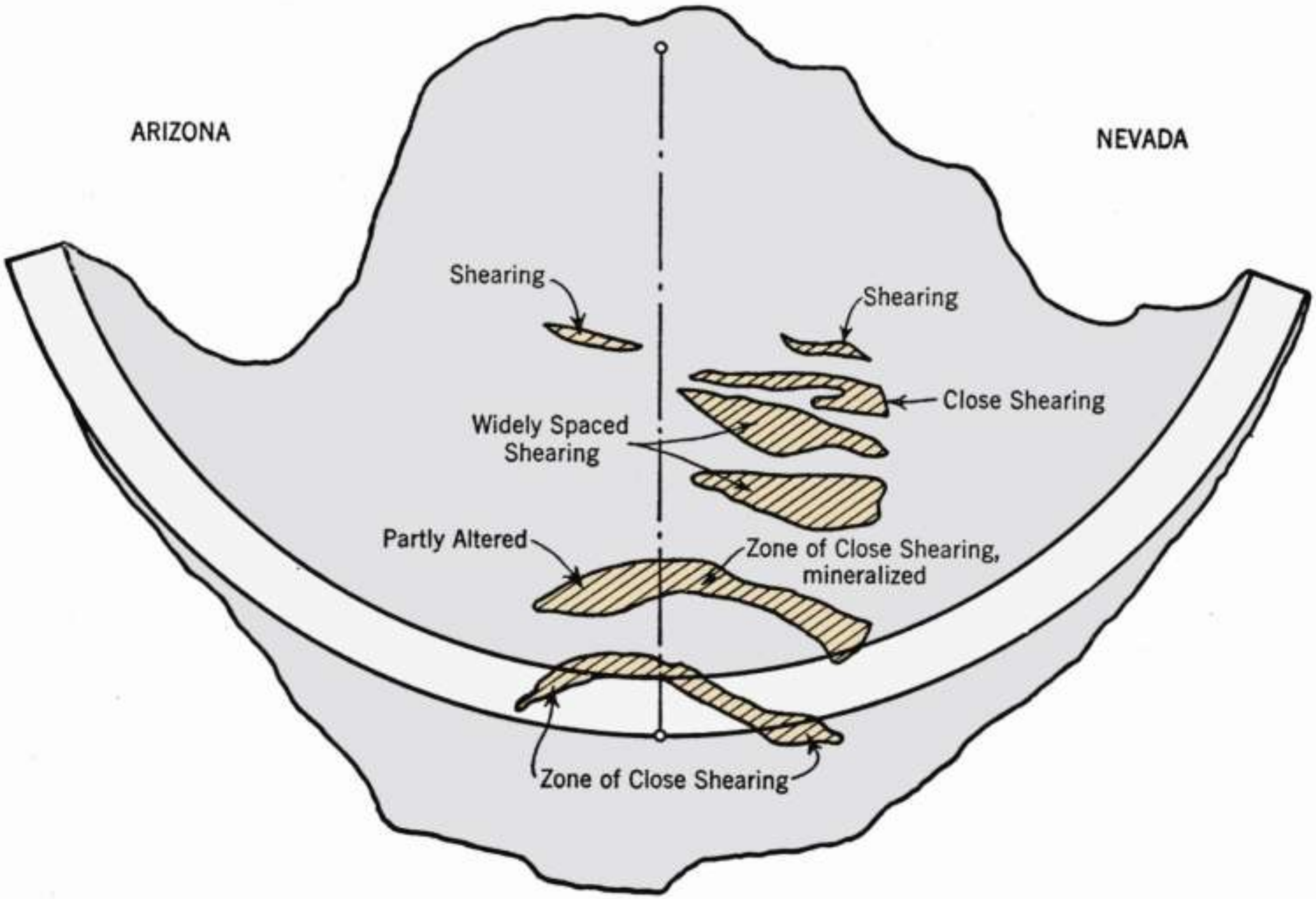
Note increased pressures on Nevada side and the brecciated fault zones

1938-39 exploration program

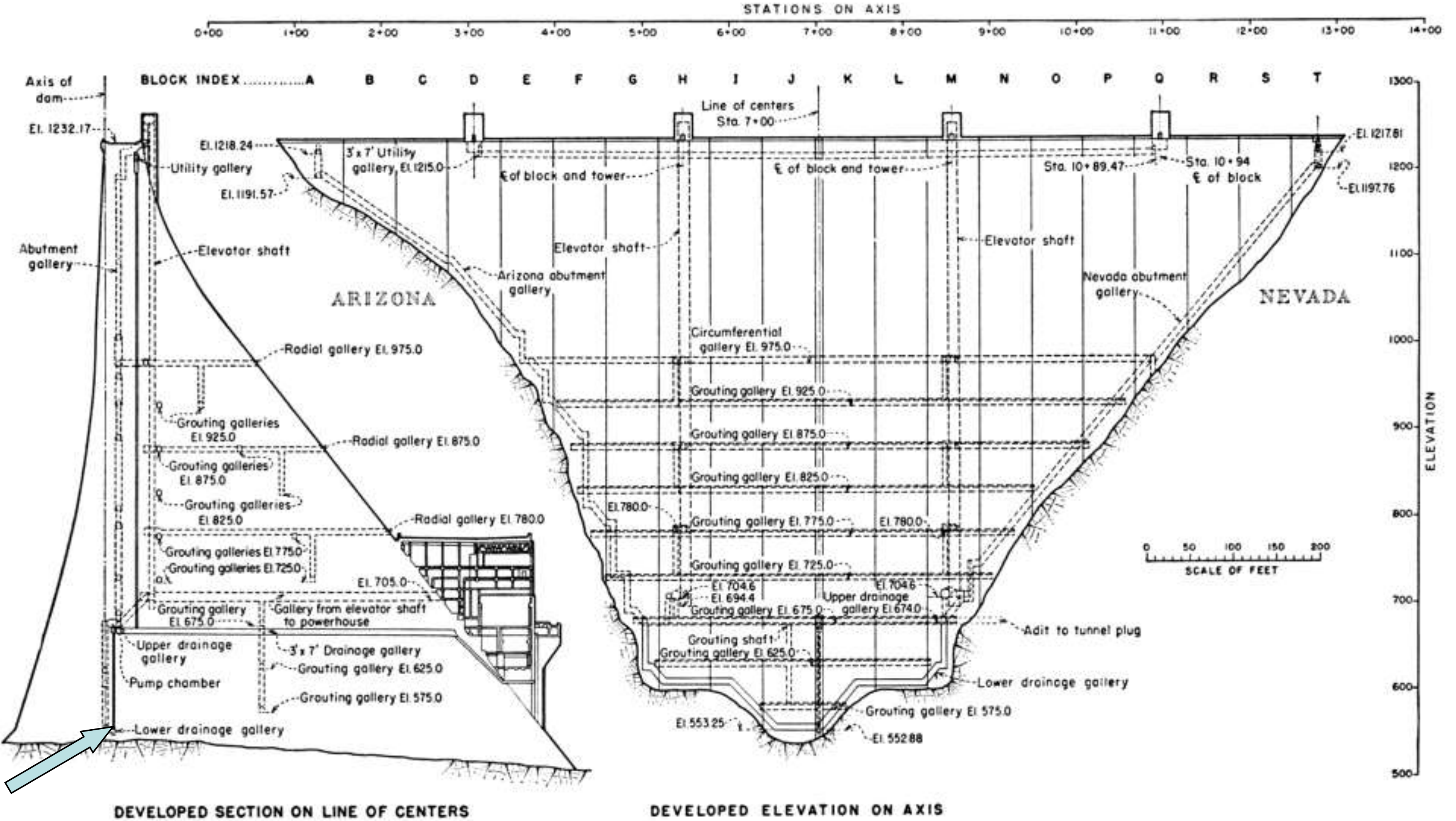
- Reservoir uplift reached its maximum levels in September 1938
- The decision was then made to drill a series of BX size cores in the foundation beneath the dam
- The drilling revealed that the grout curtain was much too shallow on the faulted abutments, because 6 zones of intensely sheared rock were feeding water into the foundation and a series of criss-crossing manganese gouge seams were perching the underseepage, causing abnormally high pore pressures to develop



