HOOVER DAM:

Grout Curtain Failure and Lessons Learned in Site Characterization

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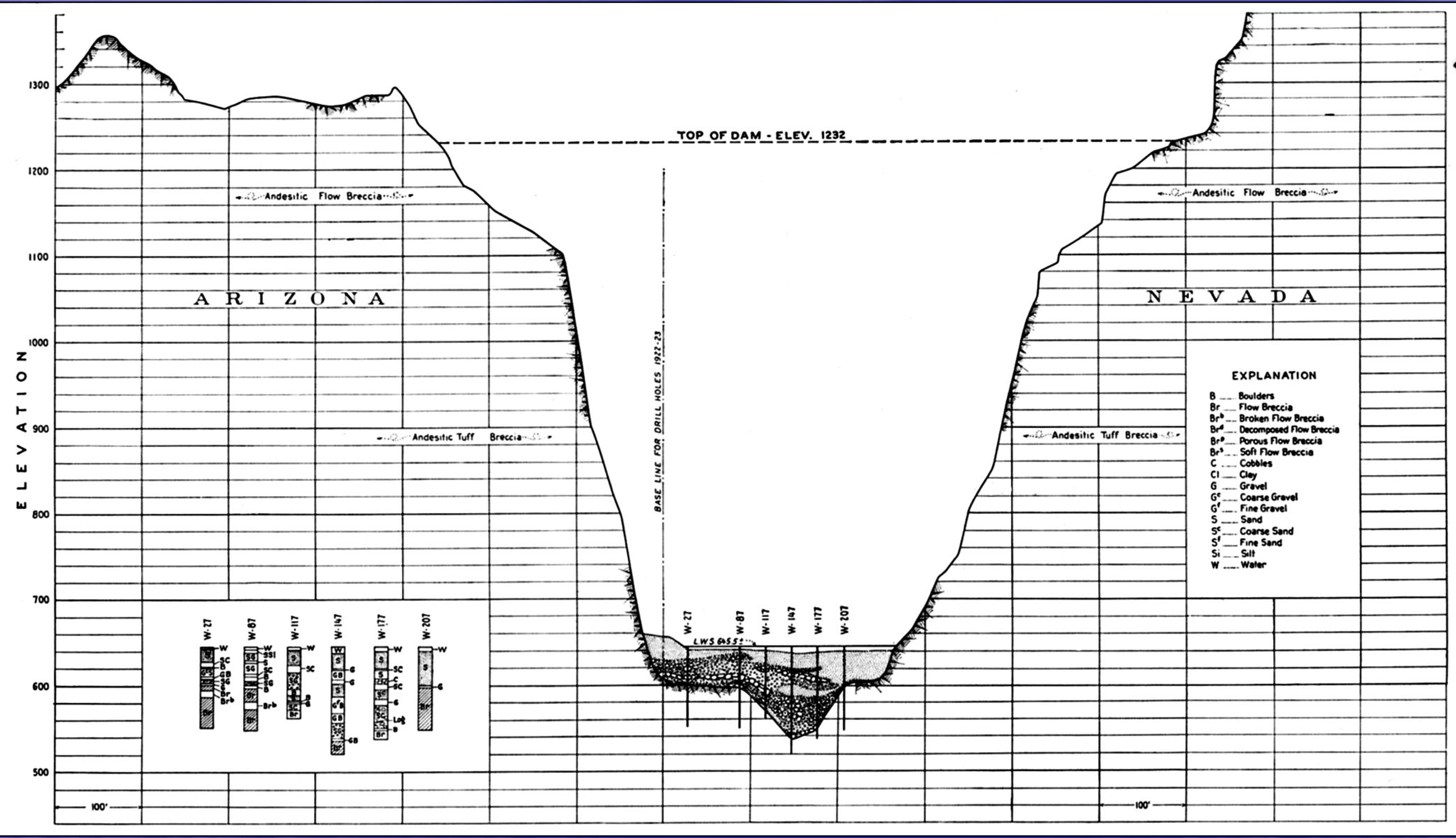
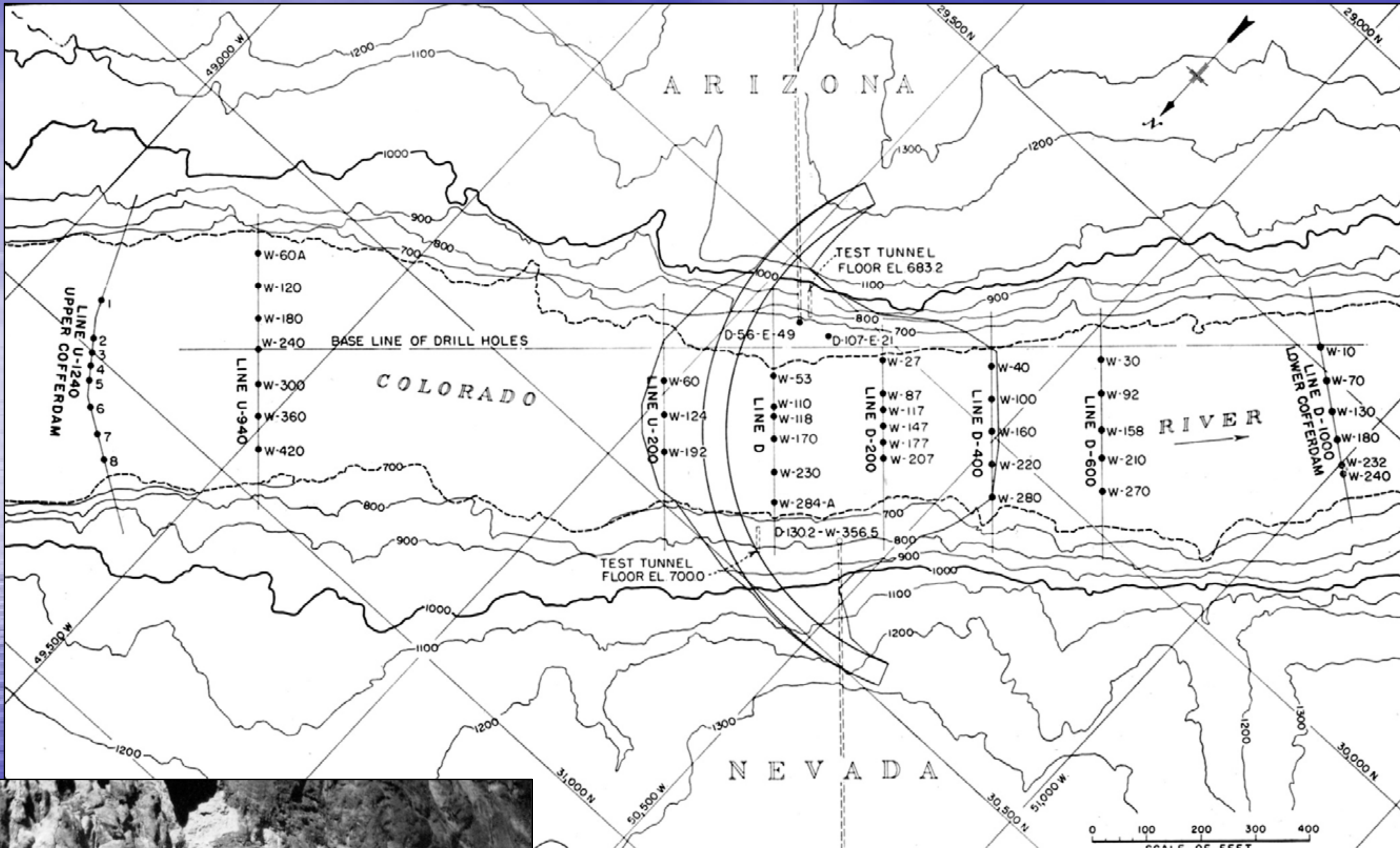
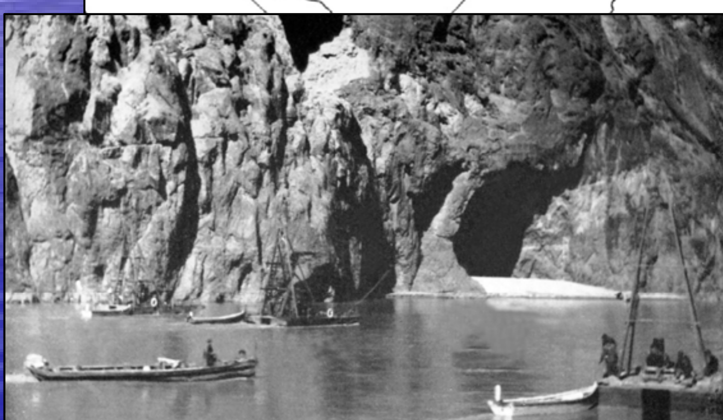
The initial characterization of the Hoover Dam site focused on the channel infill.

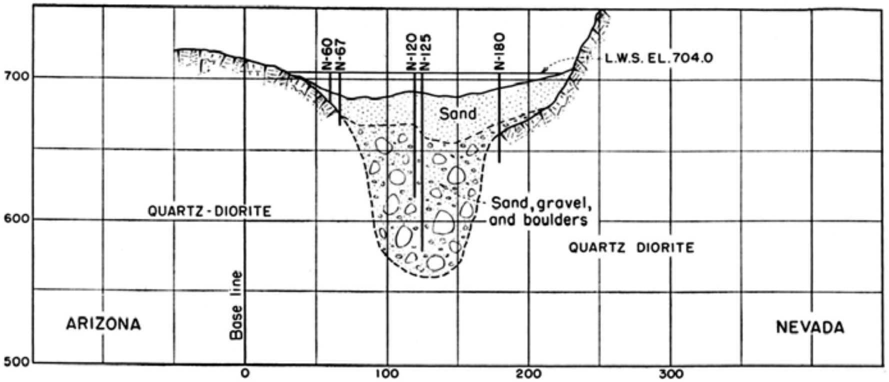


Canyon cross section in Black Canyon at Hoover Dam site.

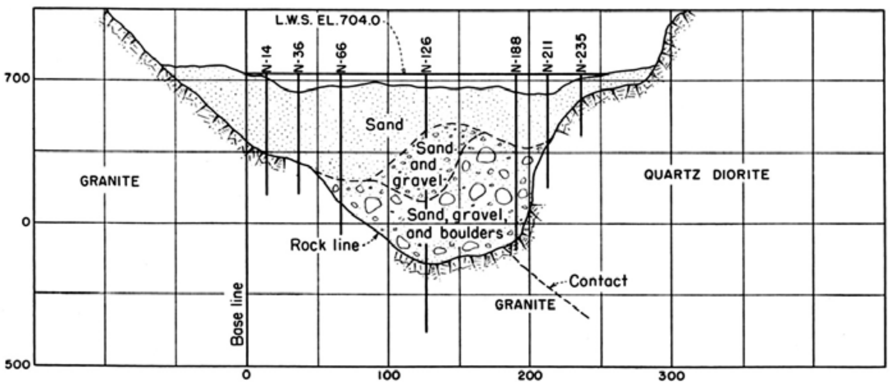




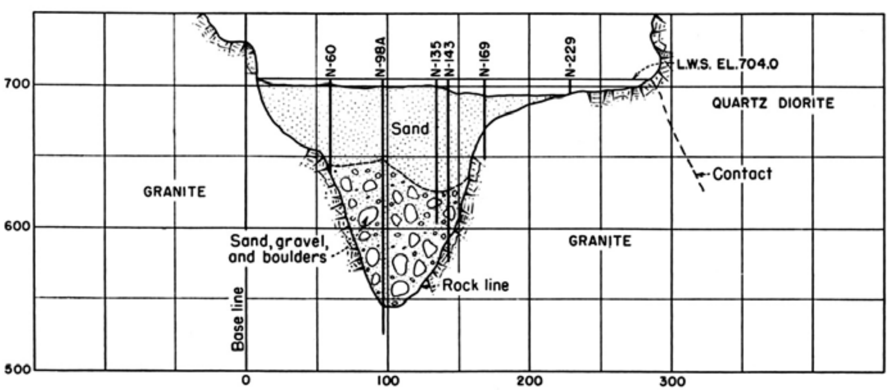
22 borings were advanced in the Colorado River channel beneath the proposed dam, along 4 lines, shown above.



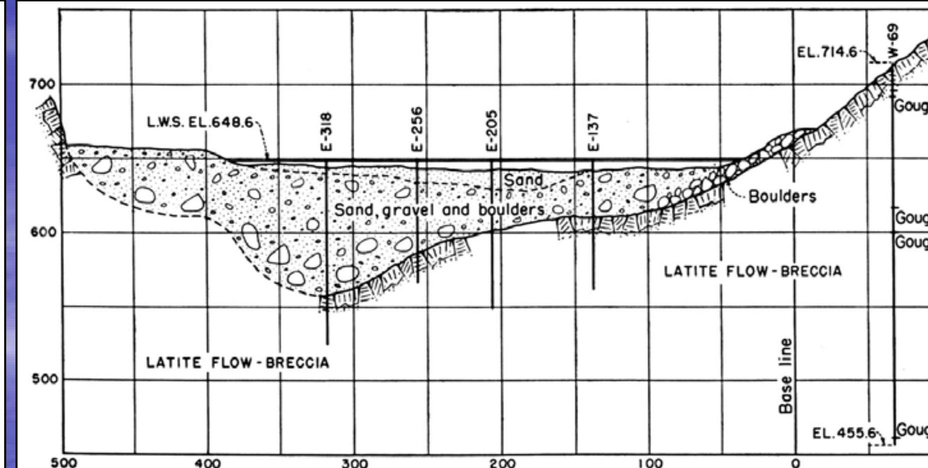
A. LINE U-200



B. LINE C-1



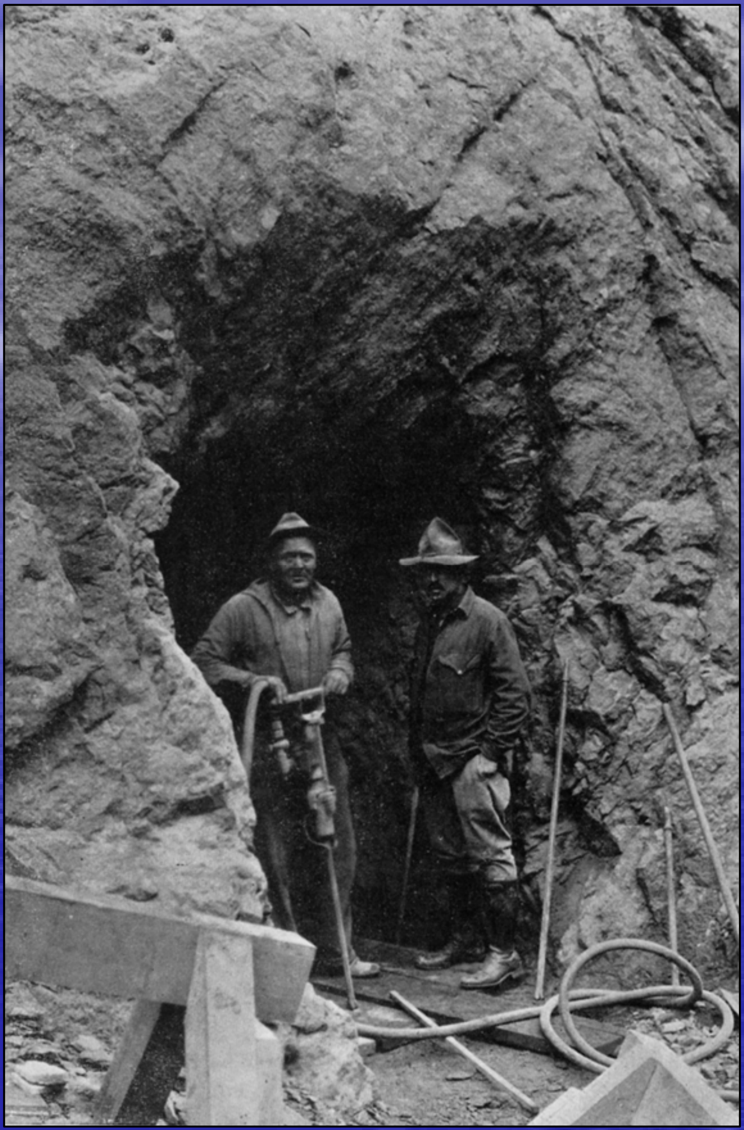
C. LINE D-200



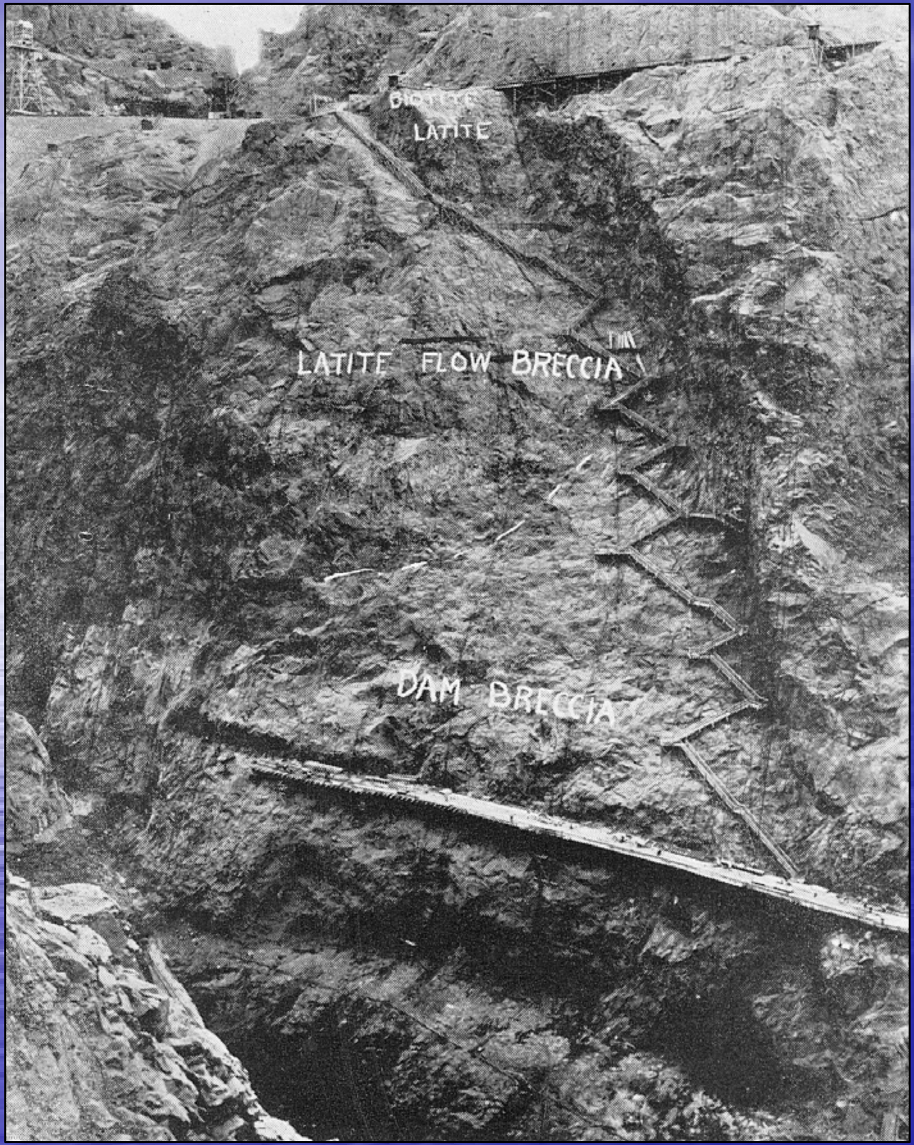
The primary focus of the exploratory borings was to ascertain the depth and character of the channel fill and the profile of the bedrock.

