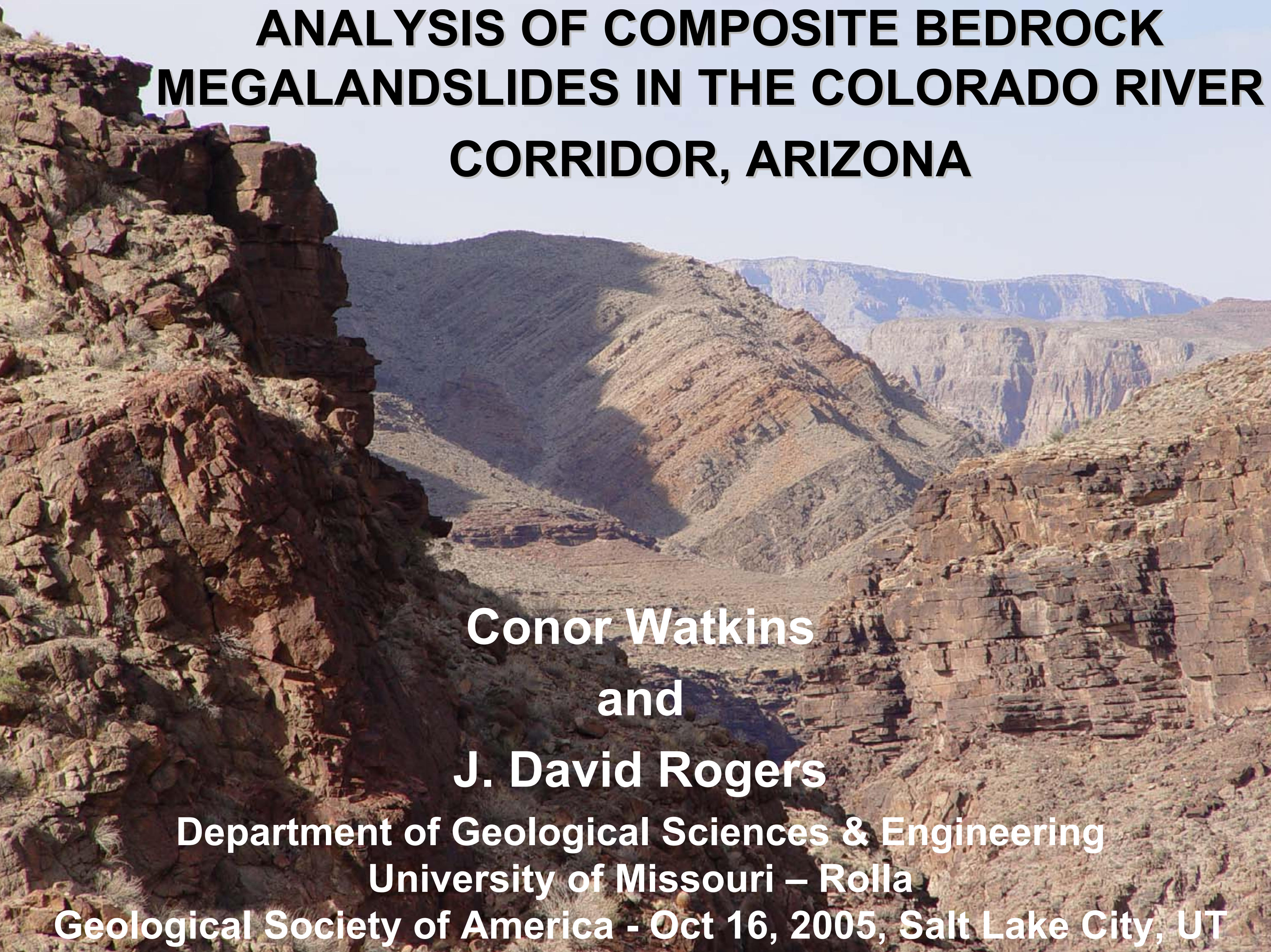

ANALYSIS OF COMPOSITE BEDROCK MEGALANDSLIDES IN THE COLORADO RIVER CORRIDOR, ARIZONA

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Background

- Landsliding is present throughout the Colorado River Corridor in Arizona.
- Sliding in the Chinle Formation begins along the Vermilion and Echo Cliffs just upstream from Lee's Ferry.
- As the river cuts down into the Cambrian age Bright Angel Shale in Marble Canyon, sliding begins and continues intermittently until reaching the end of the Grand Canyon at the Grand Wash Cliffs.
- The larger slides flooring in the Bright Angel Shale involve the displacement of over 600 m of strata.

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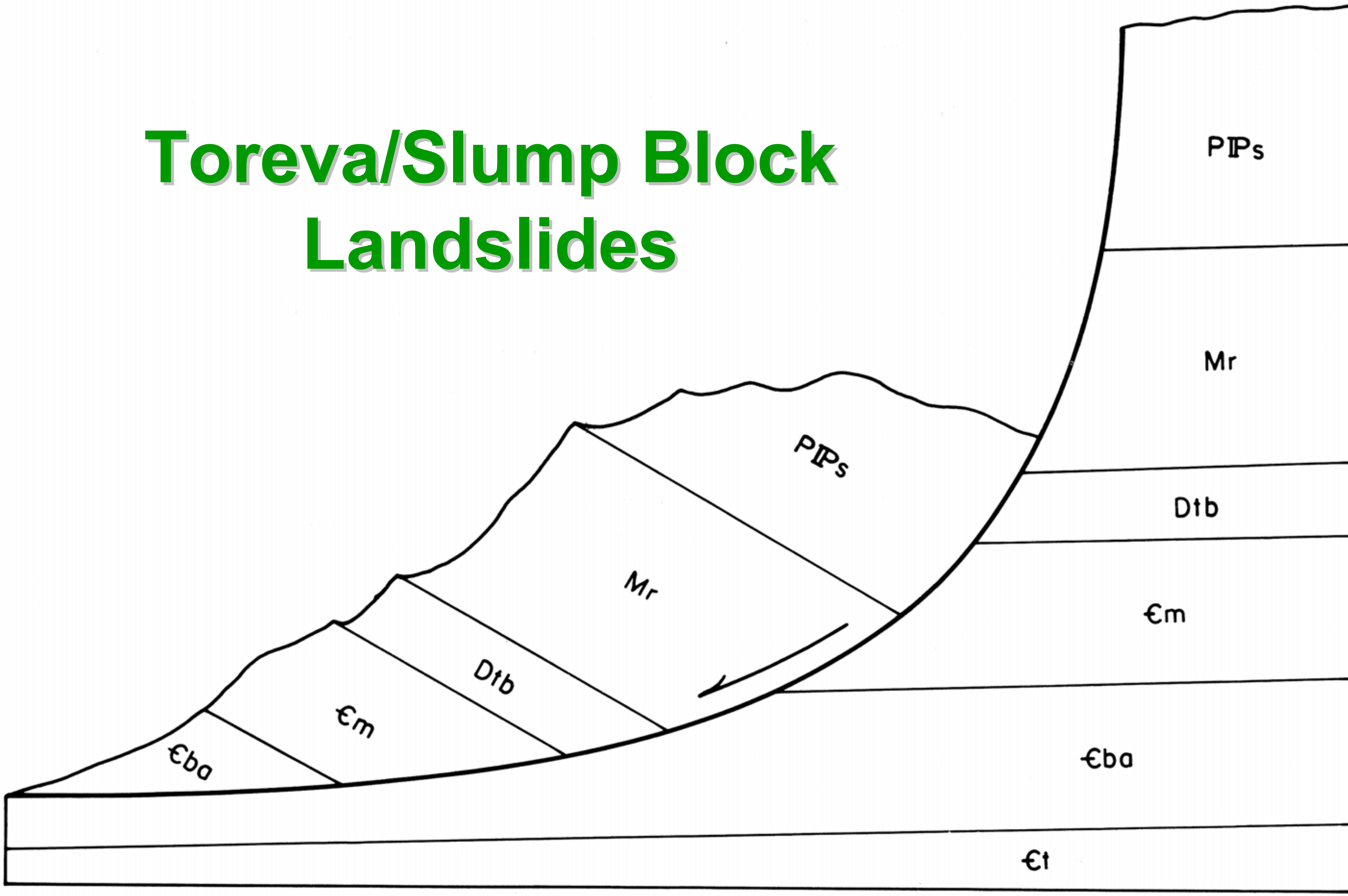
Toreva/Slump Block Landslides



Schematic of a simple Toreva or slump block typical of Surprise Valley in Grand Canyon (from Huntoon, 1978). This type of landslide exhibits rotational motion during movement.