- **System of block faults identified during construction. Note absence of data beneath the dam.**

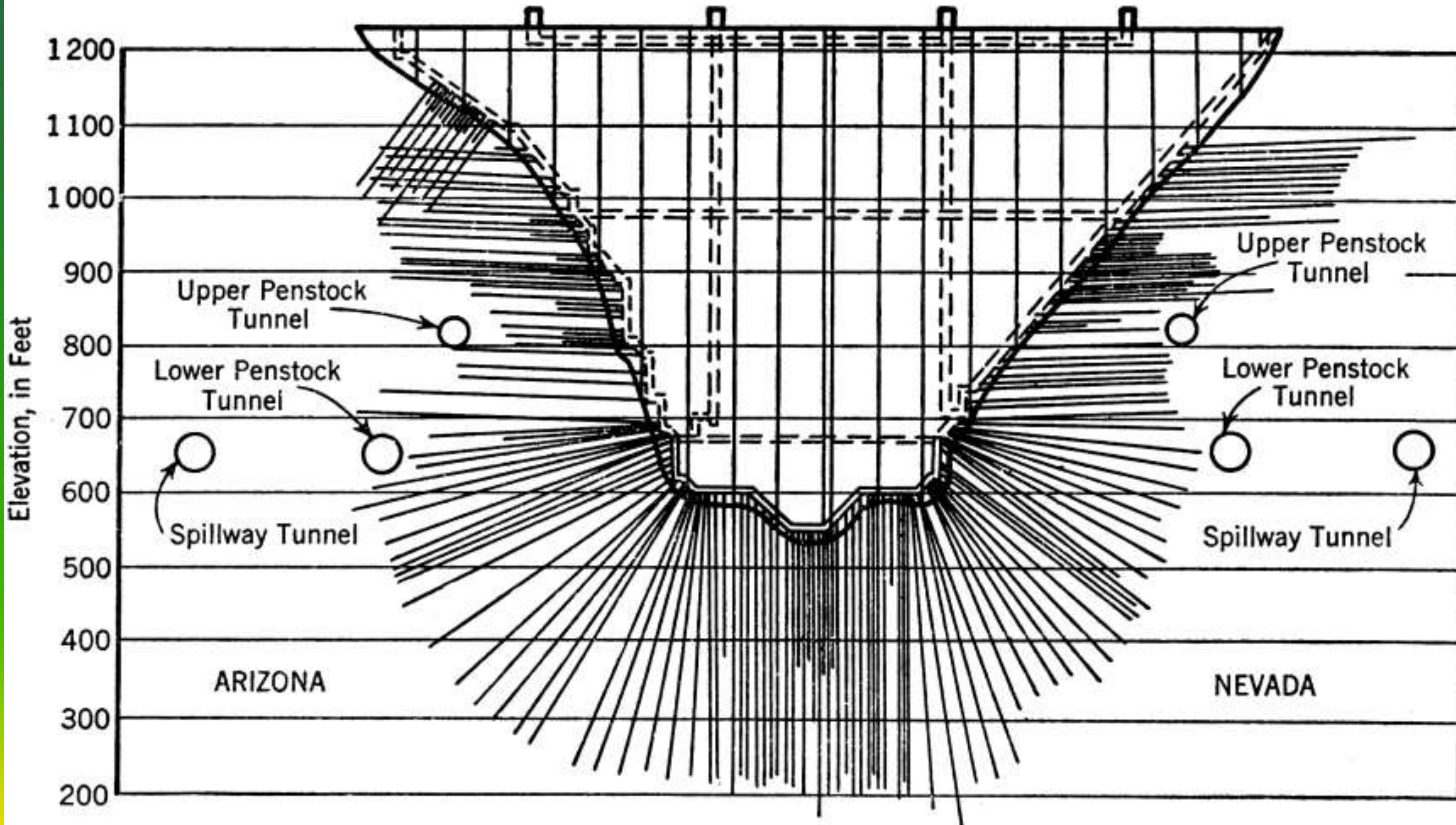


Manganese-rich gouge zones discovered in the dam foundation, along faults and shear zones.

