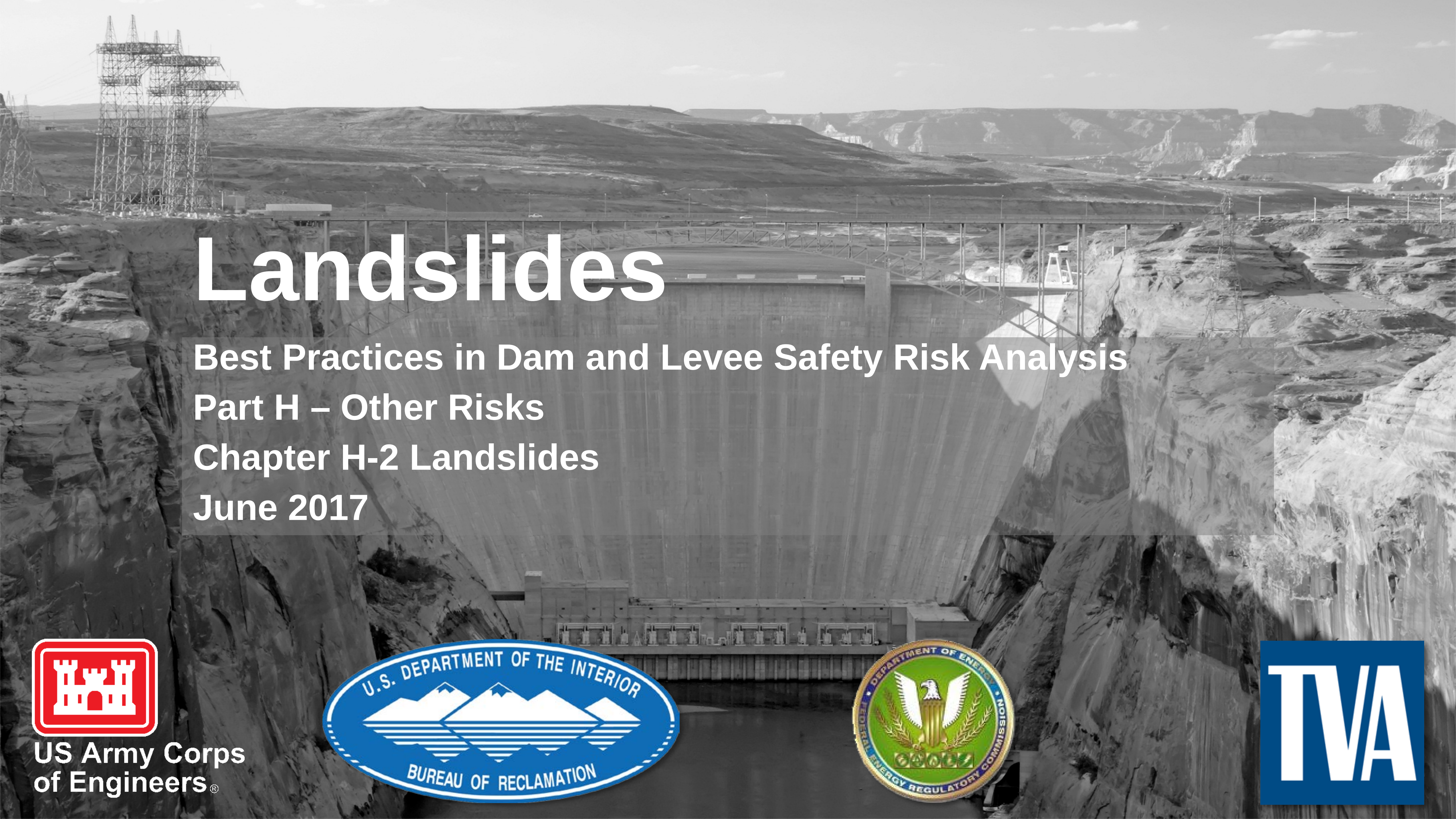


Landslides

Best Practices in Dam and Levee Safety Risk Analysis

Part H – Other Risks

Chapter H-2 Landslides

June 2017

US Army Corps of Engineers®

U.S. Department of the Interior Bureau of Reclamation

Department of Energy Federal Energy Regulatory Commission

TVA

Outline

- Objective
- Key Concepts
- Case Histories
  - Vaiont, Italy
  - Quake Lake, MT
  - Costilla Dam, New Mexico
  - St. Francis Dam

Objective - Develop familiarity with landslides and their impact on structures, rivers or reservoirs