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This landslide complex floors in the Chinle Formation adjacent to Lee's Ferry and appears to have once blocked the Colorado River (arrow)

Progress on Evaluation of Complex Landslides

- Over the past 3 years we have undertaken a systematic inventory of the largest landslides in the western Grand Canyon, with a focus on analyzing their occurrence.
- Smaller landslides were also identified in the eastern Grand Canyon and Marble Canyon.
- Most of the slides appear to have temporarily blocked tributaries or the main channel of the Colorado River.
- Variables common to the landsliding in Grand Canyon have been identified.
- These slides likely underwent a progressive failure caused by the strain softening of the Bright Angel Shale before catastrophic failure.

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Variables Common To Landsliding

- The largest slides floor in the Bright Angel or Petrified Forest Member of the Chinle Shales (only one exception).
- Regular systematic jointing of the rock mass appears to control headscarp geometry
- Faulting seems to play a important role in the western Grand Canyon.
- Erosion of the landslide toes appears to have triggered secondary failures at most sites, including two of the largest slides, at RM 205L and 205R.
- Saturation of the Bright Angel Shale is theoretically sufficient to trigger movement; but environmental factors capable of causing saturation appear to have disappeared during the Holocene.

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Other Contributing Factors

- Wetter paleoclimate
- Inundation from lava or landslide dams
- Rapid drawdown from catastrophic failures of such dams
- Local seismicity within Colorado Plateau
- Facies changes and local variability within the formations
- Fluctuation of groundwater
- Other factors

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Analysis of Landslides

- Savage et al. (2002) employed finite element methods to study the mechanics behind the landslides and have suggested that a southwesterly regional dip in the central Grand Canyon might explain the asymmetric cliff retreat along the Colorado River.
- Limit equilibrium methods are of limited utility in steep terrain with extreme relief.
- Slides in overconsolidated shales typically exhibit strain softening, losing significant strength after shearing ~ 10 m.

Slope Stability Analysis

- Past analysis has lacked sufficient detail to adequately explain the megalandslides in the region.
- We are comparing finite elements (FEM), finite difference (FD), and discontinuous deformation analysis (DDA) to study the initiation and motion of complex and compound slides.
- Most commericail programs lack ability to apply strength anisotropies and discontinuities to adequately characterize the situation, but have revealed some interesting findings.

Strain Softening Likely Occurred Before And During Failure

- The Bright Angel Shale is a highly overconsolidated micaceous fissile shale.
- The inner gorge of the Grand Canyon have been unloaded by incision of the Colorado River, removing lateral confinement. Unknown residual stresses.
- The Cambrian age strata exposed at river level was buried under around 5 kilometers of Paleozoic and Mesozoic formations. This equates to approximately 120 MPa of overburden stress on the rock that has been removed

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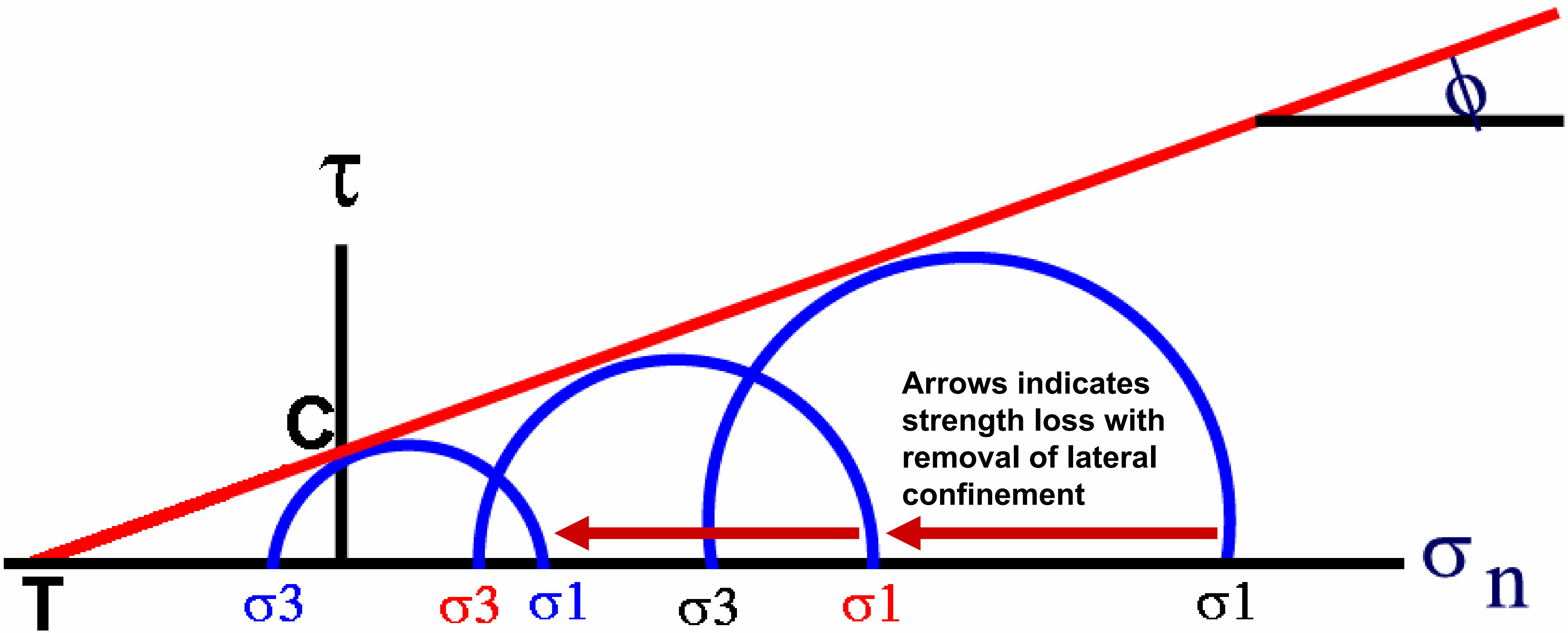
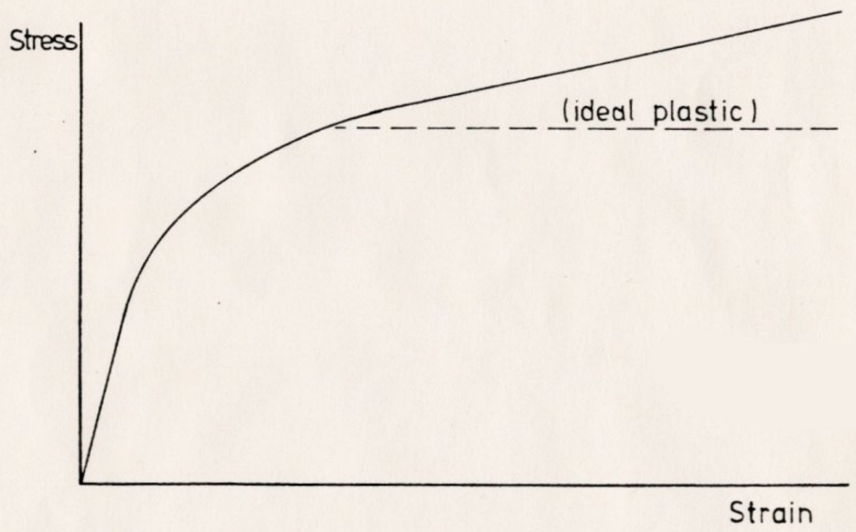
Effect of Lateral Confinement On Strength