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

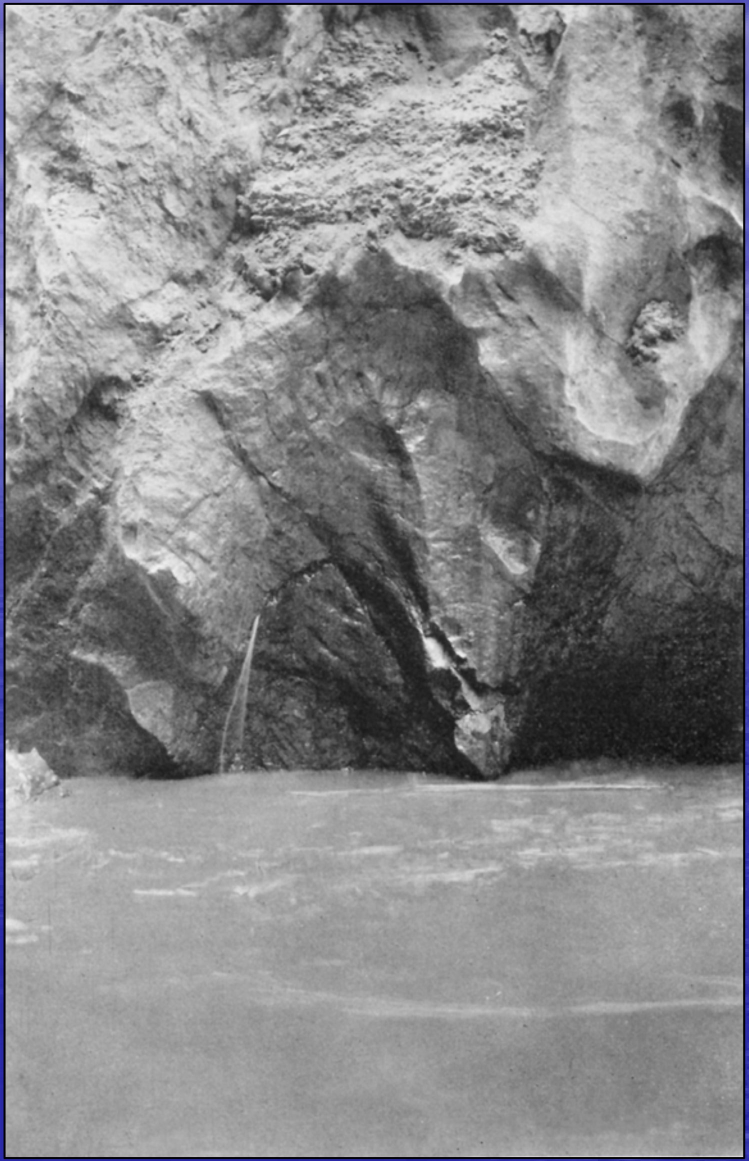
6-inch cores were extracted from the abutments for unconfined compression tests



Portal of exploratory adit on Arizona abutment, at elev. 683

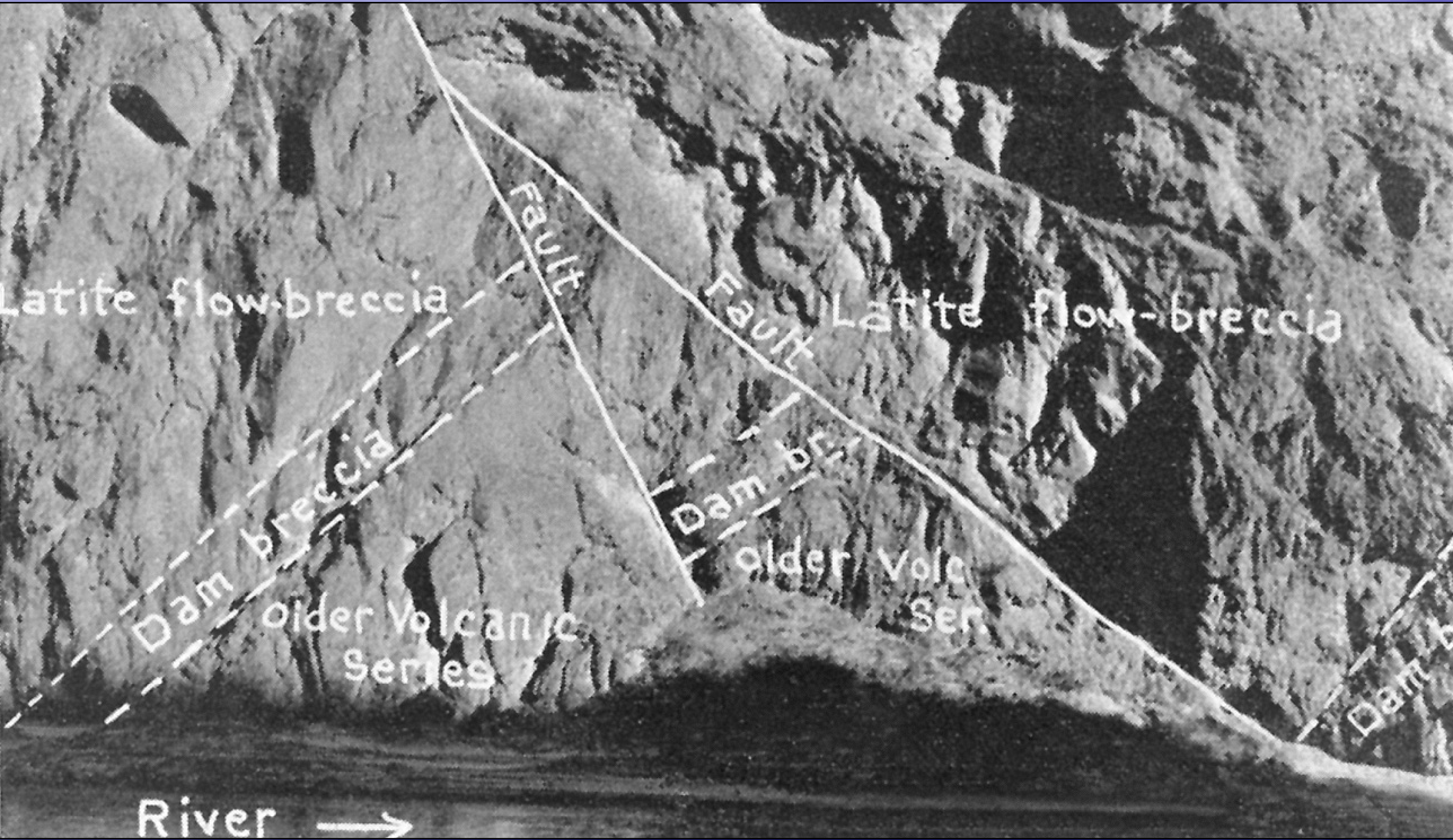


Right abutment excavation, showing contact between latite flow breccia and dam breccia.

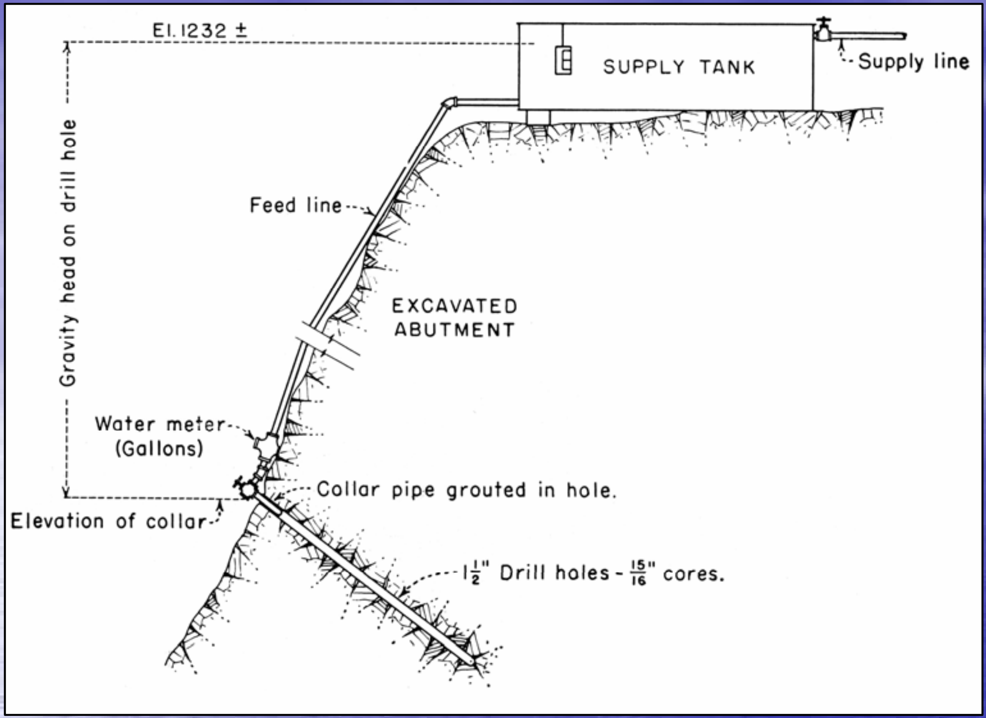


Hot springs at upstream base of right abutment, at river level.

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

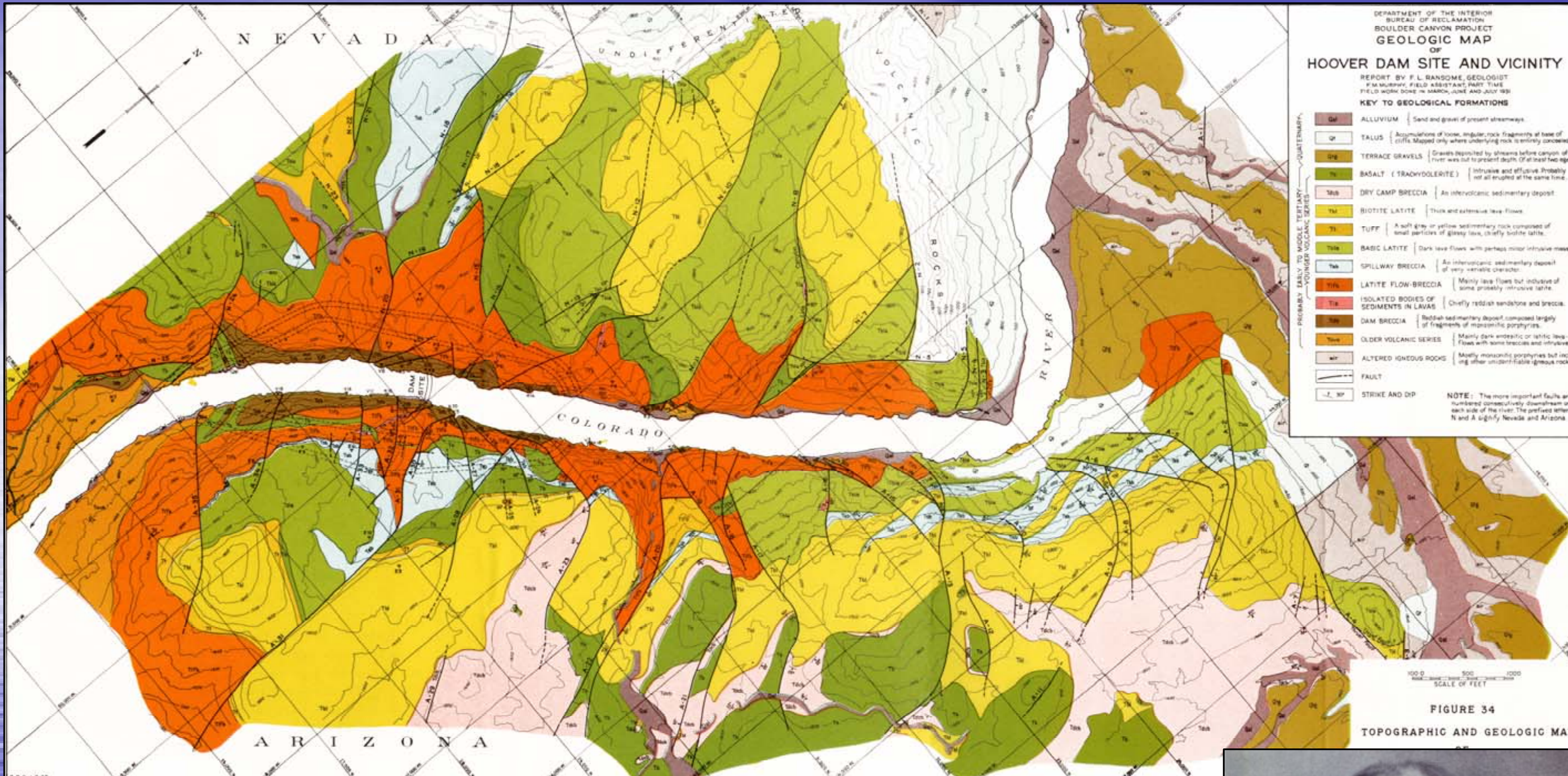


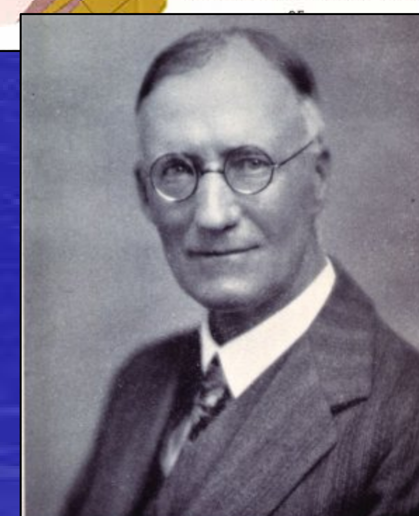
Normal faults mapped near base of the left (Arizona) abutment.



Crude percolation tests employed a gravity-feed reservoir that fed to drill holes through sealed pipes. These could not replicate pore pressures induced by 500 to 800 feet of head.

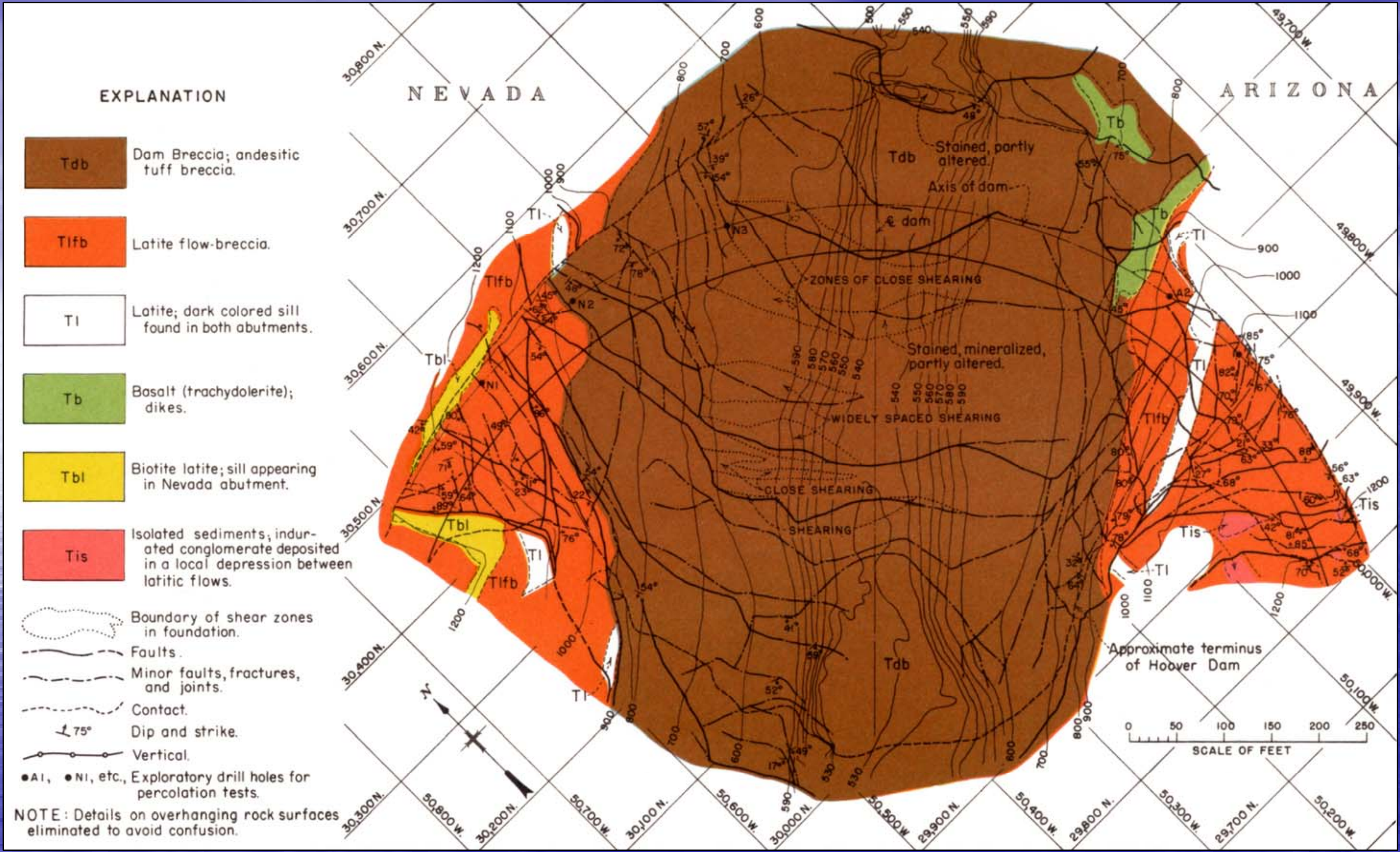
The latite breccia was characterized by locally intense fractures, especially along faults and shear zones. These inclined faults also crisscrossed one another.