Key Concepts

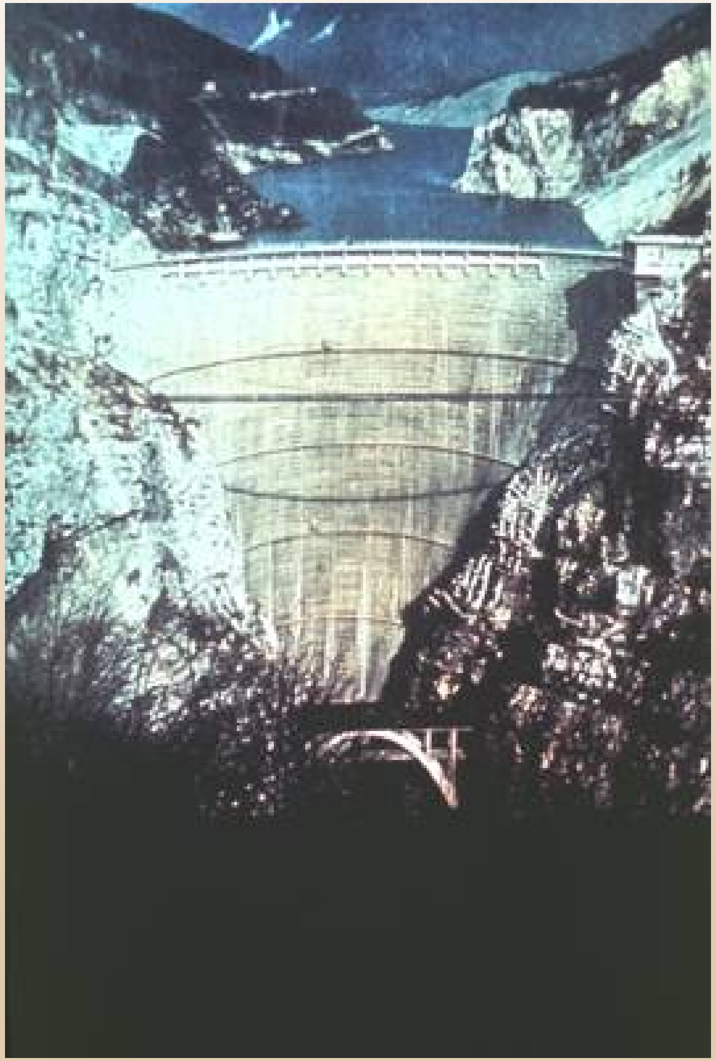
- There are direct and indirect impacts
- Always look beyond the footprint of the facility (Vaiont, Quake Lake)
- Many dams in mountainous terrain where landslides are common
- Landslides can be triggered by
  - Hydrologic hazards (heavy rainfall, snowmelt)
  - Operations (e.g. reservoir drawdown)
  - Seismic hazards (Large earthquake, fault offset)

Key Concepts (Cont.)

Landslide related PFM's

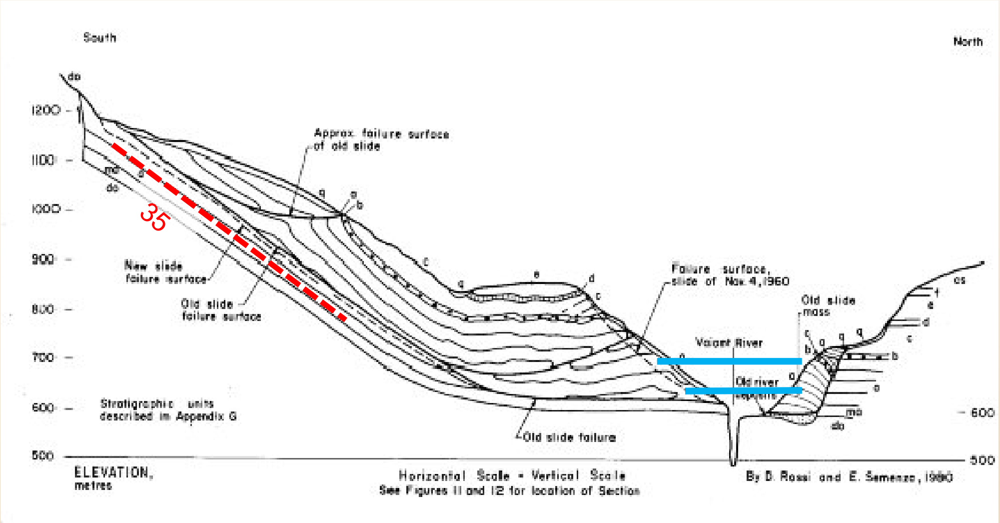
- Upstream – rapid failure into reservoir can create overtopping
- Downstream - river blockage affects dam access/monitoring and releases
- Dam site – abutment landslide can lower crest, create cracking and scour/concentrated leak erosion (embankment), or concrete deformation and cracking
- Dam site - spillway blockage hinders reservoir-release operations

Vaiont Dam, Italy



- 870’ high arch dam on Vaiont River near Longarone, Italy
- Completed in 1960
- The foundation and reservoir slopes composed of bedded limestone
- Left bank slide mass from post-glacial period

Vaiont Dam (Overtopping Wave)



From Hendron and Patton

- A part of the mountain side slid into the reservoir on Oct. 9,1963
- Filled the entire reservoir for a mile upstream of the dam creating huge wave
- Sliding occurred on clay-filled bedding planes with phi = 10 to 12º with dip of 35º+/- to 0º
- Approx. 250 million yd^3

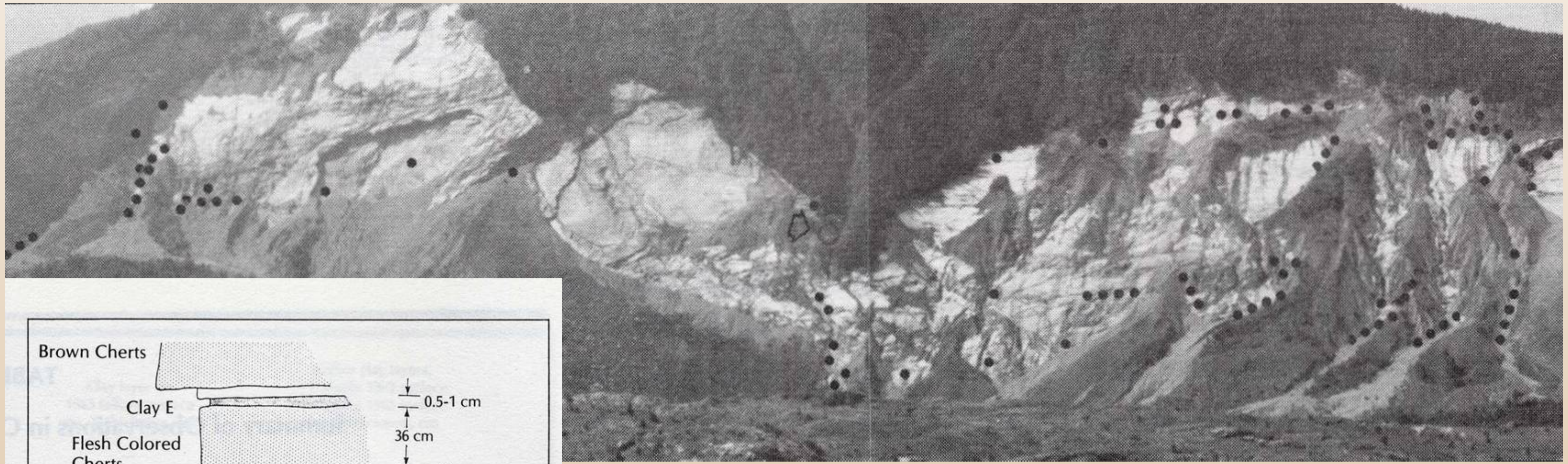
Vaiont Dam

Slide sent wall of water 330’ high over the top of the dam downstream (dam survived)