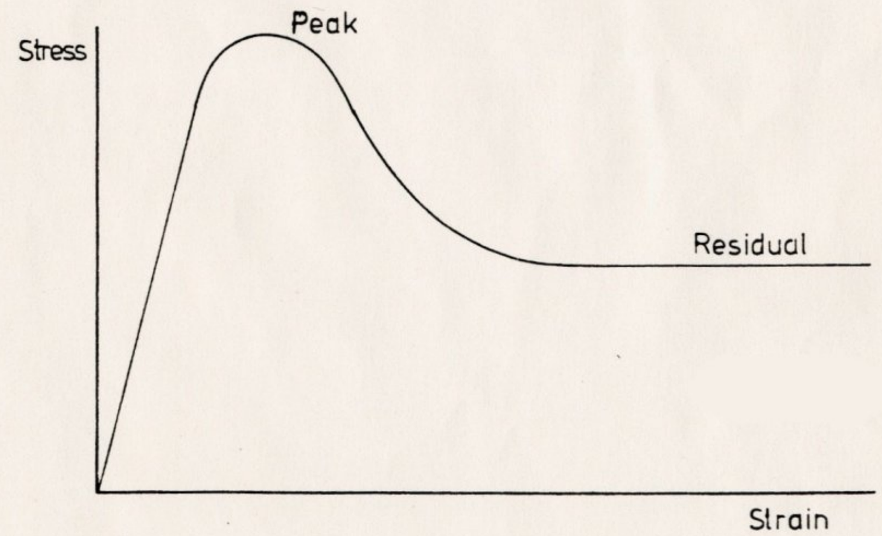
- Mohr-Coulomb criteria: As confinement (σ_3) increases, strength increases.
- As the rock is removed, it dilates, creeps and loses strength. When lateral confinement (σ_3) is removed and vertical load (σ_1) remains the same, the load circle shifts towards the failure envelope.
- Discontinuities without secondary cementation or filling have a tensile strength (T) and cohesion of ZERO, so the failure envelope is shifted to the origin.



STRAIN SOFTENING



Strain Hardening Curve



Strain Softening Curve

- **Dense overconsolidated materials, such as shale, tend to exhibit strain softening when undergoing macro shear, causing the shear strength to degrade to residual, or remolded strength.**

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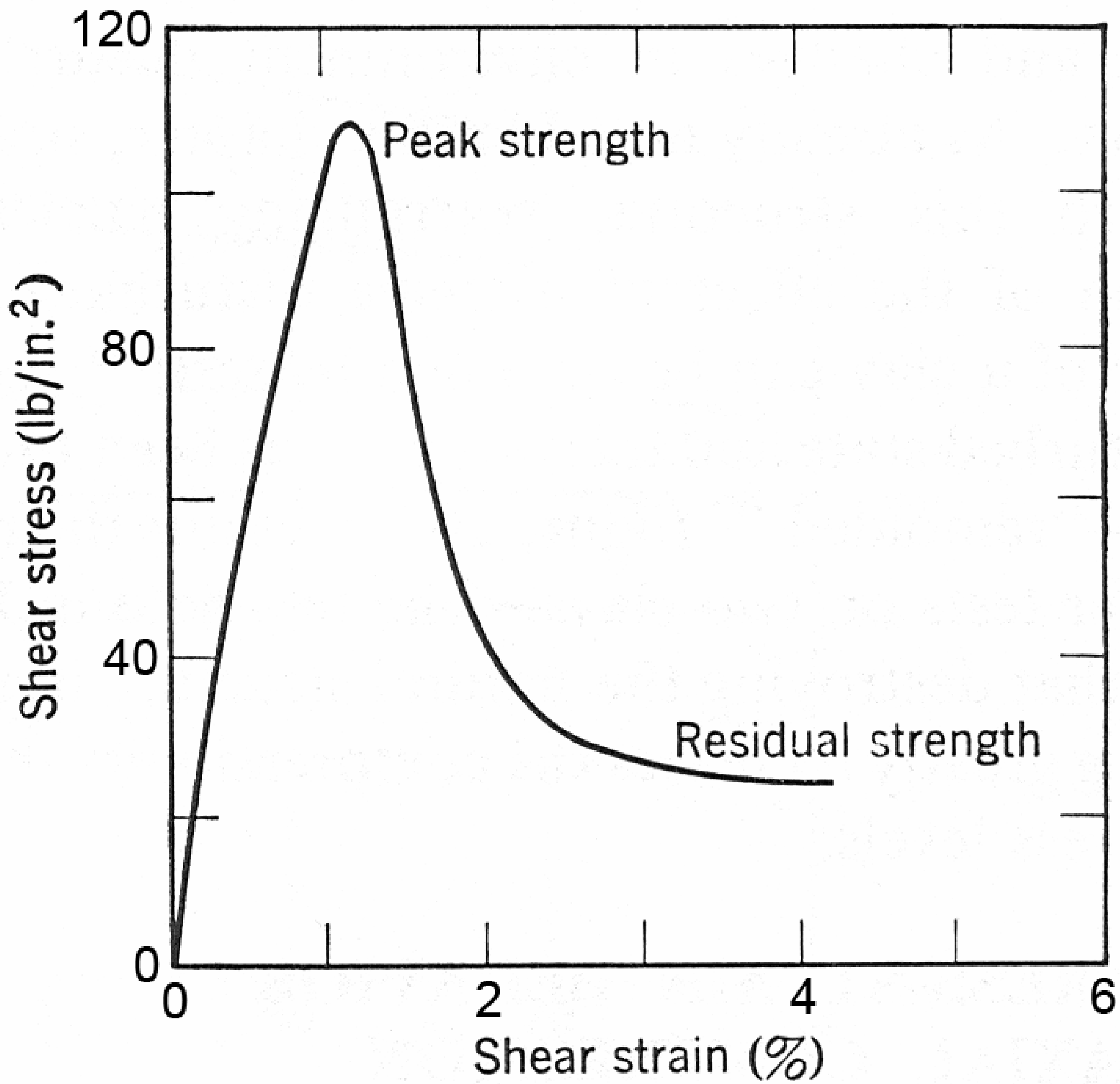

- **One of the best known examples of strain softening is the Cucaracha Shale along the Panama Canal, which exhibits a remolded shear strength only 28% of its peak strength**

