Turning Geologic Data into Knowledge; A summary of dam failure case histories

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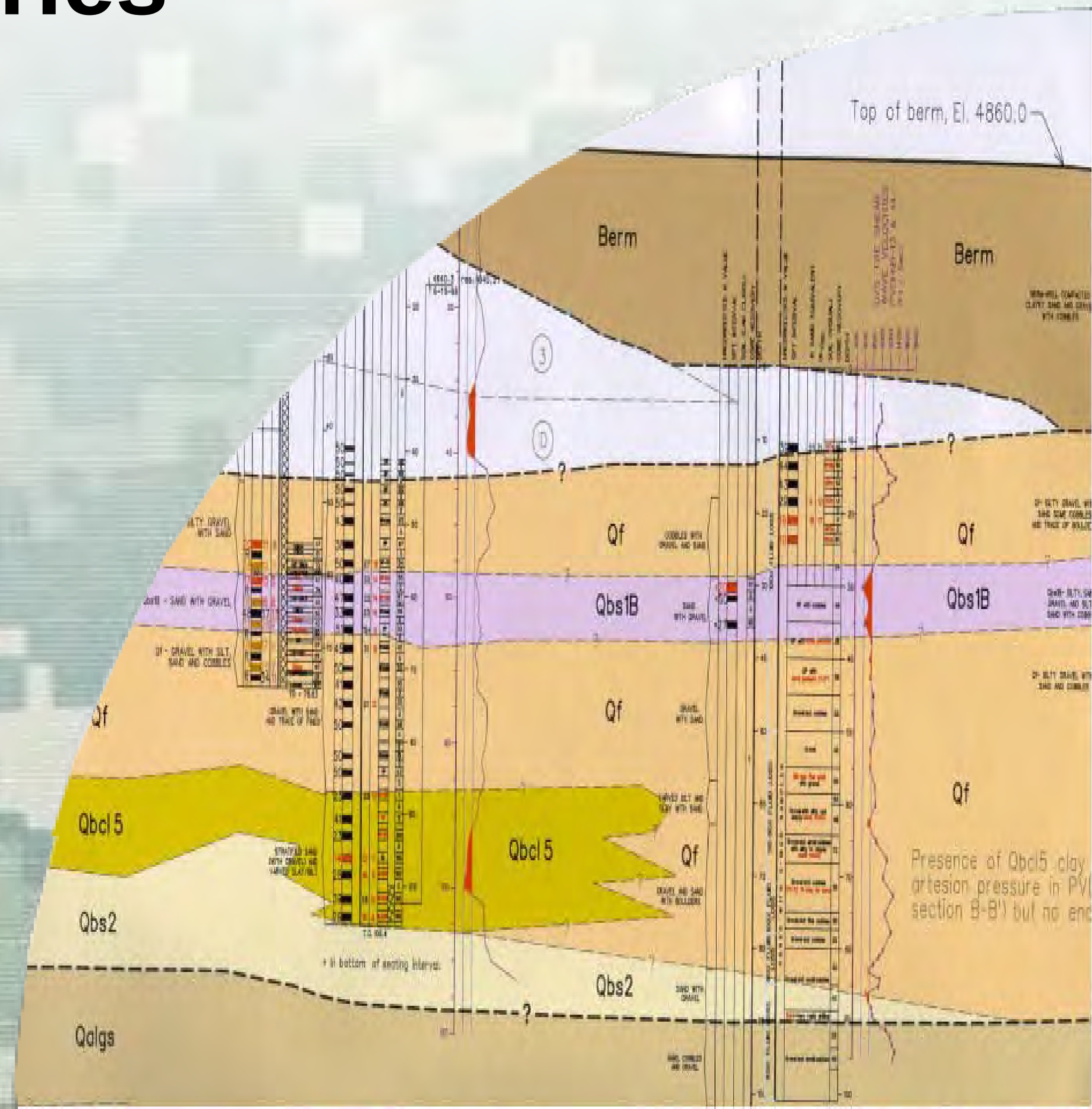

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Purpose of this Presentation:

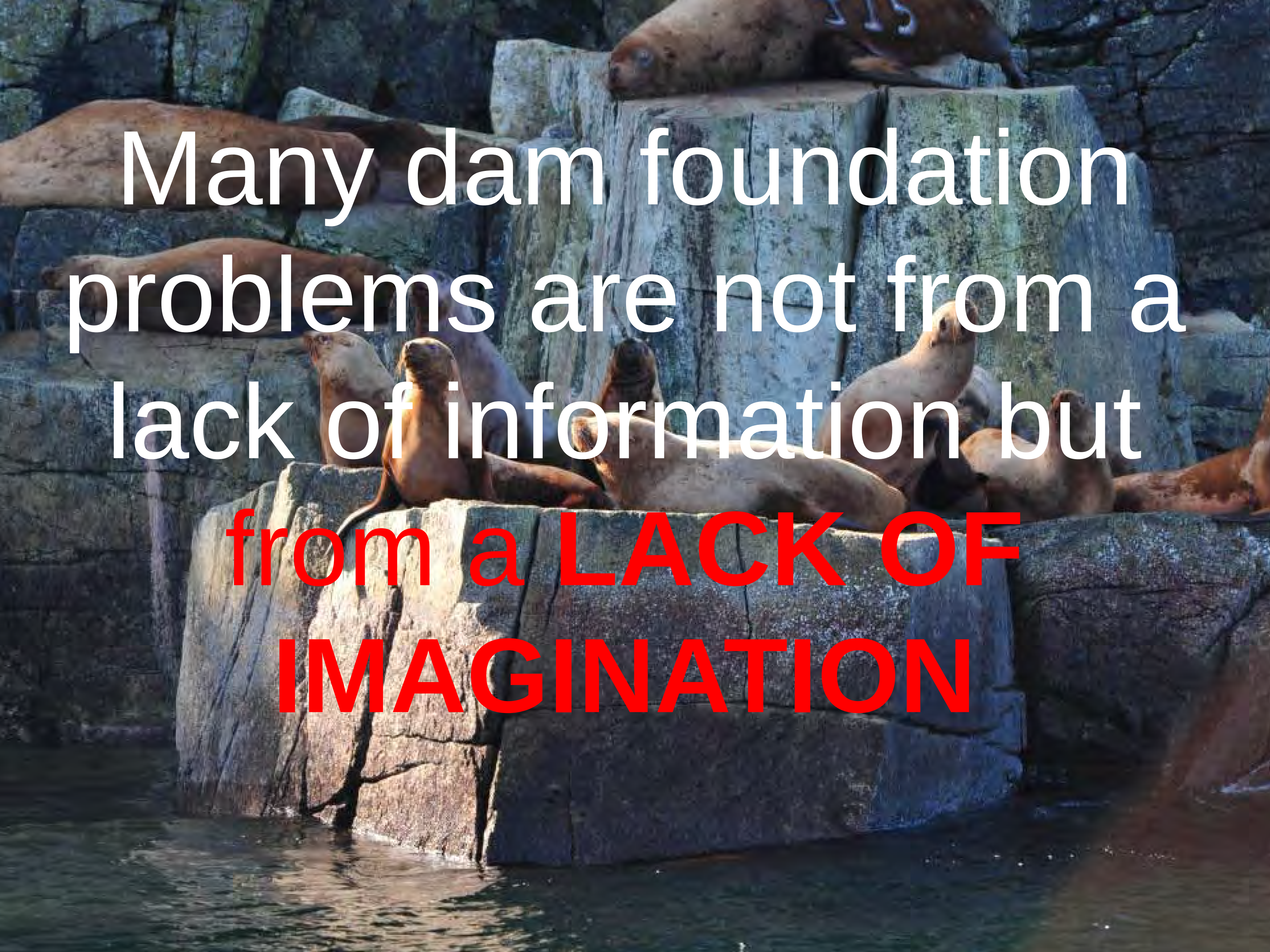
To emphasize why studying case histories is critical and demonstrate that data by itself does not solve problems or prevent failures

To emphasize to the next generation of Dam Safety professionals that there is much homework to be done and knowledge to be transferred by studying and understanding many different dam failures from the last century

REFERENCES PROVIDED

The Sniff Test:

One of the most important questions we can ask ourselves when collecting or portraying geologic information is "SO WHAT?"


Many dam foundation problems are not from a lack of information but
from a **LACK OF IMAGINATION**

Some Case Histories of Dam Failures and Incidents that Must be Studied and Understood

(Each deserving several hours discussion)

- Saint Francis Dam Failure
- Malpasset Dam Failure
- Vaiont Dam Failure
- Teton Dam Failure
- Fontenelle Dam Incident
- Bayless Dam (Austin) Failure
- Camara Dam Failure
- Baldwin Hills Dam Failure
- Quail Creek Dike Failure

Many of these failure case histories had:

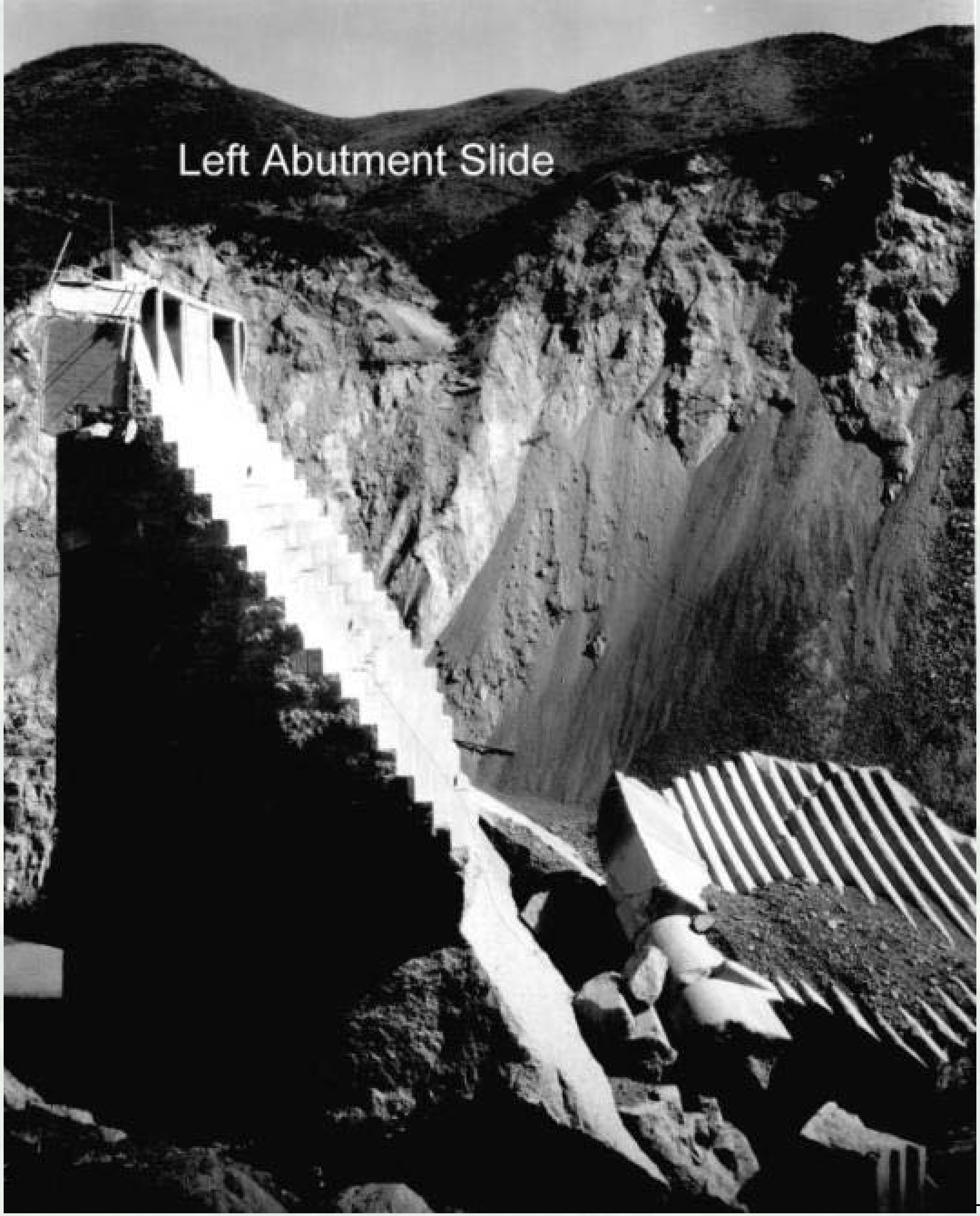
- Geologic data was collected and reported, but was NOT understood in terms of potential failure modes
- Experienced the limits of current state of knowledge in engineering or geology
- Inadequate geologic exploration
- Lack of engineering knowledge by a geologist

Why Geologic Data Alone is Not Enough by Itself

- Data must be synthesized
- Data must be understood in terms of the dam’s vulnerabilities (Failure Modes)
- The significance of the information must be clearly communicated (Dam Safety Case)
- Geologists must take responsibility for understanding and portraying uncertainty
- Communications can require assertiveness

St. Francis Dam

- Failure midnight March 12, 1928
- 450 lives lost
- Left abutment sliding initiated failure
- Re-analyzed by J. David Rogers and Karl F. Hasselmann
- Geology was evaluated and believed adequate
- Paleo landslides were completely missed