2600 fatalities in the village of Longarone downstream

Vaiont Dam

- Definitive study by Hendron and Patton, 1985 (COE)
- Occurred on old slide
- Moved on clay layers (φ ~ 12^{o})



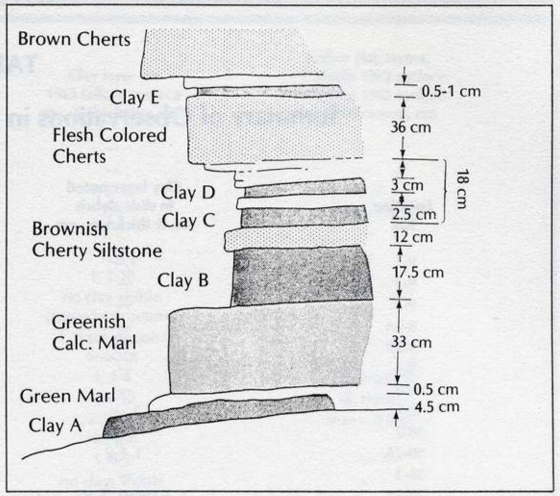
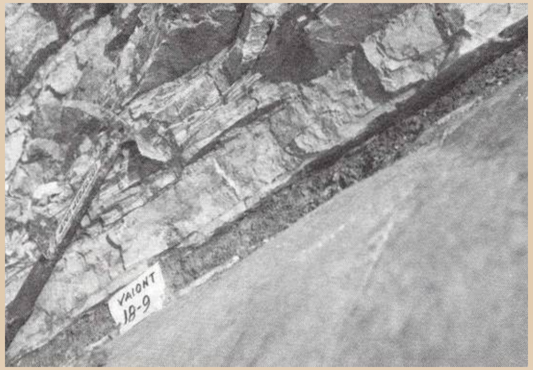


FIGURE 19. A sketch of the outcrop of Malm rocks southwest of Casso. This outcrop lies in the same stratigraphic sequence as those at the base of the Vaiont Slide.