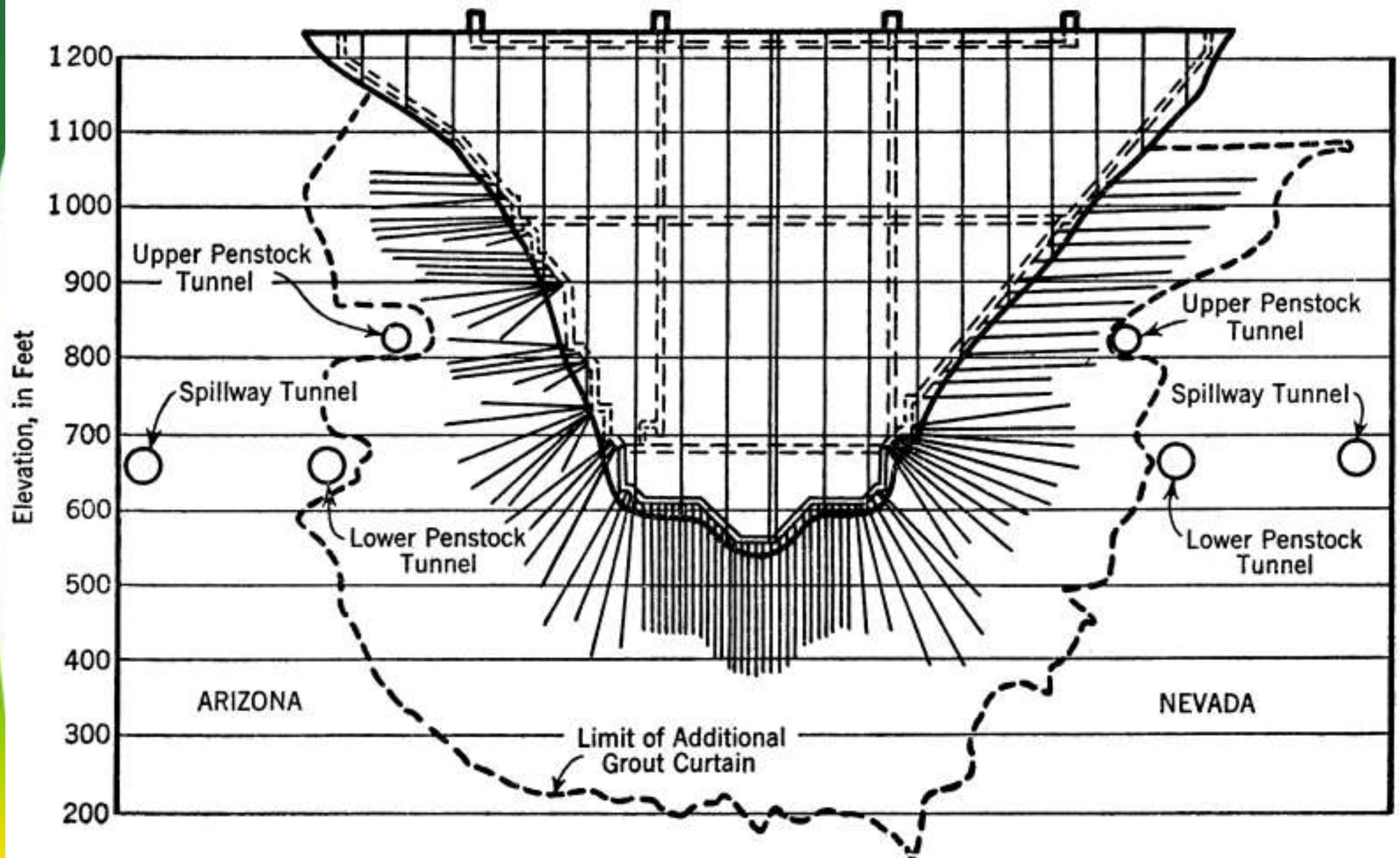


- **Inspection galleries inside Hoover Dam. Deepened grout curtain was extended from the lower drainage gallery (arrow).**

- **Tight working spaces typified the 9 year program of extending the grout curtain, between 1938-47.**
- **During the supplemental drilling program 410,000 linear feet of grout and drainage holes were drilled, and 422,000 cubic feet of grout were injected under pressure. This cost an additional $3.86 million, about 7% of the dam’s cost.**