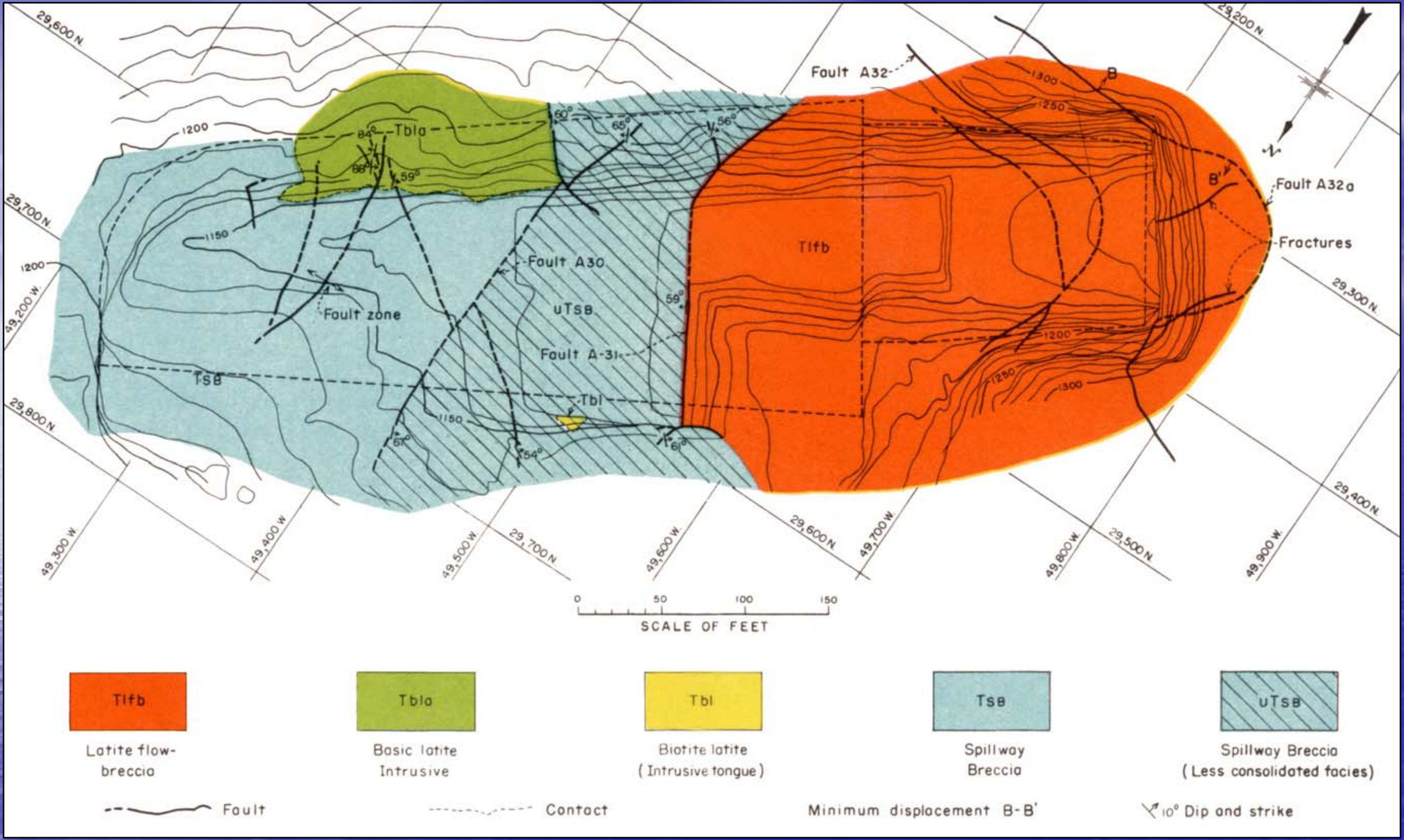


- **Cal Tech Geology Professor Leslie Ransome mapped the geology of the Black Canyon dam site ahead of construction.**

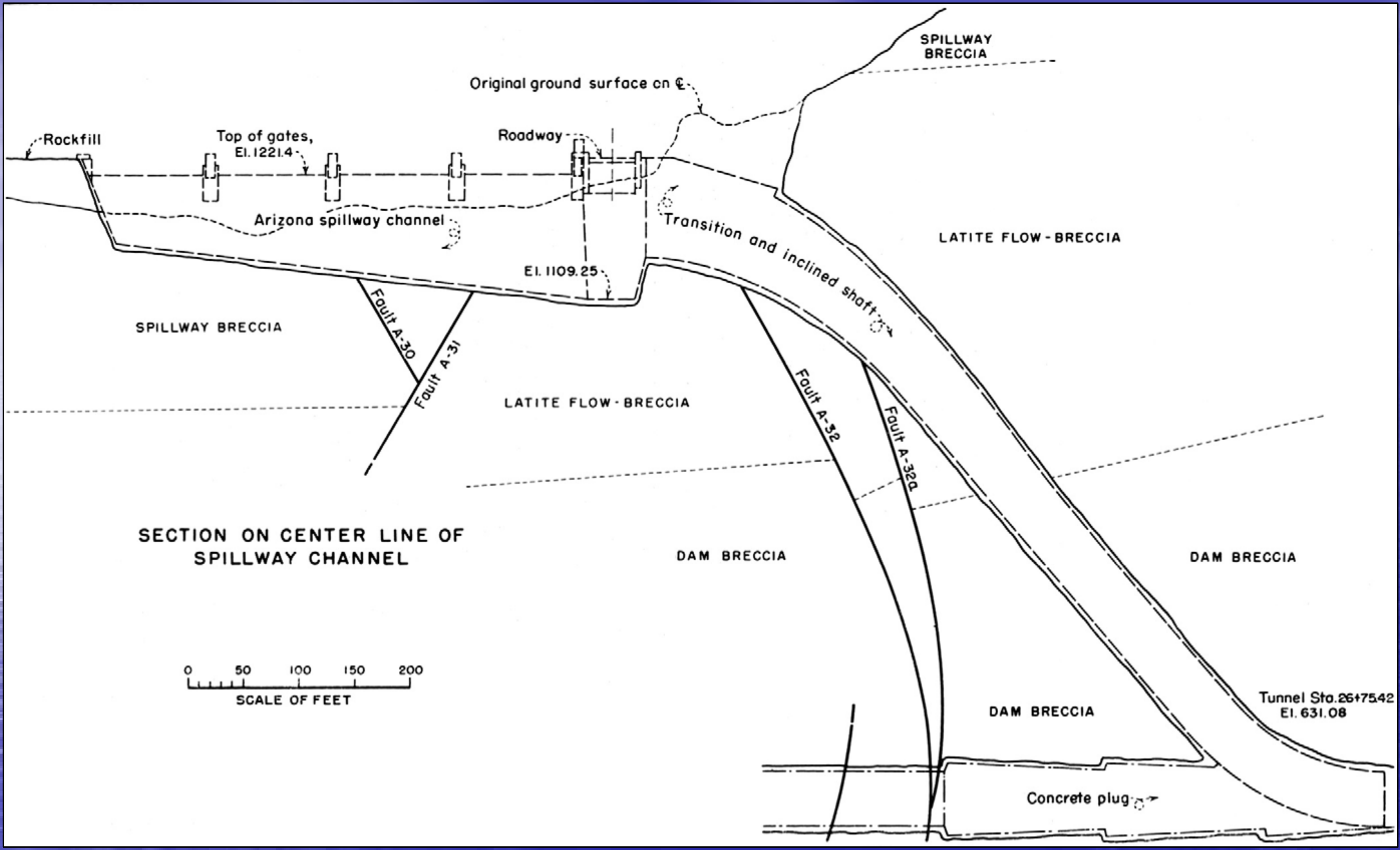
- Excavation of Inner Gorge in Colorado River channel beneath the dam.



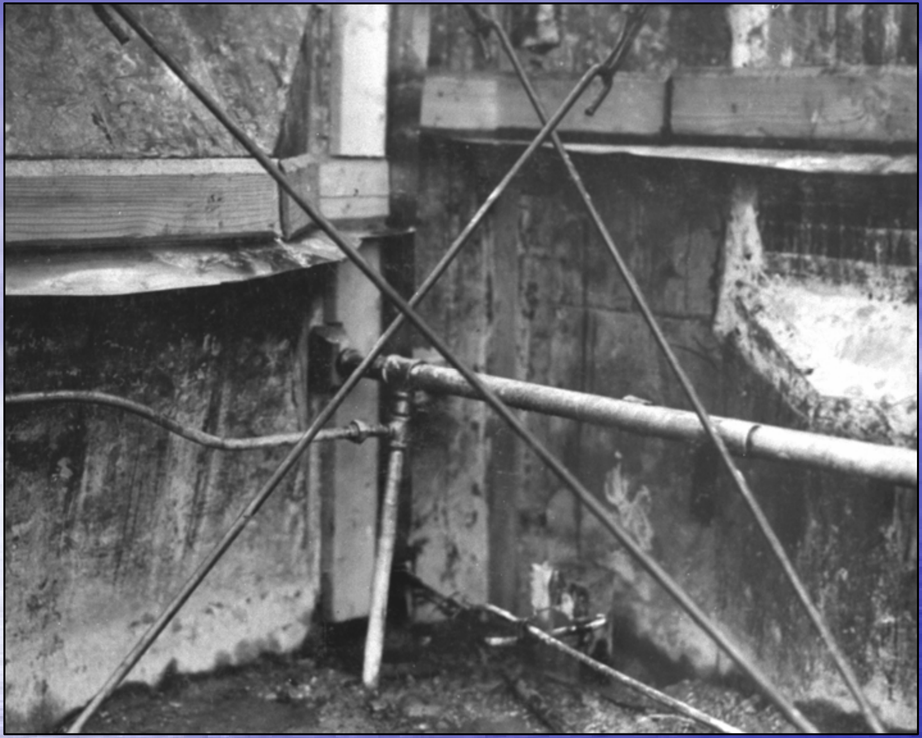
- The geology of the dam base was mapped after excavation of the channel gravels. Note faults and adjacent zones of intense shearing.



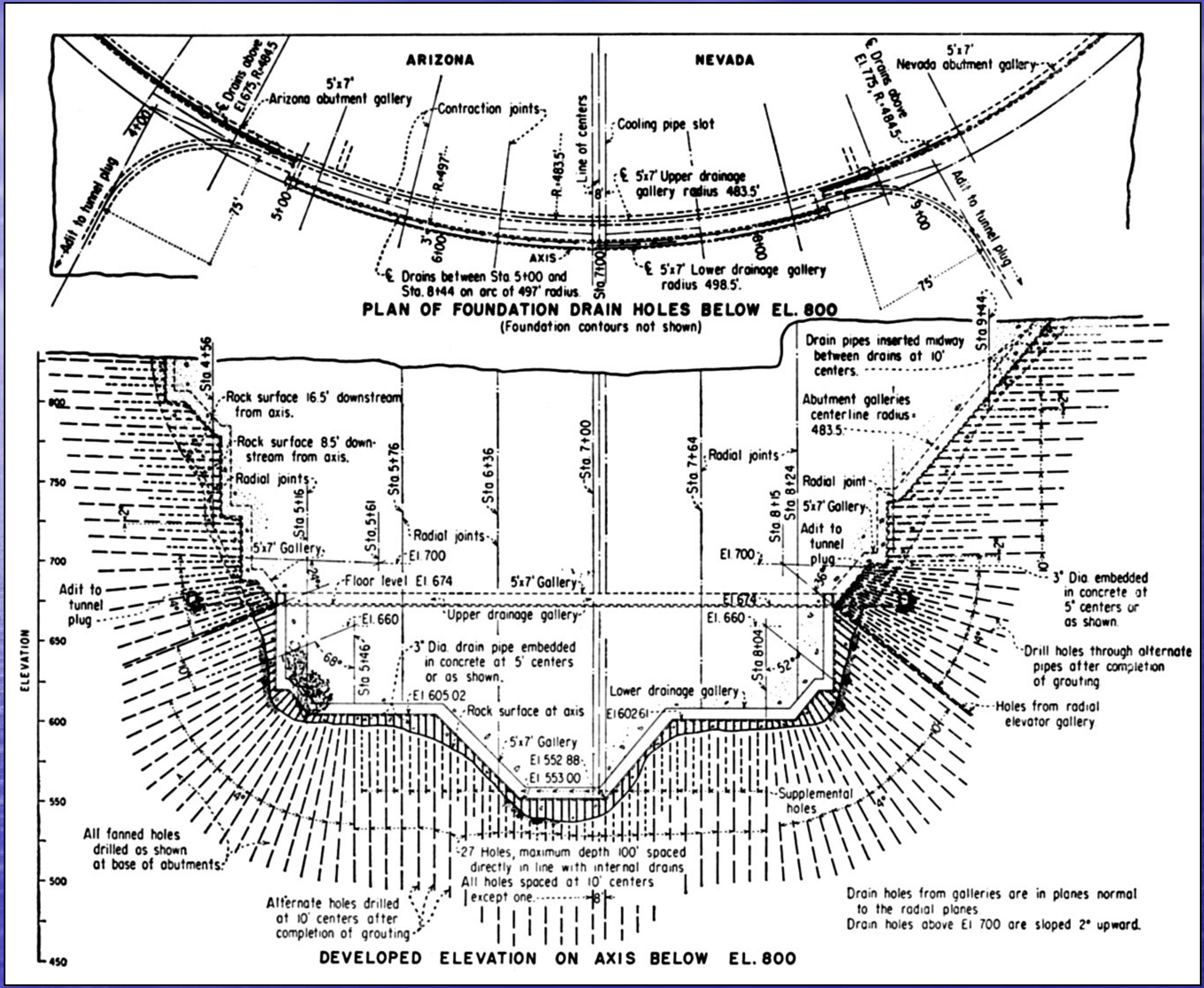
- Geologic map of the Arizona Spillway excavation. Faults were designated with alphanumeric nomenclature, @ to AZ or NV side of the canyon.



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



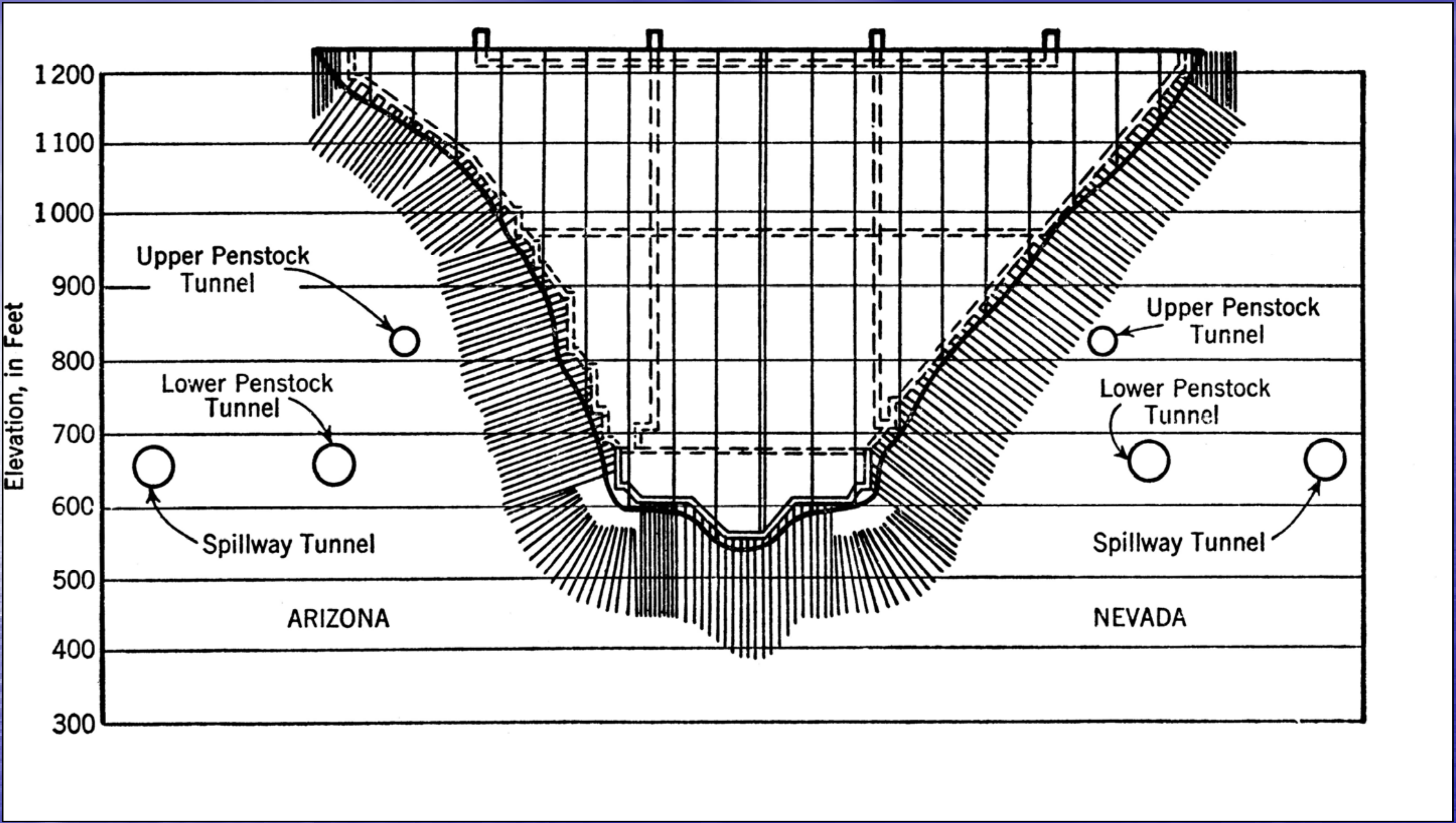
- A specially designed joint was employed between the dam concrete and the rock abutments. These joints were not grouted prior to the reservoir filling because the designers believed the dam would deflect downstream under full reservoir load.



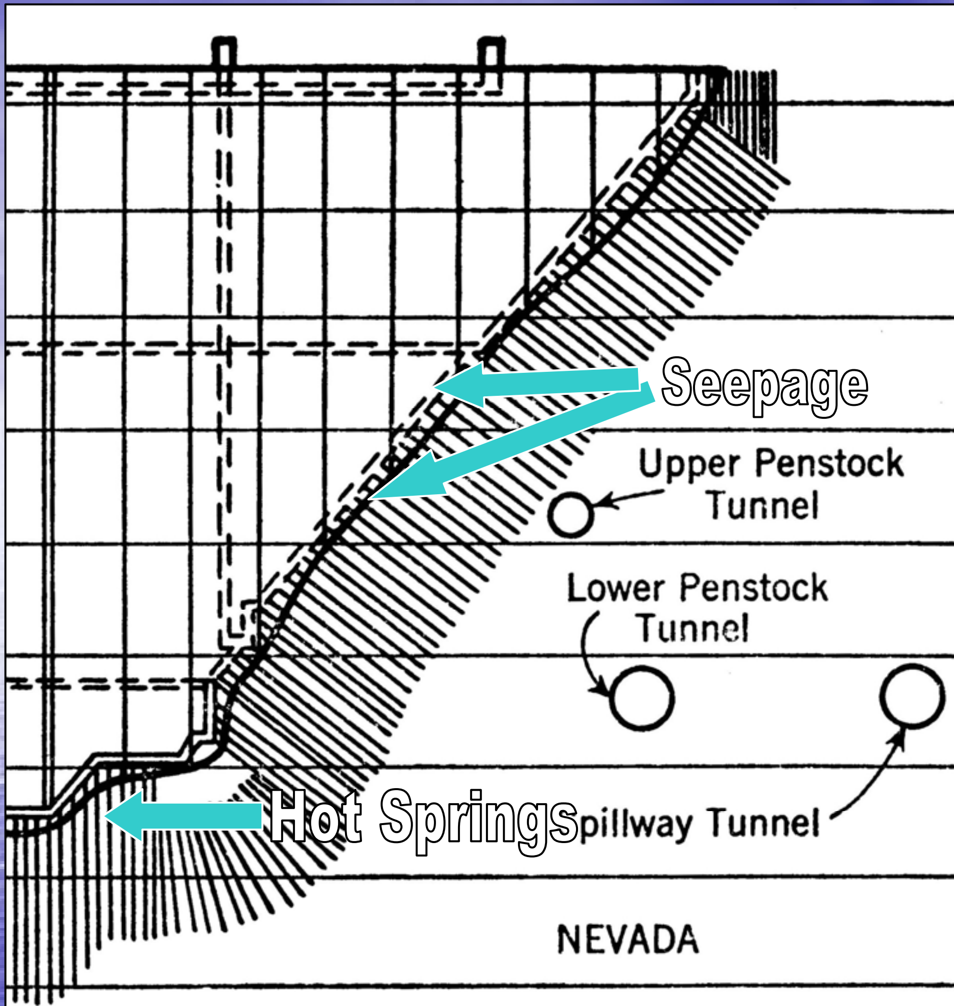
The grout curtain included a single line of holes 100 to 125 feet deep; about 14 to 21% of the dam height.