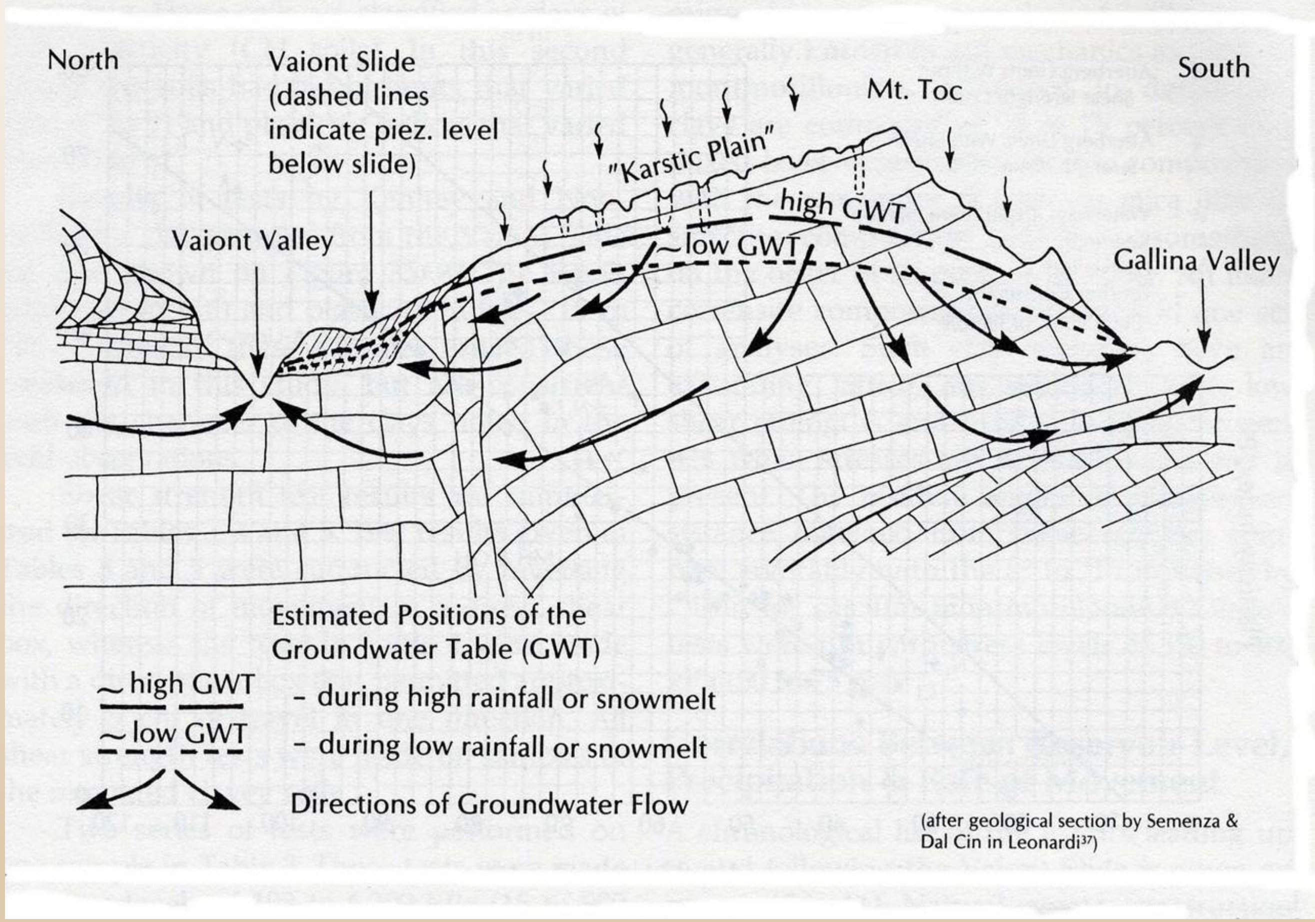
Similar sequence outside slide area



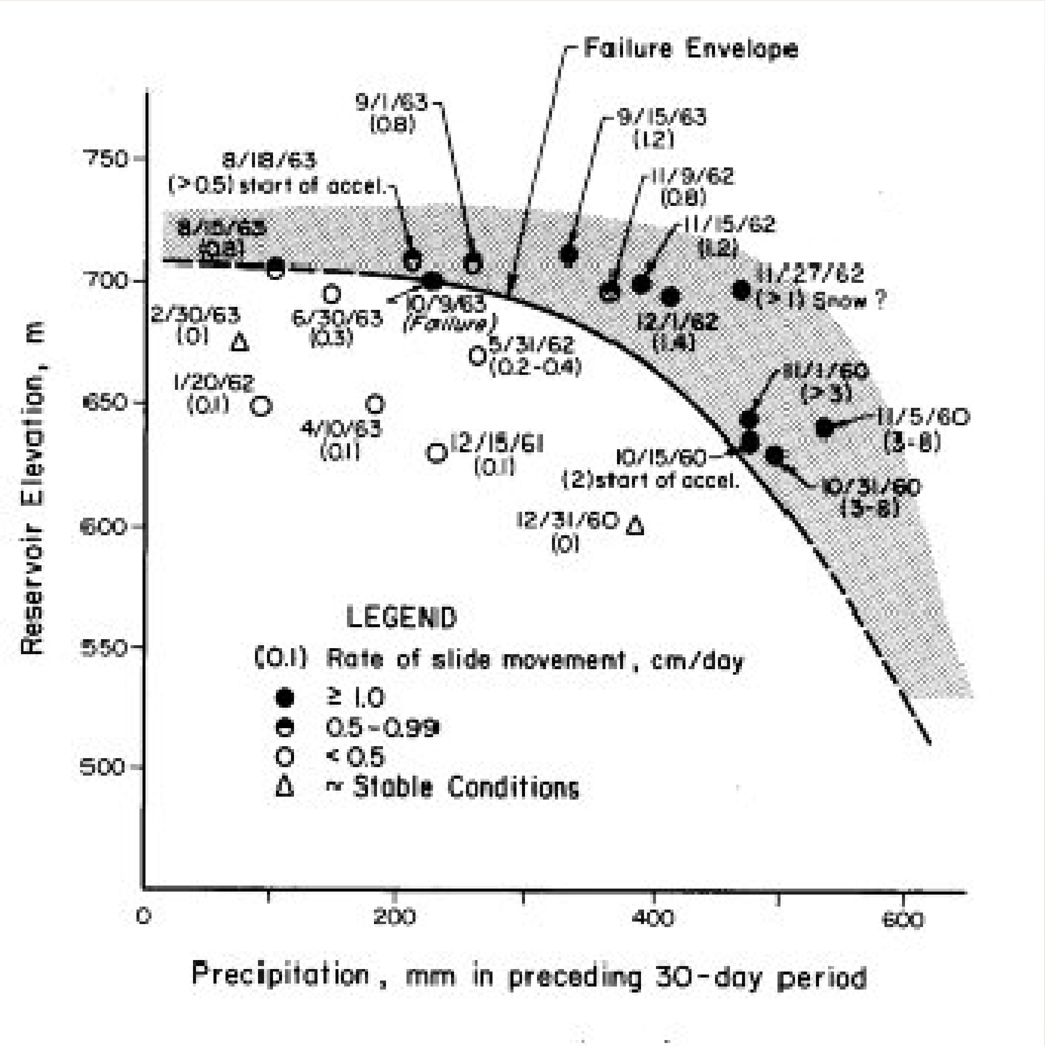
Clay layer at slide plane

Vaiont Dam

- Karstic terrain groundwater system
- What effect does this have on the landslide mass?