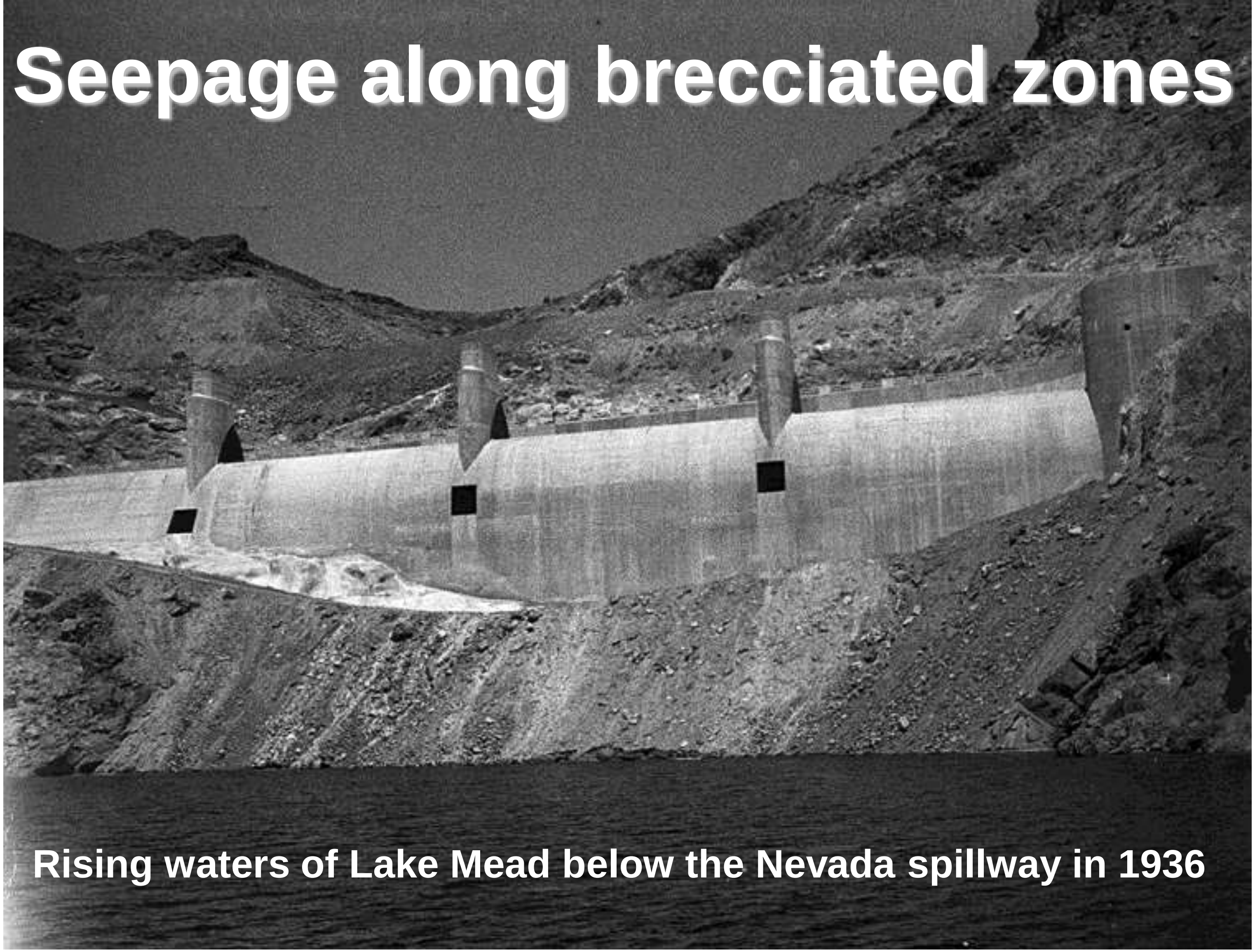


- **Profile of dam centerline showing deepened grout curtain, extended between 1938-47. This time grout holes were extended 300 feet, then pumped under pressure of full reservoir head.**



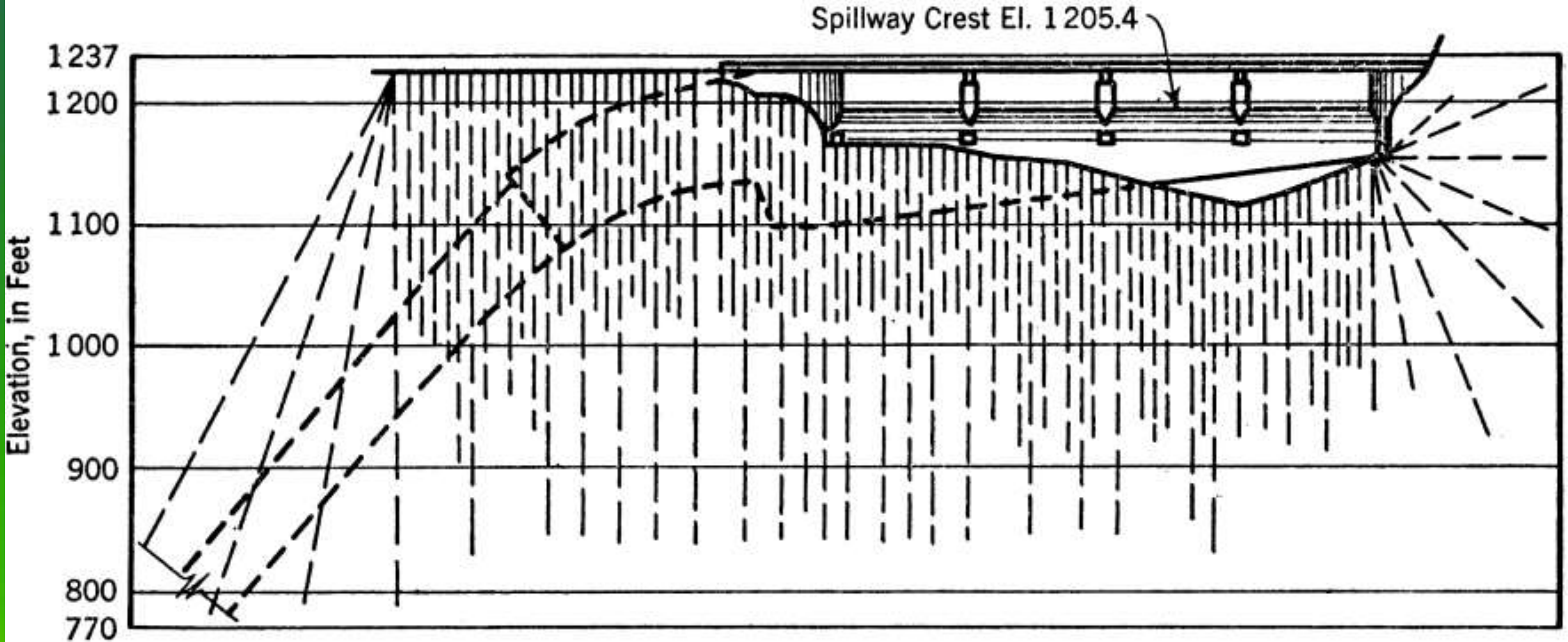
- **Centerline profile showing much deeper drainage system installed between 1938-47; and outline of extended grout curtain.**