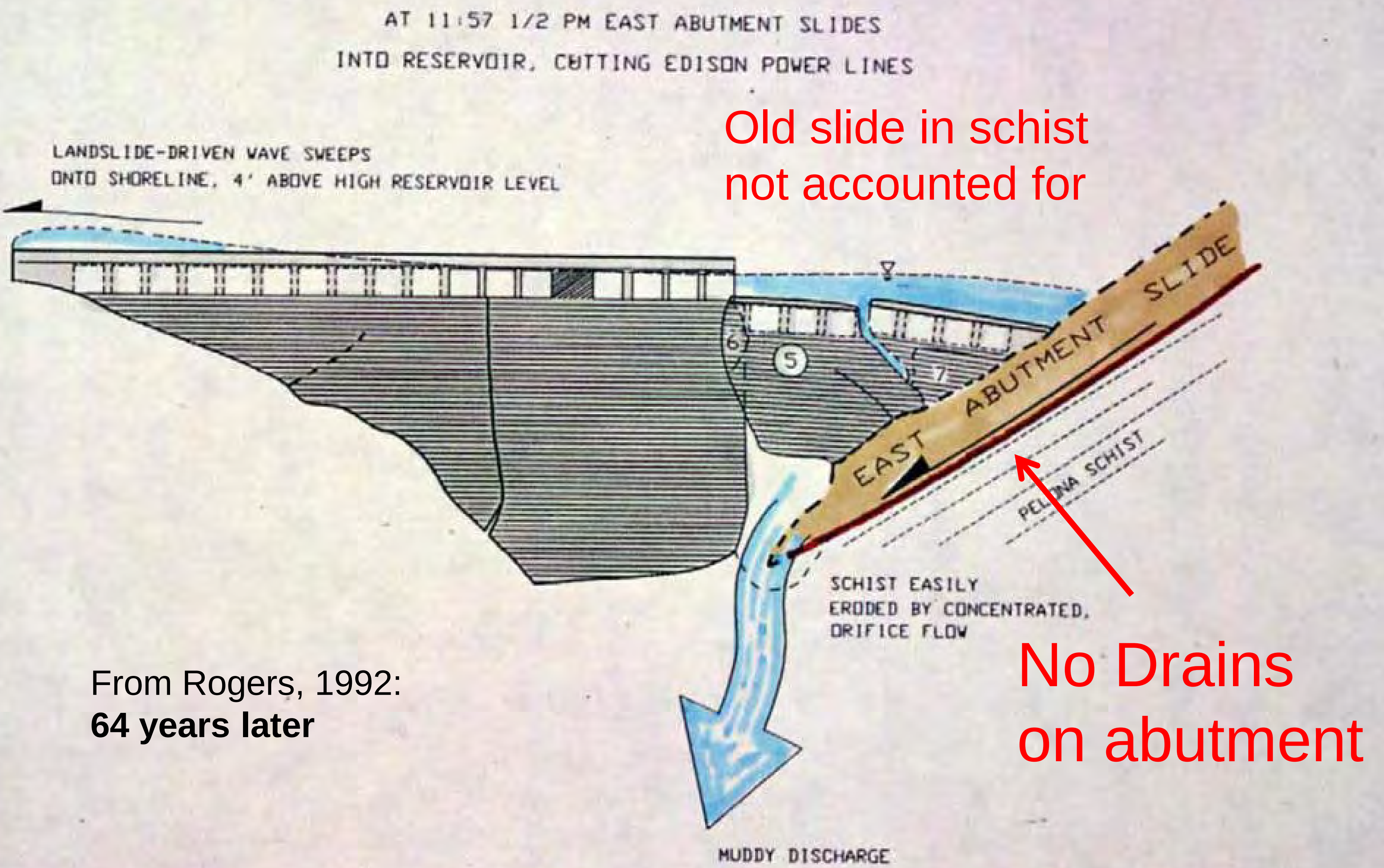


St. Francis Dam 1928

Re-evaluation by David Rogers 1992

Two of the world's leading geologists at the time, John C. Branner of Stanford University and Carl E. Grunsky, found NO major problems with the foundation.

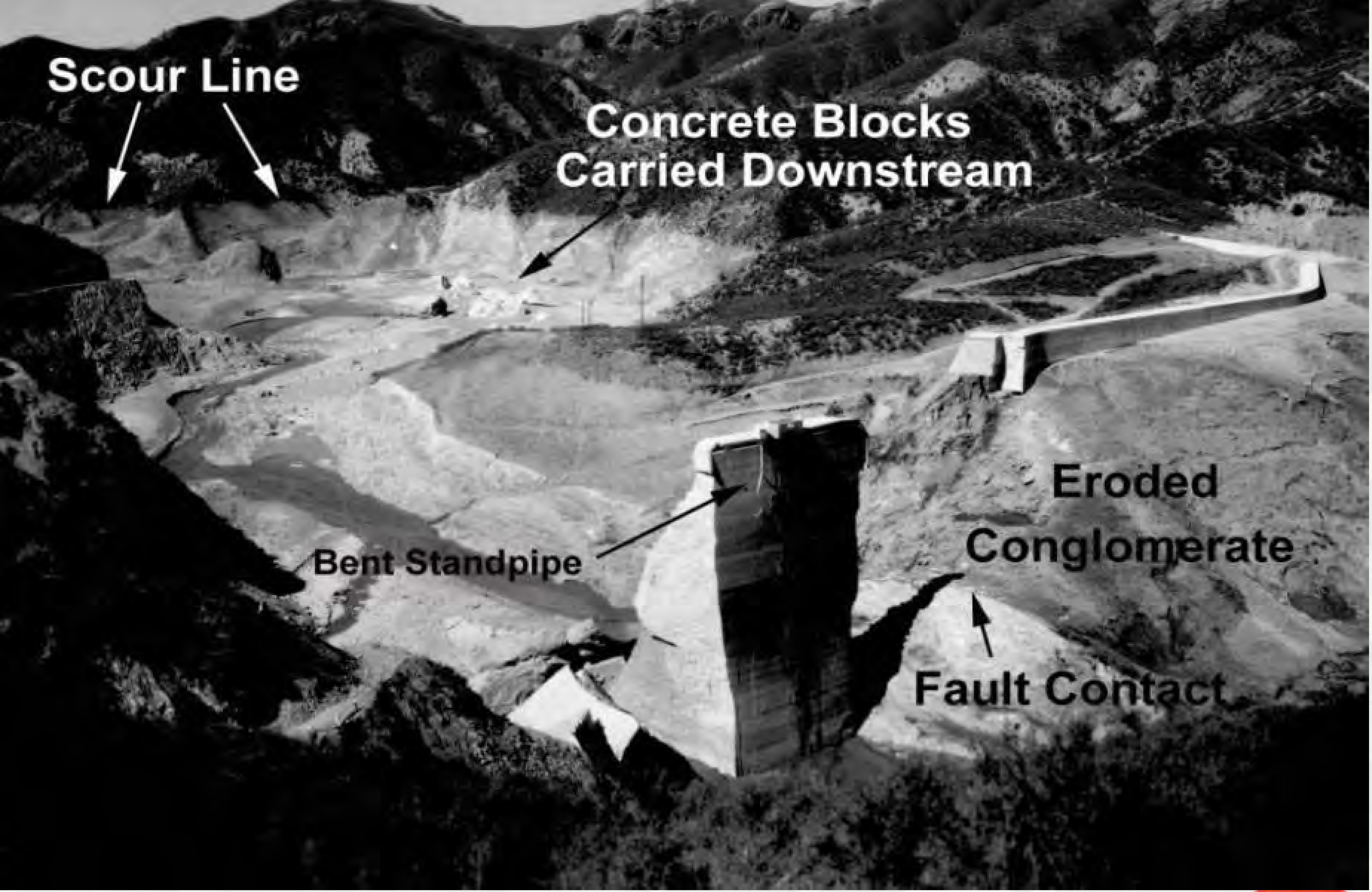
After failure Bailey Willis recognized paleo landslides.