Vaiont Dam Landslide



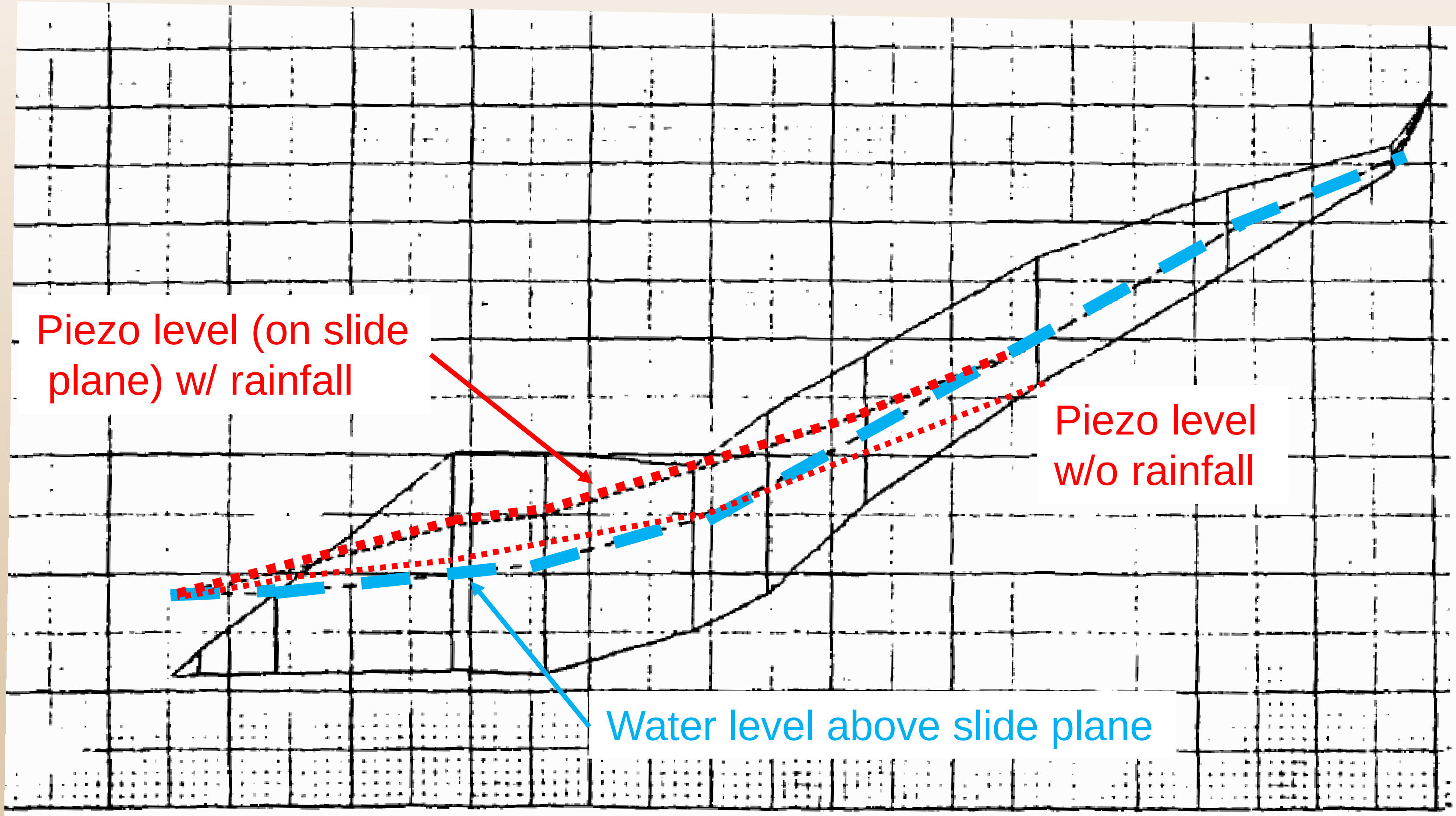
From Hendron and Patton

Combination high reservoir and high rainfall caused slide

Vaiont Dam 3-D

Res (m)	Rain	F.S.
710	High	1.00
710	Low	1.10
650	High	1.08
650	Low	1.18
None	High	1.12
None	Low	1.21