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

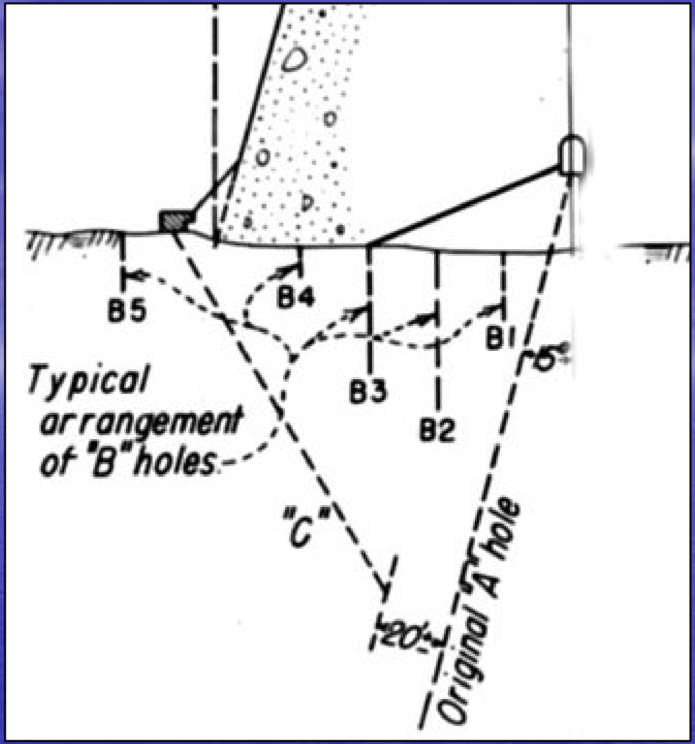


- **Profile of dam centerline showing pattern of original grout curtain. Note ratio of dam height to depth of the curtain.**

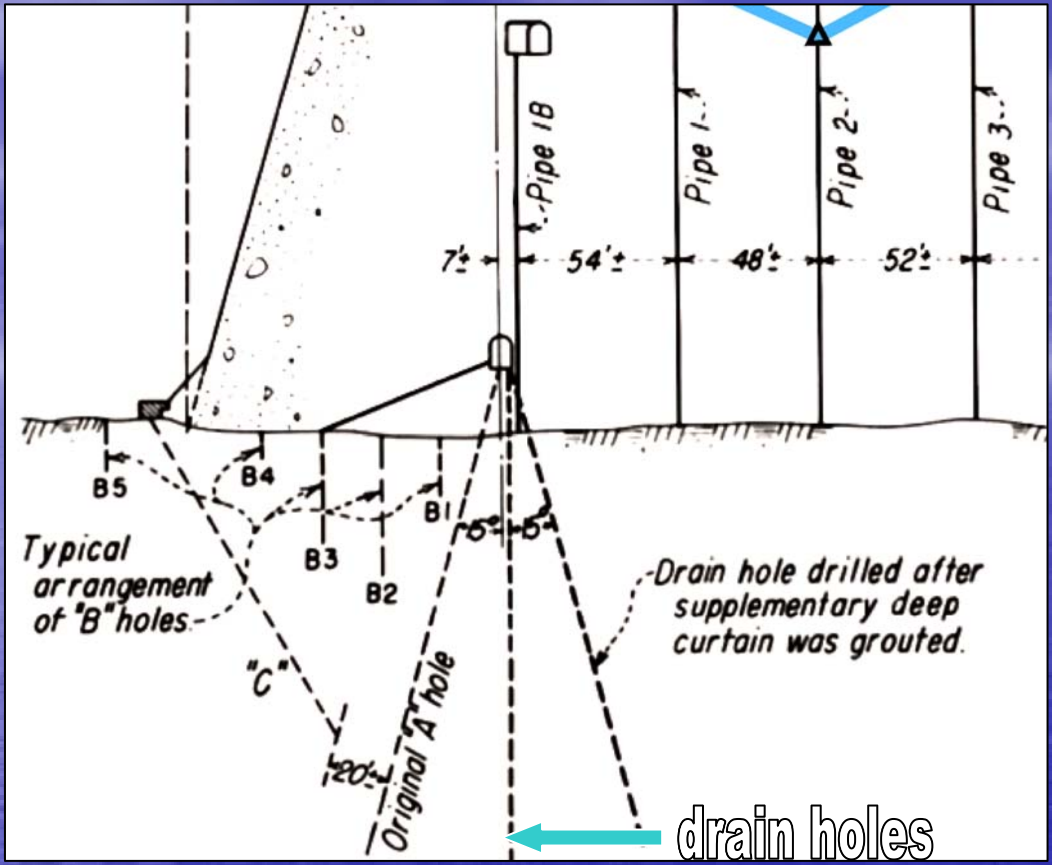


- **On the Nevada abutment** between elevations 840 and 940, several gout holes penetrated two distinct minor faults, and four holes had to be abandoned, because excessive grout take and leaks.
- When the reservoir reached 1100 feet elevation, the faults daylighted in the right abutment, and water began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

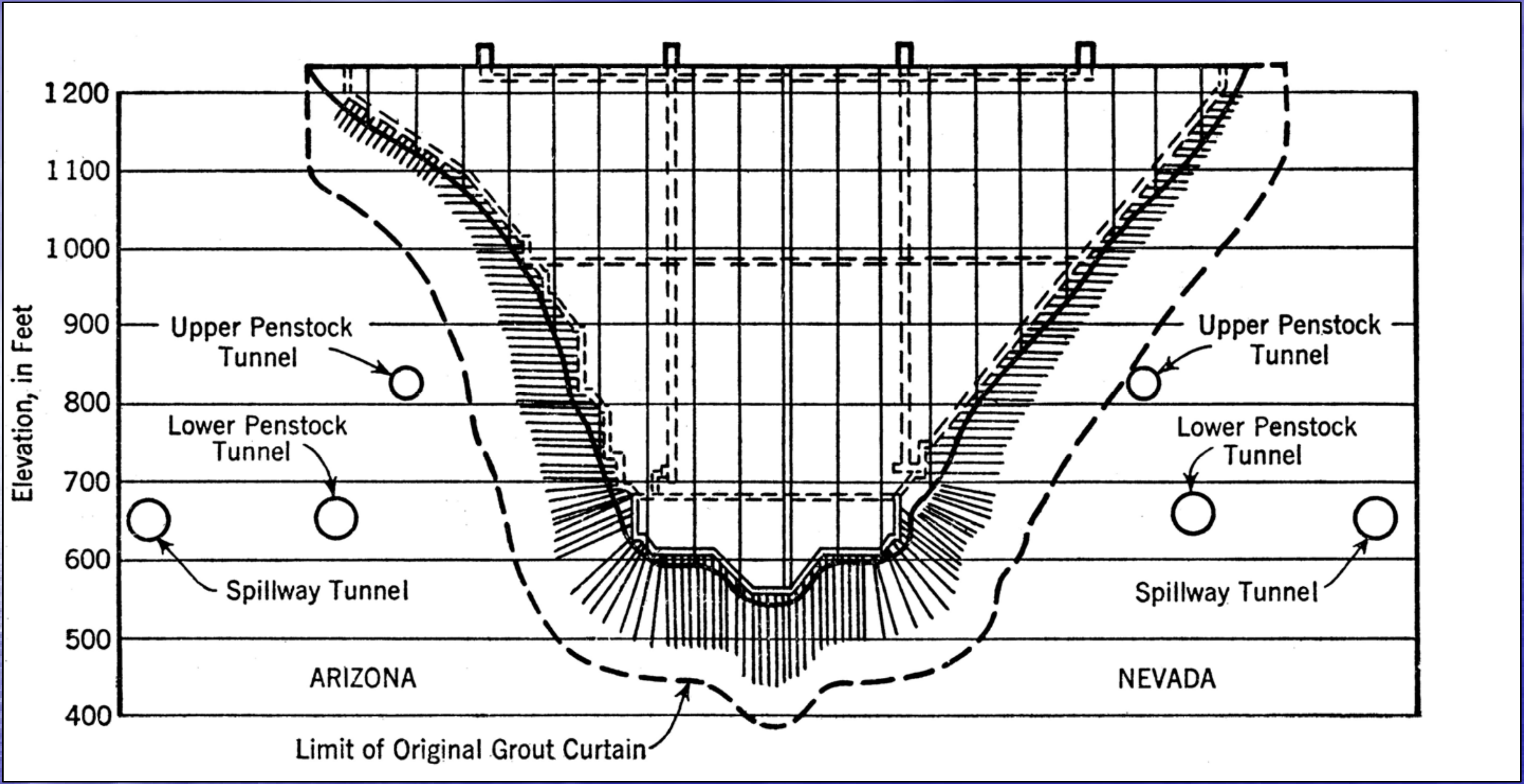
- Warm water from the natural hot springs was collected along the right abutment drainage gallery near elevation 555, emanating from several "shattered zones." During the original construction, grouting of this area was ineffective due to premature set of the cement grout.



- Four rows of shallow **B holes** were drilled 30 to 50 ft deep, spaced 20 ft apart. These would be considered "dental work."
- The **C holes** were drilled on an incline from outside the upstream heel of the dam (above left) on 10-foot spacings to a maximum depth of 100 feet.
- The C holes were grouted with pressures of up to 900 psi prior to drilling of the **A holes**, which were inclined upstream, from the lower drainage gallery (upper right).

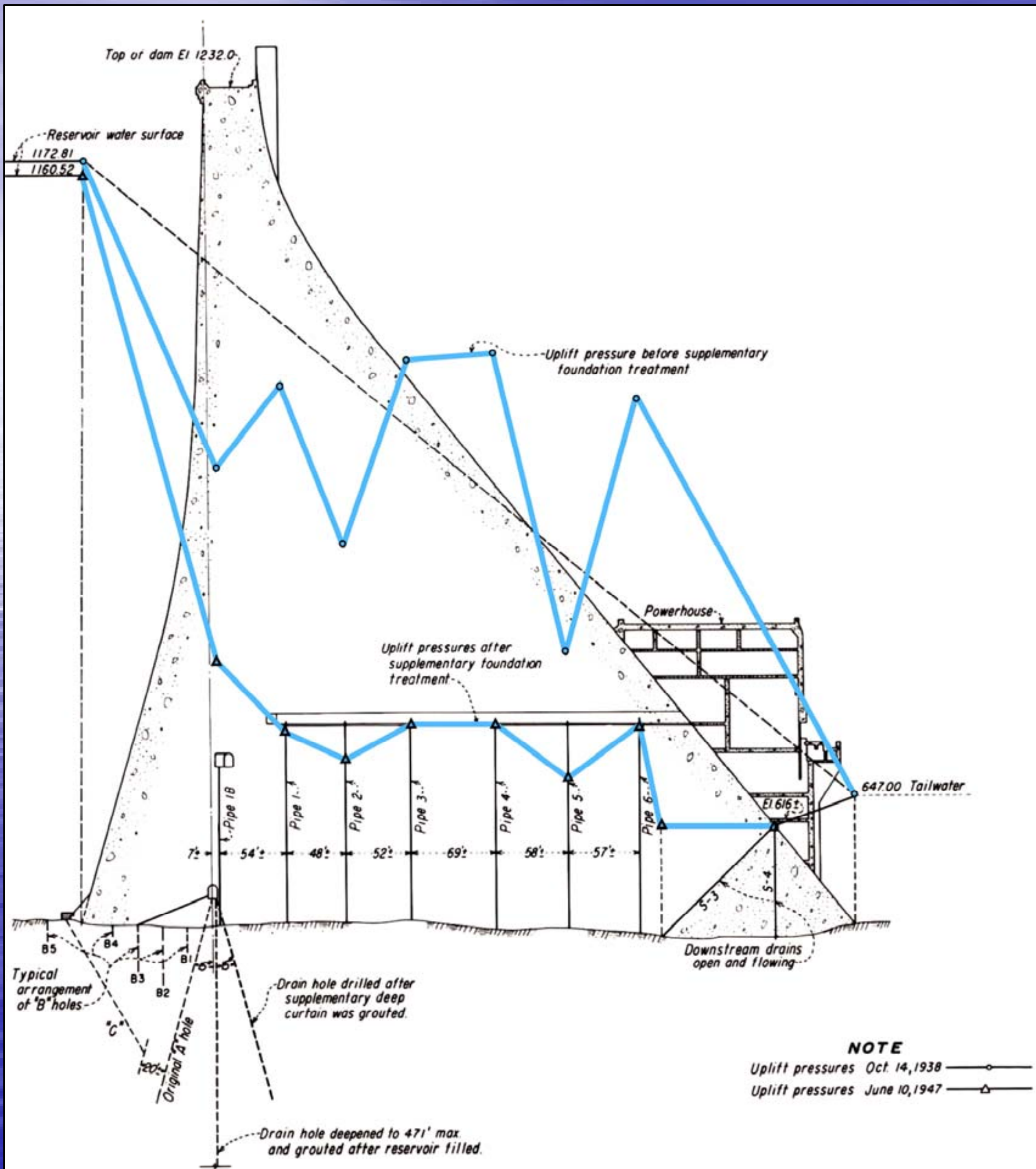


- The "**A holes**" forming the curtain were 150 feet deep, on 5 –ft centers, inclined 15 degrees upstream
- 191 A holes on Nevada side, 33 being abandoned
- 202 A holes on Arizona side, 21 abandoned
- Vertical drain holes 100 feet deep



- **Profile of dam centerline showing pattern of original drain holes, which extended a maximum of 100 feet. Note ratio of dam height to depth of the uplift relief holes.**

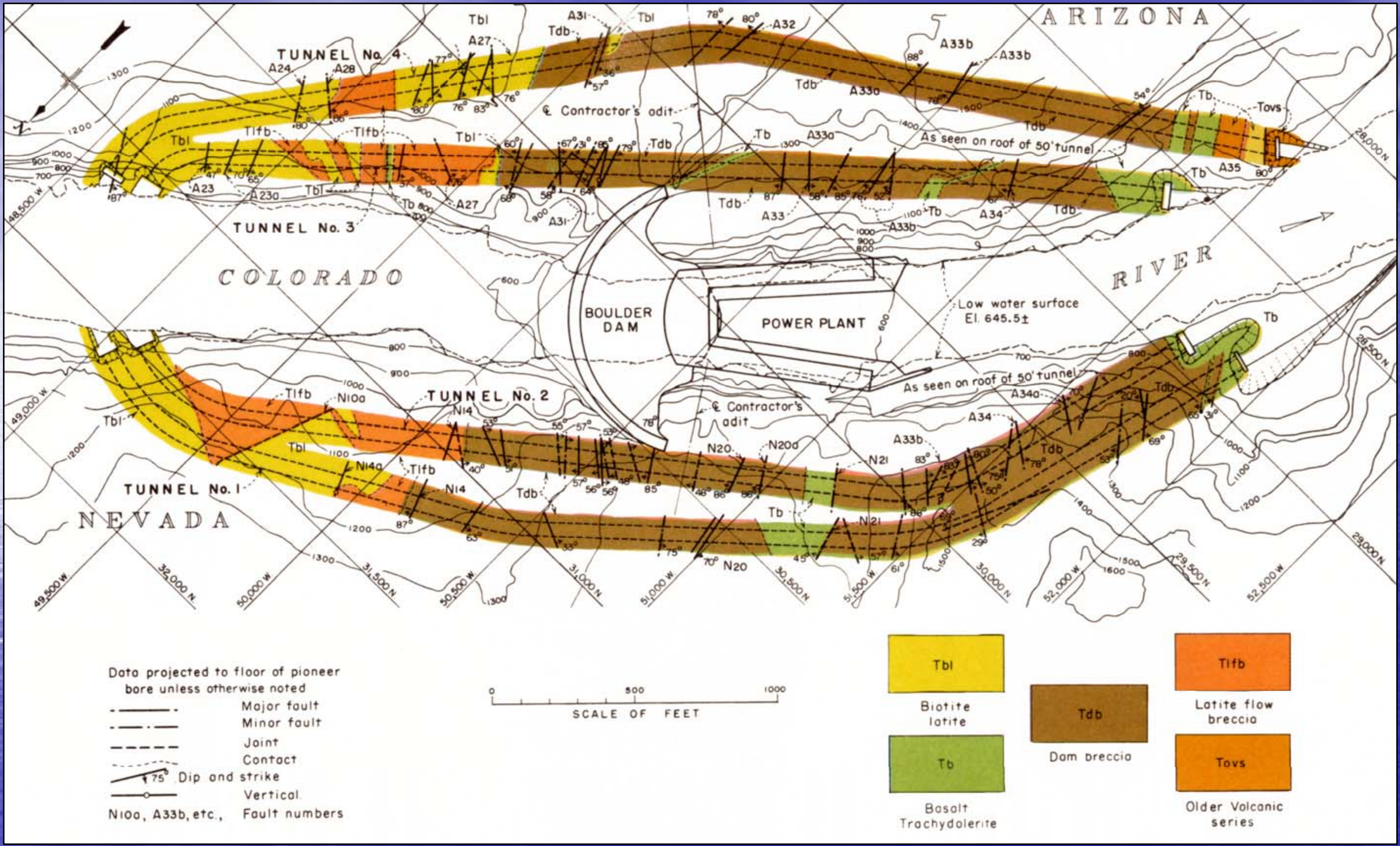
Failure of the Grout Curtain



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

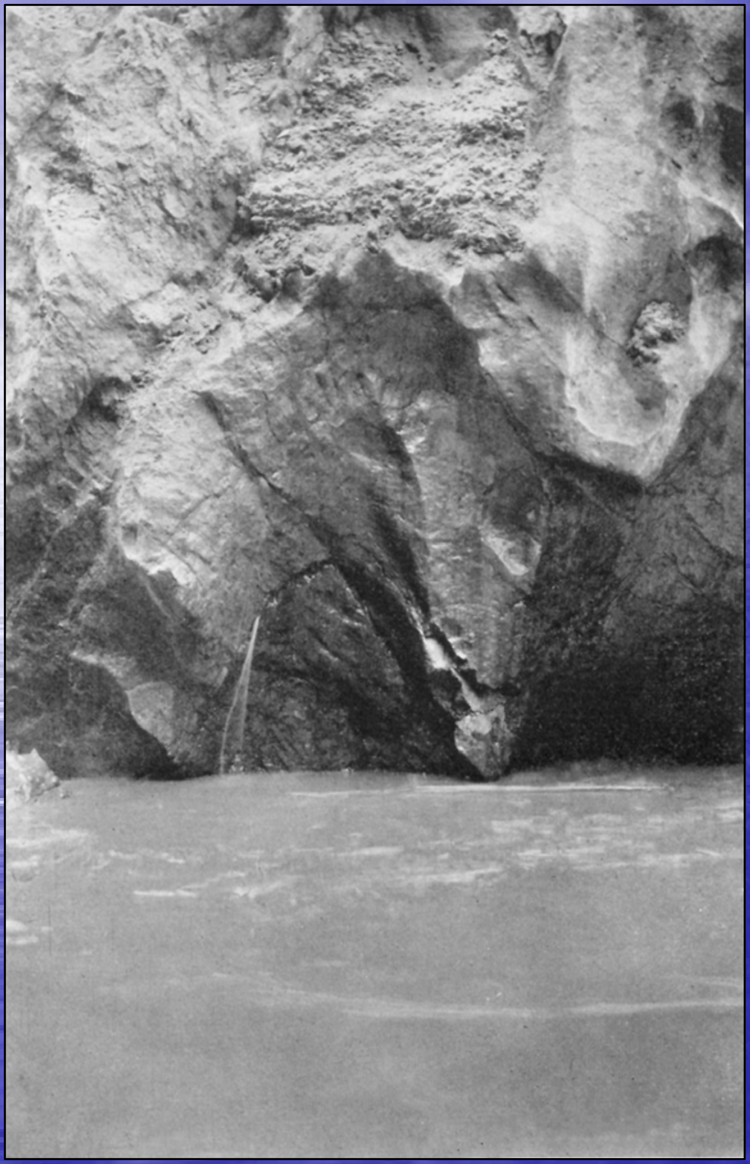
Abnormally high uplift pressures developed beneath the center of the dam