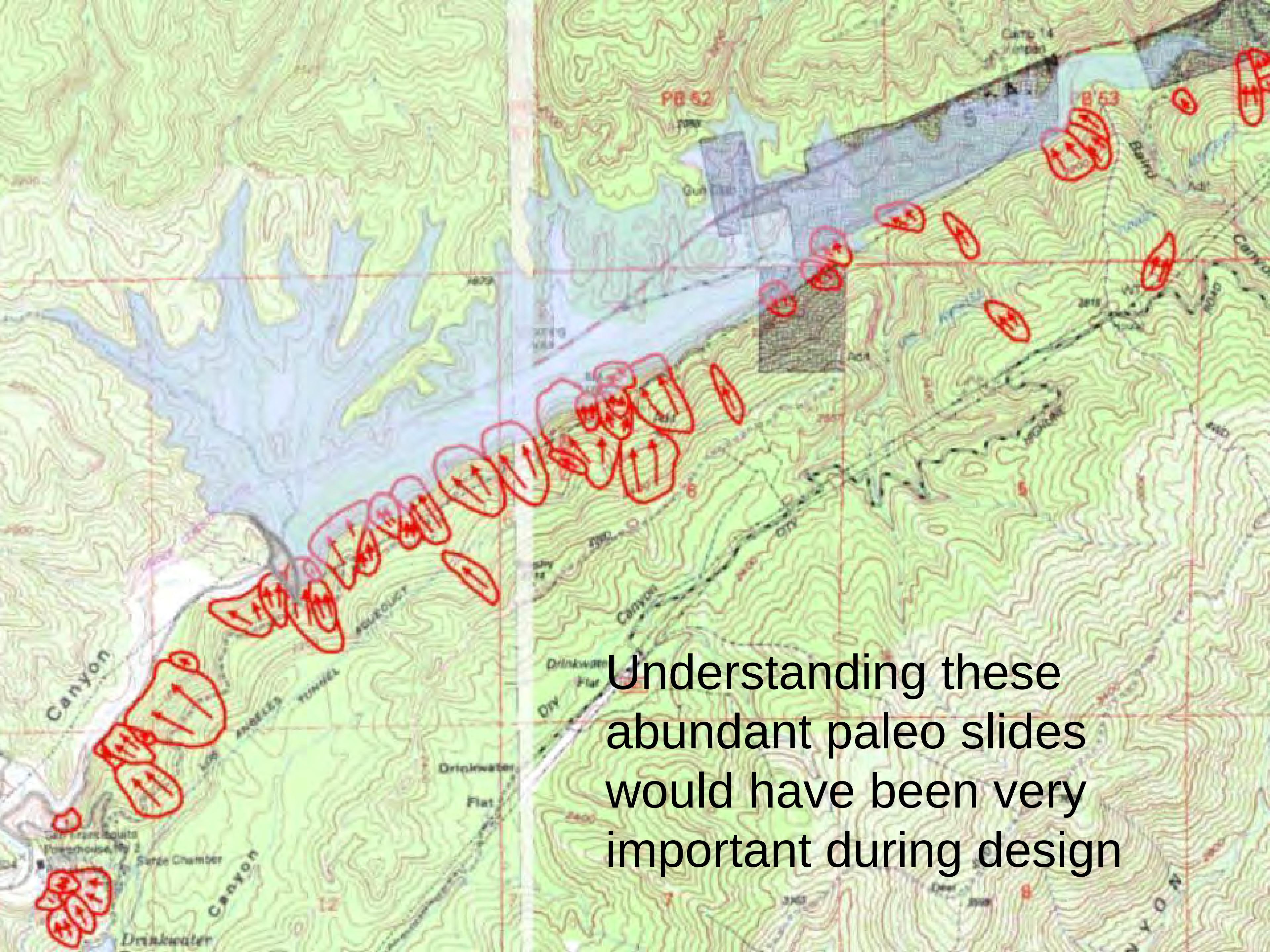


Old slide in schist
not accounted for

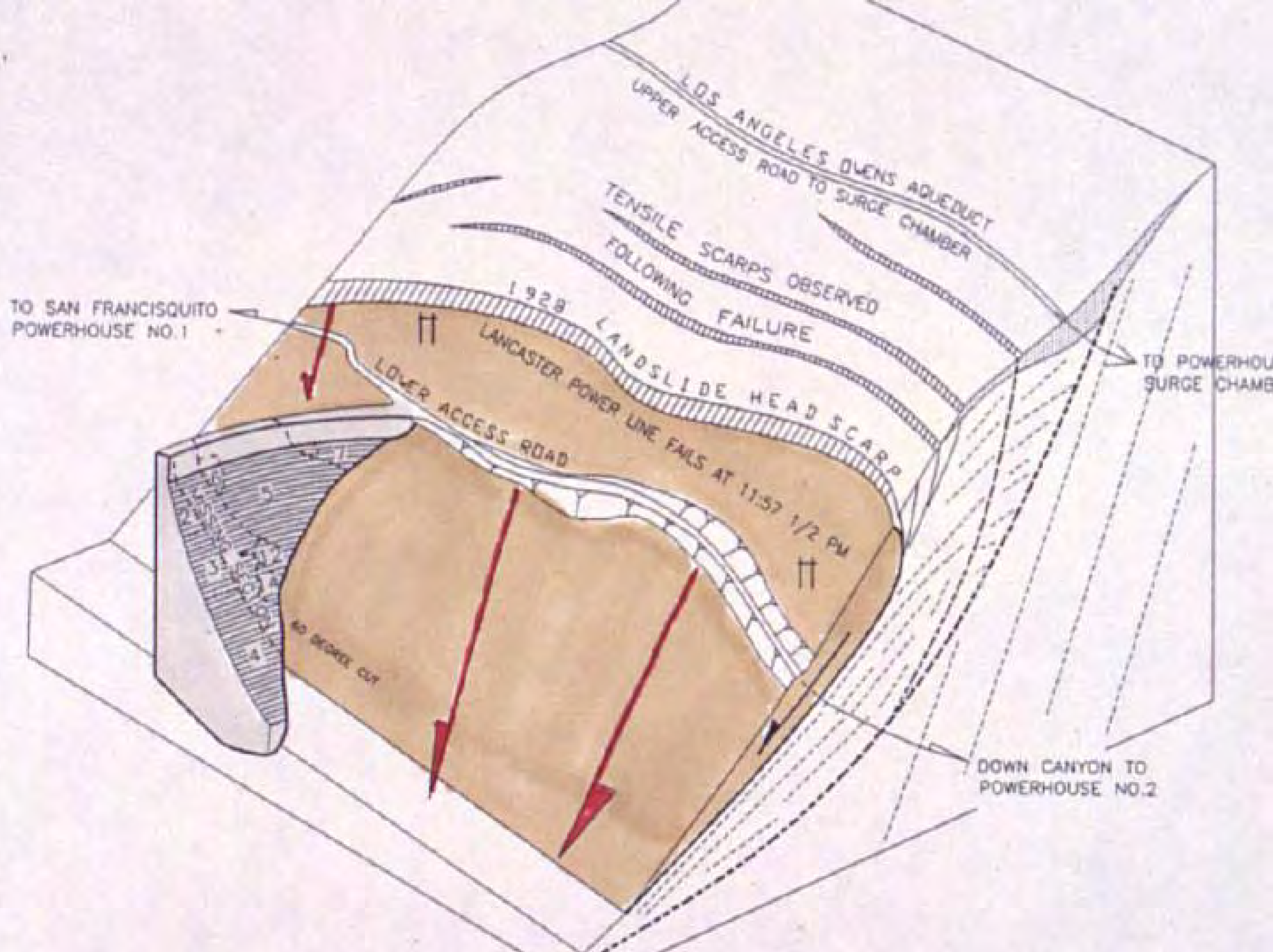
No Drains
on abutment

From Rogers, 1992:
64 years later

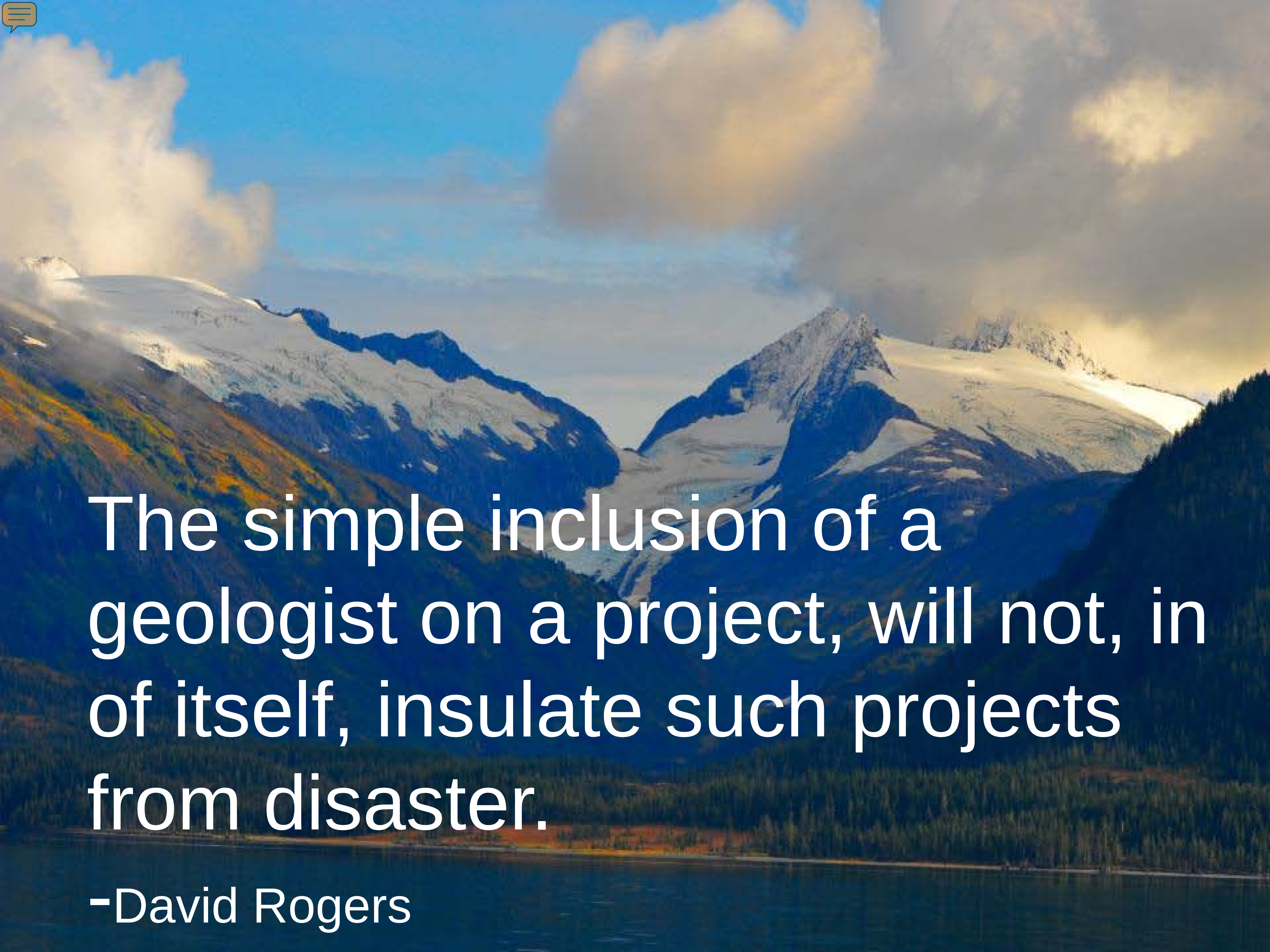

Scour Line
Concrete Blocks
Carried Downstream
Eroded
Conglomerate
Bent Standpipe
Fault Contact



Understanding these abundant paleo slides would have been very important during design



LOS ANGELES OWENS AQUEDUCT
UPPER ACCESS ROAD TO SURGE CHAMBER
TENSILE SCARPS OBSERVED
FOLLOWING FAILURE
1928 LANDSLIDE HEAD SCARP
LANCASTER POWER LINE FAILS AT 11:57 1/2 PM
LOWER ACCESS ROAD
TO SAN FRANCISQUITO
POWERHOUSE NO.1
TO POWERHOU
SURGE CHAMB
DOWN CANYON TO
POWERHOUSE NO.2
60 DEGREE CUT

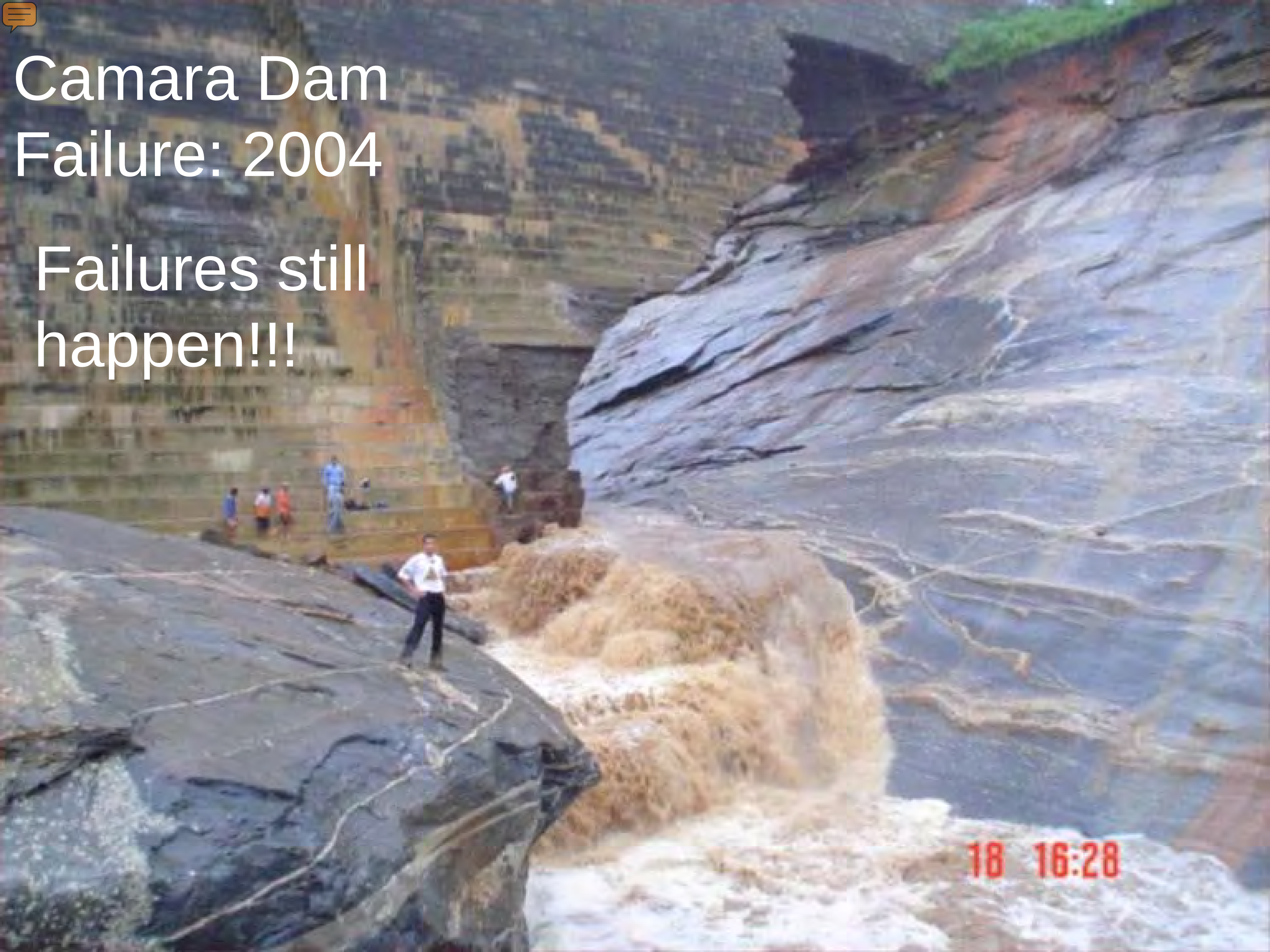

The simple inclusion of a geologist on a project, will not, in of itself, insulate such projects from disaster.
-David Rogers

What would geologists do today that was not done at St. Francis Dam in the 1920’s?

- Use aerial photographs to specifically map scarps and search for paleo landslides at the dam and reservoir
- Look specifically for daylighting planes in the foundation that could result in failures (map downstream abutments!)
- Define rock lithology and structure in terms of the dam’s vulnerabilities and potential failure modes
- Perform more detailed investigations specifically targeting potential weaknesses
- **Design for geologic uncertainty tied to potential failure modes and past case histories!**

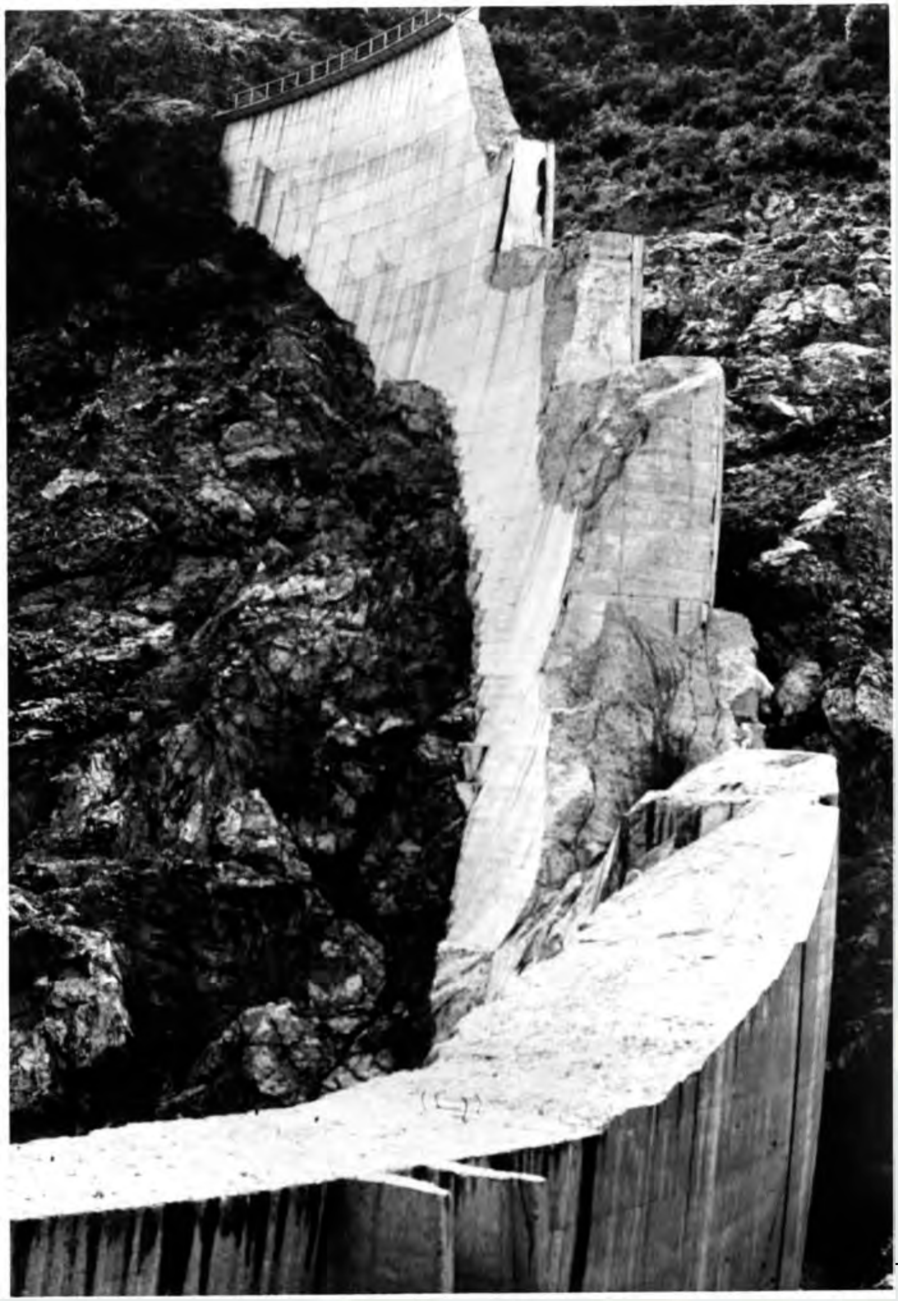
Camara Dam Failure: 2004

Failures still happen!!!



Malpasset Dam

- **Designed by Dr. Andre Coyne, the world's foremost expert in arch dam engineering**
- **Geologists mapped the local area when a <u>gravity dam</u> was considered**
- **The design was switched to an arch dam**
- **A large rock wedge slid along a shear zone in the left abutment upon first filling in 1959**
- **421 people were killed**
- **Pierre Londe spent 8 years studying the failure**



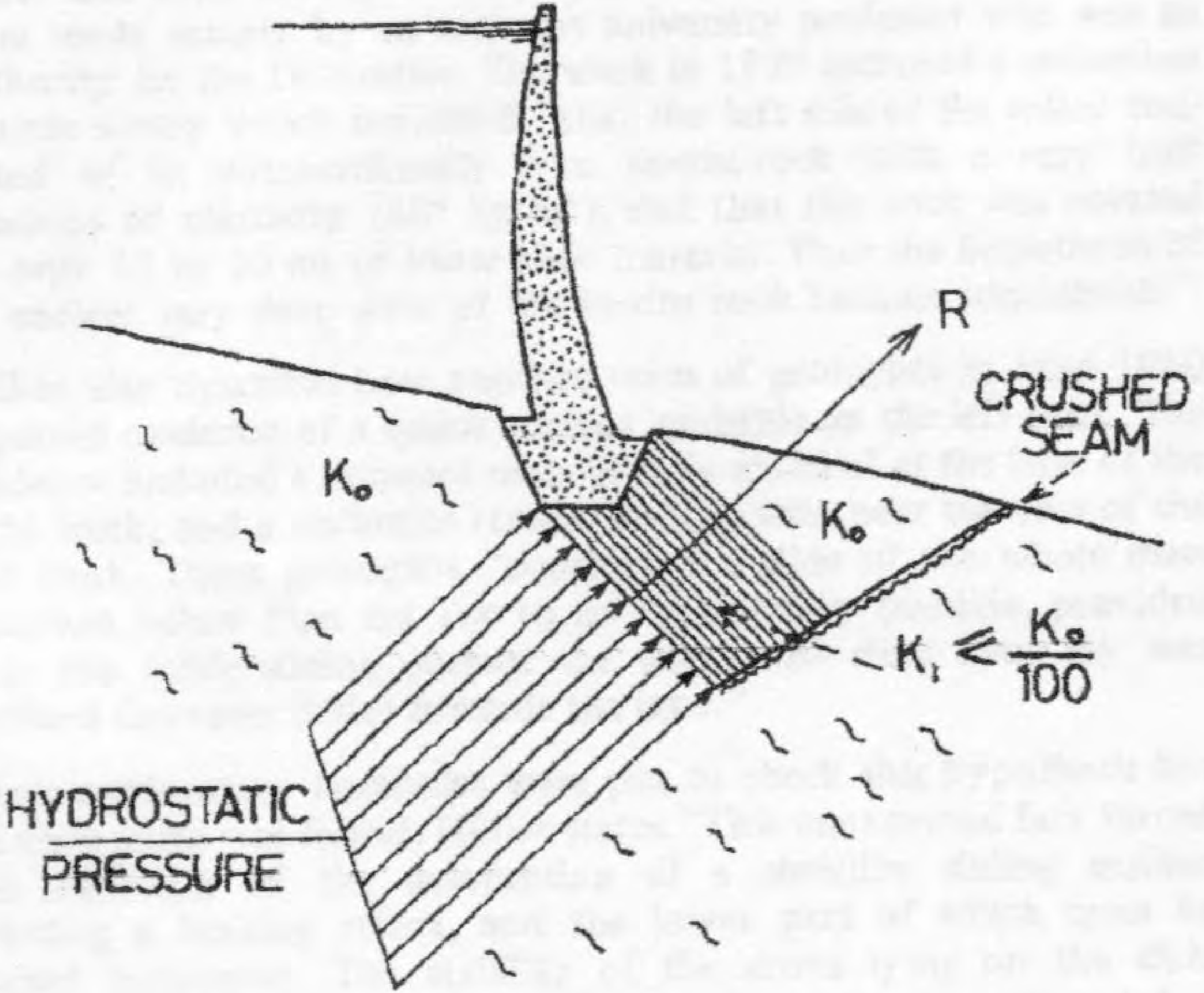
Malpasset Dam 1959

421 deaths

Very important engineering and geology lessons, but it took at least 15 years for some dam building organizations to understand this failure mode and design for it.