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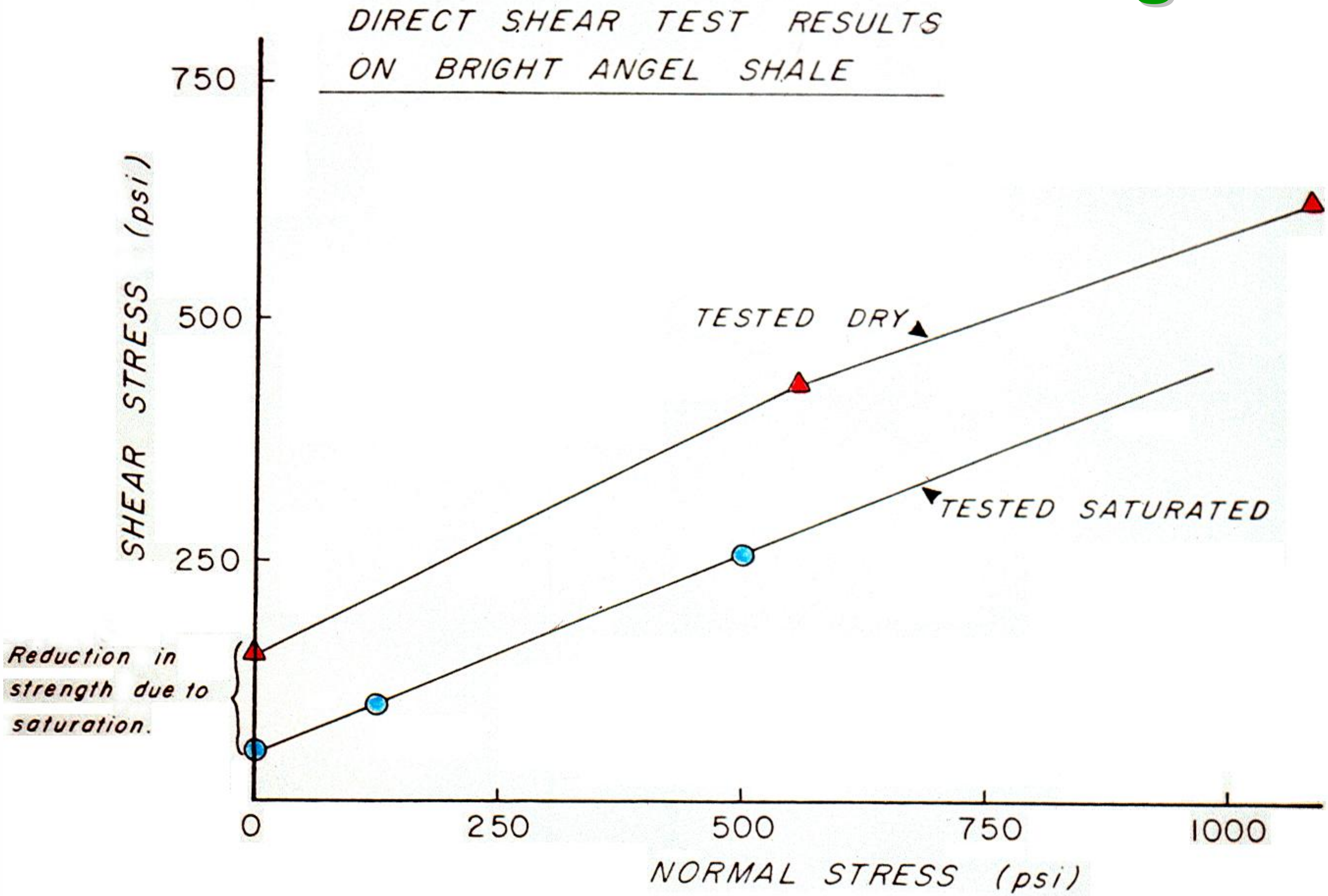
Effect of Saturation On Strength

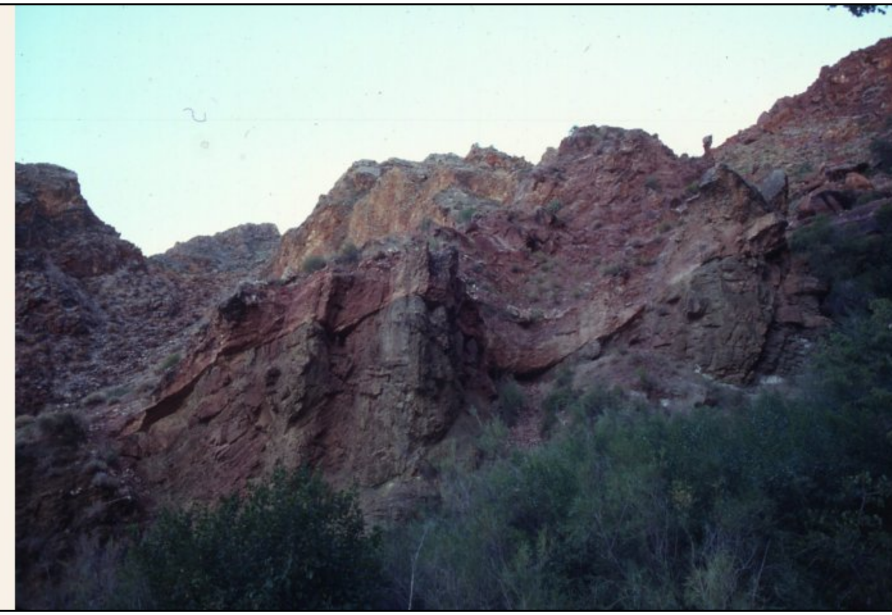


- The Bright Angel Shale exhibits marked strength loss upon complete saturation, losing 2/3 cohesion

THUNDER RIVER LANDSLIDE

- **The Thunder River slide dropped about 600 m and translated horizontally about 800 m.**

BASAL SLIP SURFACE



- The basal rupture surface of the Thunder River Slide is well preserved and accessible. It is curvalinear at the transition (above right) and follows a bedding plane in the shale for several hundred meters (shown at left). A breccia zone up to 12 m thick lies above the slip surface, cemented with travertine.