Seepage along brecciated zones

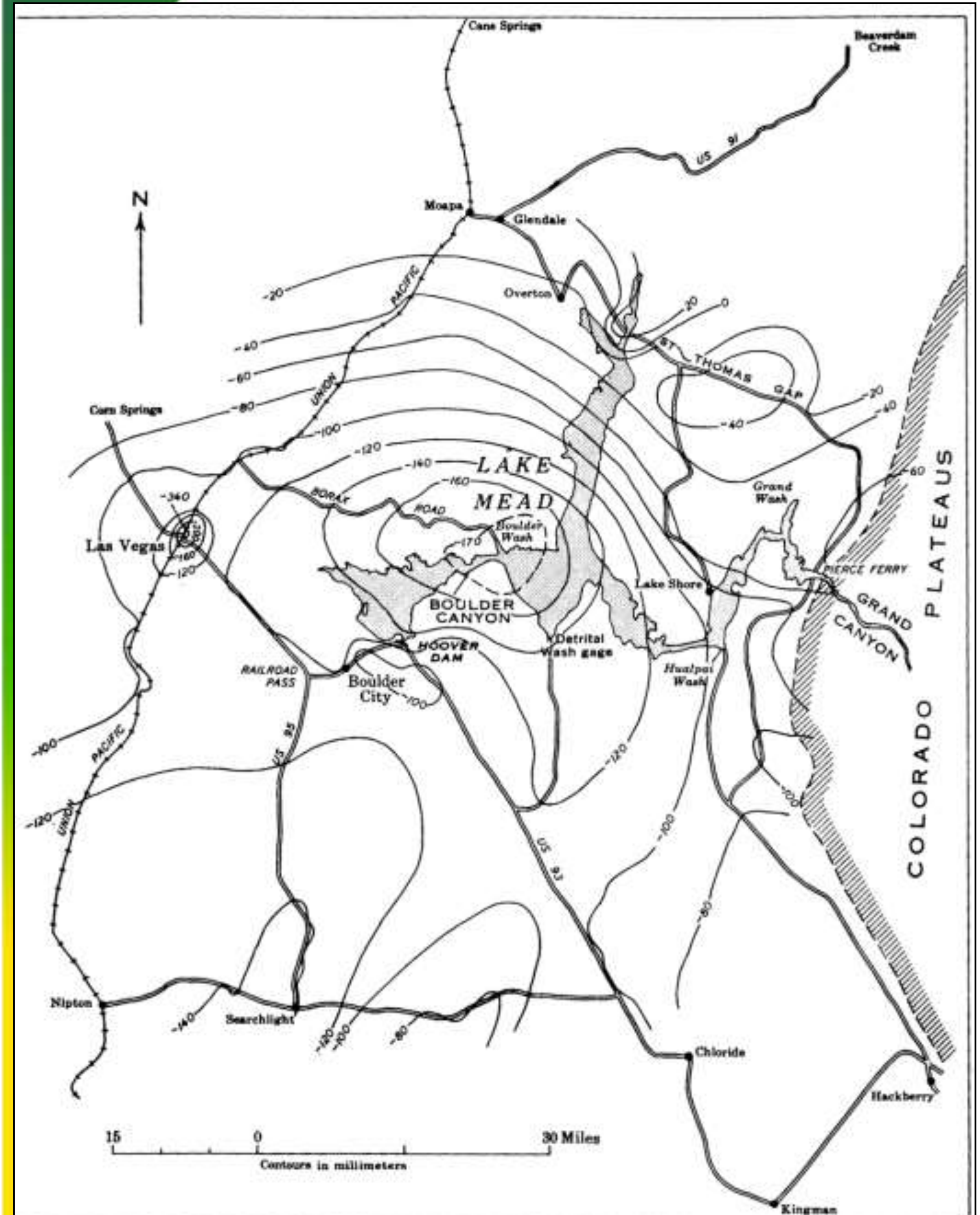


Rising waters of Lake Mead below the Nevada spillway in 1936

- **As the reservoir began rising, increasingly severe leakage began infiltrating the Nevada Spillway chute along the faults Frank Nickell had mapped back in 1932.**



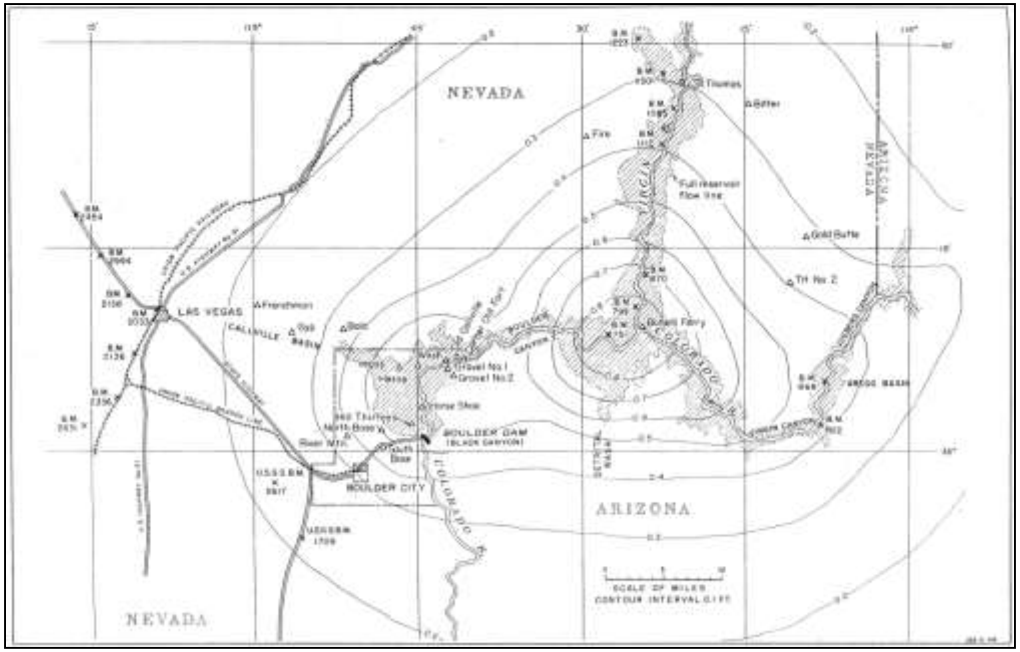
- **An extensive program of extending the grout curtain beneath the Nevada Spillway Intake was also undertaken in the 1940s, shown here. This was to combat seepage leaking into the system after the reservoir level reached an elevation of 1100 feet.**