Malpasset Dam

- Failure was caused by hydraulic uplift of a large rock wedge lying beneath the dam's left abutment



Left Abutment Section as depicted by Pierre Londe

Five Geologic Reports were developed by Professor Corroy, Univ. of Marsailles - 2 reports prior to construction and 3 reports during construction

- There were no plan, sections or borehole logs included in any reports
- The geologic language was likely NOT understood by design engineers
- Prof. Corroy obviously had no understanding of engineering
- He was investigating a dam site without knowing the type of dam being considered
- No discussion of forces, direction of forces, angles, stresses, deformation, etc.
- Even during the subsequent inquiry into the failure the comments by the geologists indicate a complete lack of understanding of the engineering aspects

Geologic Lessons Learned from Malpasset Dam Failure

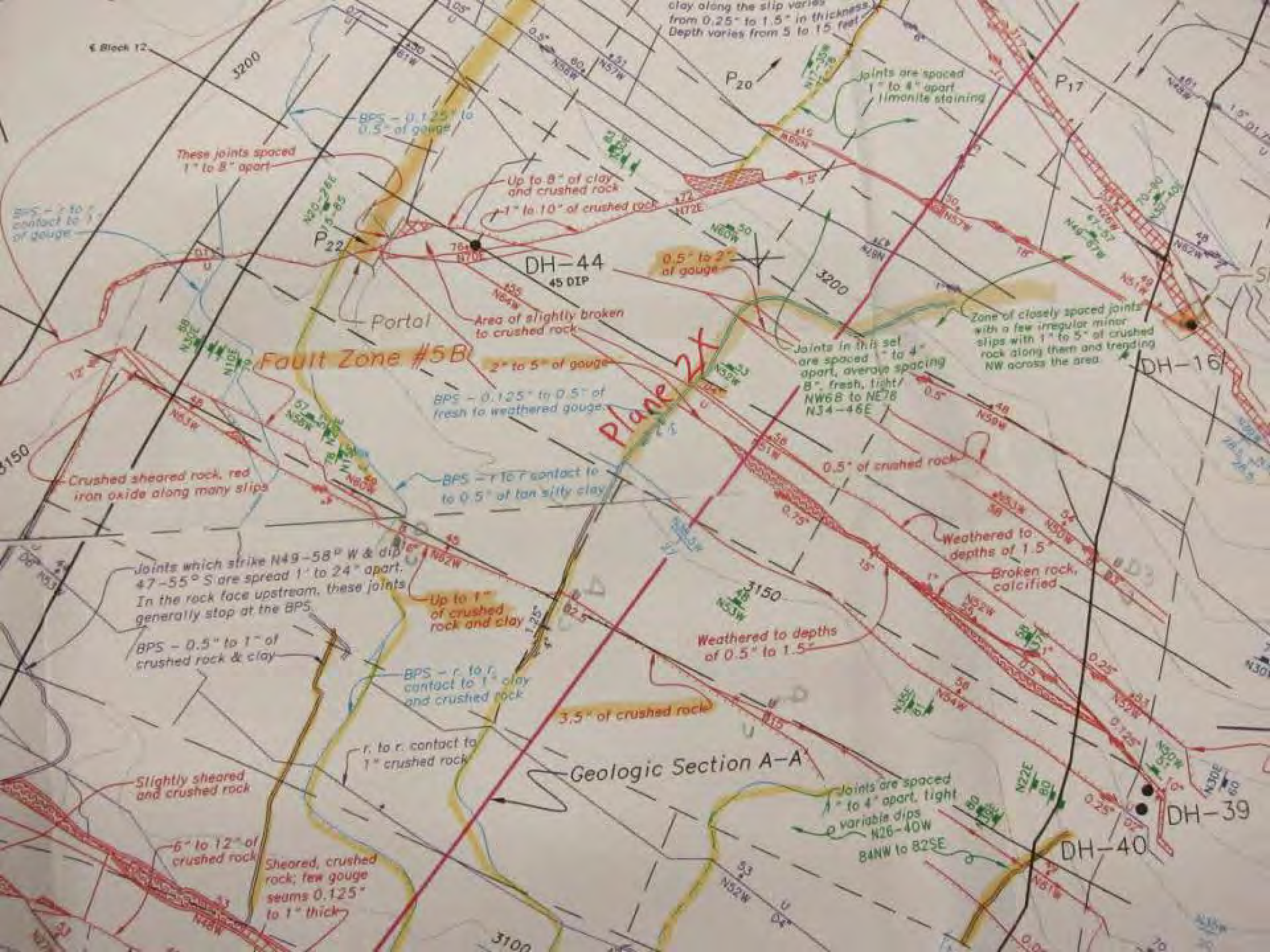
- Geology must ***not*** be treated as a separate and independent science, it must be integrated into answering the important engineering questions
- Collecting geologic data without consideration of the most important engineering questions is not productive or very useful
- Understanding a structure's vulnerabilities (potential failure modes) is key to focusing data collection and exploration priorities (was this was a "new" failure mode or unlearned lesson (St Francis)??)
- Geologists need to avoid using language that is not universally understood by non-scientists, and learn to write simply and concisely
- It is usually impossible to investigate, understand and communicate foundation conditions without detailed geologic sections and plan maps

Geologic Lessons Learned from Malpasset Dam Failure

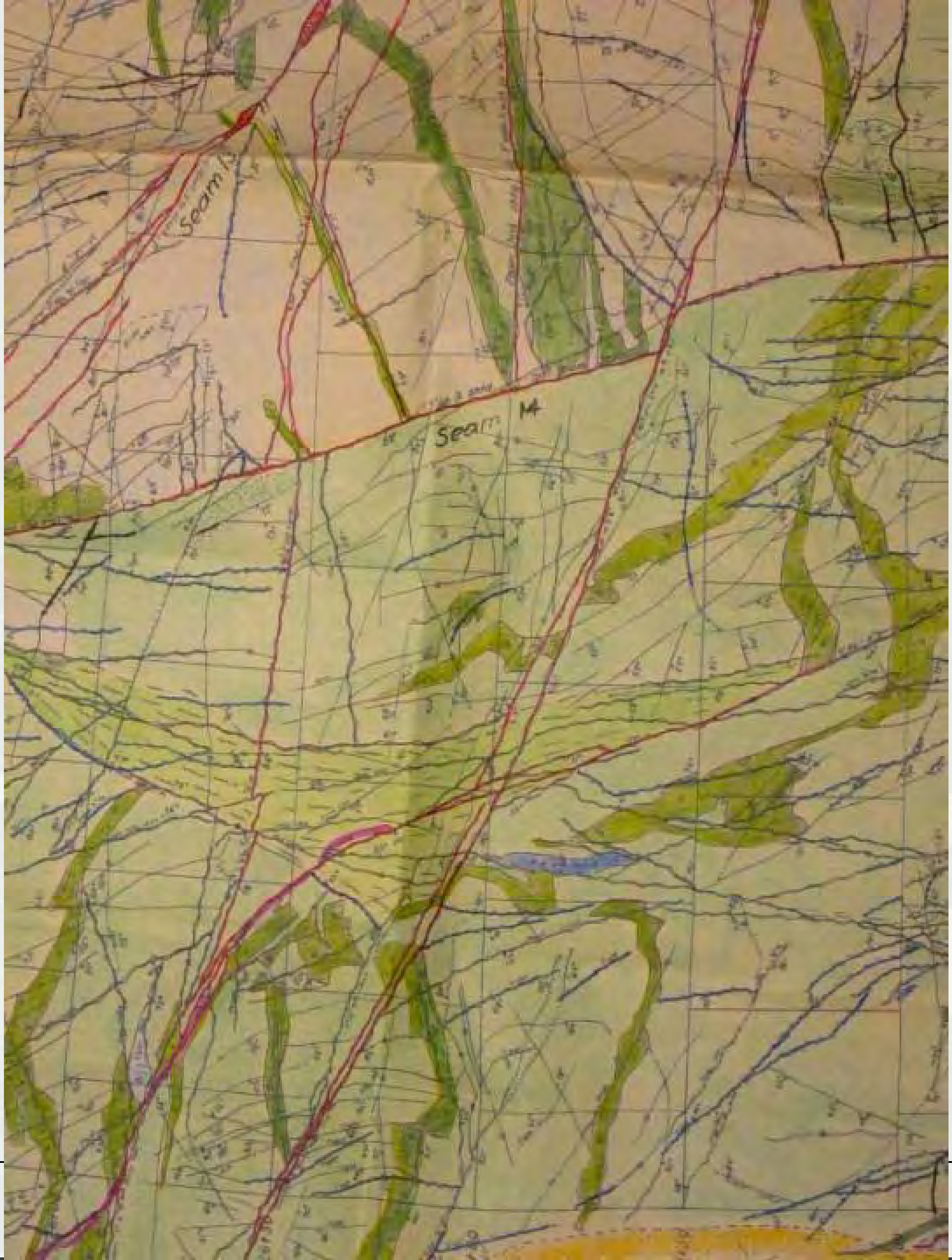
- Uplift forces acting on the foundation block were not understood or accounted for ("new" vulnerability?).
- The geometry of the "system" was not understood or analyzed
- Today we would incorporate grouting upstream and drainage downstream
- Geologic mapping of the foundation and downstream abutments to define the geologic discontinuities and potential sliding blocks is essential
- Some of these lessons were not incorporated into the investigations, design and construction of concrete dams for over a decade
- Some of these lessons are still being ignored today

1
2
3
4
4
3
4
5
5
EXPLANATION
foliation
joints
MORROW POINT DAM
Left Abutment Joints &
Foliation


Overexcavated Clayseam
Approximate area of flush-
sh-grouted

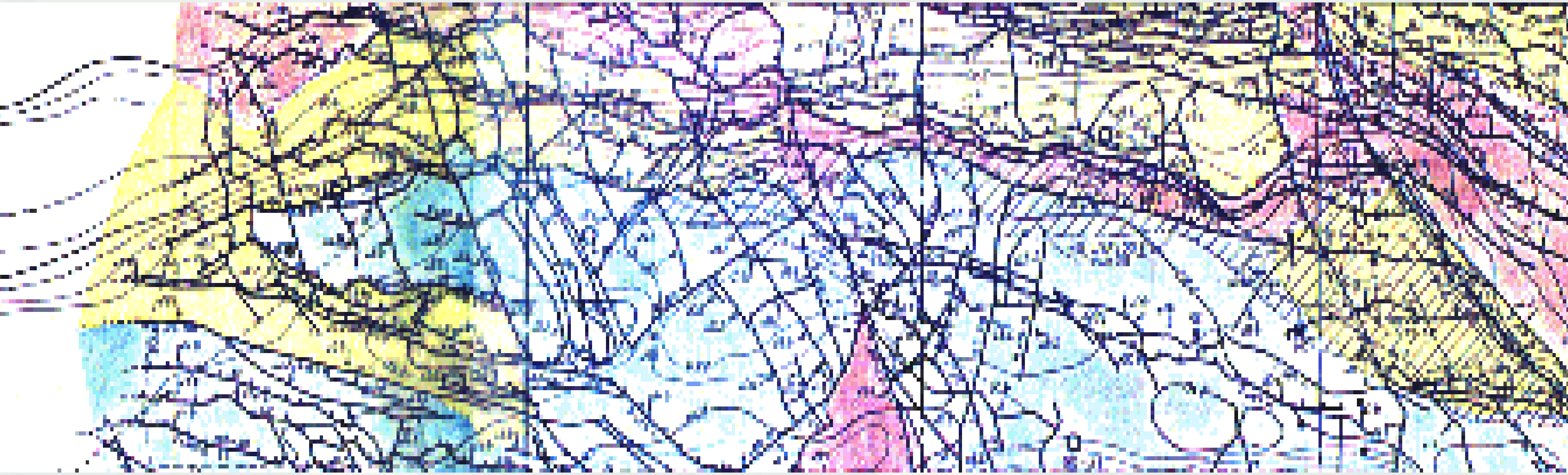


clay along the slip varies from 0.25" to 1.5" in thickness. Depth varies from 5 to 15 feet
Block 12
3200
P20
P17
Joints are spaced 1" to 4" apart limonite staining
BPS - 0.125" to 0.5" of gouge
These joints spaced 1" to 8" apart
BPS - r to r contact to 1" of gouge
Up to 8" of clay and crushed rock
1" to 10" of crushed rock
P22
DH-44
45 DIP
0.5" to 2" of gouge
3200
Portal
Area of slightly broken to crushed rock
Zone of closely spaced joints with a few irregular minor slips with 1" to 5" of crushed rock along them and trending NW across the area.
DH-16
Fault Zone #5B
2" to 5" of gouge
Plane 2X
Joints in this set are spaced 1" to 4" apart, average spacing 8", fresh, tight/ NW68 to NE78 N34-46E
BPS - 0.125" to 0.5" of fresh to weathered gouge
3150
Crushed sheared rock, red iron oxide along many slips
BPS - r to r contact to to 0.5" of tan silty clay
0.5" of crushed rock
Weathered to depths of 1.5"
Joints which strike N49-58° W & dip 47-55° S are spread 1" to 24" apart. In the rock face upstream, these joints generally stop at the BPS.
Up to 1" of crushed rock and clay
3150
Broken rock, calcified
BPS - 0.5" to 1" of crushed rock & clay
Weathered to depths of 0.5" to 1.5"
BPS - r. to r. contact to 1" clay and crushed rock
3.5" of crushed rock
r. to r. contact to 1" crushed rock
Geologic Section A-A'
Slightly sheared and crushed rock
Joints are spaced 1" to 4" apart, tight variable dips N26-40W 84NW to 82SE
DH-39
DH-40
6" to 12" of crushed rock
Sheared, crushed rock; few gouge seams 0.125" to 1" thick
3100