200 ft x 200 ft



Vaiont Slide - Semenza Section 2, 710 m reservoir, October 1963, with rainfall

From Hendron and Patton

Displacement and Reservoir Level vs Time

Glastonbury and Fell

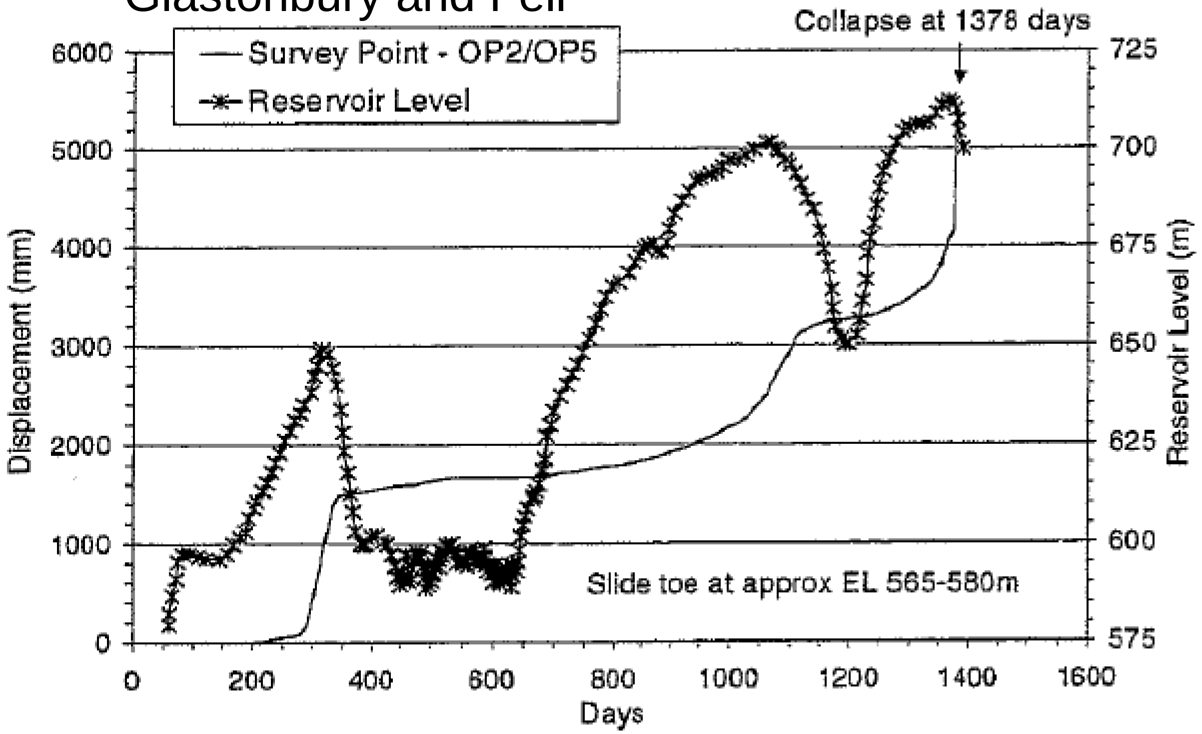
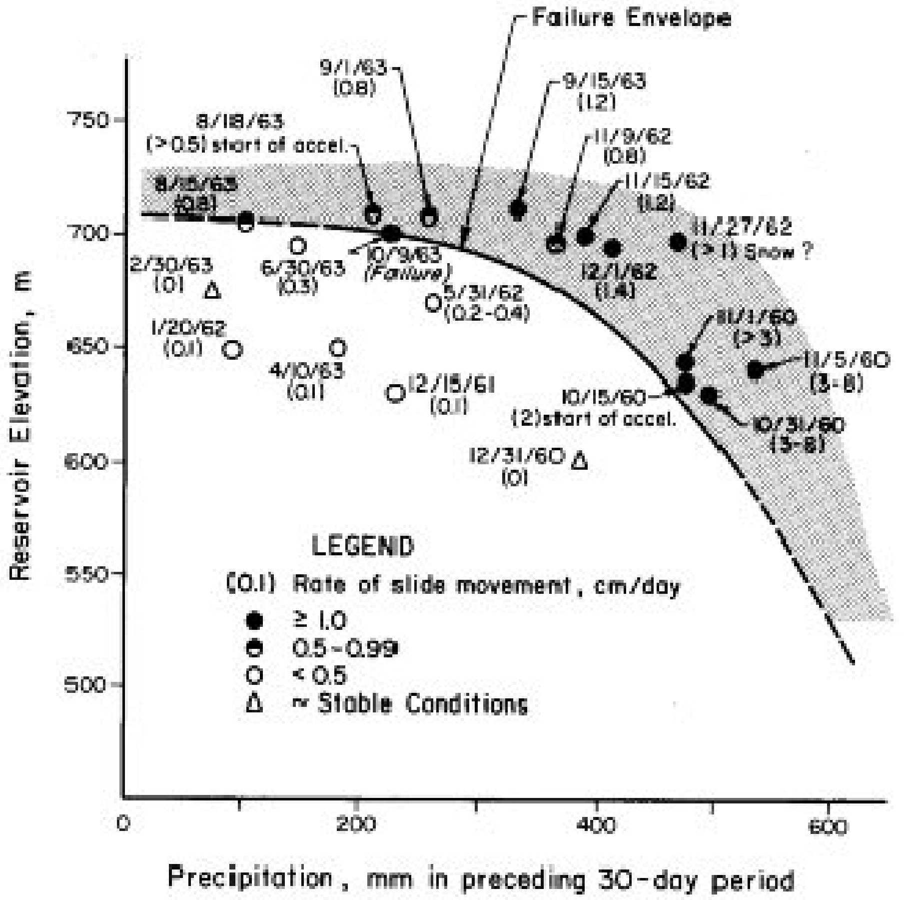


Figure Q : Displacement-time data for Vaiont showing relationship with reservoir level (Data modified from Hendron and Patton, 1985).



Key Landslide Characteristics

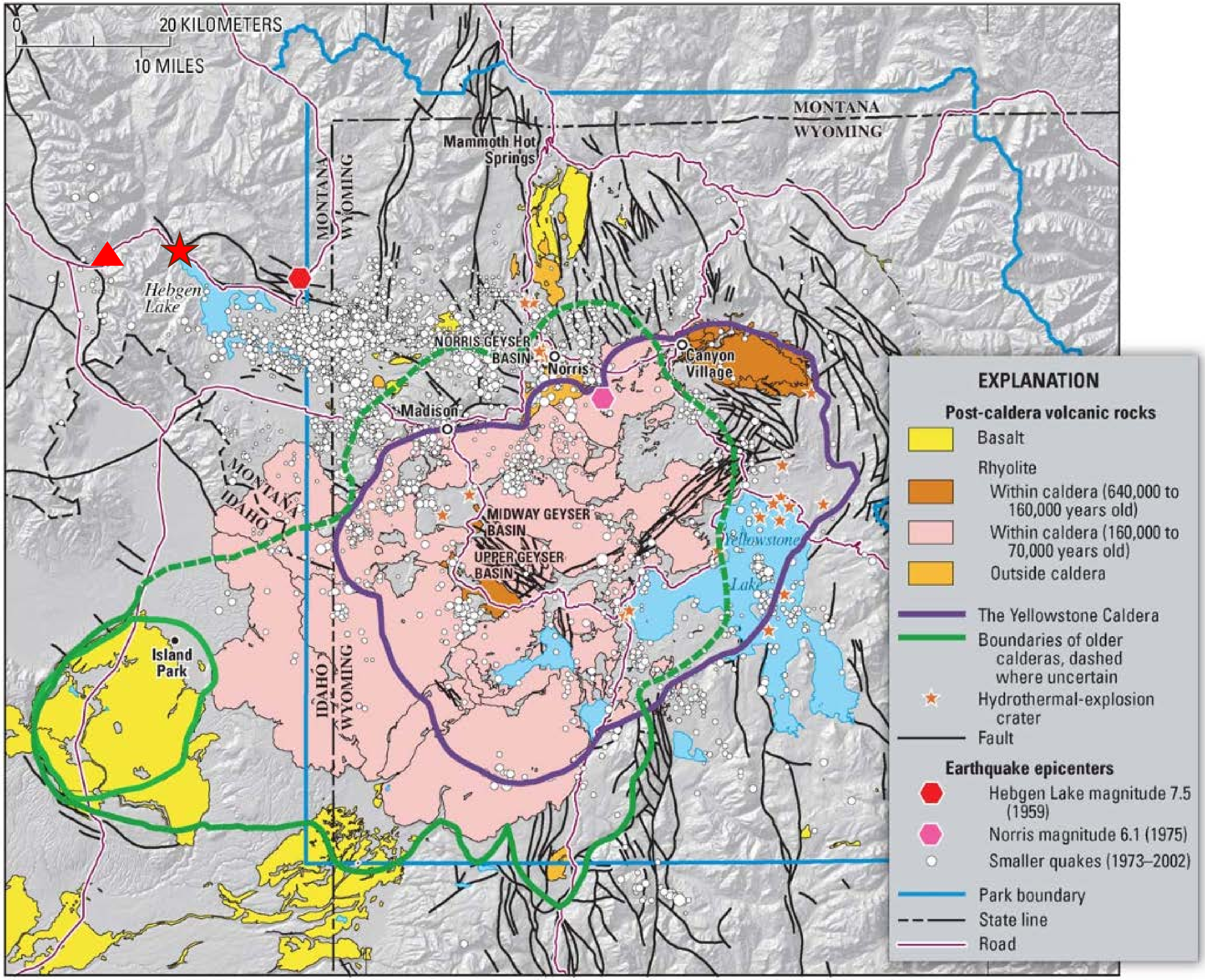
- Important to understand
  - Rainfall data
  - Reservoir operations
  - Groundwater conditions
  - Geology (including 3-D effects)
  - Geometry and failure mechanism
  - Slide characteristics (slide mass, rupture surface and lateral margins)
  - Slide history (first time or reactivated)
  - Movement surveys and rates of movement
  - Limit equilibrium (including reliability analyses or other analyses)