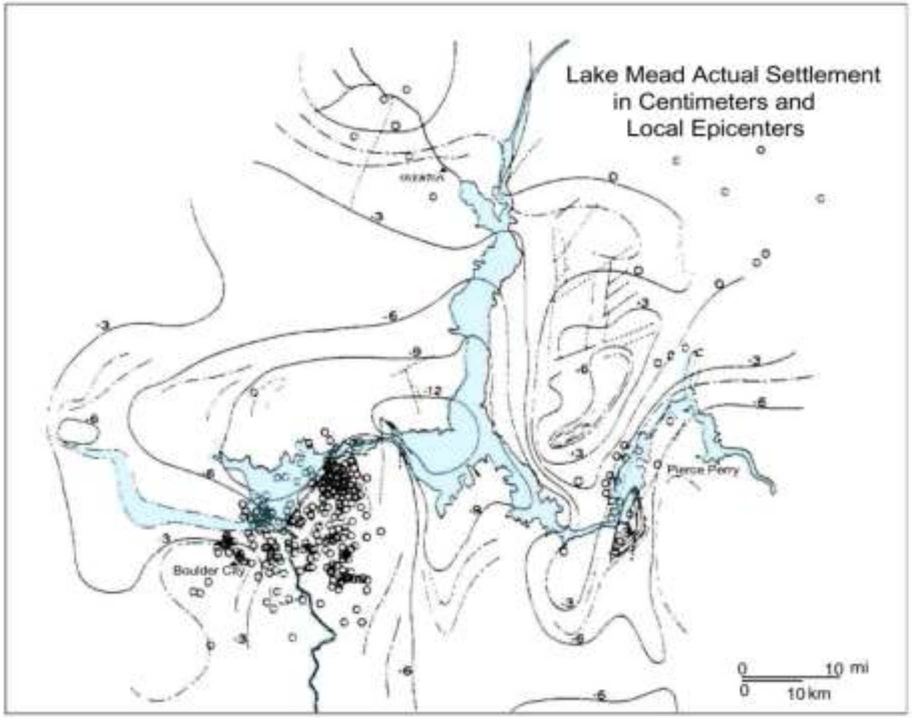


First Reservoir Induced Seismicity and Crustal Deflection Studies

Three precise leveling surveys performed 1935, 1940-41, and 1949-50. A seismic array was also monitored.

Credible estimates

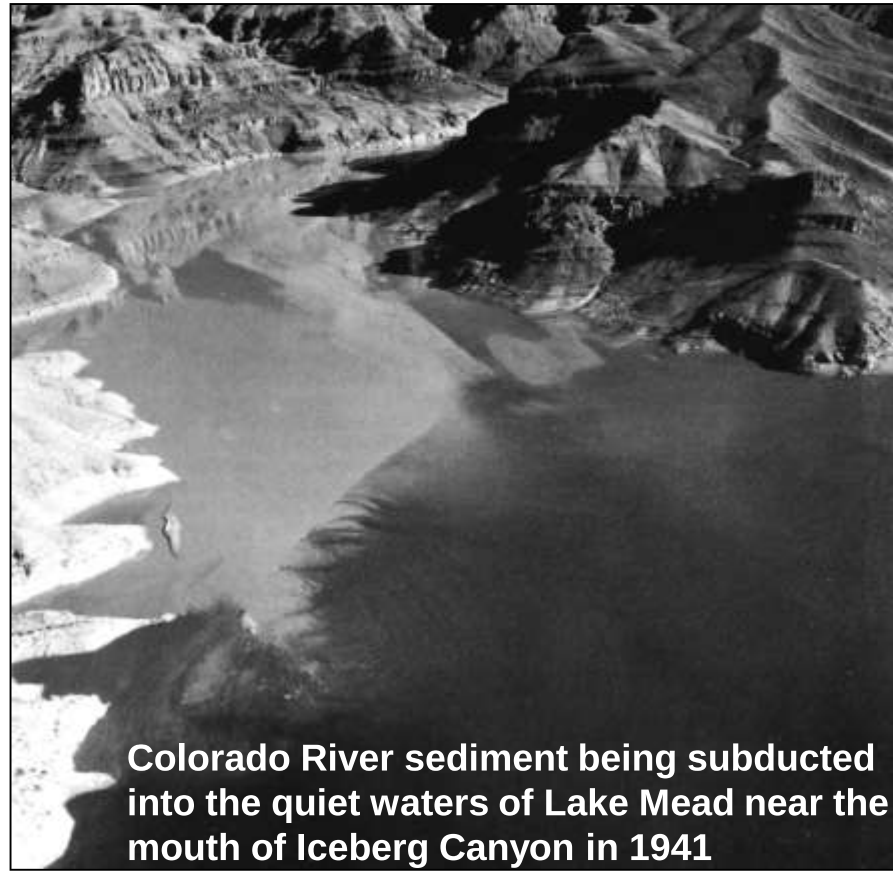




- **Crustal settlement** was very close to that predicted by Reclamation engineers, for an assumed mass of **granite crust** behaving elastically, under 41,500 million tons of water
- **Predicted deflections** up to 10 inches; actual deflections were up to 7.5 inches.

Siltation studies

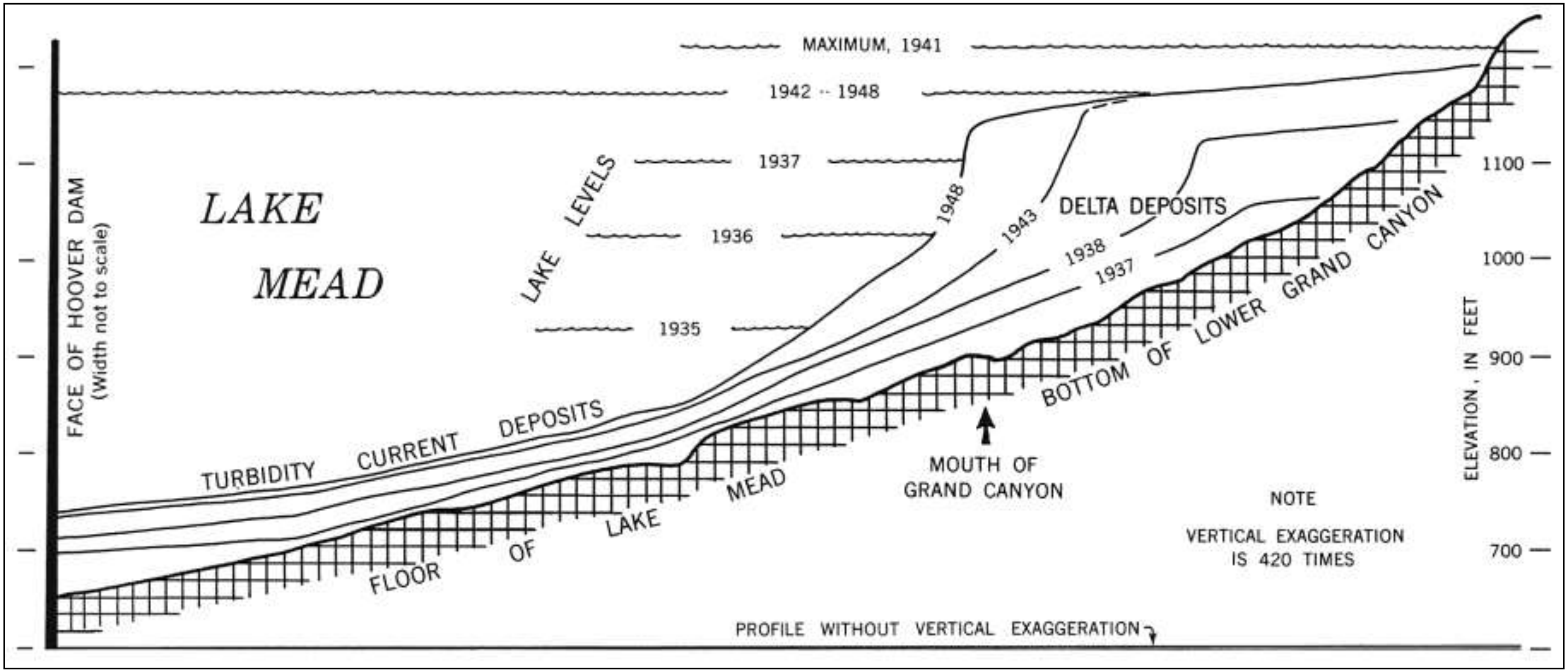
Silt beds exposed in Pierce Basin by low water in 2008