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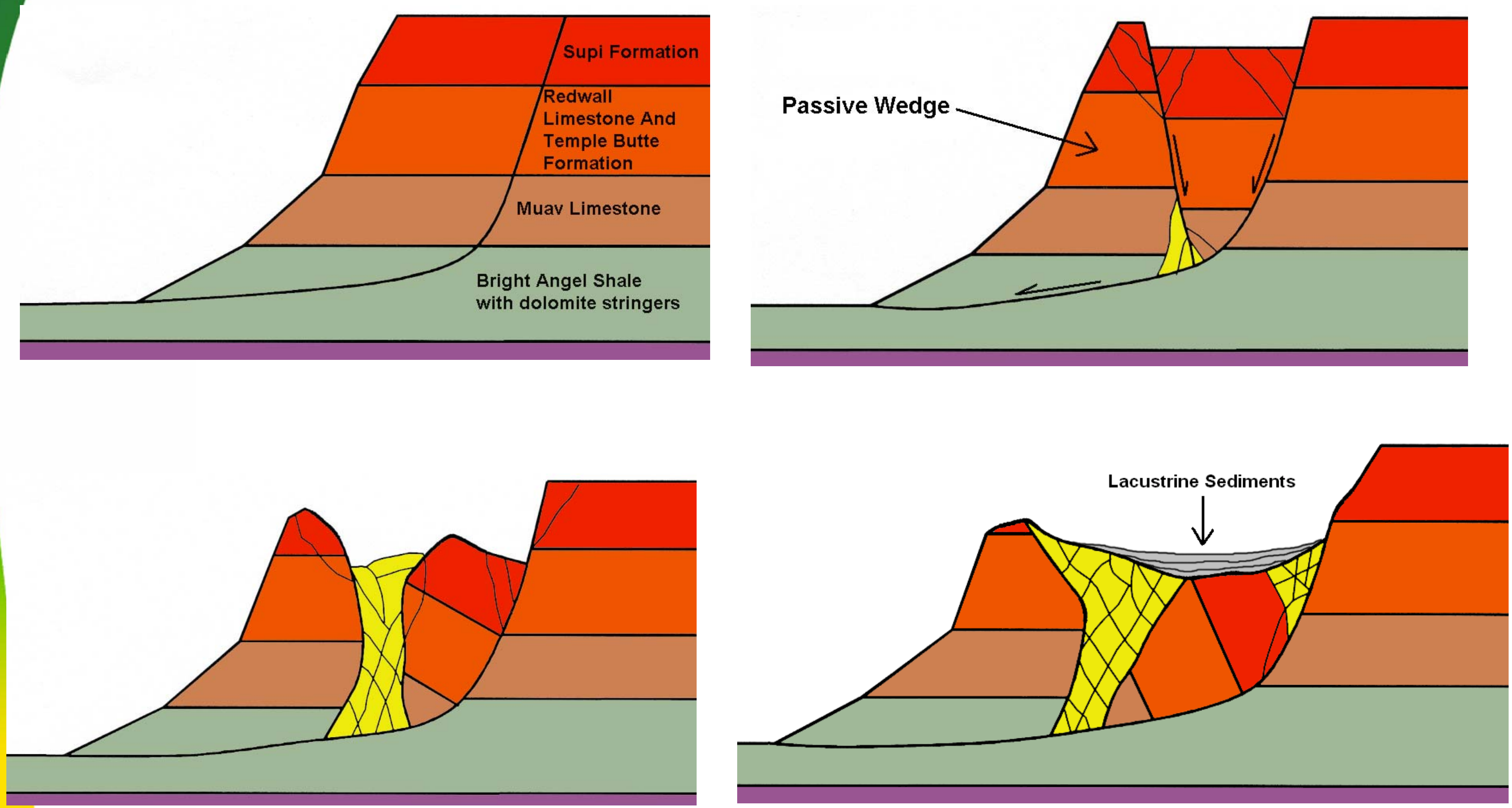
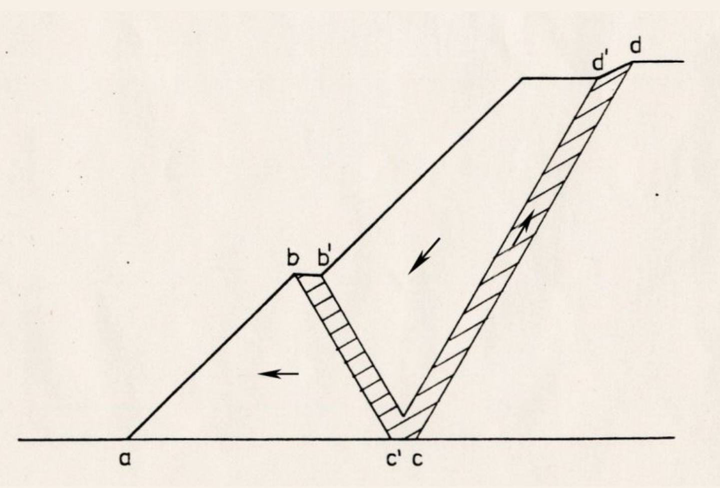
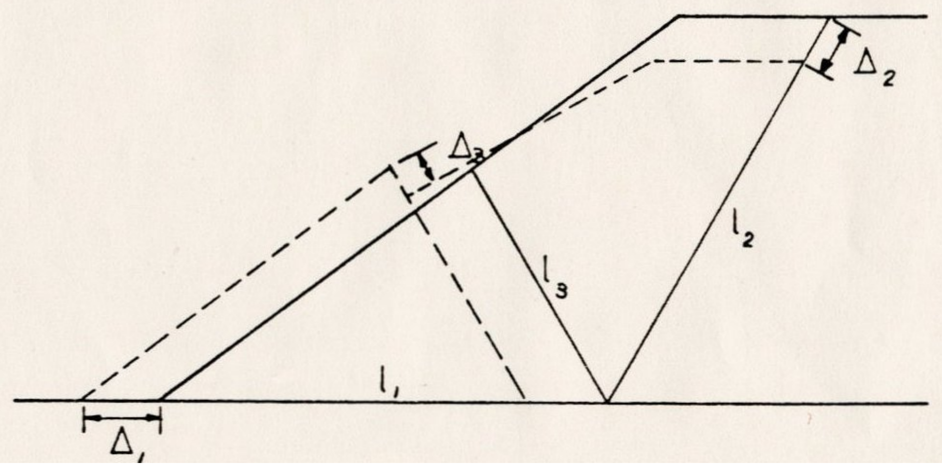
BLOCK GLIDE WITH ROTATED GRABEN



A passive wedge of bedrock translated outward about 800 m while a brecciated zone developed between the active and passive blocks.

Composite wedge failures





Active-passive wedges will tend to develop before an arcuate surface if the following kinematic conditions are met:

C1 Δ4 L4 > C2 Δ1 L1 + C1 Δ2 L2 + C1 Δ3 L3

An essential aspect of composite wedge failures is that the toe wedge abc first moves laterally. In doing so it develops a zone of dilation shown aboive left as cc'd'd. Within this zone even a dense layered rock will degenerate into a blocky granular material, or a highly sheared zone where none existed previously.

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Effect of Saturation On Strength

- A wetter climate could allow the concentration of water within vertical discontinuities in communication with the ground surface. This could build significant hydrostatic pressure and possibly be the conduits promoting saturation of the underlying formations, resulting in a large driving force and loss of strength.

Open joint planes on the Esplanade along a tributary of Kanab Canyon.

Effect of Saturation On Strength

- **Although their duration is unknown, Lava flows and landslides dammed the canyon to significant depths, possibly saturating the Bright Angel Shale and, thereby, triggering the massive landslides.**

Lava flows cascaded into the western Grand Canyon during the Pleistocene. Fenton et al. (2004) has shown they impounded water behind temporary dams.

Regression of Deer Creek Landslide

- The landslide complex just west of Deer Creek appears to have undergone multiple episodes of regression.
- The modern landslide is only the latest step in what is likely a long history of landslippage at this location.
- Jointing, perennial springs, and a southwesterly regional dip appear to play a role here.
- An pre-slide canyon profile has been reconstructed by comparison with the canyon profile downstream of Fishtail Canyon, where the Bright Angel Shale hasn't been incised nearly as deep. The canyon profile is much steeper.