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



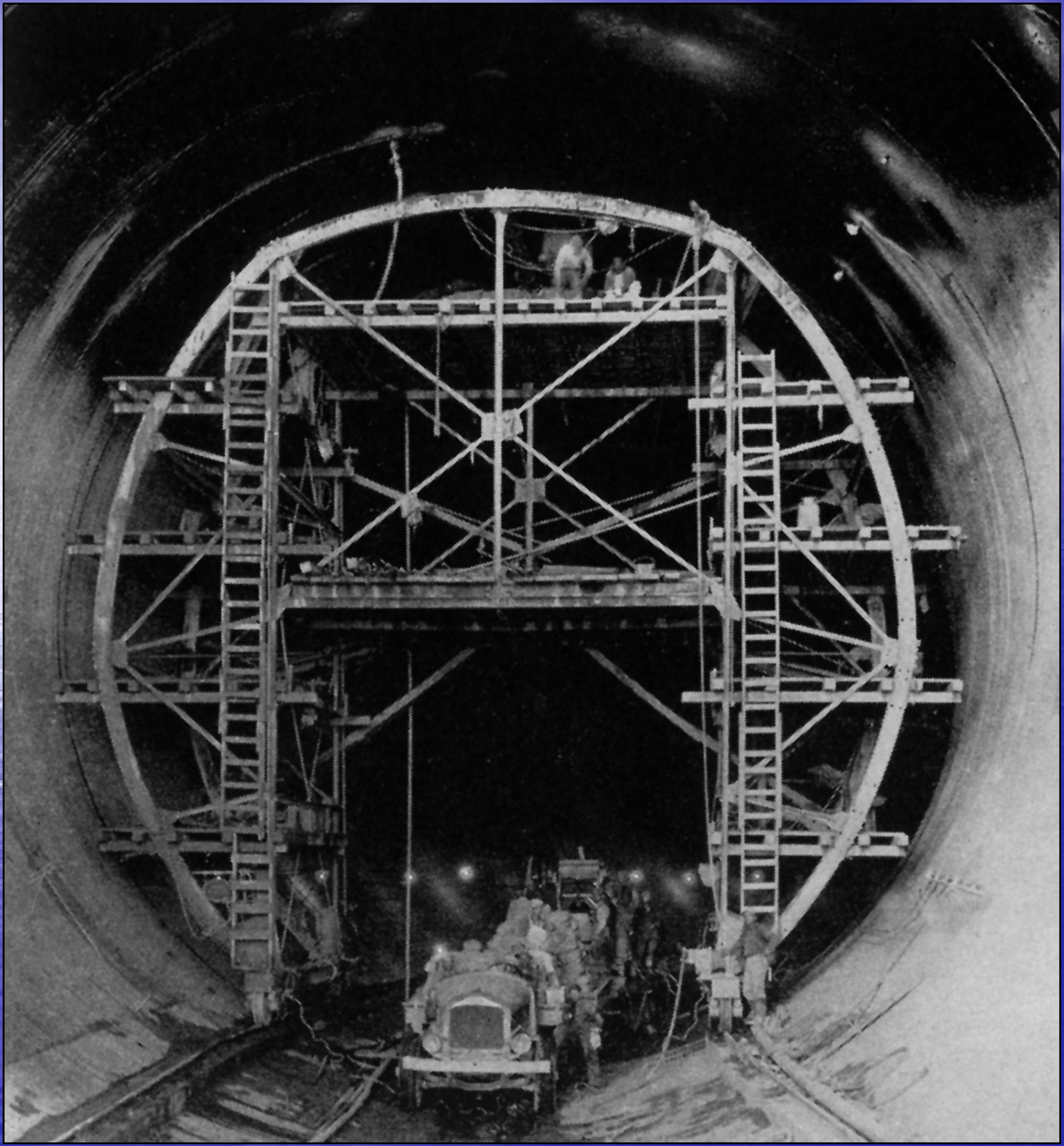
- **Geology encountered in the four massive diversion tunnels. Note the number of faults.**

Alkaline water accelerates corrosion of lower penstock feeder



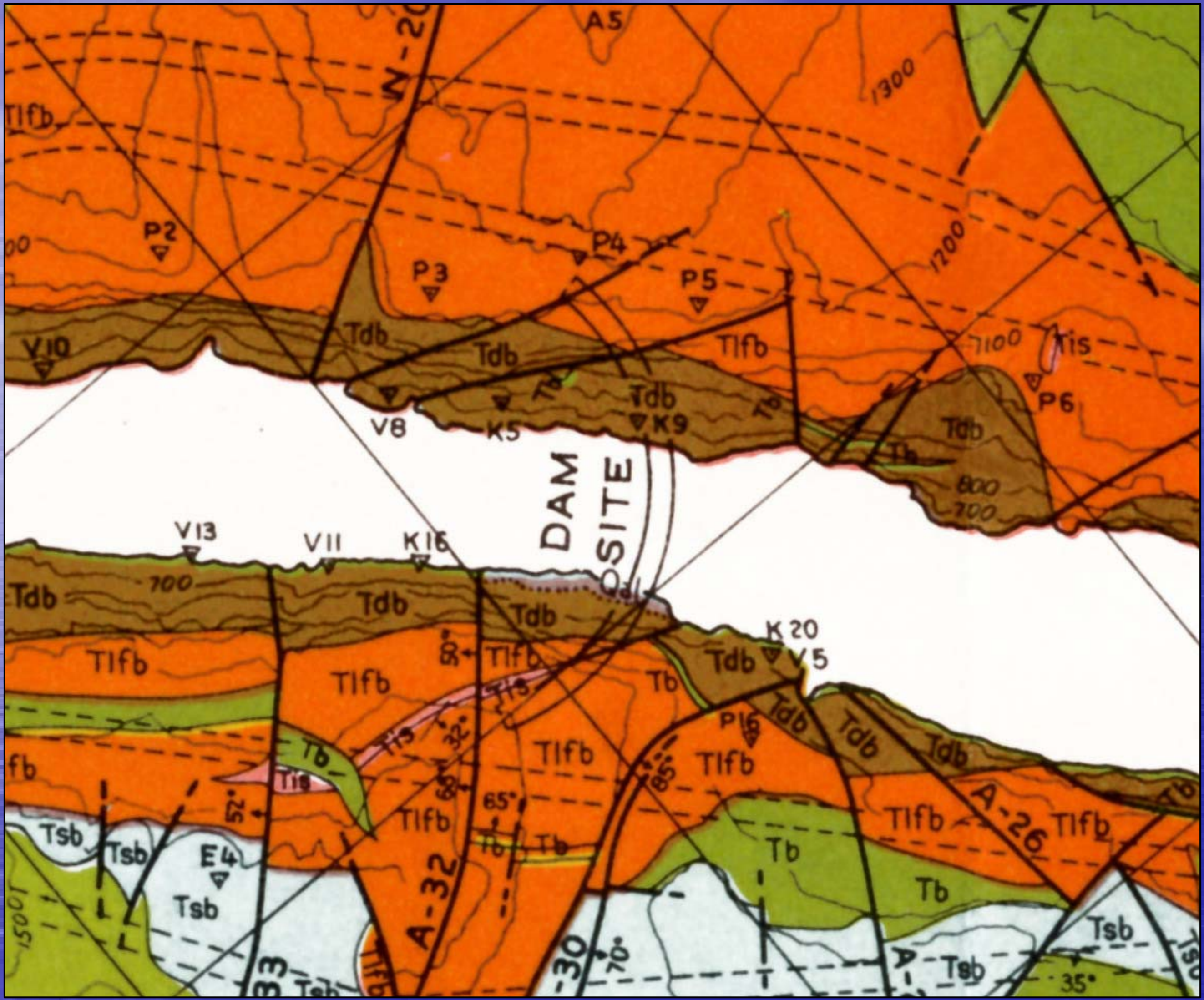
Hot springs on Nevada abutment

- 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

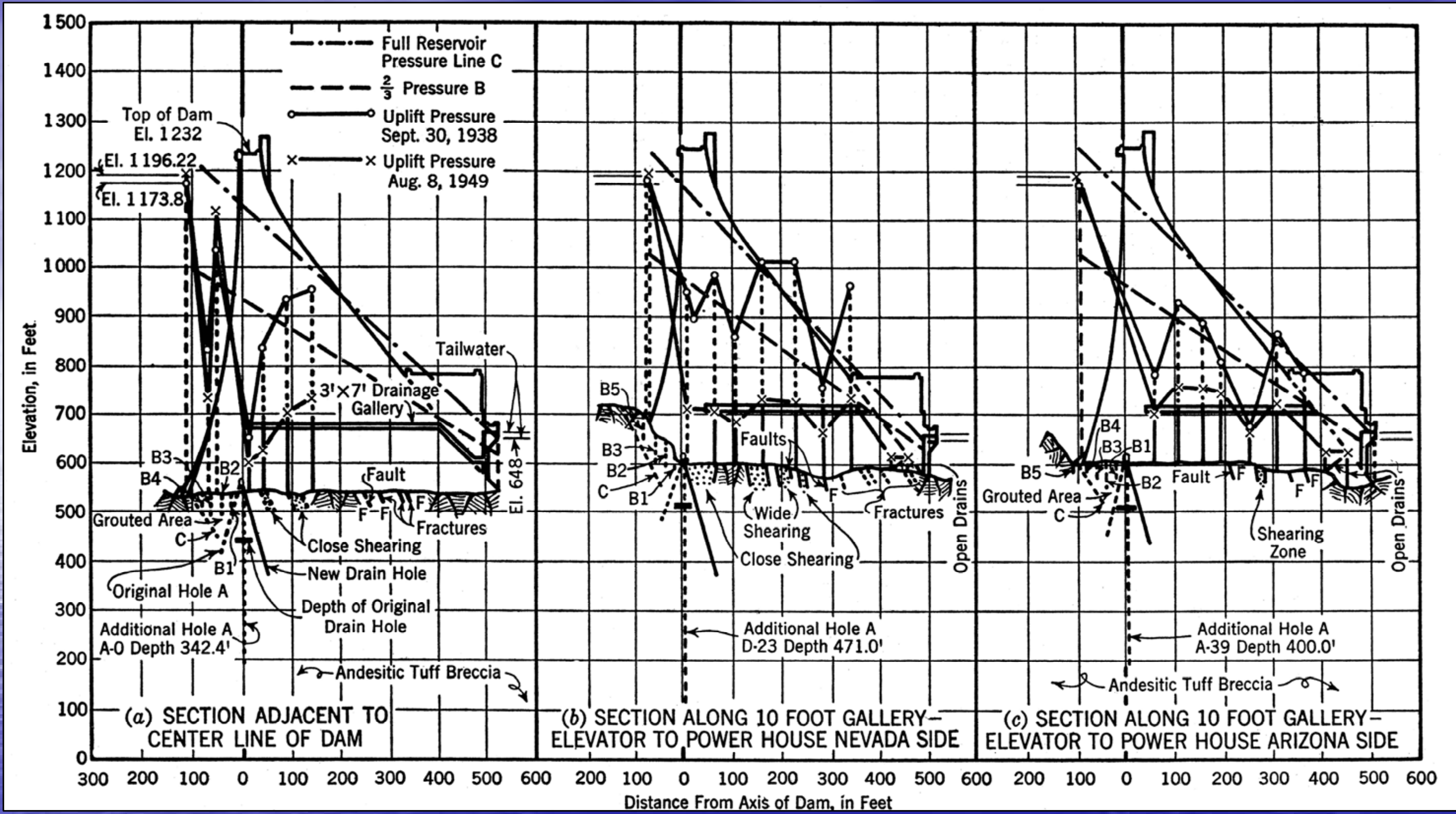


Grout drilling jumbo used in diversion tunnels

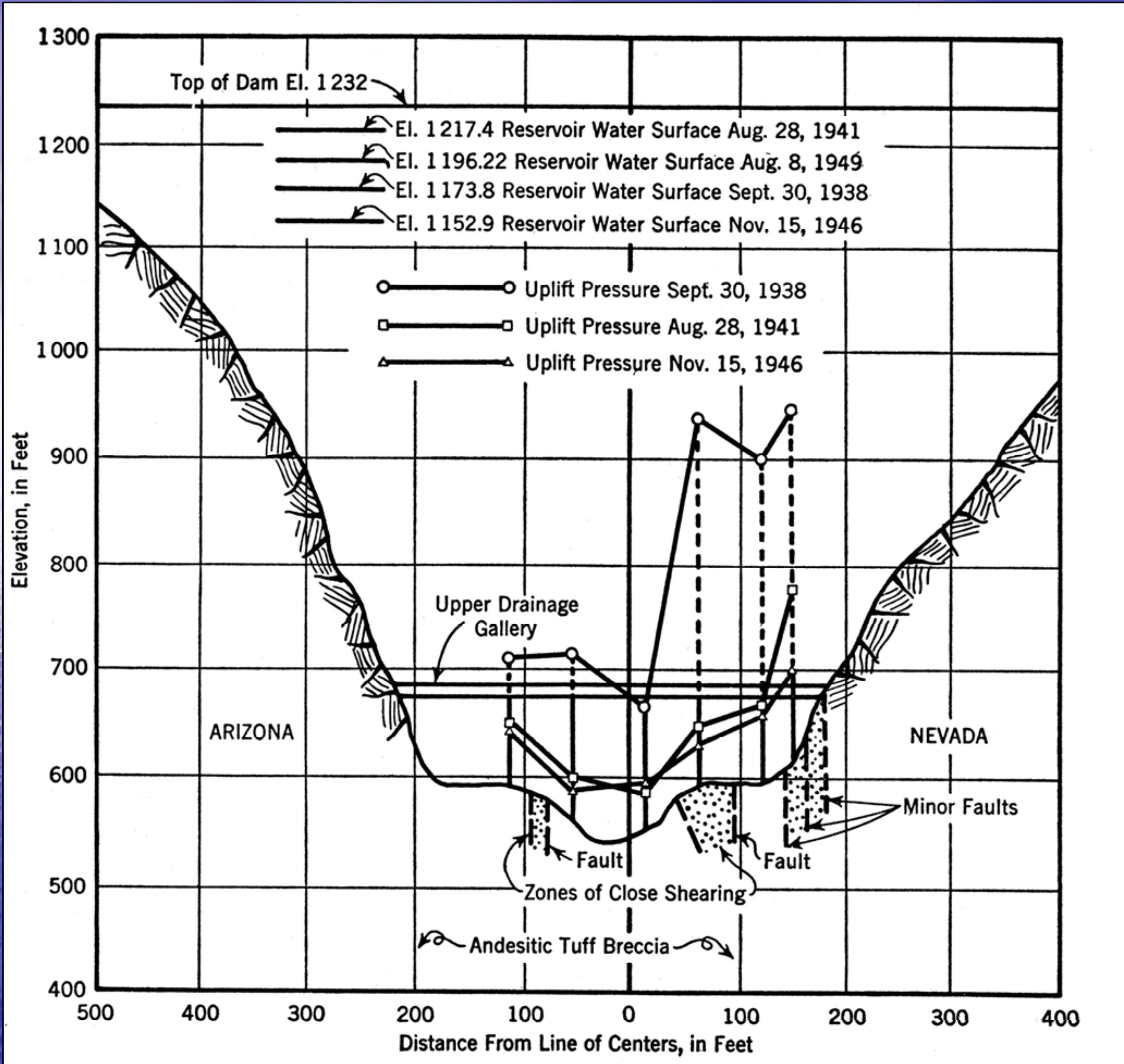
- The rock around the massive 56 foot diameter diversion tunnels was grouted after tunnel lining
- The lining of the inboard Nevada penstock leaked when the reservoir was filled