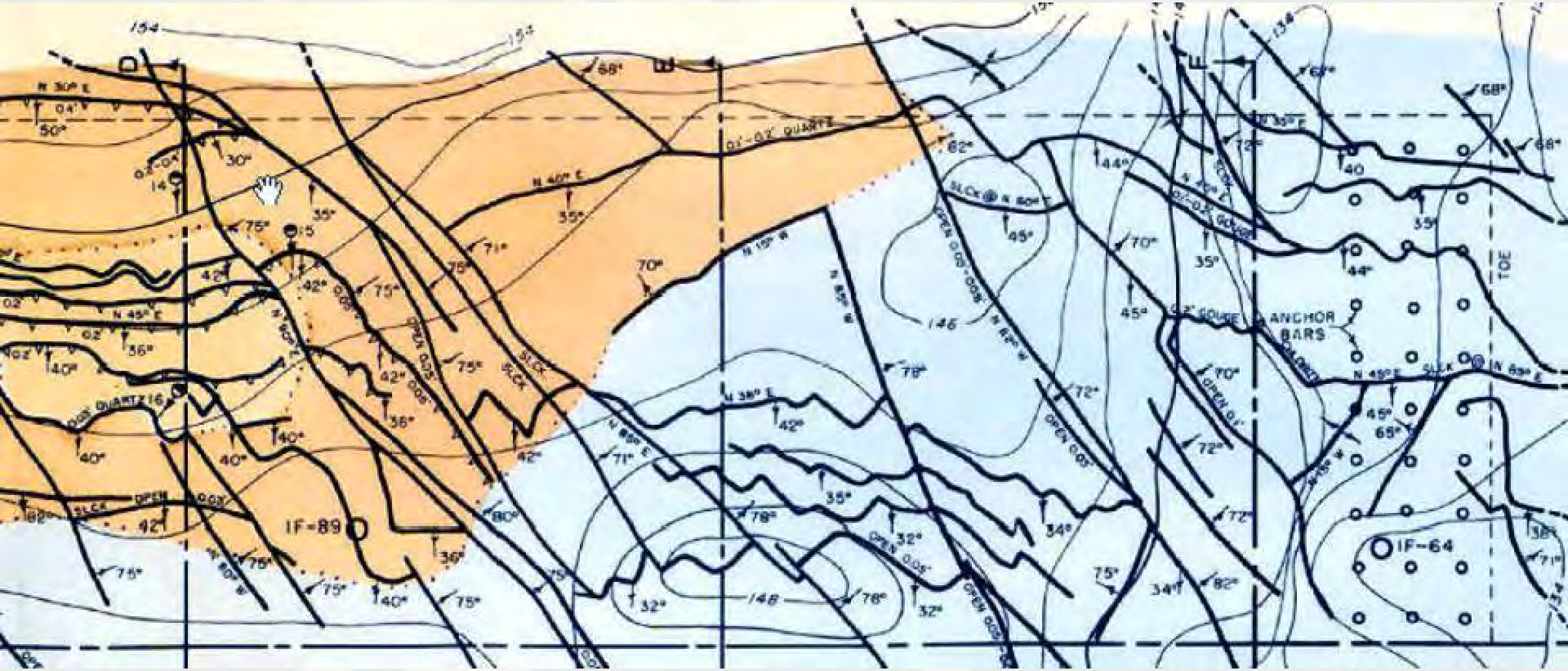

Seam 14
Seam 13

This is the full sized drawing

Dam Foundation Map



This is not very helpful in its original form

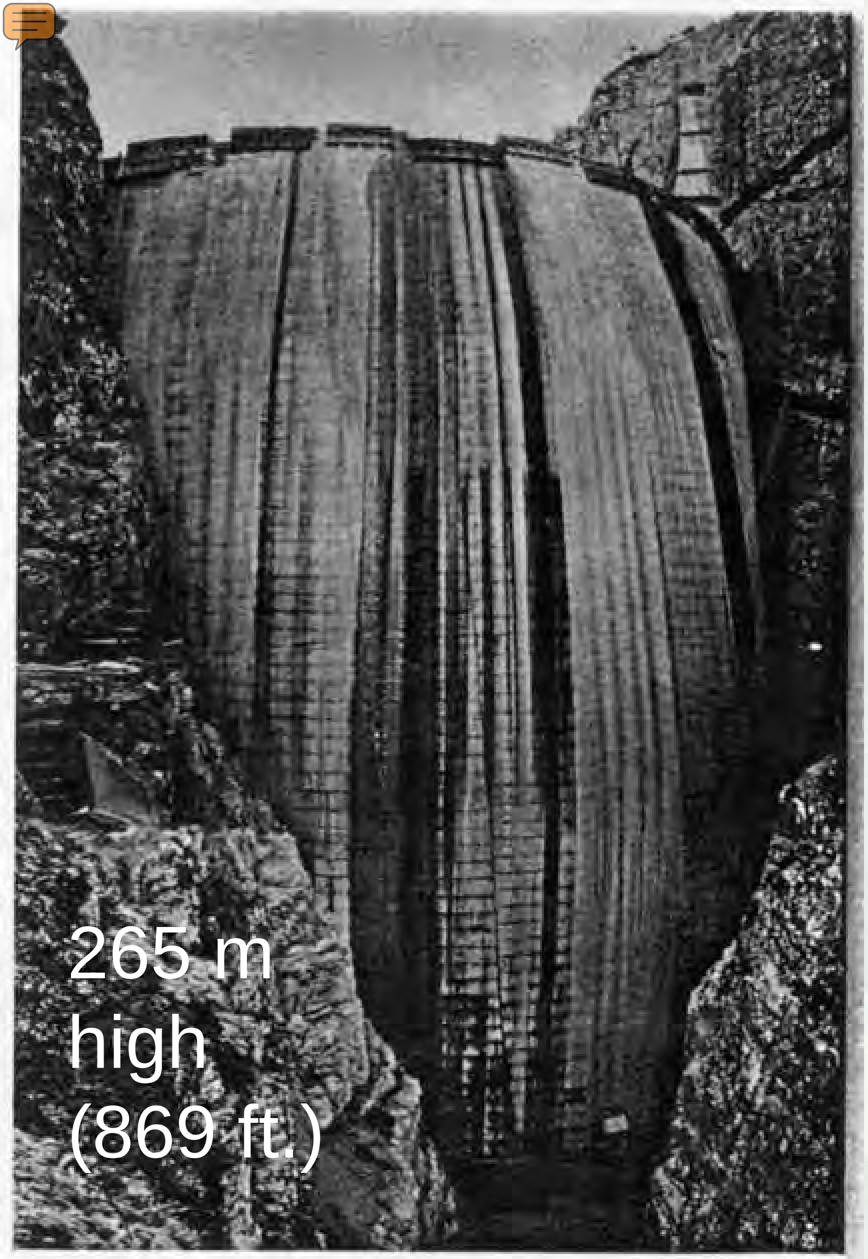

ANCHOR
BARS
IF-89
IF-64
TOE
OPEN 0.05'
N 40° E
N 45° E
N 30° E
0.1'-0.2' QUARTZ

Vaoint Dam

(Also spelled “Vajont”)
Northern Italy

- **Enormous landslide into reservoir in 1963**
- **Dam 860 ft tall (328 ft wave over dam!)**
- **Dam survives, 2600 lives lost by overtopping**
- **Sliding was being monitored closely up to failure**
- **Creep measured as 40 inches per day before failure**
- **Designers ignored seriousness of slide**
- **Local residents were nervous, could feel ground shakes from displacements**
- **Failure blamed on geologists and engineers**


Landslide Scarp
Landslide Mass
Vaoint
Dam
First Filled 1959
1963 landslide killed
2,600 people



Vaiont Dam nearing completion as seen from upstream.

The dam itself and the foundation was not the issue

The enormous consequences associated with a massive landslide into the reservoir were not accounted for.

Politics played a major role in operating the dam with known sliding issues.

This was a failure of the imagination.

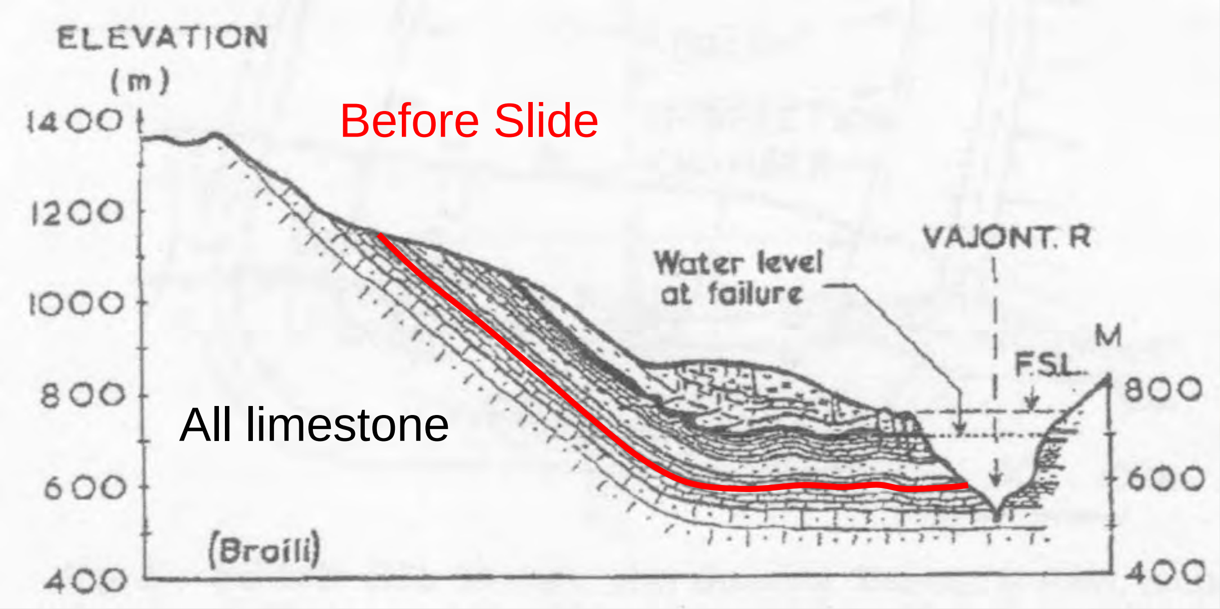
Enormous landslide scarp in limestone on left side of Vaoint Reservoir.

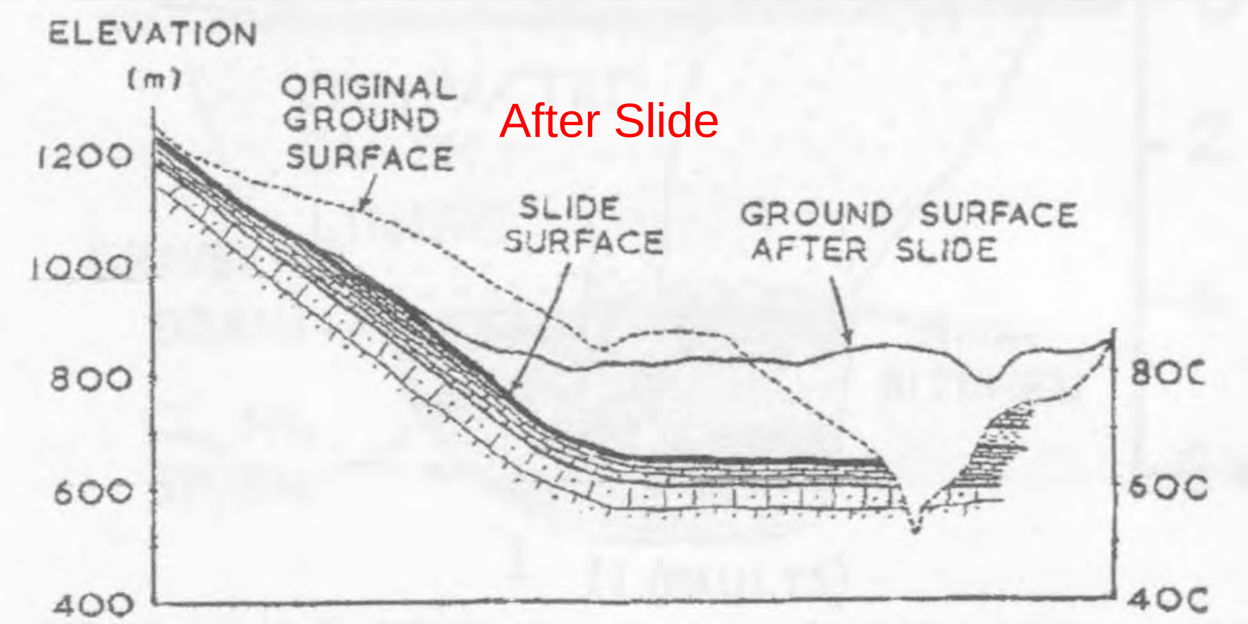
Volume estimated to be 340 million cu. yds

Resulted in a wave approximately 328 feet tall overtopping the dam.