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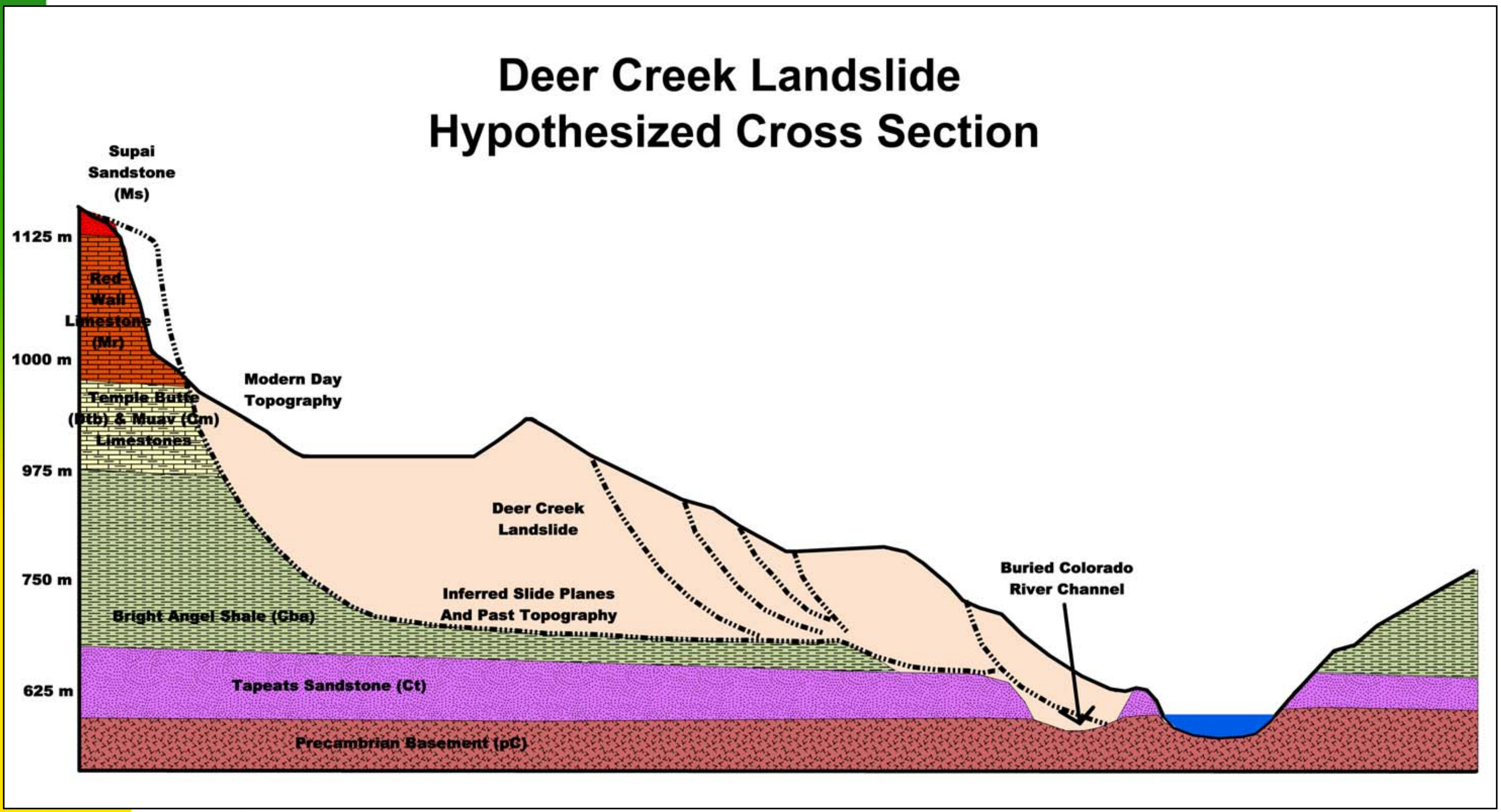
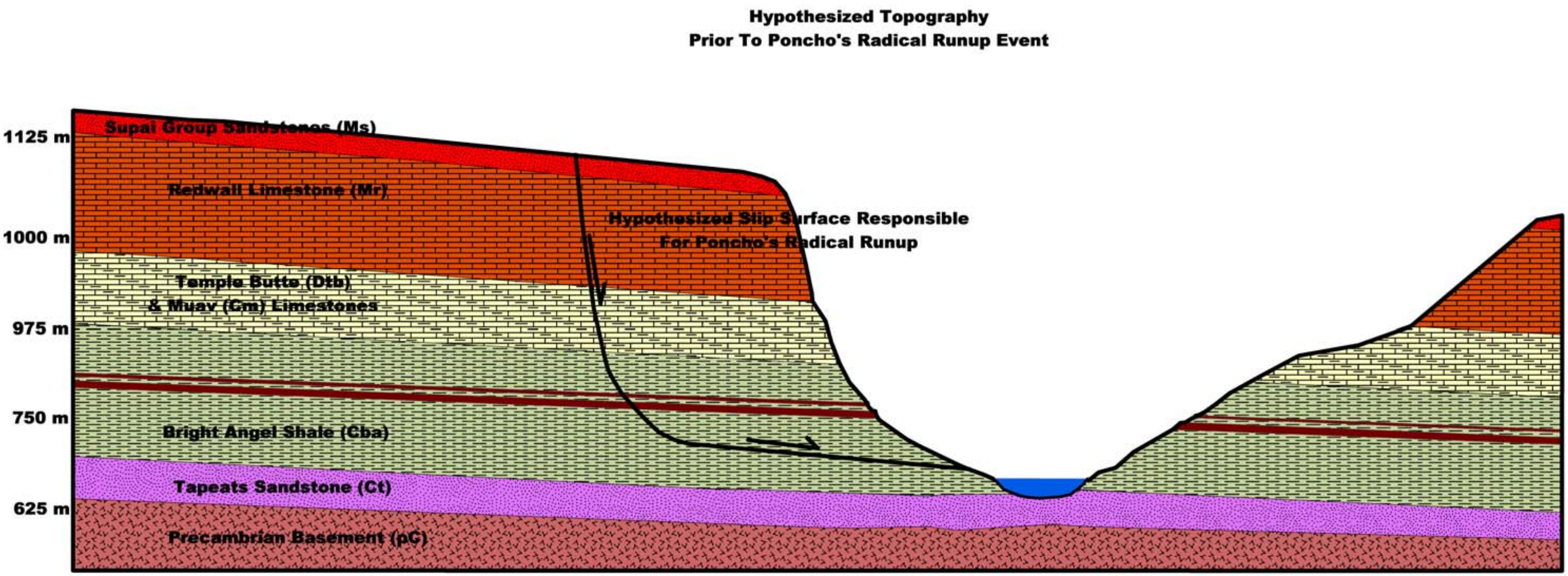
- The Deer Creek Landslide as viewed from overhead at its eastern end. It extends along the north bank of the Colorado River for 3.7 km. Enclosed depressions are indicated by arrows.

Modern Day Idealized Cross Section At Deer Creek Landslide



Hypothesized Paleotopography At Deer Creek



This hypothesized canyon profile is based on the topography west of Fishtail Canyon where incision into the Bright Angel is not yet as deep as at Deer Creek. Such a profile may have allowed a rapidly moving slide to run up the opposite canyon wall.

The main headscarp graben of the Deer Creek Landslide formed a closed basin that has been accumulating lacustrine sediments and talus since its formation. The deposits may be 100 + meters thick. In order to date the landslide one would need to obtain samples from the lower horizons of this deposit.

Fine-grained lacustrine deposits in Surprise Valley have yielded 18 types of spores, fungal hyphae, and pollen, including that of freshwater algae. Although these deposits appear red and oxidized, their parent materials (mainly Hermit and Supai Formations) are red in color.

GLACIAL CLIMATE INDICATED BY PALYMORPHS AND FUNGAL HYPHAE IN LACUSTRINE SEDIMENT WITHIN SURPRISE VALLEY

- 1) <u>Pollen and spores</u>:
- *Ambrosia* (ragweed)
- *Anemopsis californica* (Saururaceae)
- Annoniaceae?
- Bryophyte spore
- *Chrysoplenium* (dominant pollen)
- Cruciferaceae
- *Dodocatheon*? (Primulaceae)
- *Ephedra fragilis* (Ephedraceae)
- *Equisetum*
- *Mitella?* (Saxifragaceae)
- *Picea* (spruce)
- *Pinus* (pine)
- Podocarpaceae (specimens similar to fossil *Zonalapollenites*)
- *Quercus* (oak)
- *Saxifraga* (Saxifragaceae)
- *Sequioia* (Taxodiaceae)
- Solaniaceae
- *Taxodium* and one unidentified genus of Taxodiaceae
- 2) <u>Freshwater algae</u>: *Botryococcus* and algal clusters are the dominant palynomorphs in
- both samples.
- 3) <u>Fungi</u>: Fungal hyphae are present.