Quake Lake Landslide

- Triggered by August 17, 1959 Hebgen Lake E.Q.
- M7.5-7.8 in SW part of Yellowstone Park
- 43,000,000 c.y. slid across canyon and up opposite side nearly 400’
- 27 fatalities in campground on opposite side of river

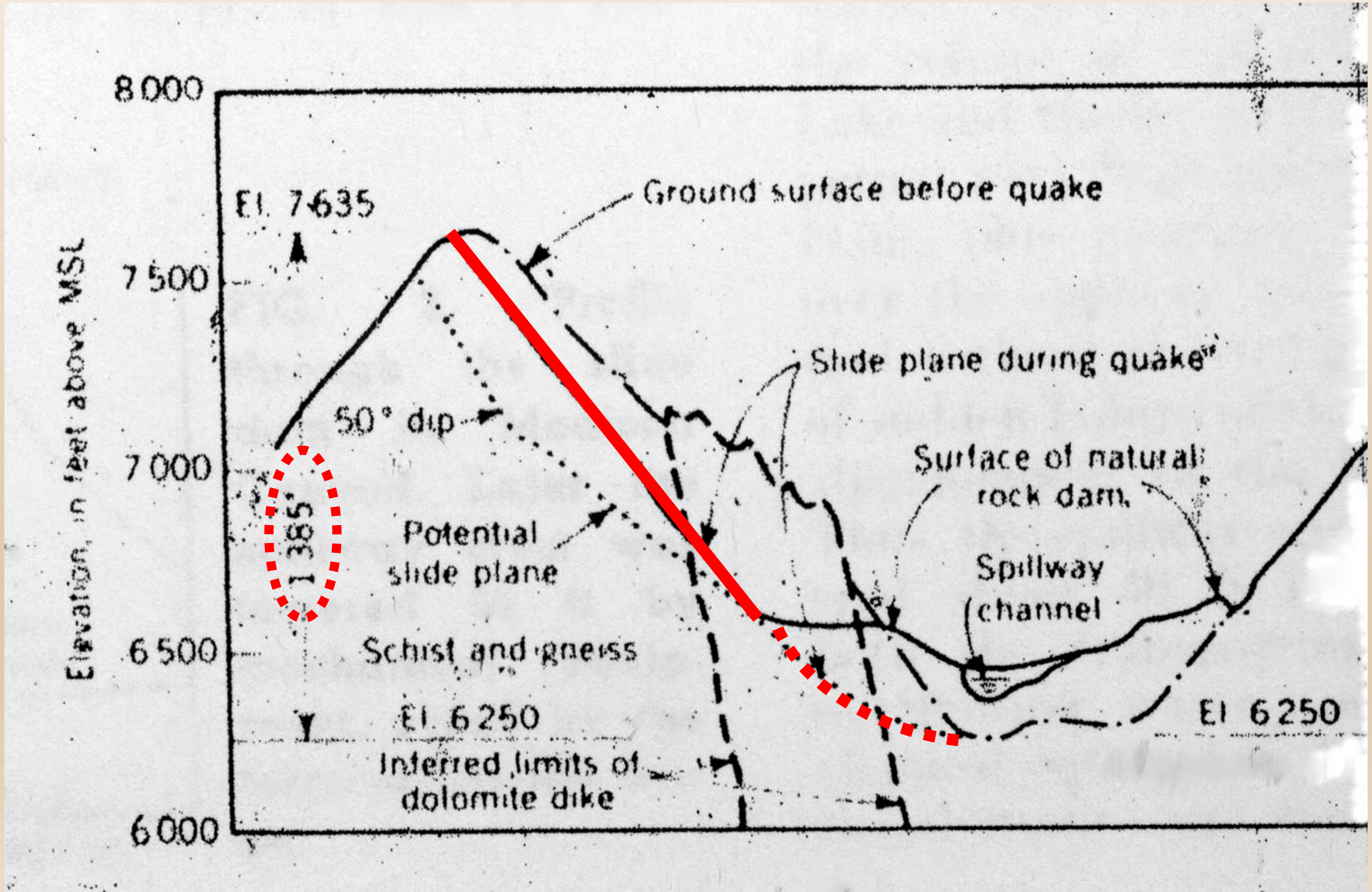
The Quake

- Magnitude 7.5
- Max Intensity X
- Lasted 30-40 secs
- Up to 20 feet vert. offset
- Epicenter ⬣
- Dam ★
- Quake Lake ▲



Quake Lake Landslide

- Buttress of jointed dolomite collapsed
- Sliding occurred along 50º foliation toward canyon