Vaoint Landslide

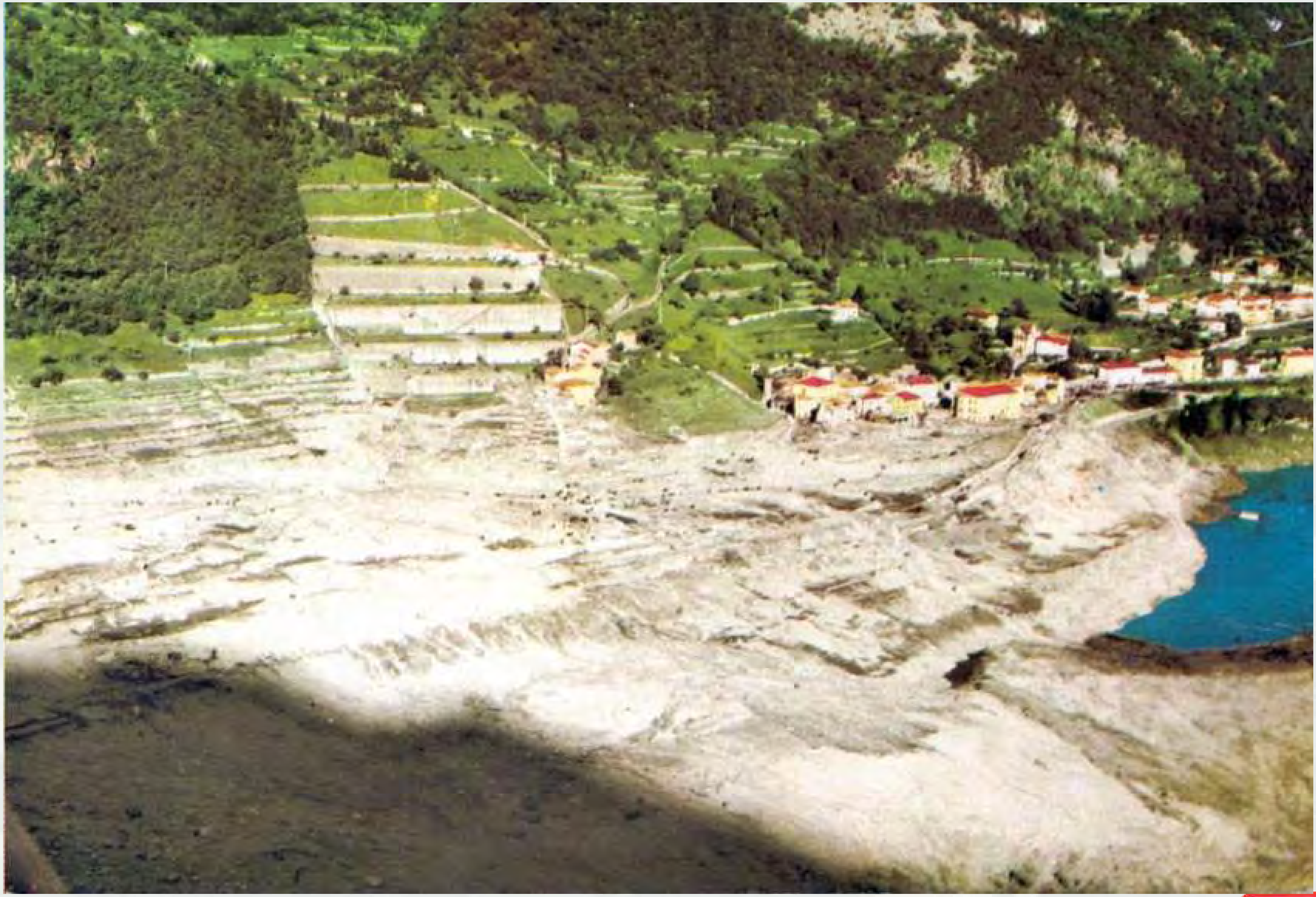
View of left bank, looking downstream





300 million C.Y slide moved at 70 mph: Oct 9, 1963

Langarone Italy



1963; 2600 people killed

Vaiont Landslide Summary Facts

- Geologic work and slope stability first studied in 1928
- Eminent university professor was expert in dolomites
- 1959 Refraction survey concluded a slide plane did not exist
- 1960 team of geologists reported evidence of a major ancient landslide on the left bank, noting a remnant mass and a mylonite zone
- Geologists considered a large slide mass a possibility
- Three boreholes were drilled and the slide plane was not recovered
- Assumed the slide if it existed was “stable”
- October 1960 noted accelerated slope movements and large scarp
- Failed in 1963

Vaiont Landslide Summary Facts

- pre-existing gullies and saddles defined the ancient slide mass on topo maps and aerial photos, but the aerial photos were likely not used
- By 1963 it was obvious that a large landslide was moving. The toe had stopped moving and was "locked" but the upper mass continued to move
- No individual or group had the political willpower to stop the project
- At the time of failure, a drainage tunnel was being constructed and the reservoir was restricted – the slide was a known "concern".
- Like many other failures, the design of Vaoint Dam <u>failed to account for the geologic uncertainties</u>
- There was no independent review with authority to take serious and drastic action to protect the public.

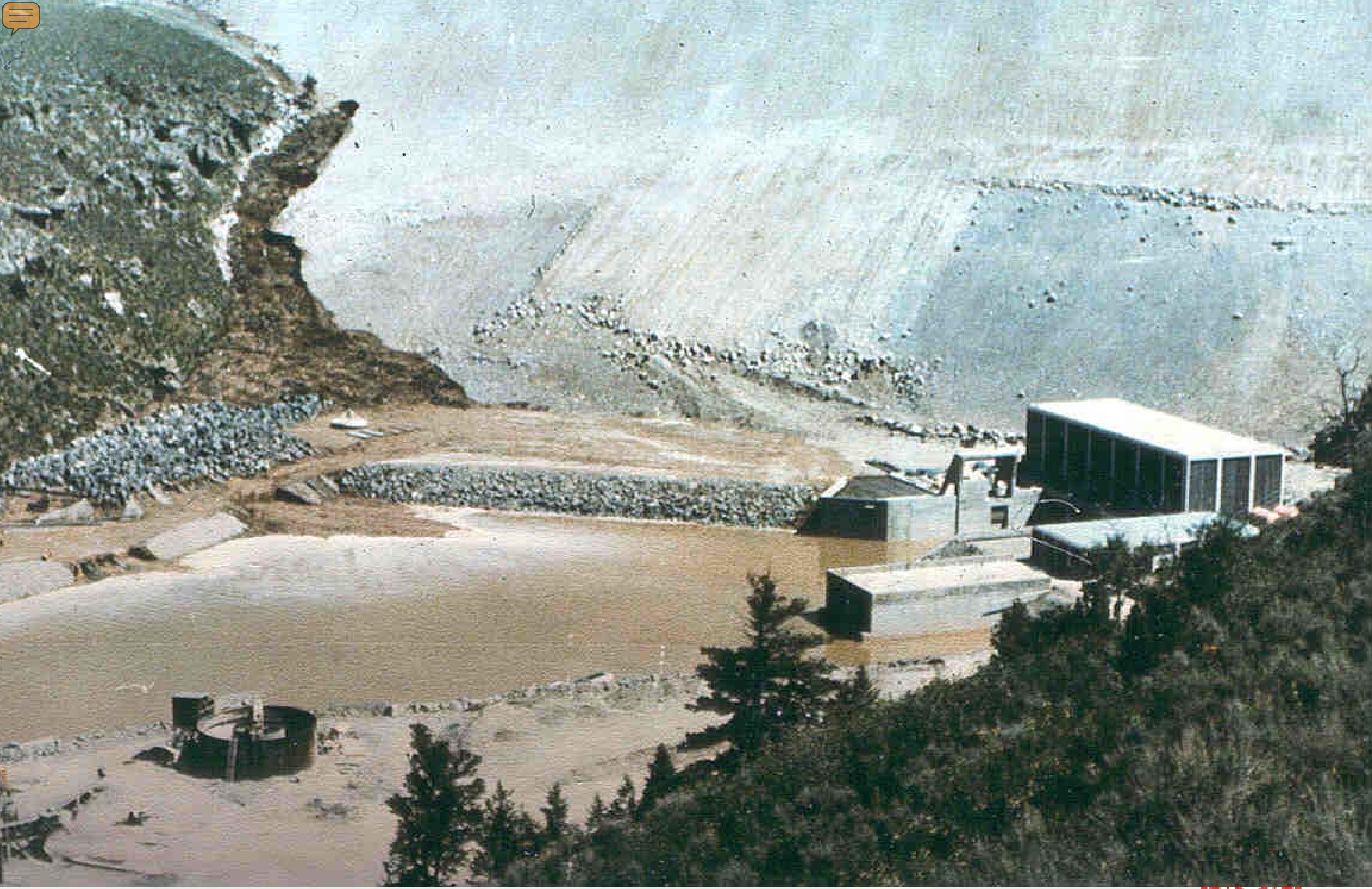
What would geologists do today that was not done at Vaoint Dam in the late 1950's and early 1960's?

- In steep terrain, look specifically for potential sliding in the reservoir and evaluate the hazard using maps and aerial photographs
- Capitalize on the Vaiont Failure to help focus attention on the need for robust geological investigations beyond the dam footprint.
- Pay more attention to instrumentation thresholds and establish "triggers" for emergency actions
- Be more involved in design decisions and account for geologic uncertainty in the design
- Communications can require assertiveness, some battles are worth fighting.

Teton Dam

Teton Dam Failure 1976

- June 4th, 1976: 11 people killed
- Only 20 gpm at 8 a.m. and 2 CFS at 9 a.m.
- 15 CFS at 10:30 a.m.
- Sinkhole at 11:30 a.m.
- Breach at 11:55 a.m.
- Intensely jointed volcanic rock known
- Untreated rock discontinuities with high gradients
- Very steep and deep cutoff trench
- No grouting of rock above bottom of trench
- Rock was mapped and joint intensity known
- Significance of information not understood