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



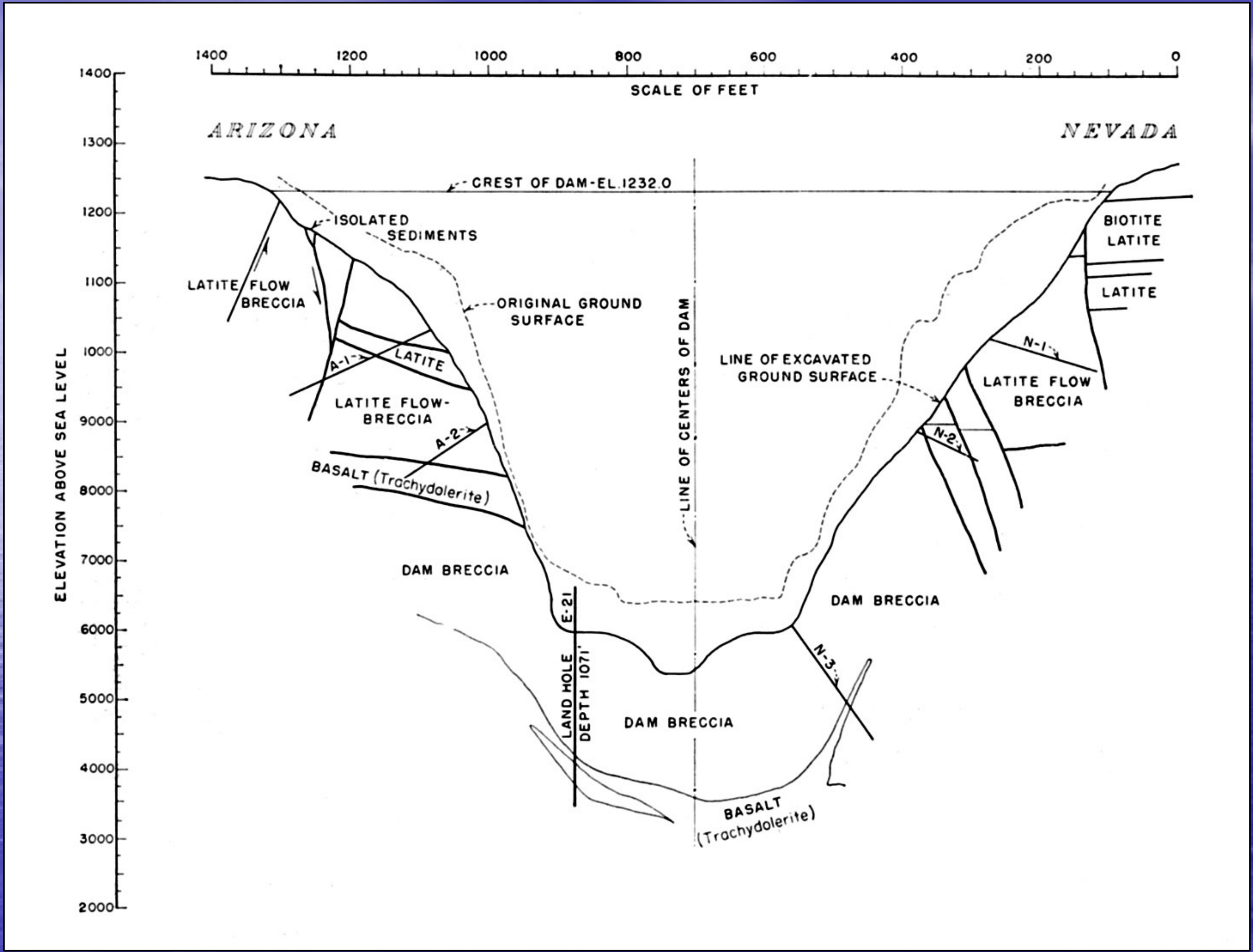
- **Uplift pressure gradient plots**: a) at dam centerline; b) along gallery elevator Nevada side; and c) along gallery elevator on Arizona side



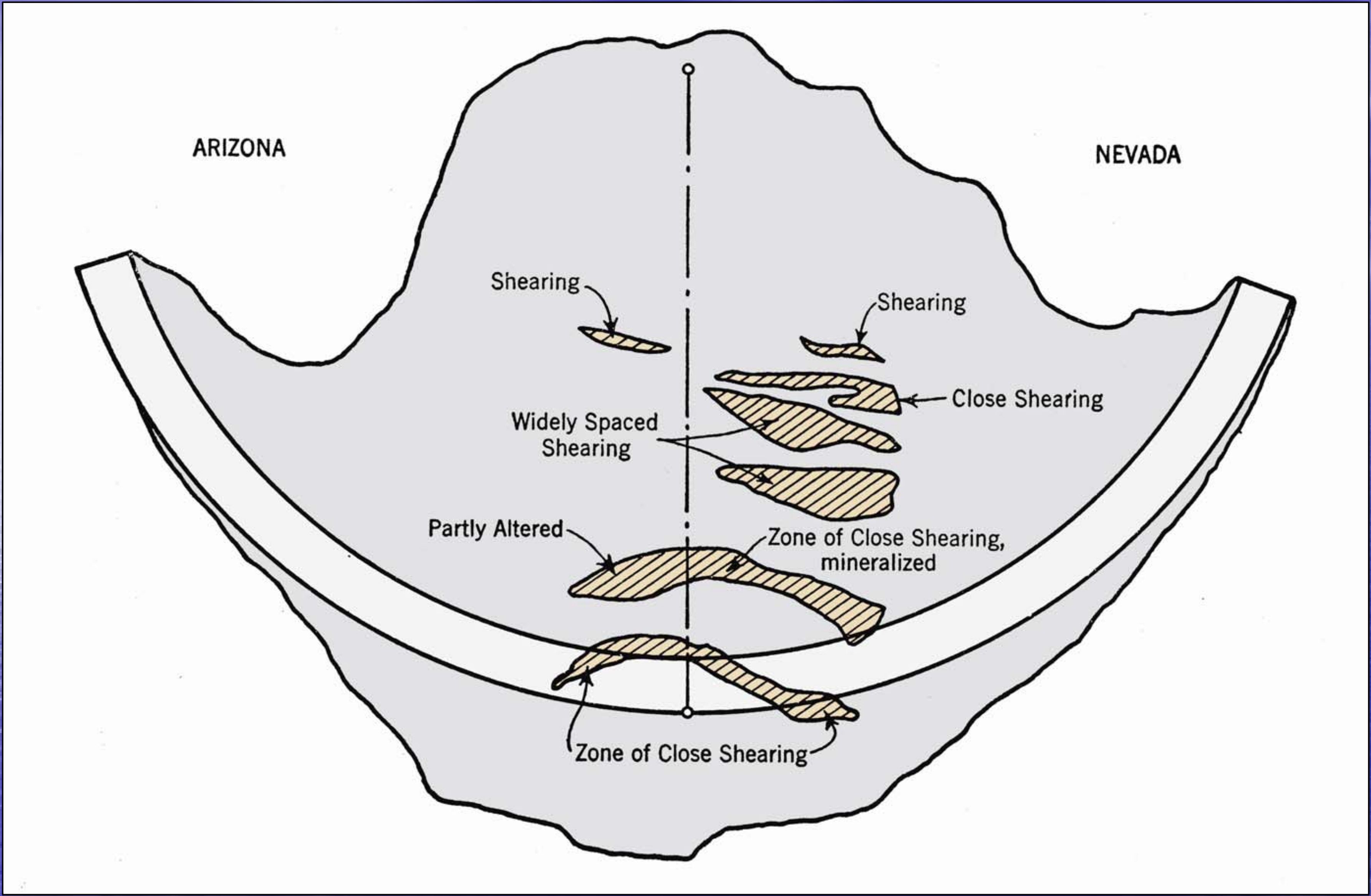
- Uplift pressure gradients along centerline of upper drainage gallery.
- Note increased pressures on Nevada side and fault zones

1938-39 exploration program

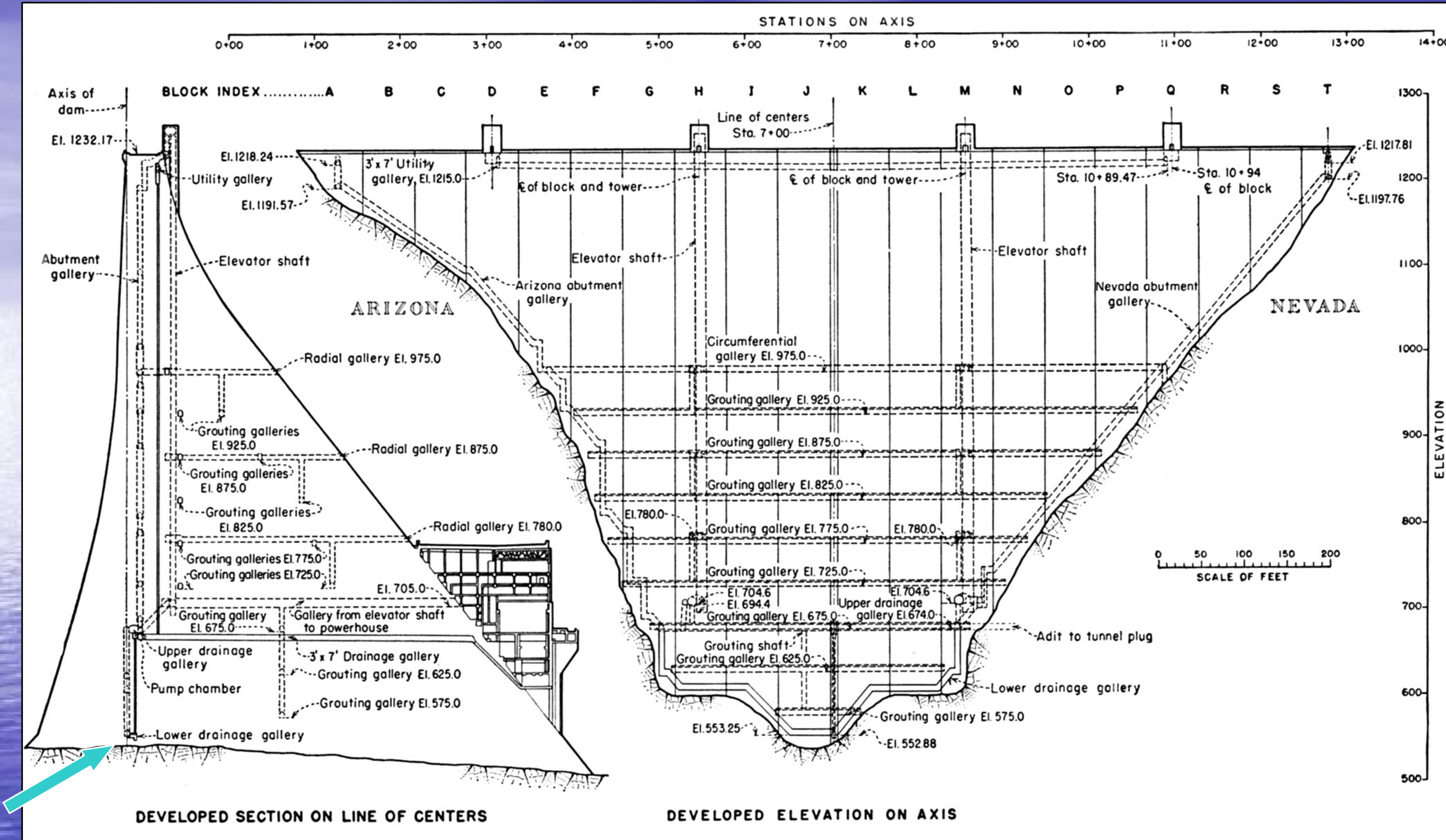
- Reservoir uplift reached its maximum levels in September 1938
- The decision was made to drill a series of BX size cores in the foundation beneath the dam
- The drilling revealed that the grout curtain was much too shallow on the faulted abutments, because 6 zones of intensely sheared rock were feeding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



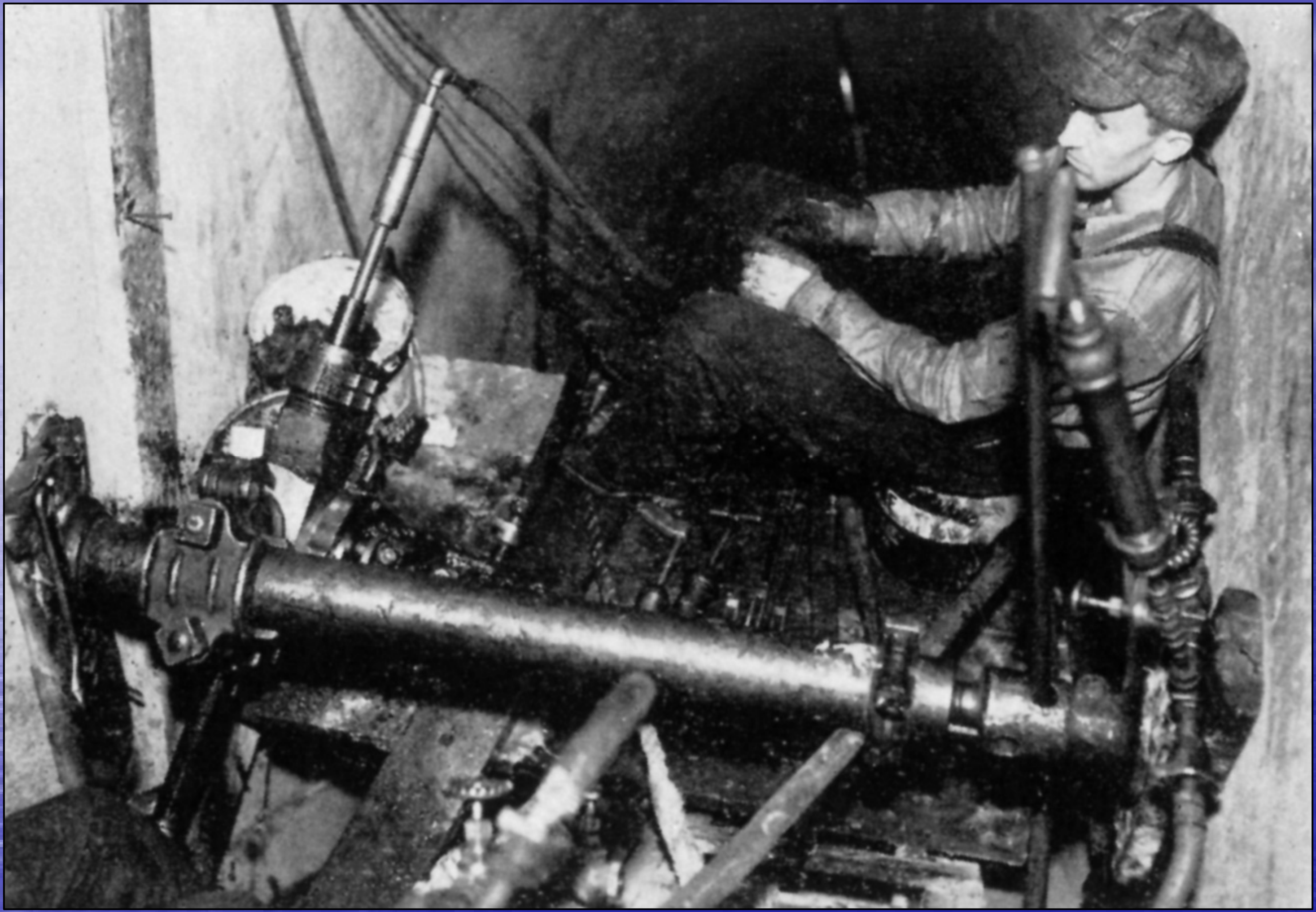
- System of block faults identified during construction. Note absence of data beneath the dam.



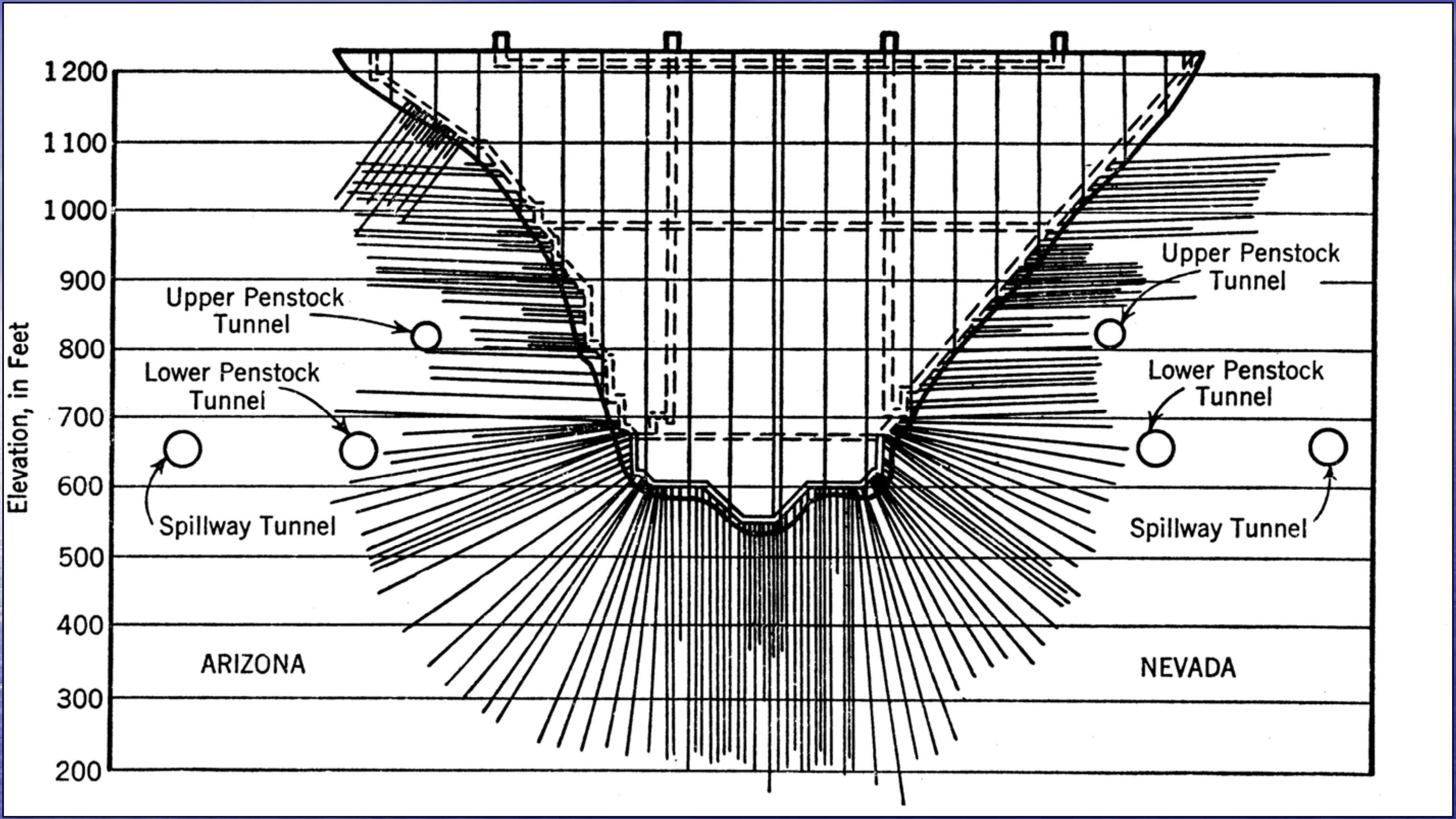
Manganese-rich gouge zones discovered in the dam foundation, along faults and shear zones.