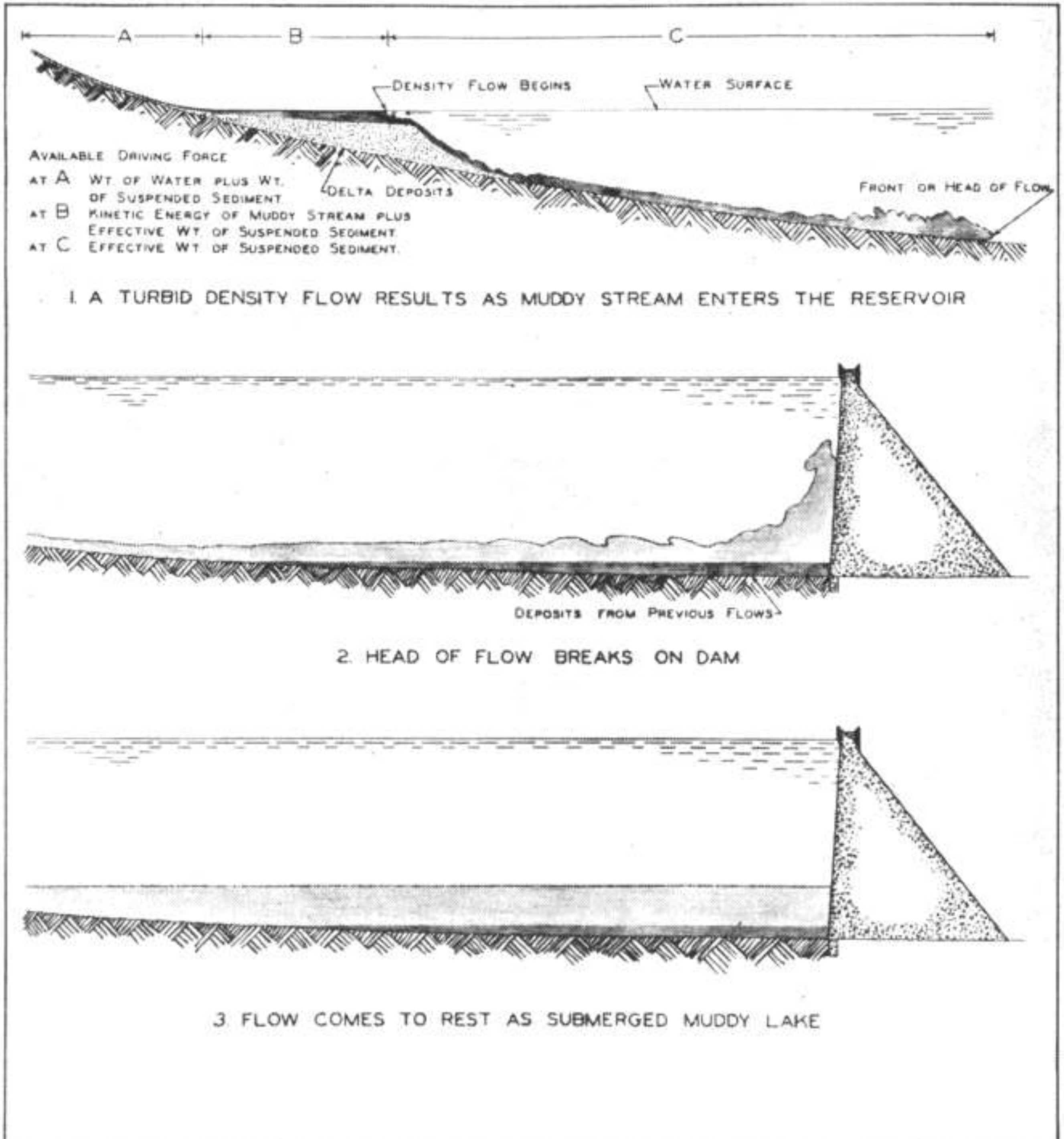
Colorado River sediment being subducted into the quiet waters of Lake Mead near the mouth of Iceberg Canyon in 1941

Lake Mead had a design life of just 150 years before it was expected to silt up, absent any upstream dams. One of the biggest mysteries concerned "missing sediment;" when it was learned that almost 50% more silt entered Lake Mead than passed Lee's Ferry (360 miles upstream). The lion's share of this silt was subsequently found to have emanated from the San Juan and Little Colorado River Basins.