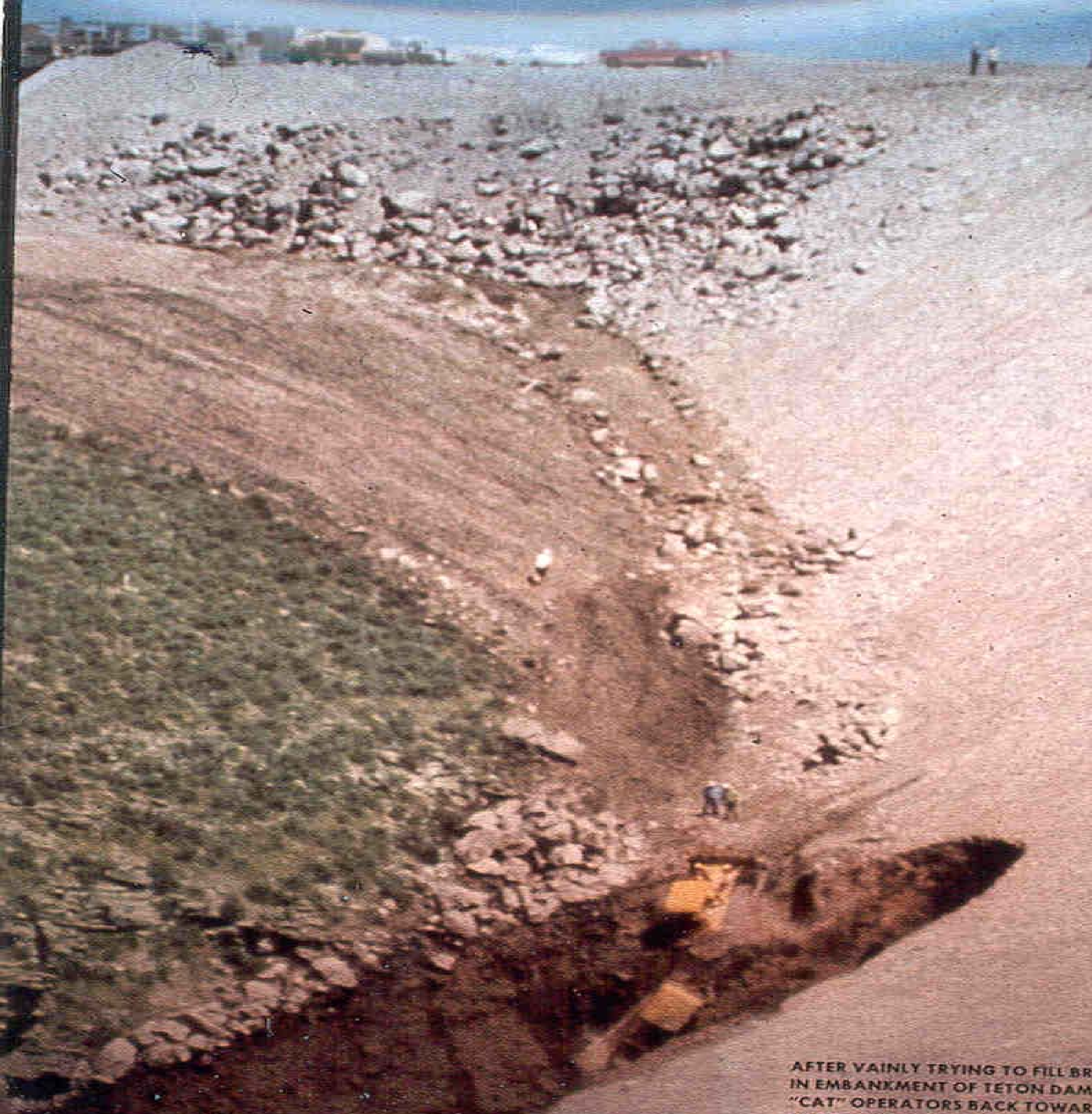


About 10:45 am


10:45


Flow Increasing, Dozers Sent to Fill Hole
at Elevation 5200 about 10:45 am

Dozers Lost In Hole About 11:20 am


AFTER VAINLY TRYING TO FILL BRE
IN EMBANKMENT OF TETON DAM,
"CAT" OPERATORS BACK TOWARD

About 11:25 am, June 5, 1976

Less than 4 hours from 20 gpm detected seepage to total breach

Only FOUR hours to get from 20 gpm to breach

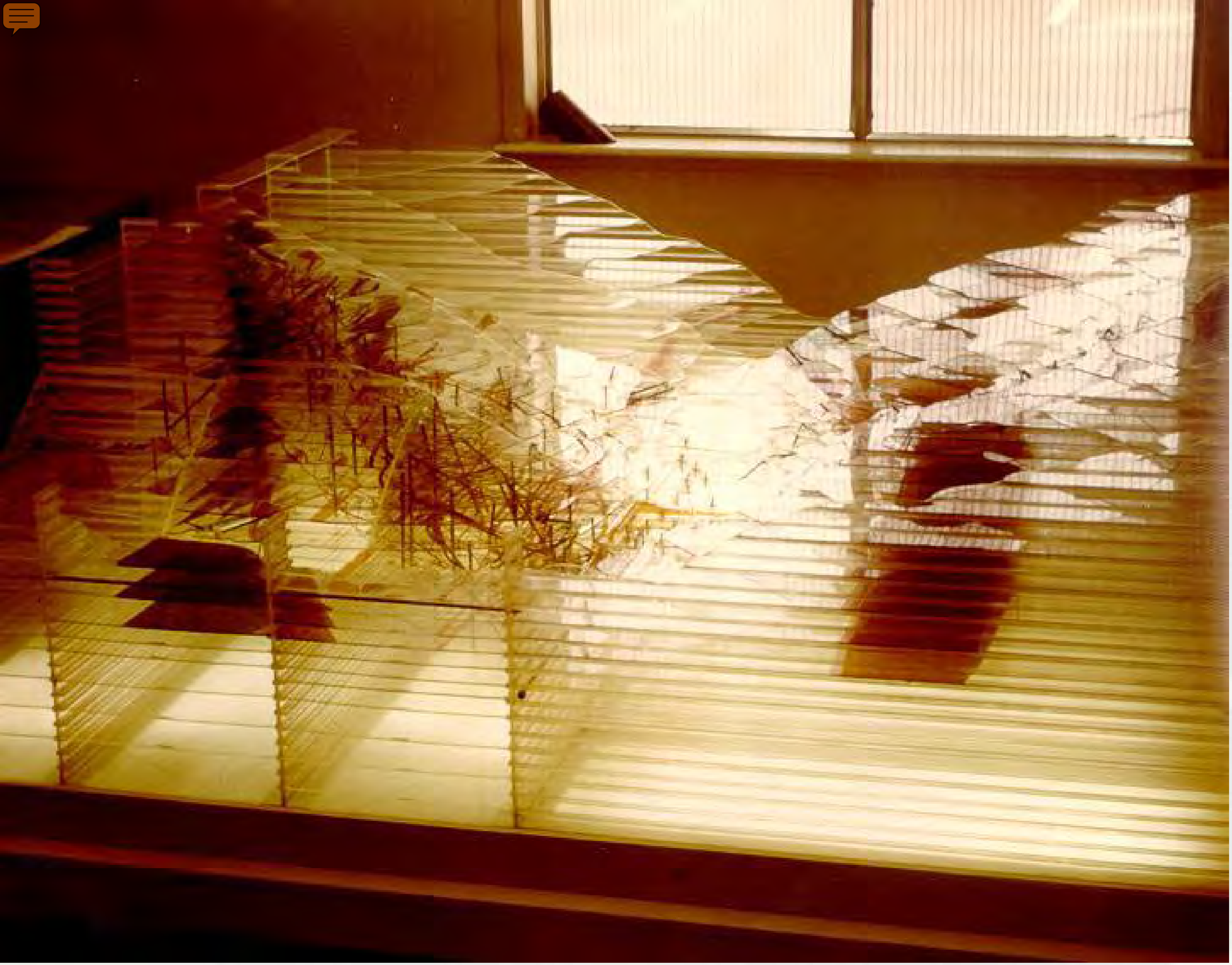
The designers failed to understand and incorporate actual geologic information into the design and <u>geologists failed to present any strong resistance</u> against the misinterpretation of this data.

- The jointing in the bedrock was known and measured
- The geology of the site was well-defined and explored
- Geologic plan and profile drawings were developed
- A robust exploration program was performed

BUT

- Communications between designers, construction forces, and geologists were very poor
- The VULNERABILITY of the dam to seepage and erosion was not understood (silty embankment on open joints)
- The designers learned nothing from the major seepage incident at Fontenelle dam a decade earlier - it was not published or discussed
- The schedule and budget pressures were enormous to make NO CHANGES during construction
- **This was a failure of the dam community to learn from past experiences**

- The existence of geologic reports, logs, maps, cross sections and other data did not result in a robust design or prevent failure.
- The potential problems were not imagined or understood by geologists or engineers.
- **Geologists need to do more than collect data!**
- Everyone needs to assure they understand the geology related to the dam’s vulnerabilities (potential failure modes)
- Geologic data must be collected with specific questions and potential failure modes in mind
- **The design must never be considered complete until the foundation is exposed, inspected, understood and approved**
- Past incidences and failures MUST be shared, publishded, studied and understood and applied to current designs.
- There is no place for HUBRIS in dam design



Auburn Dam Foundation Model, 1970's

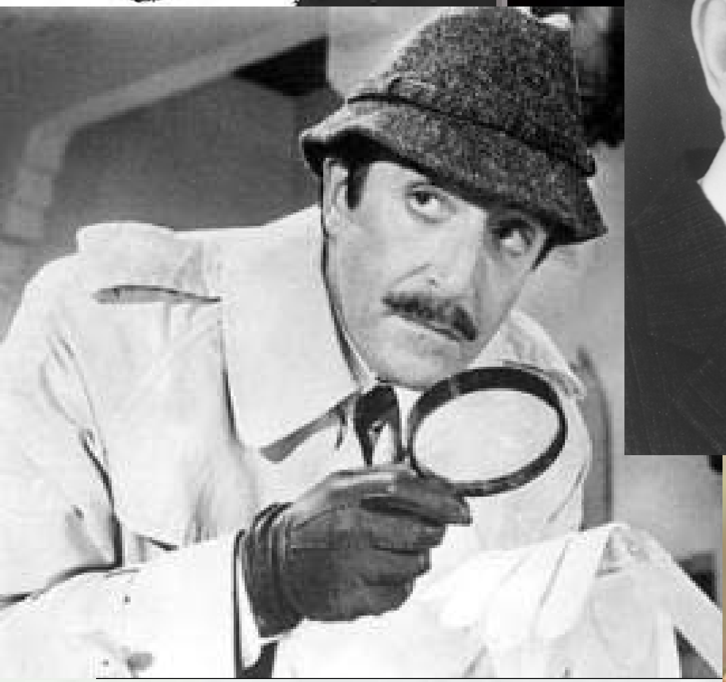
The Auburn Dam Geologic Exploration Philosophy

- Integrated team of geologists, engineers and technicians
- Real Time updating of plans, sections and 3D physical model
- Principal leadership by experienced individual versed in understanding failure mode case histories and analytical requirements: Guru teacher concept
- Geology collected, analyzed, synthesized and used for ongoing engineering analyses rapidly on site
- Mentoring and teaching was a critical aspect of all work, complete with site-specific training manuals explaining how and why things are done

Engineering Geology involves high level detective work







Fontenelle Dam Incident: 1965

“FONTENELLE DAM, RIRIE DAM, AND TETON DAM – AN EXAMINATION OF THE INFLUENCE OF ORGANIZATIONAL CULTURE ON DECISION-MAKING”

Interviews Conducted by Snorteland, Shaffner and Paul

2009 ASDSO proceedings

Fontenelle Dam Incident
(1965 – 10 years before Teton)

- Open bedrock fractures with high water flow connected to reservoir
- Discontinuities known but dam vulnerability not understood
- Failure mode was not imagined
- Large outlet works prevented failure
- Incident was not published or shared resulting in no learning and leading to Teton failure
- Better communication of this incident with the dam safety community may have saves lives!

Leakage at Fontenelle in 1965

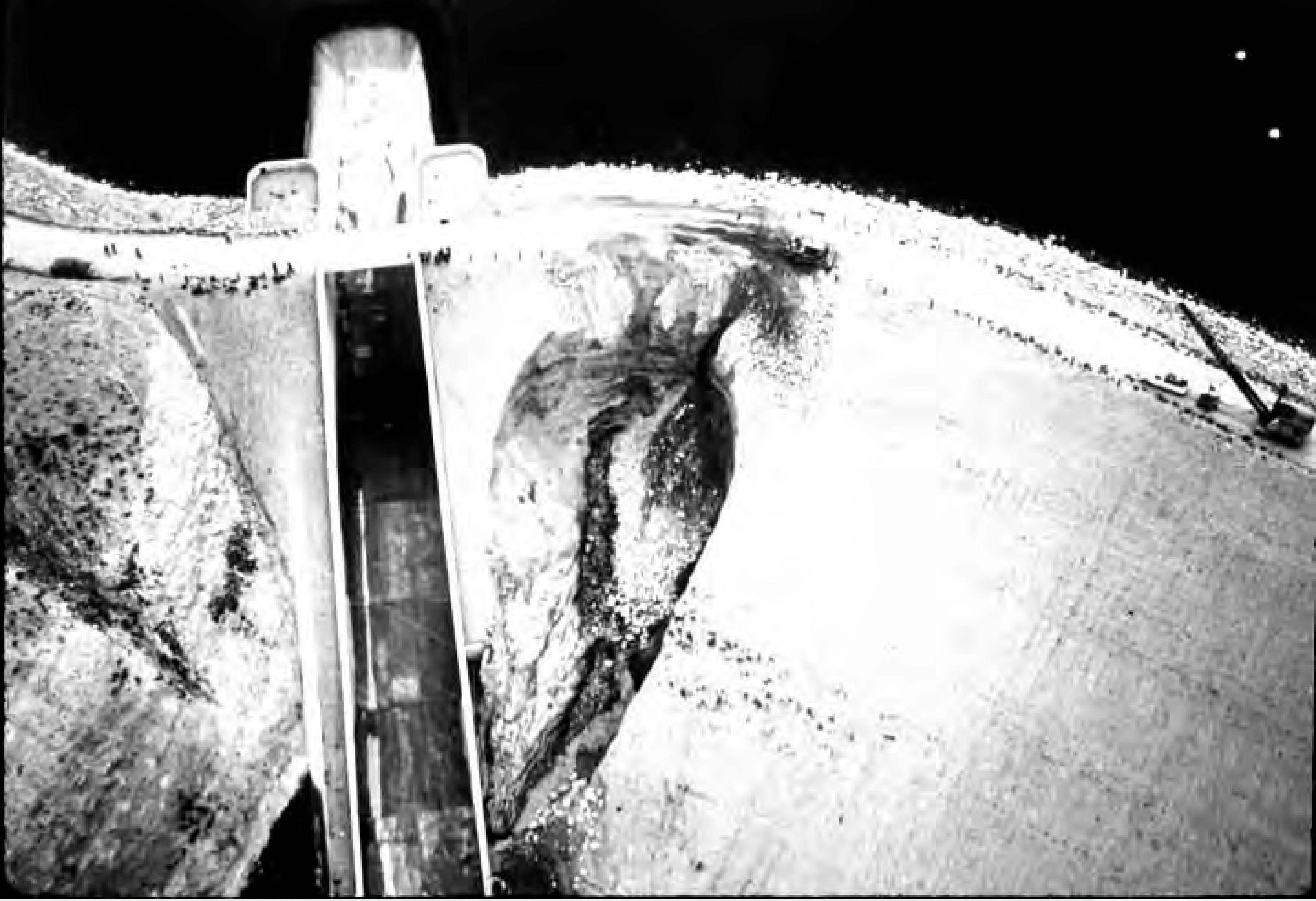
Fontenelle near-failure: First Filling in 1965

Saved only by a large outlet works

See detailed notes on slides

Piping Erosion Conduit 9-9-65

9-5-65



This erosion incident several months earlier was labeled as a “slope stability failure” and backfilled with more permeable material.

There were two of these “incidents” prior to the main problem, but engineers failed to comprehend the seriousness of the problem

If the Fontenelle Dam incident was understood by engineers and geologists working on the design and construction of Teton Dam 10 years later, it may have prevented a catastrophe and saved lives.

Dam Safety Case Histories must be widely shared and studied!!!


Mapping must single out and highlight specific features important to specific potential failure modes

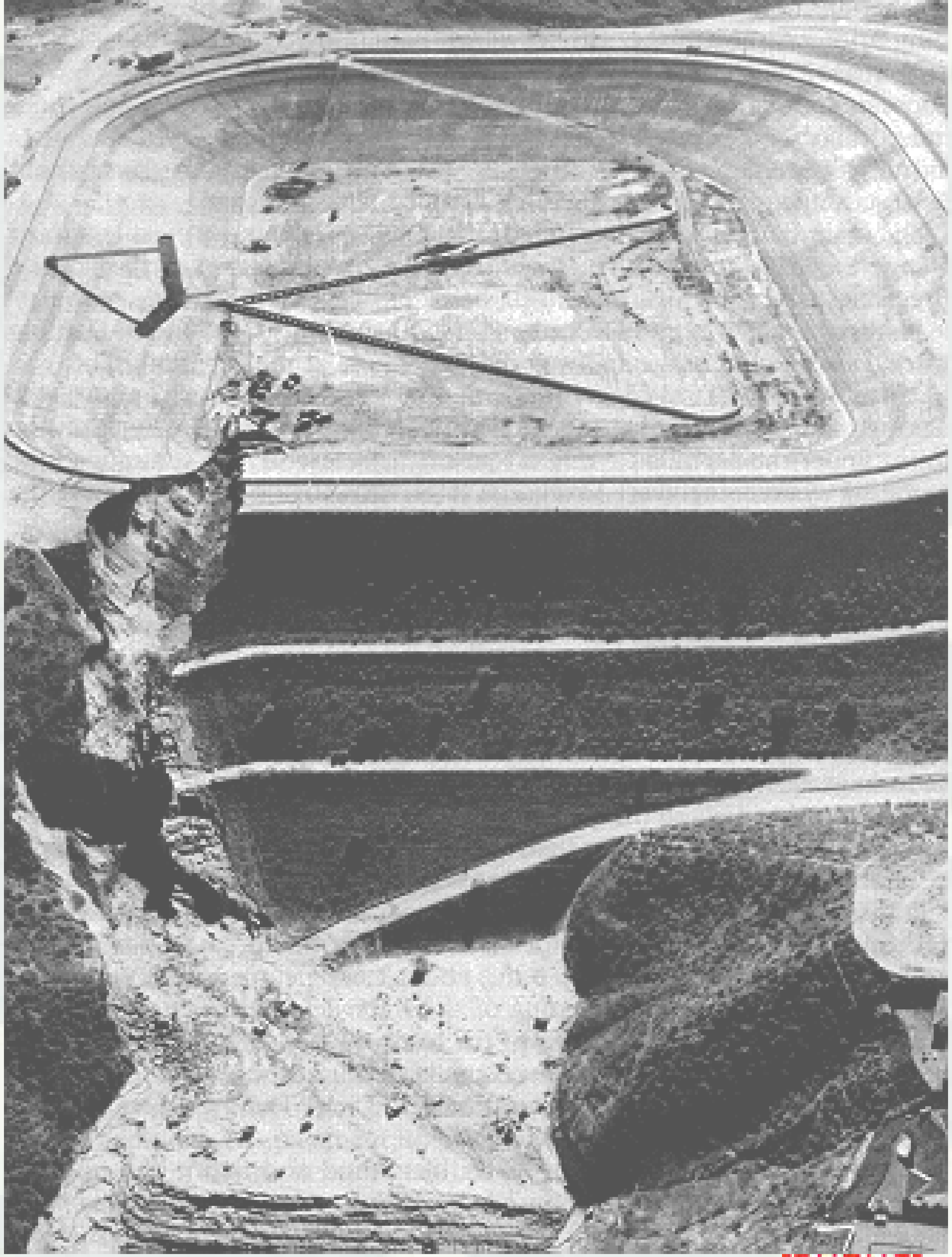
Baldwin Hills Dam

California

- Completed in 1951, Failed in 1963
- 5 fatalities, 1000 homes damaged
- Over 11 million in property damage
- Reservoir had earth lining sandwiched between asphaltic membranes and poor monitoring of drain
- Several minor, steeply dipping faults were mapped as passing through the reservoir
- Differential settlement likely from oil wells or fault consolidation
- Failed to account for geologic conditions