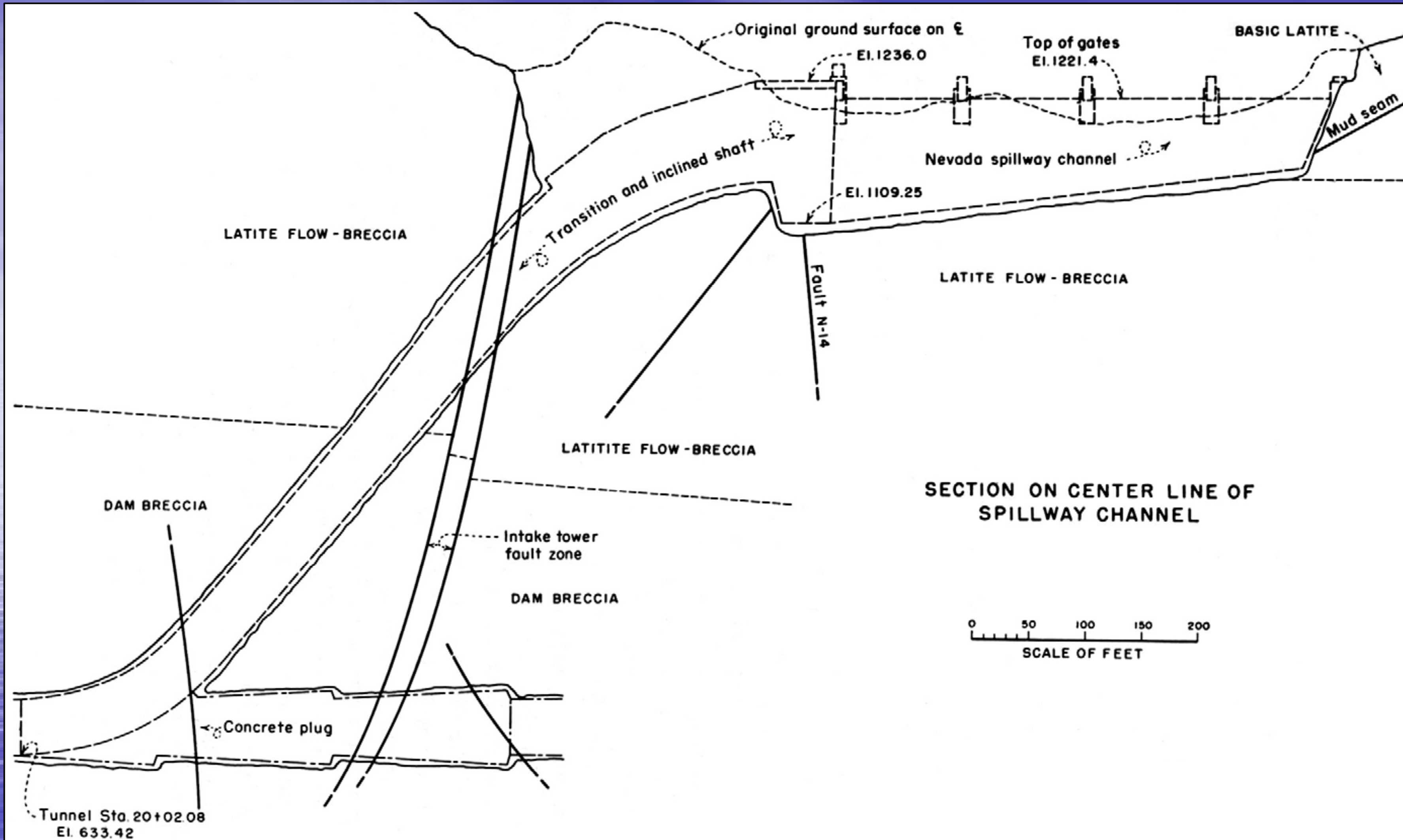
- **Distribution of internal galleries in Hoover Dam. Note lower drainage gallery (arrow), from which the new, deeper grout curtain and drainage holes were drilled.**



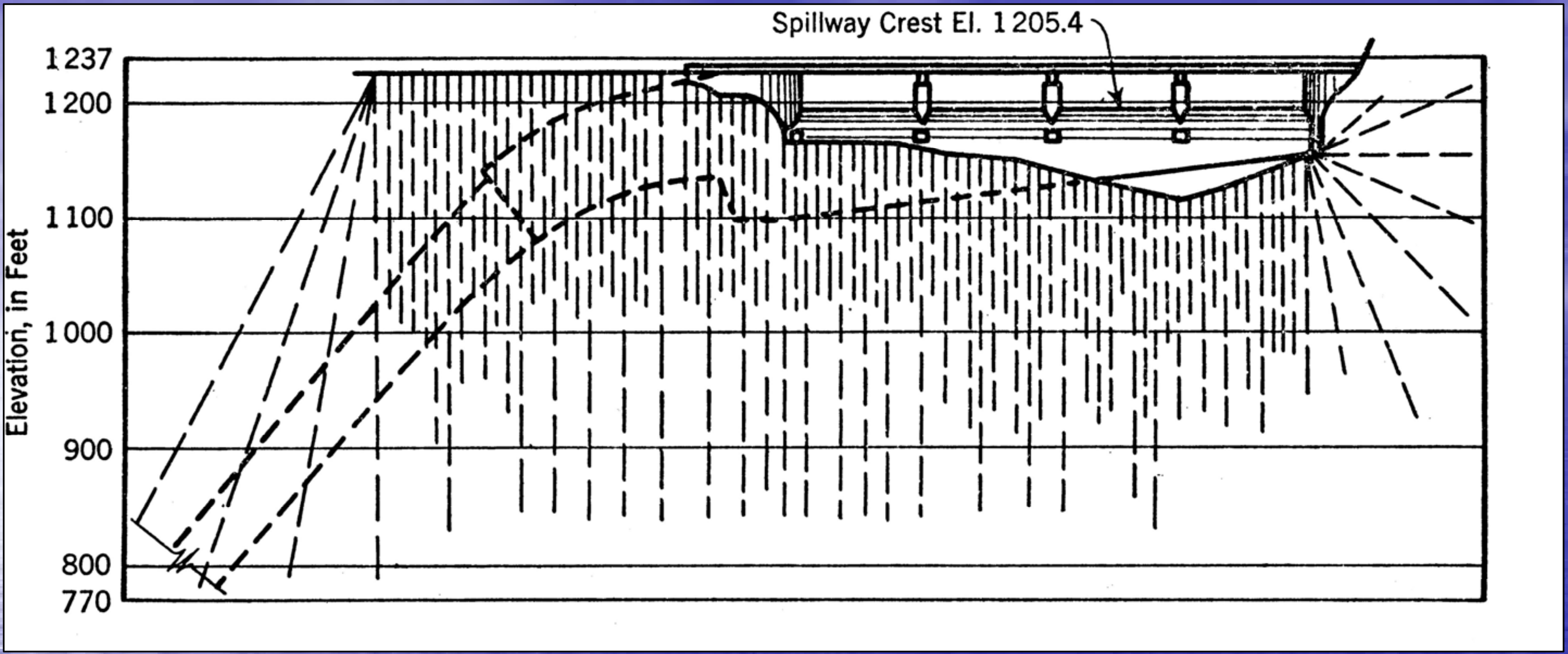
- **Tight working spaces typified the 9 year program of extending the grout curtain, between 1938-47.**



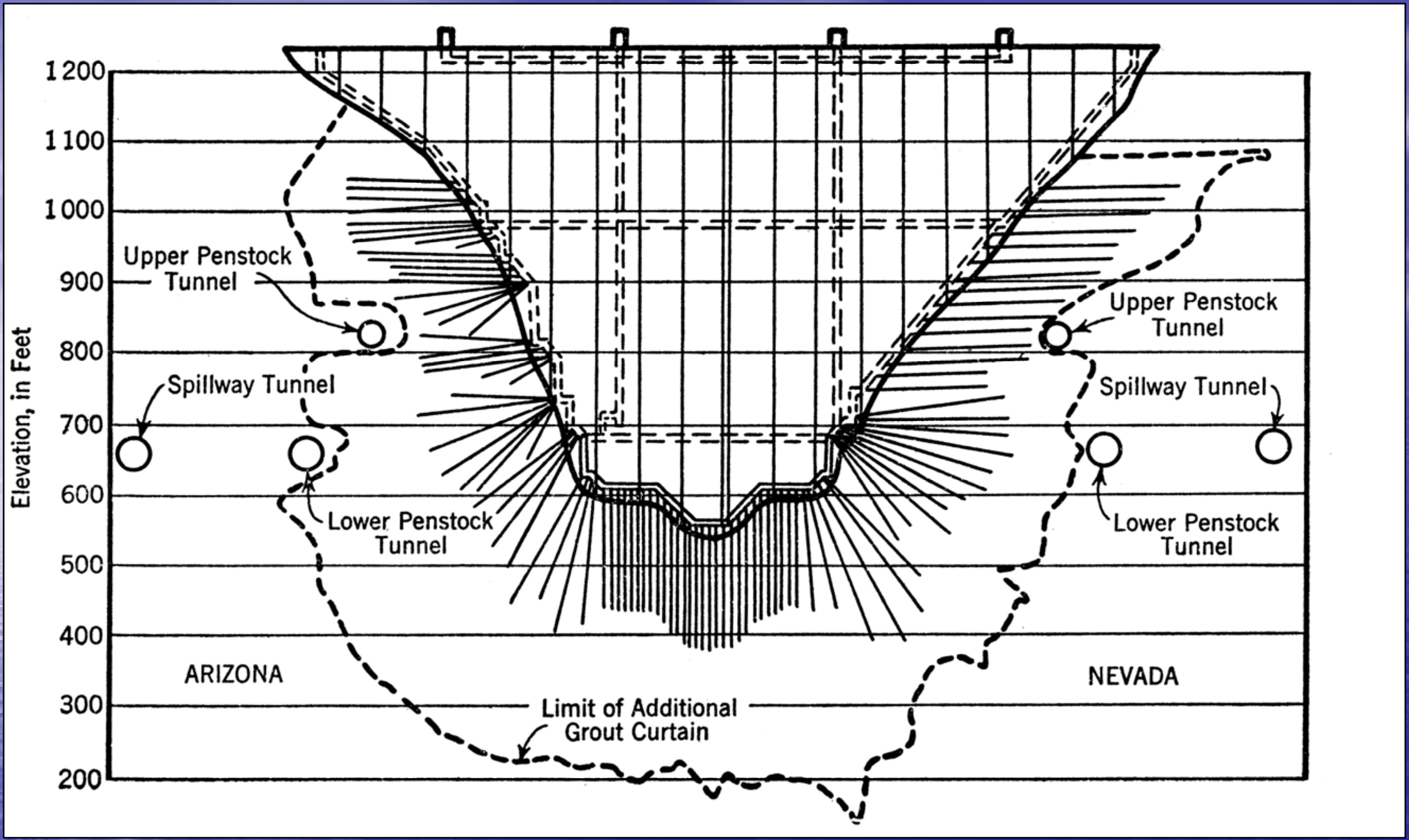
- **Profile of dam centerline showing deepened grout curtain, extended between 1938-47. This time grout holes were extended 300 feet, then pumped under pressure of full reservoir head.**



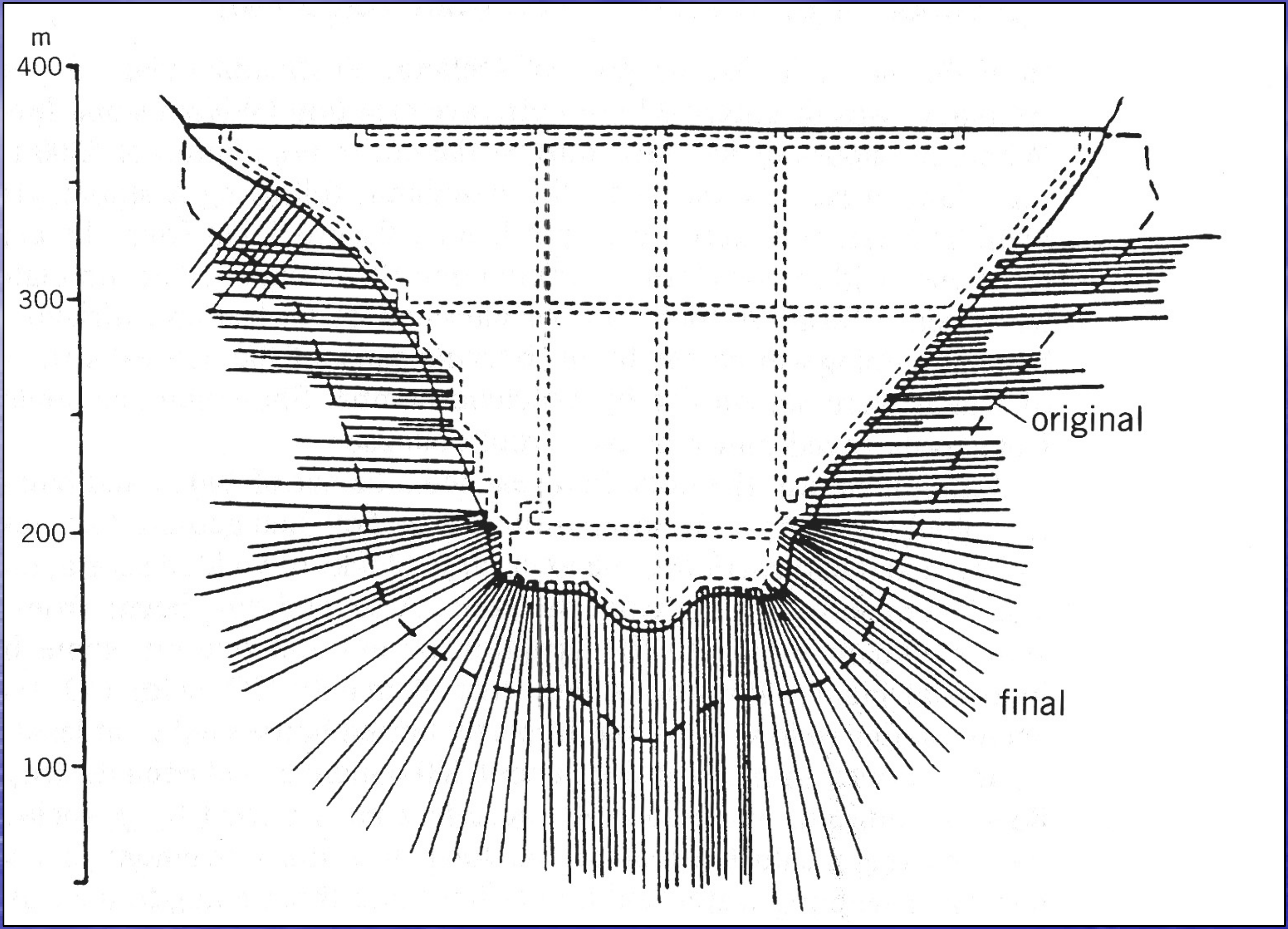
- **Faults exposed in Nevada Spillway excavations. Note “mud seam” at upper right. The spillway shaft experienced significant seepage after the reservoir filled, along brecciated zones adjacent to faults.**



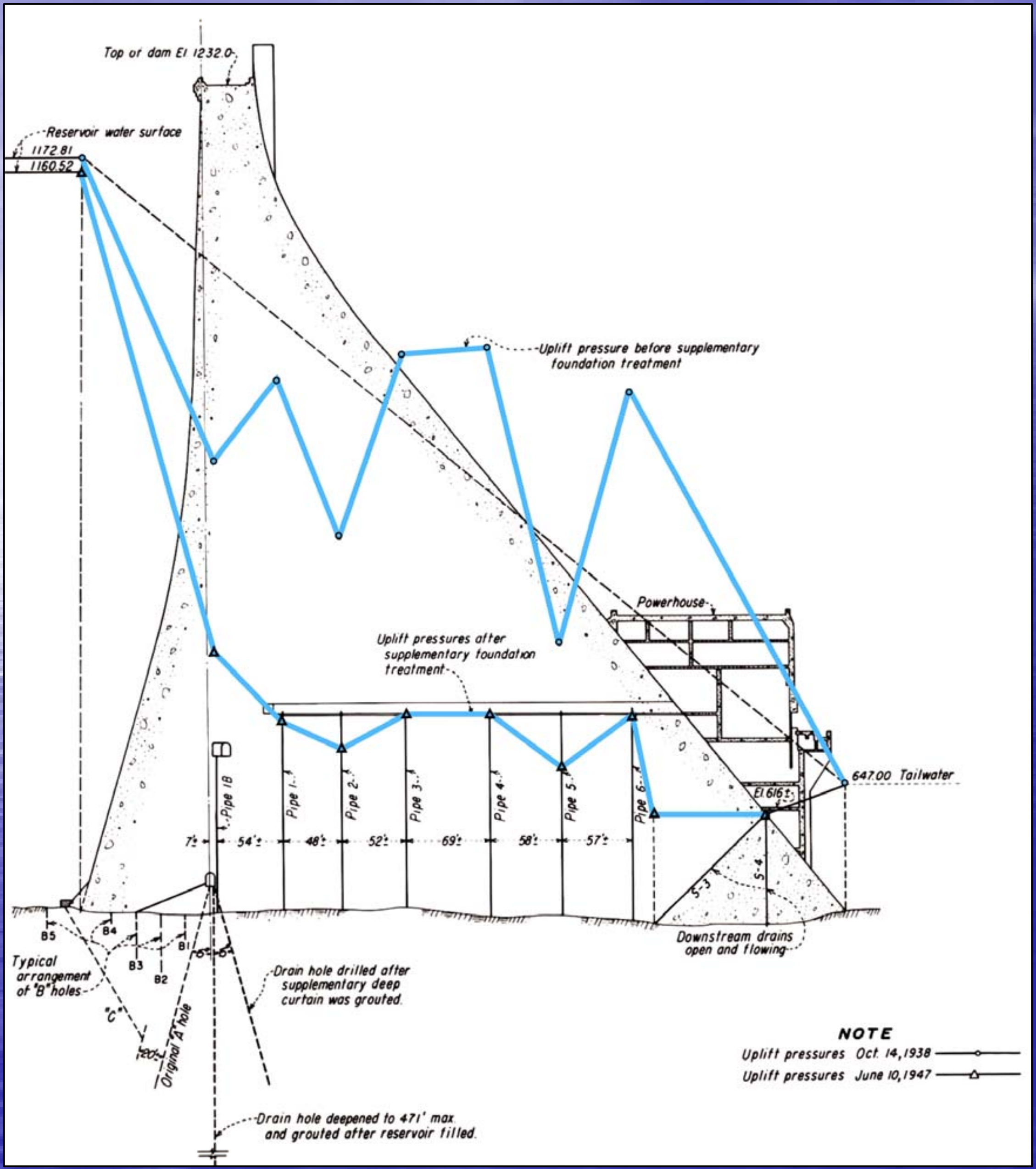
- An extensive program of extending the grout curtain beneath the Nevada Spillway Intake was also undertaken in the 1940s, shown here. This was to combat seepage leaking into the system after the reservoir reached 1100 feet.