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Landslides In Vicinity of River Mile 205

- A large bedrock landslide similar to the Deer Creek Slide has long been recognized on the right (west) side at River Mile 205.

RM 205 Left Landslide

A short walk up 205-Mile Canyon gives a side view of the massive 205-Mile River Left Landslide. Only then does the whole scope of the landsliding in this area begin to show. The bedrock slumps visible from the river are secondary failures off of this enormous backrotated block.

This view of the 205-Mile River Left Landslide was taken from atop the 205-Mile River Right Landslide. This enormous landslide block spans more than two miles and is outlined here in red.

The River Mile 205-Left Slide is fairly easy to discern from atop the River Right Slide. It encompasses about 2 billion m^3.

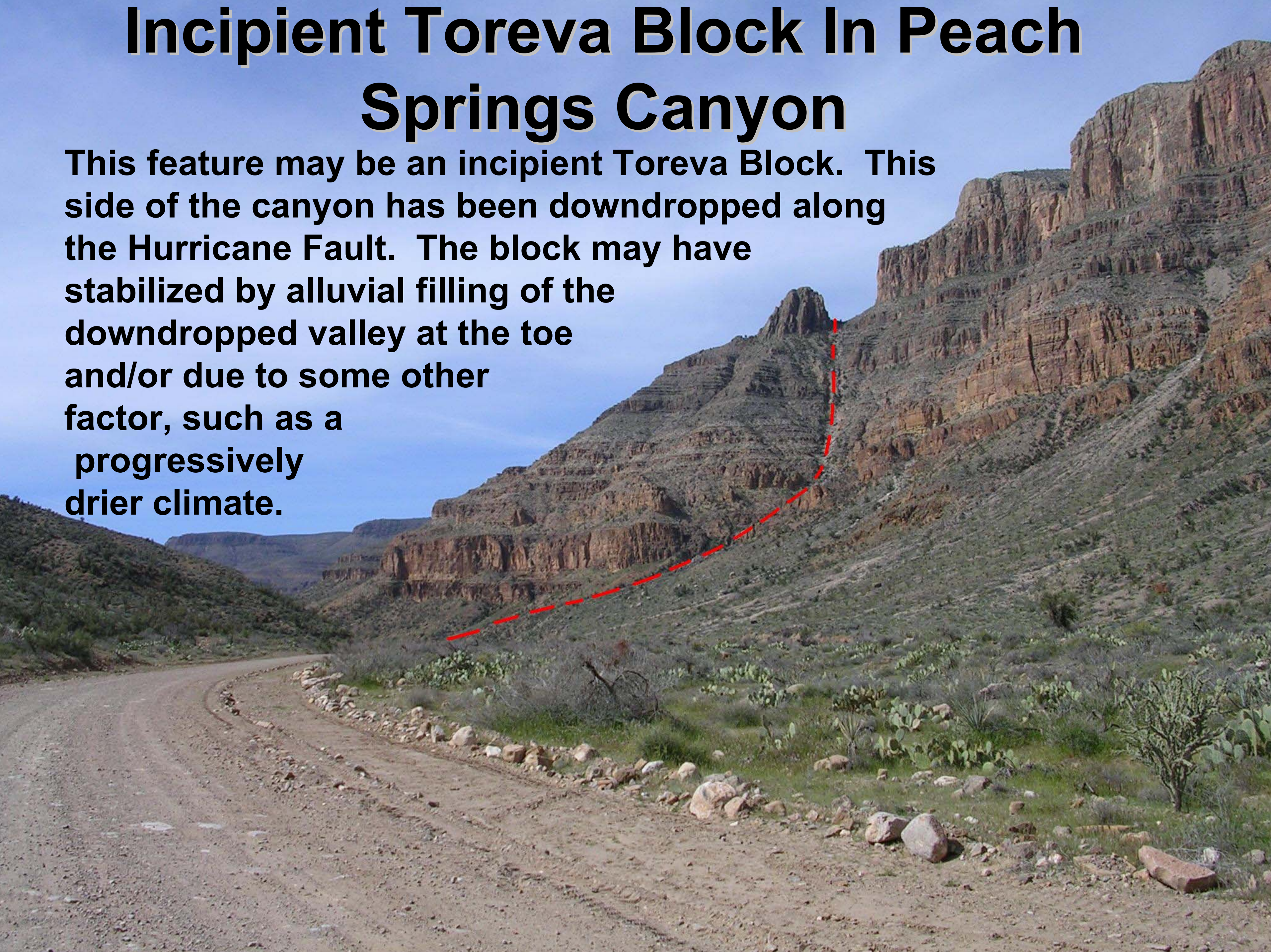
218-Mile Toreva Block

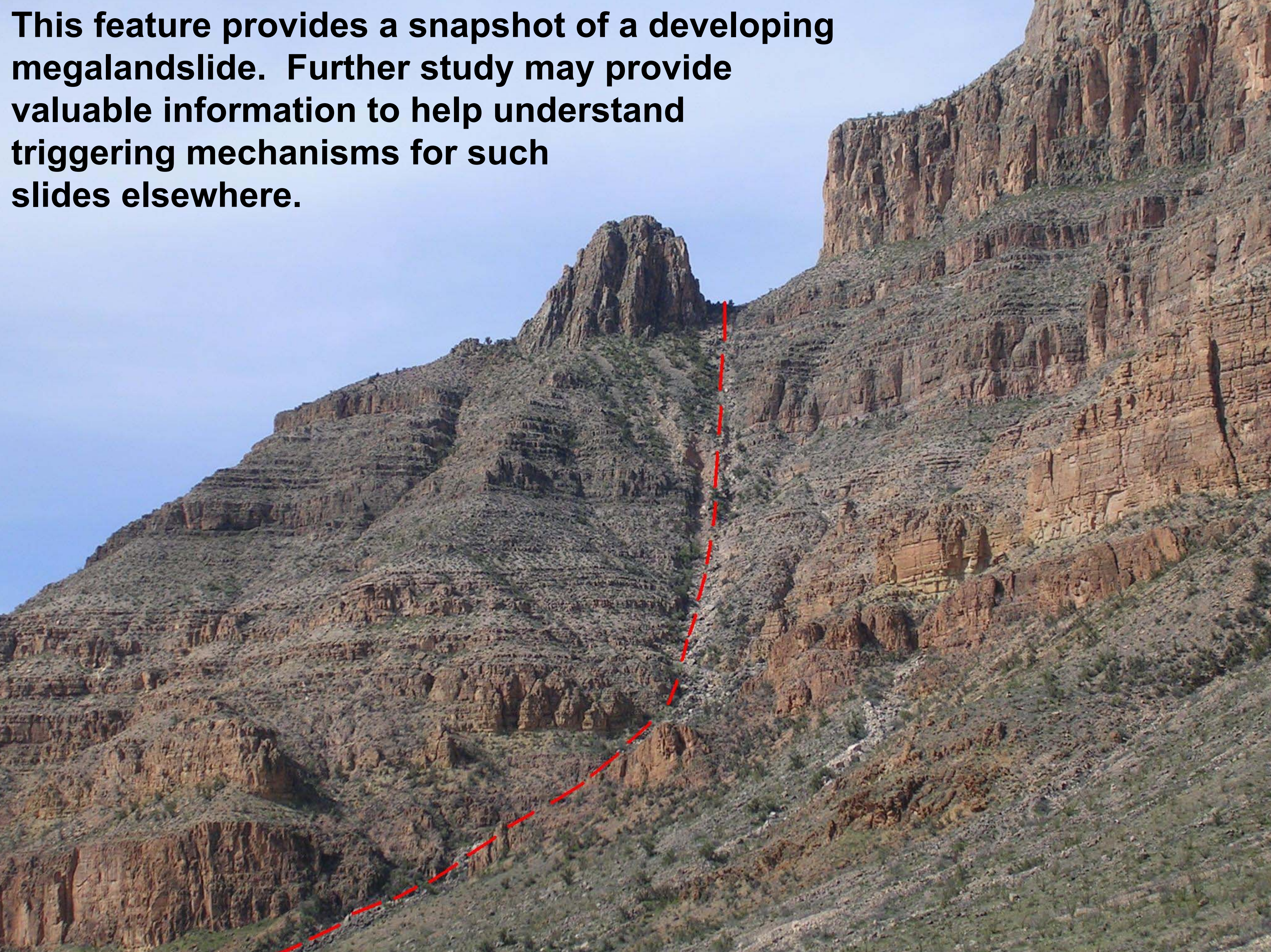
Textbook example of a Toreva Block showing its intact backrotated beds. Although many slides in the Colorado Plateau exhibit back-rotation, few are this intact.