Slide Mass Immediately Afterward

Quake Lake Landslide (D/S of a dam)

- Landslide debris dam 4,000’ long and 200’ high across Madison River d/s Hebgen Dam formed “Quake Lake” - leakage to ~ 200 cfs
- Hebgen Lake nearly full at the time and dam was damaged by earthquake (inspection desirable)
- Volume in Hebgen Lake nearly 4 times that which could be accommodated in Quake Lake
- In time allowed, spillway notch 250’ wide cut through slide with capacity of 10,000 cfs
- Simultaneous armoring with 2-3’ rock

Final Solution

- Consulting Board hired, including A. Casagrande
- Need to lower crest to reduce gradient and pool
- Spillway channel later lowered 50 ft reducing Quake Lake from 81,000 to 35,000 acre-ft
- Used flowing water to aid with excavation – erosion got away from them – dumped rock to redirect flow

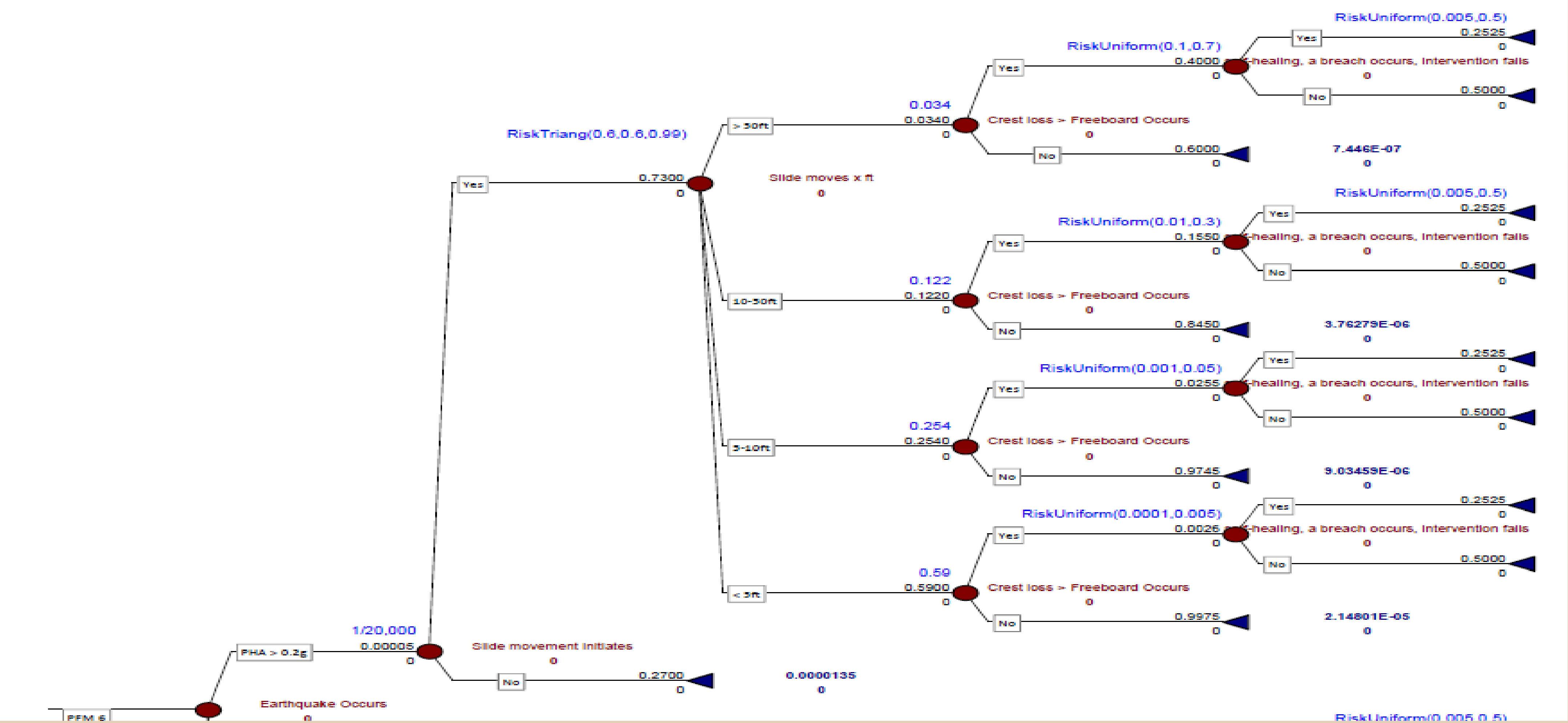
Other Landslides Upon Which Dams are Founded

Rockfalls Can Also Be Damaging

Equations for Quick Estimates

- Displacements during earthquake shaking
  - Jibson (2007) based on yield acceleration and magnitude
  - Kramer et al (1997) Modified Newmark Model for Seismic Displacements
- Wave heights generated by landslides moving into reservoirs
  - Pugh and Chang (1986) block slides based on Morrow Point
  - Huber and Hager (1997) debris slides
  - Perez (2006)

Example Event Tree



Takeaway Points

- Landslides occurring upstream (reservoir waves, inundating operating structures, landslide dams), beneath (distress, cracking, sliding in foundation) , or downstream (landslide dams) of a dam can cause dam safety issues
- Landslides can also cause problems with dam operations
- Understanding, assessing and monitoring landslides that are likely to move is prudent

Added References

- “Landslides Investigation and Mitigation” Special Report 247

Transportation Research Board, National Research Council

- “Landslide Dams: Processes, Risk and Mitigation”

Edited by Robert L. Schuster

- “Landslides Analysis and Control” Special Report 176

Transportation Research Board, National Academy of Sciences

- “Report on the Analysis of Rapid” Natural Rock Slope Failures” and “Report on the Analysis of Slow, very slow and Extremely Slow Natural Slides” both by Glastonbury and Fell