Sedimentation Studies



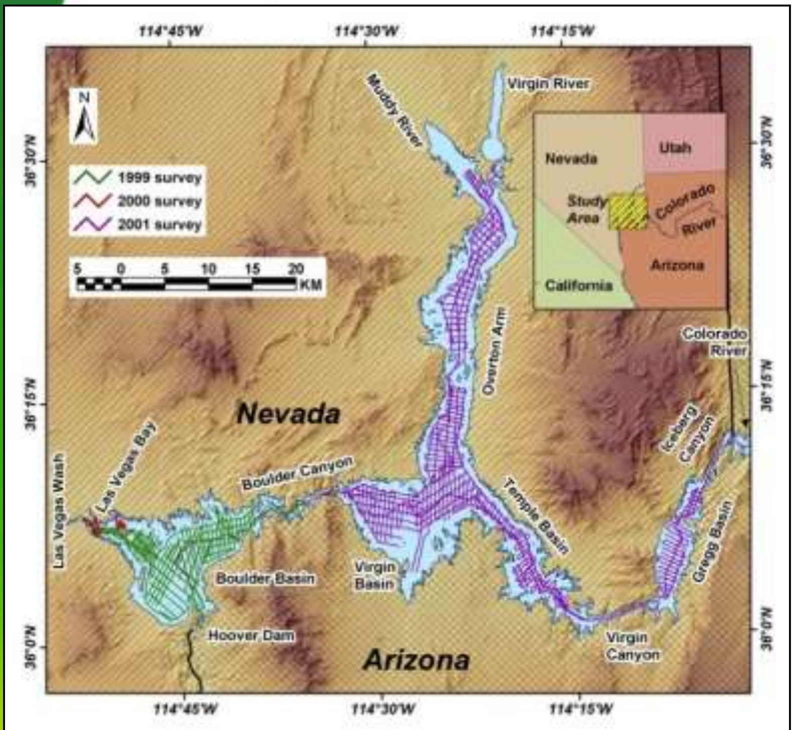
Bathythermography tests adjacent to the dam's upstream face revealed unusually high temperatures from biologic reduction of nutrient rich silts brought 115 miles across the sinuous course of the old river channel by turbidity currents.

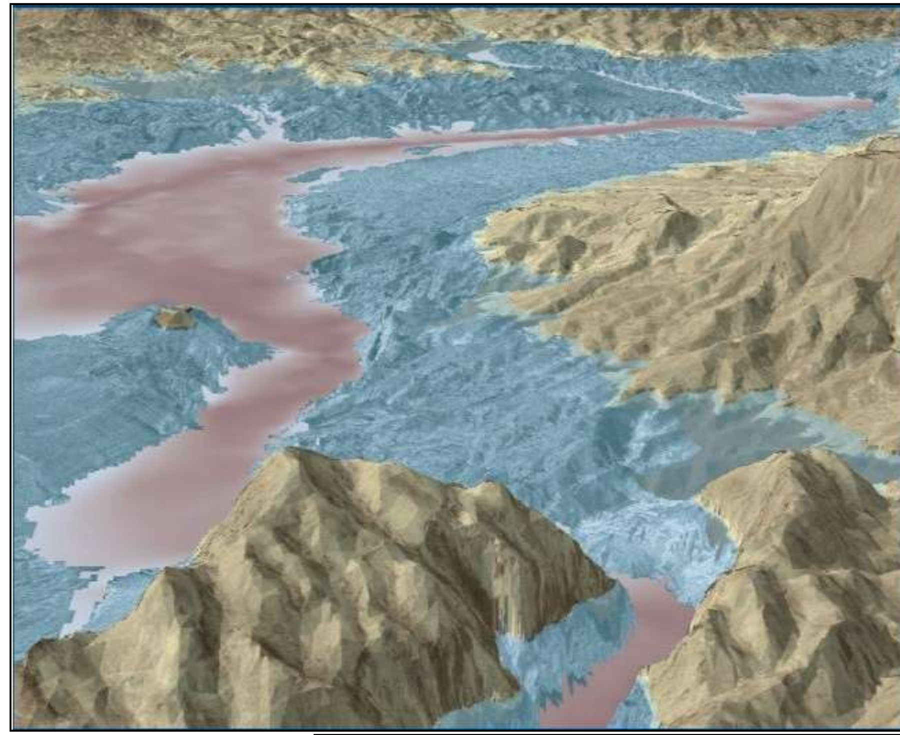


Turbidity Currents

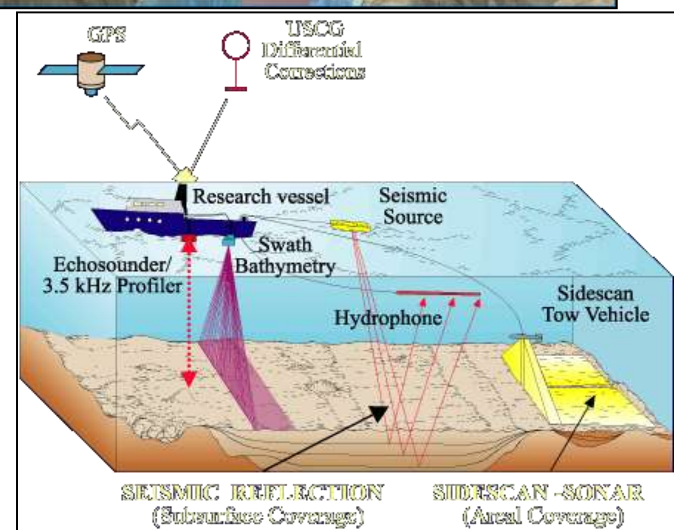
- The discovery of turbidity currents in the early 1940s triggered intense studies under the aegis of USGS, Caltech, and the AGU at Hoover, Elephant Butte, and Norris Dams.

Lake Mead sediment studies





The tailwater channel and deep basins of Lake Mead are being infilled with silt emanating from the Grand Canyon. The annual influx was reduced substantially when Glen Canyon Dam closed its gates in March 1963.



Missouri University of Science and Technology
MISSOURI S&T

Special thanks to:

U.S. Bureau of Reclamation
National Archives and Records Service,
Rocky Mountain Region
Trent Dames Civil Engineering Heritage Fund
Dibner Research Fellowship of
The Huntington Library
AEG Foundation
U.C. Water Resources Center Archives
U.S. Geological Survey
American Heritage Center of the University of Wyoming

This lecture will be posted at:

www.mst.edu/~rogersda/dams

As a .pdf format for easy downloading

Missouri University of Science and Technology