As with other large landslides in Grand Canyon, this one experienced basal failure in the Bright Angel Shale. It sits on river right, 150 to 215 m above river level. Many smaller Toreva Blocks dot the Lower Granite Gorge, at similar elevations above the river.

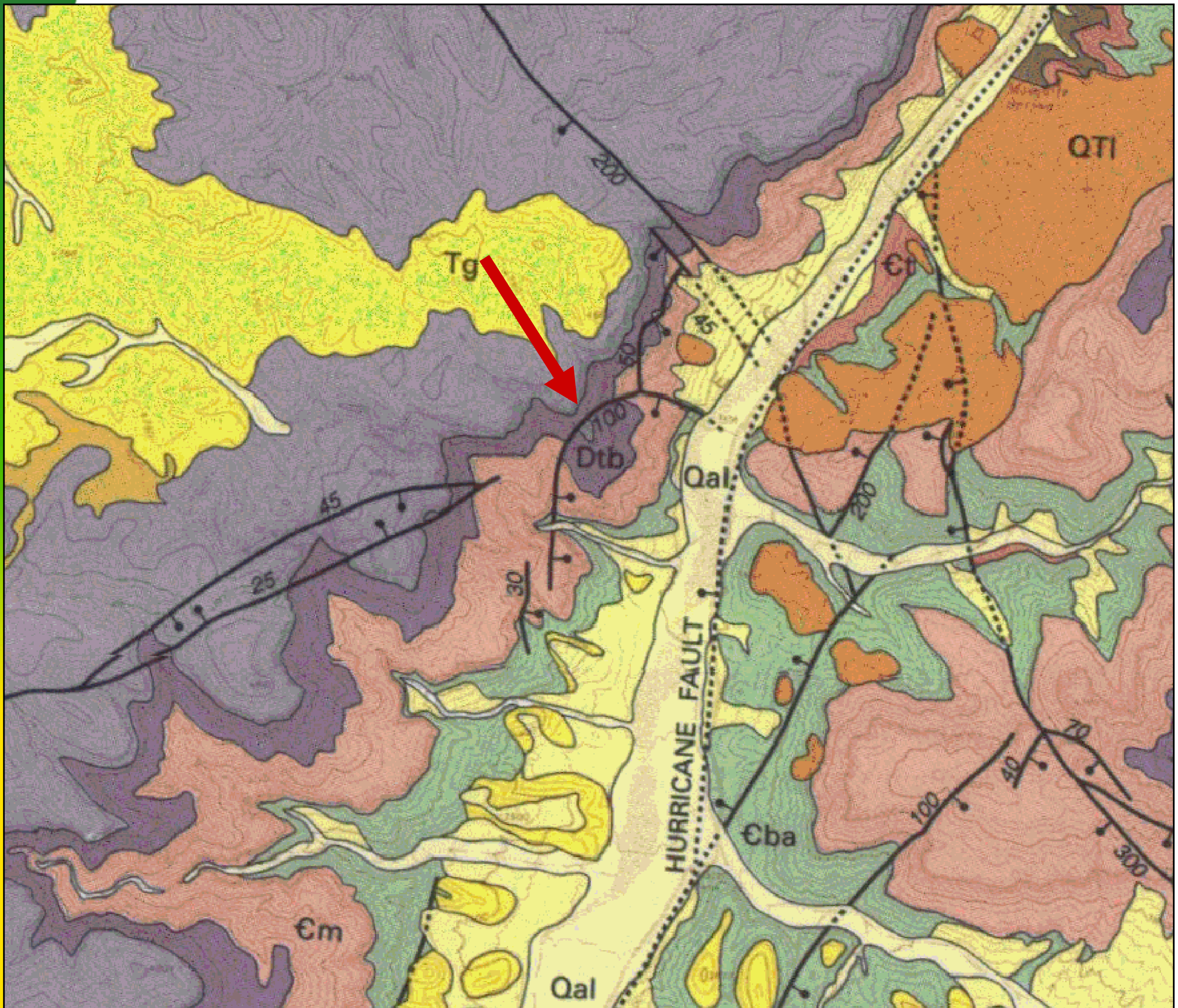
Incipient Toreva Block In Peach Springs Canyon

This feature may be an incipient Toreva Block. This side of the canyon has been downdropped along the Hurricane Fault. The block may have stabilized by alluvial filling of the downdropped valley at the toe and/or due to some other factor, such as a progressively drier climate.




This feature provides a snapshot of a developing megalandslide. Further study may provide valuable information to help understand triggering mechanisms for such slides elsewhere.

Incipient Toreva Block In Peach Springs Canyon



The feature is presently mapped as a crescent shaped fault on geologic maps of the Hualapi Reservation. The arcuate shape is typical of landslide headscarps.

Where We Want To Go From Here

- We are looking to unravel the likely causes of these composite landslides, from a kinematics viewpoint.
- A bonus would be ascertaining approximate dates and indicators of the paleoclimate when the slides were triggered.
- Landslide surfaces may remain active long after the initial movement, biasing cosmogenic dates (age of most recent movement, not original movement).
- Sedimentary (mostly lacustrine) deposits are preserved in several landslide headscarp grabens and behind remnants of old landslide dams.
- So far, OSL dating complemented by palynology would seem to be the most doable method for dating the younger sediments associated with the slides.
- Some debris and lava flows have been deposited atop landslides, making cosmogenic dating potentially useful to establish constraints.
- We are open to suggestions as how to best study this material.

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Conclusions

- Although the geology of Grand Canyon has been studied in great detail, there are still many unanswered questions.
- Although multiple factors seem to play a role, discontinuities, such as faults and joints seem to influence stability in our models.
- Each analytical program has its own set of limitations; handling strength anisotropy, strain softening, joints, transient pore pressures, etc.

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Conclusions (cont)

- It is unlikely that palynology would provide exact dates. Instead, it will likely complement cosmogenic and/or OSL dates recovered from the landslides by providing insights on the paleoclimate at the time of landsliding.

- Looking at a paleo-landslide is much like looking at a plane crash without a flight data recorder; a variety of factors can all lead the same result. Much of the prima facia evidence is obscured/destroyed by subsequent secondary movements, so the precise causes may never be known. Important variables may be isolated by further analyses.

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