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



- **Schematic view of the deepened grout curtain, as it appeared in 1947; 12 years after the dam's completion.**

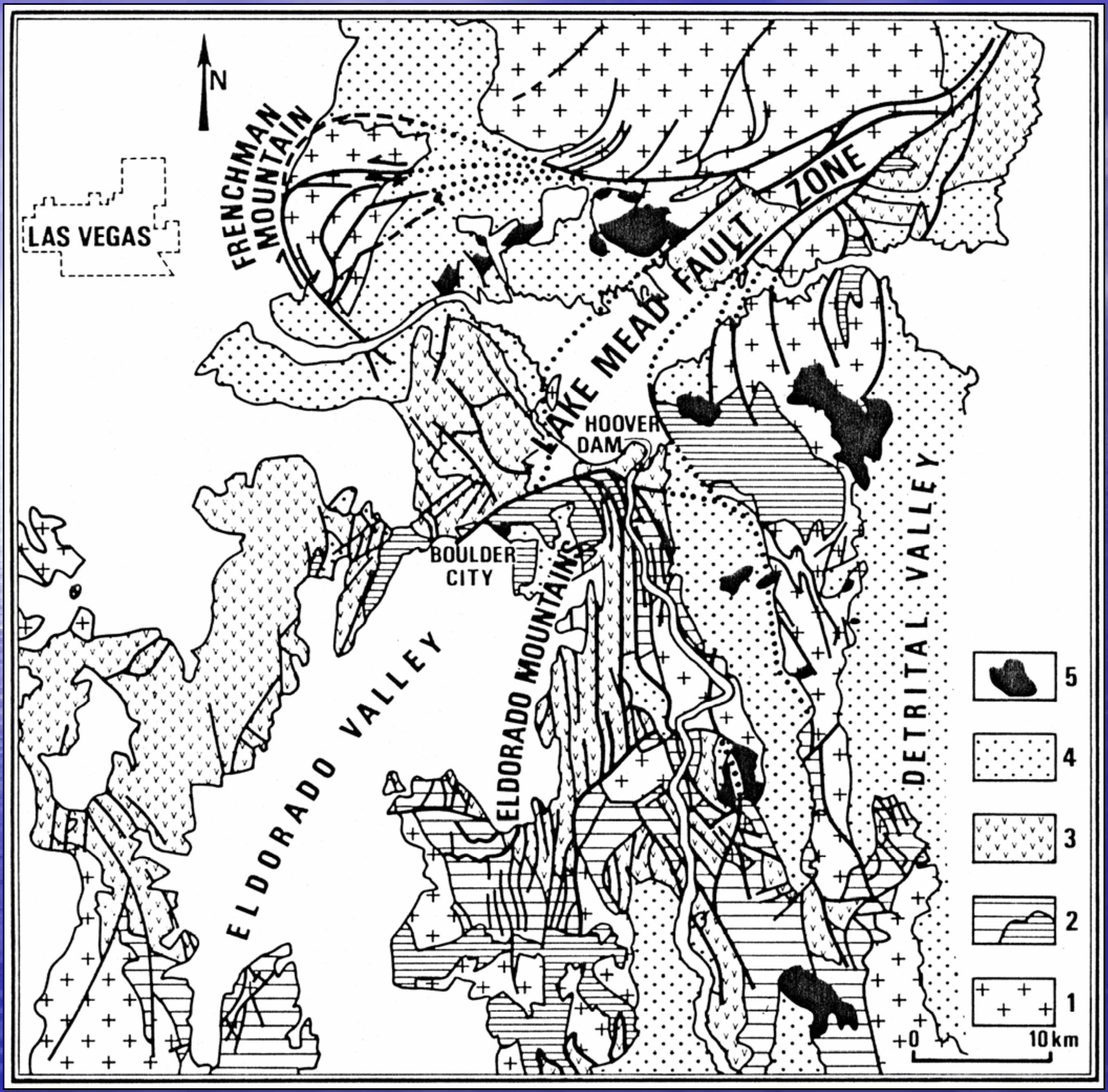


Problem Solved

- The 9 year supplemental grouting program eventually succeeded
- Uplift pressures were significantly reduced, shown as the lower blue line in the drawing at left.

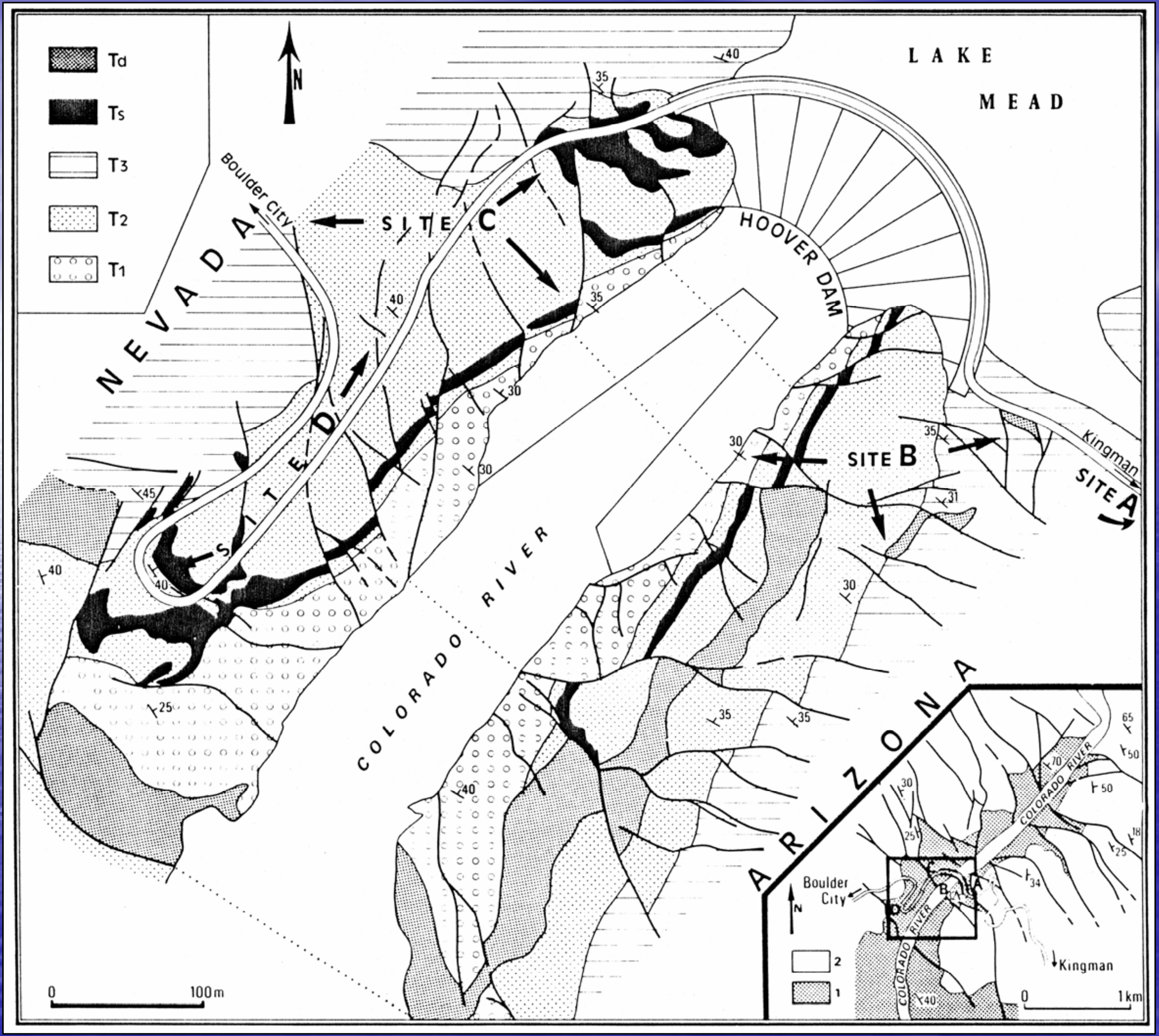
SO, WHAT WENT WRONG ?

- Mapping surficial geology in detail doesn’t help anyone unless that effort is accompanied by a cogent understanding of how the geologic conditions might impact the proposed structure; and
- The Hoover Dam Board of Consultants did not include an engineering geologist; so there was no technical oversight of the geological information collected in the field during construction.
- If the design assumptions about foundation conditions are shown to be invalid, some sort of action needs to be taken.

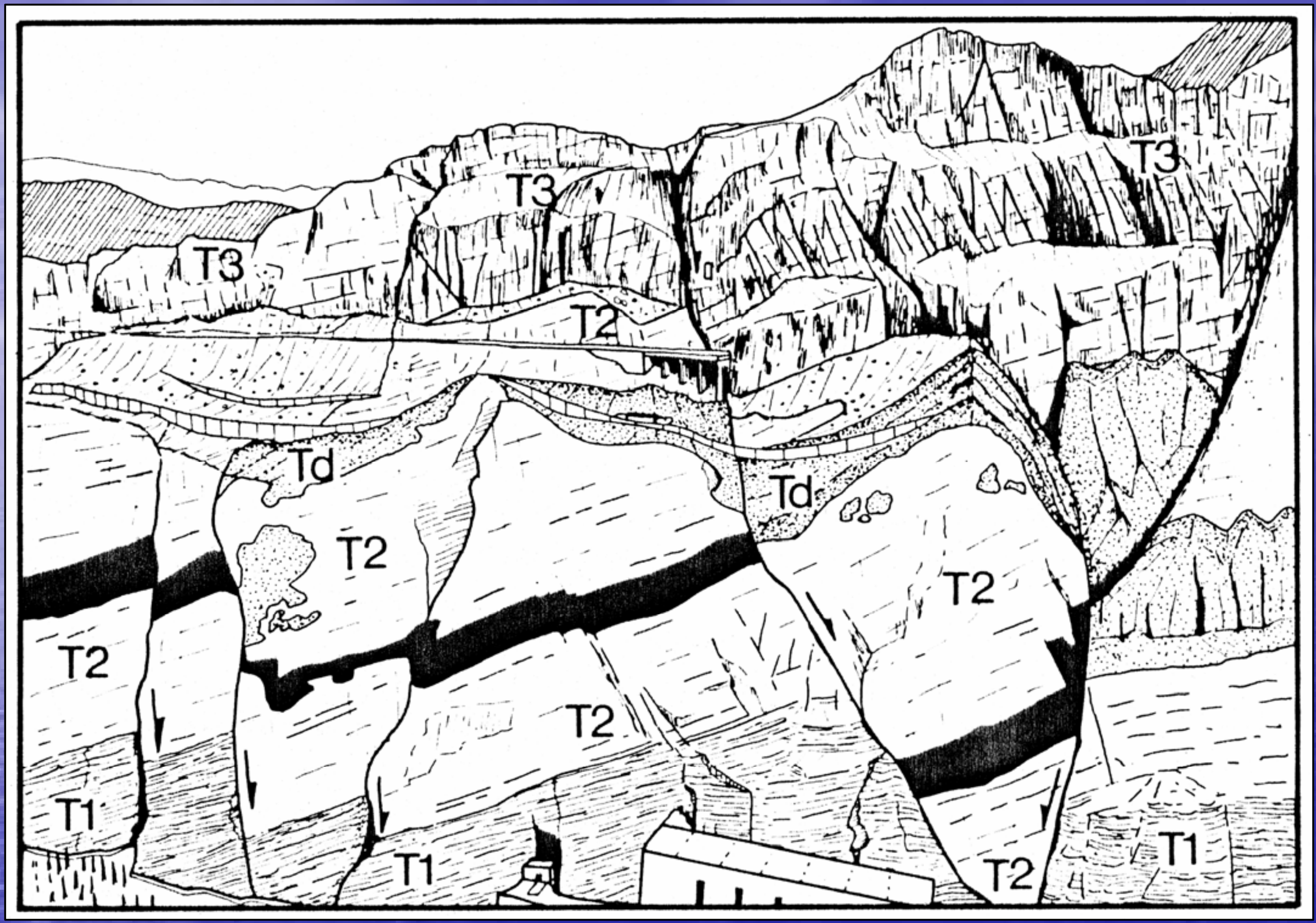


Simplified geologic map of the Lake Mead area, prepared by Angelier, Colletta, and Anderson in 1985

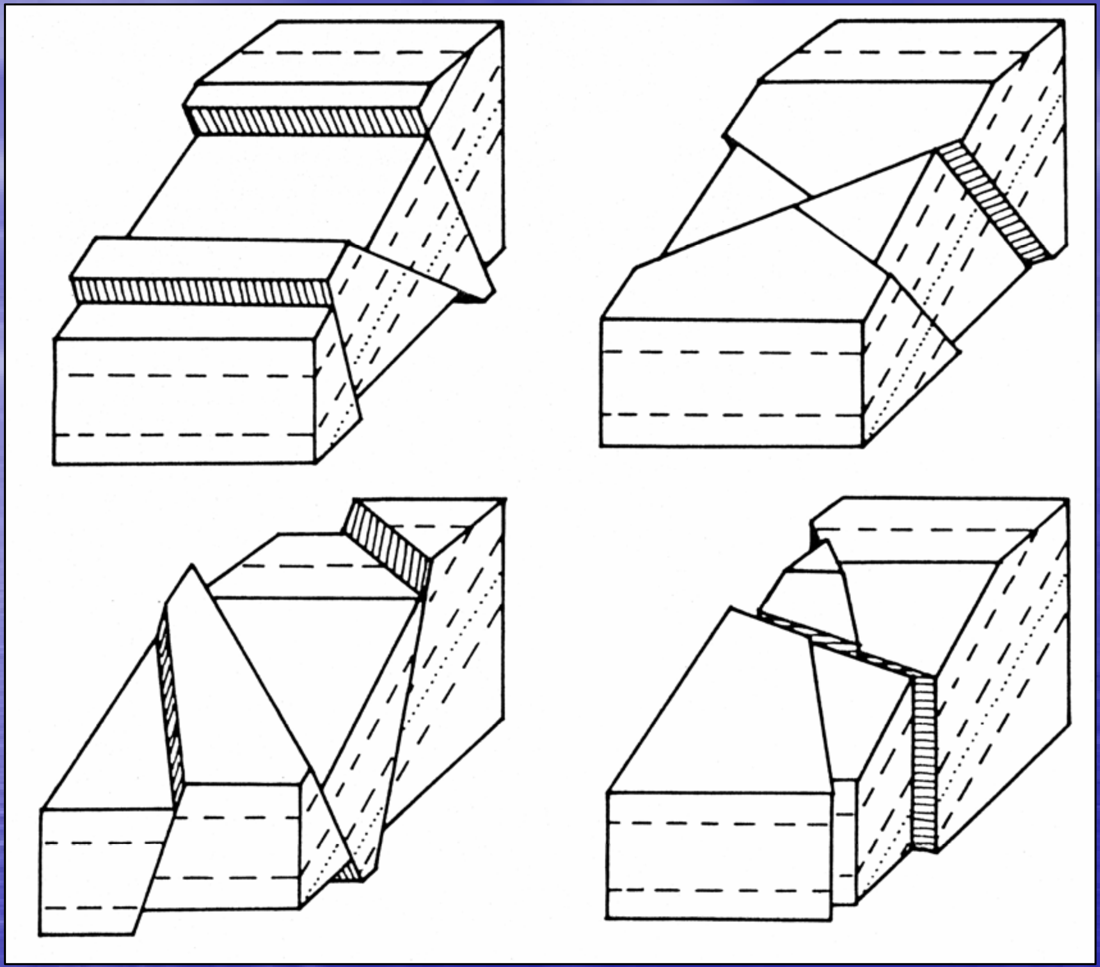
The area is pervasively sheared by more than 500 mapped faults



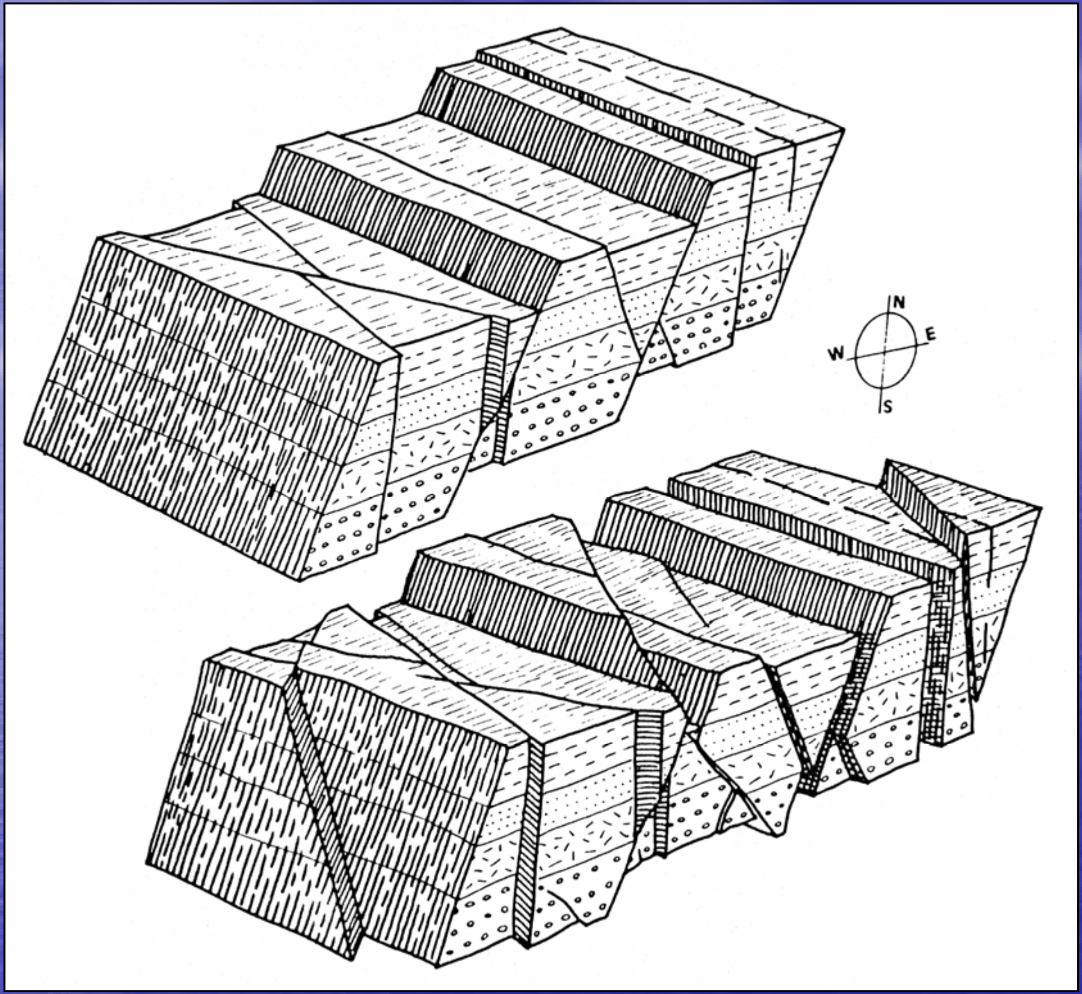
- **Detailed geologic map** of exposed faults and volcanic units downstream of Hoover Dam



- 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.



- 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.**

CONCLUSIONS - 1

- Two stages of extensional tectonism occurred at the dam site
- Extensional tectonism can be expected to perturb a brittle ground mass, creating numerous shears, faults and breciated zones
- Hydrothermal activity can cause mineralization and infilling of voids with secondary products not visible from the ground surface

CONCLUSIONS - 2

- There was insufficient exploration and characterization of the foundation materials beneath and adjacent to the dam; especially the faults, shears, and breccia zones.
- The grouting program was not sufficiently deep or redundant to provide an adequate seepage cutoff
- The cost of the supplemental grouting program cost $1.84 million; 2.37% of the cost of the dam.
- As a percentage figure, only Marshall Ford and Owyhee Dam exceeded this cost (thru 1953).