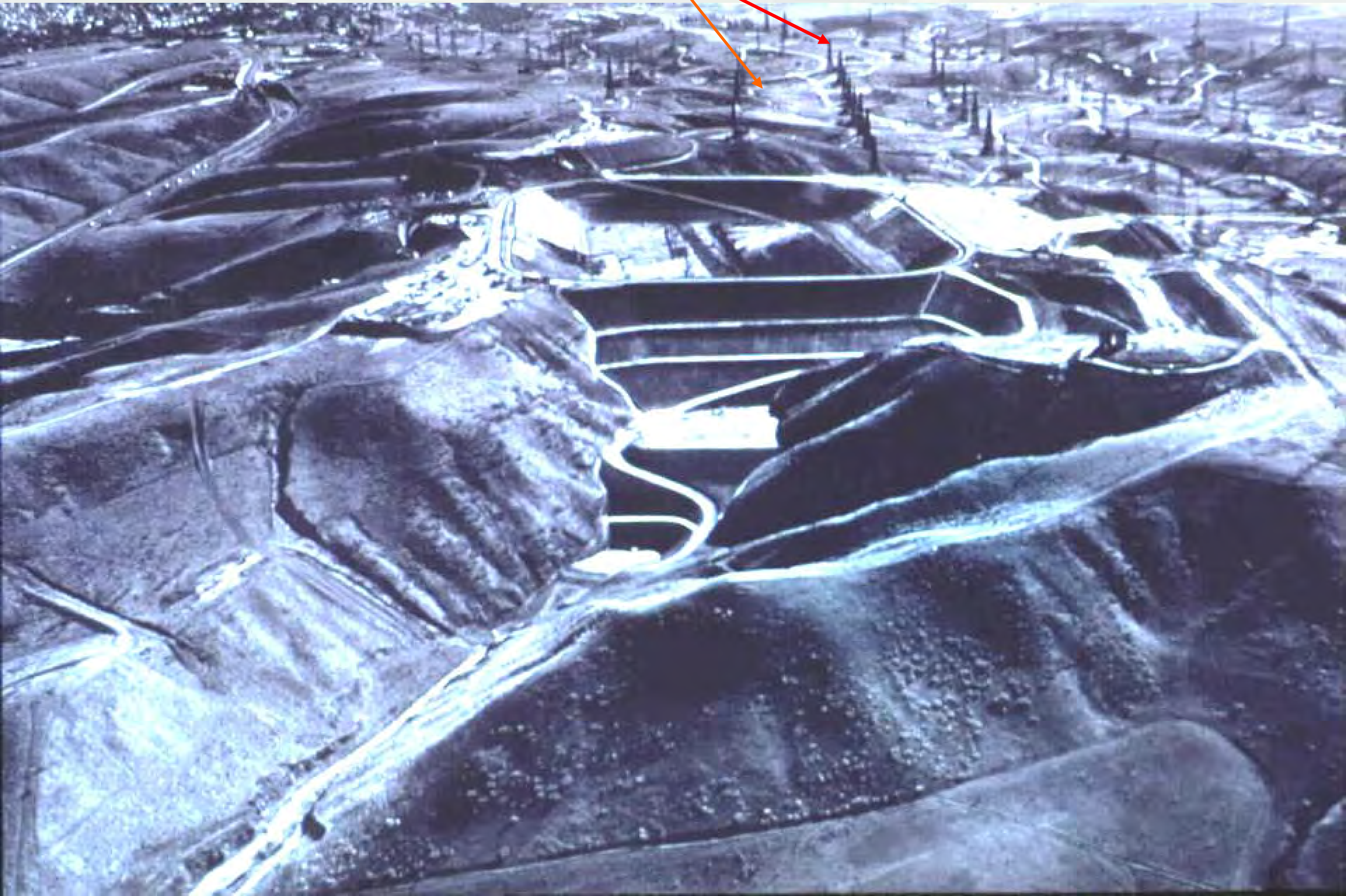
Baldwin Hills Dam California

Aseismic Movement of Fault



Note Population at risk: Evacuation saved many lives

Note Oil Field



Camara Dam
Brazil

June 4, 2004

Information from personal correspondce, Milton Kanji to Robin Fell


Where were the geologists?
18 16:32

Two days after first filling and failure

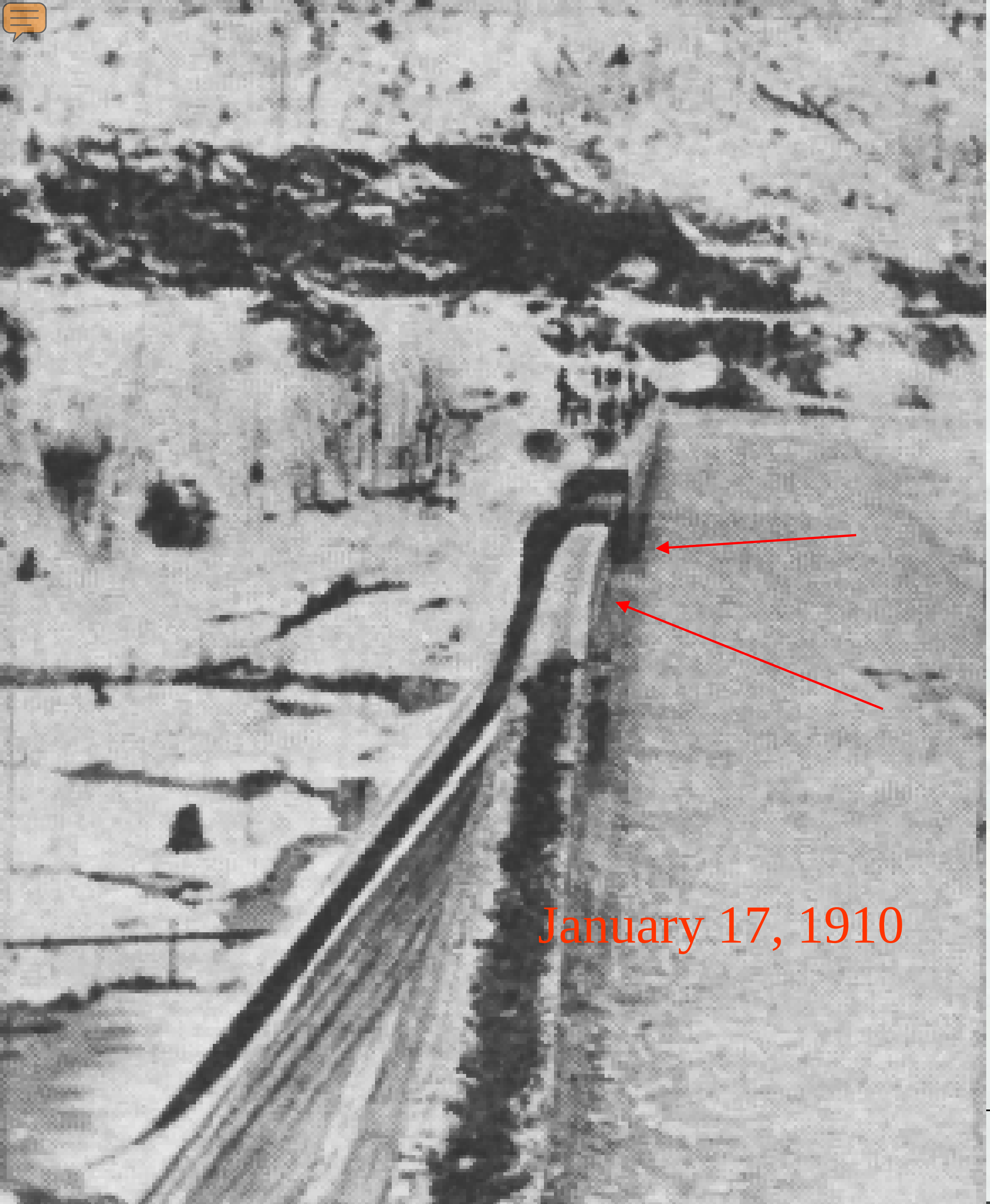
View of left abutment from downstream

View along crest showing failed bridge and continuous infilled fracture plane at left abutment

Austin Dam (Bayless Paper Mill)

Bayless Dam, Austin Pennsylvania

- The direct evidence of foundation sliding was ultimately ignored by the owner.
- The risk of failure was either not understood or ignored.
- Weak shale layers were not accounted for in the design.
- Foundation sliding and the need for drainage were not completely understood in this era



Austin Dam-50 ft high

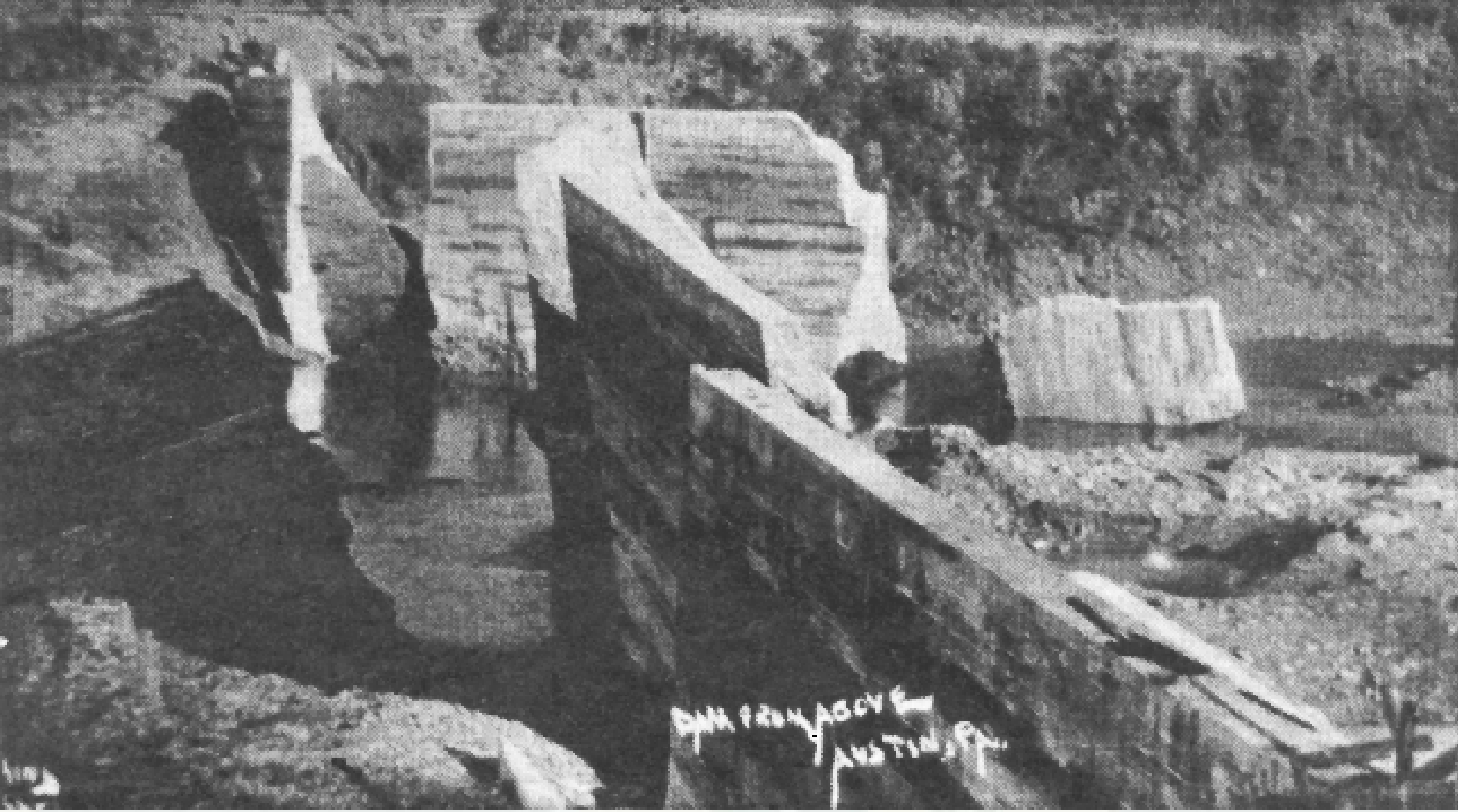
Built and operated by Bayless Pulp & Paper Co.

Failed in 1911

On January 17, 1910 a bulge appeared on the crest of the dam. Measurements indicated the dam had moved downstream on its foundation. The dam was taken out of service. A consultant review recommendation to strengthen the dam was ignored.

Austin Pennsylvania after Bayless Dam Failure

78 fatalities



Bayless Dam Failure: September 30, 1911

The dam collapsed suddenly. A review of the failure indicated that the dam failed by sliding on weak shale layers in the rock foundation.

Sophisticated calculation is too often substituted for painstaking subsurface investigation…….

Geology, the foundation of engineering

"Over the years it became increasingly apparent to me that the difference between success and failure resided not in the quality or quantity of theoretical studies, but in the success with which the fundamental properties of the geological materials had been evaluated originally or could be determined as a result of field observations during and even after construction." *-Ralph Peck*

“Sophisticated calculation is too often substituted for painstaking subsurface investigation. The ease or the fascination of carrying out calculations taking into account complex loadings, geometrics, and soil conditions leads many of us to believe that realistic results will somehow emerge even if vital subsurface characteristics are undetected, ignored, or oversimplified. Unwarranted comfort is often taken in the delusion that a range of assumed values, possibly all of which overlook a vital feature, guarantees that the correct result will be bracketed by the calculated ones. Not only does this practice lead to erroneous conclusions in specific instances, but it breeds a distaste for the painstaking field work that may be required to disclose and evaluate those subsurface features that will determine safety and performance”

–Ralph Peck

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Austin Dam

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Baldwin Hills Dam

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