

PANAMA CANAL: THE WORLD'S LANDSLIDE LABORATORY

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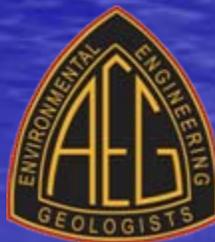
for the

2007 Annual Meeting

Association of Environmental and Engineering Geologists

Los Angeles, California

September 28, 2007



1880-89 and 1895-96
The French Descend
Upon the Panamanian
Isthmus

**They dig with vigor,
twice, but eventually
give up**



- The French arrived on the Isthmus in 1880 intending to excavate a sea level canal. They began excavating the highest cuts, across the Continental Divide, in 1884.



- Landslides began to plague the French excavations in the vicinity of Cucaracha and Culebra in 1886, severing their trunk rail lines. In addition to slides, they fought a losing battle with Yellow Fever and Malaria, and went bankrupt in 1889.

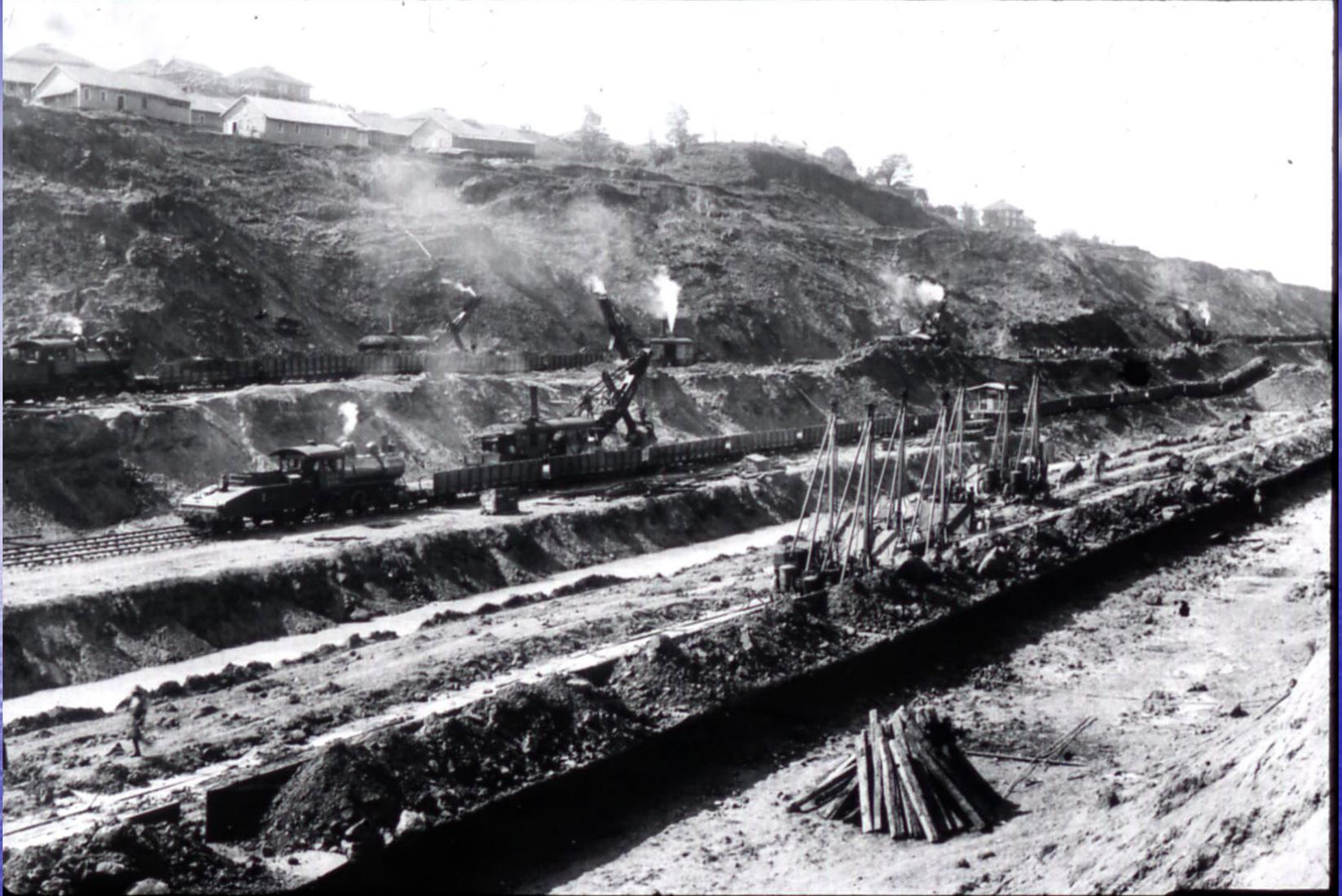


- A second French company returned in 1895, but they were insufficiently capitalized, and the canal excavations lay dormant until the United States purchased their license and assets in 1903, for \$40 million.

1904

The Americans Take Over

thinking...
"Its just a big railroad job"



- Legendary railroad engineer **John F. Stevens** conceived a plan to construct a locked canal, using water from the Chagres River to create a vast inland lake. This reduced the required depth of excavations by 70 feet.



- Stevens said the canal job was all about *logistics, logistics, and logistics...* This shows the morning work train delivering Caribbean workers. Note the faulted contact between the resistant hill and adjacent slopes.



- The 45 degree side slopes of the massive cuts can be appreciated in this view, as the Americans begin to attack the Continental Divide.



- Canal side slopes progressing on schedule at Culebra. Note suspension bridge.



- As the excavation deepens, the side slopes started caving in on the main excavation. This shows the beginning of the East Culebra side



- Shovels begin attacking a similar problem, which they name the **West Culebra Slide**, on September 12, 1912



- Outfall discharge from a suction dredge. The dredge tailings were dumped into rock-lined dikes.



- The waste muck was conveyed by rail cars and dumped into enormous fill piles at the coasts.

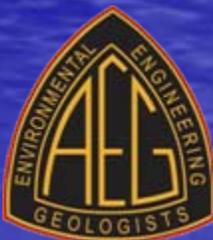


- Another view showing size of the rail dumped waste pile on the Pacific side. Note locomotive for scale.

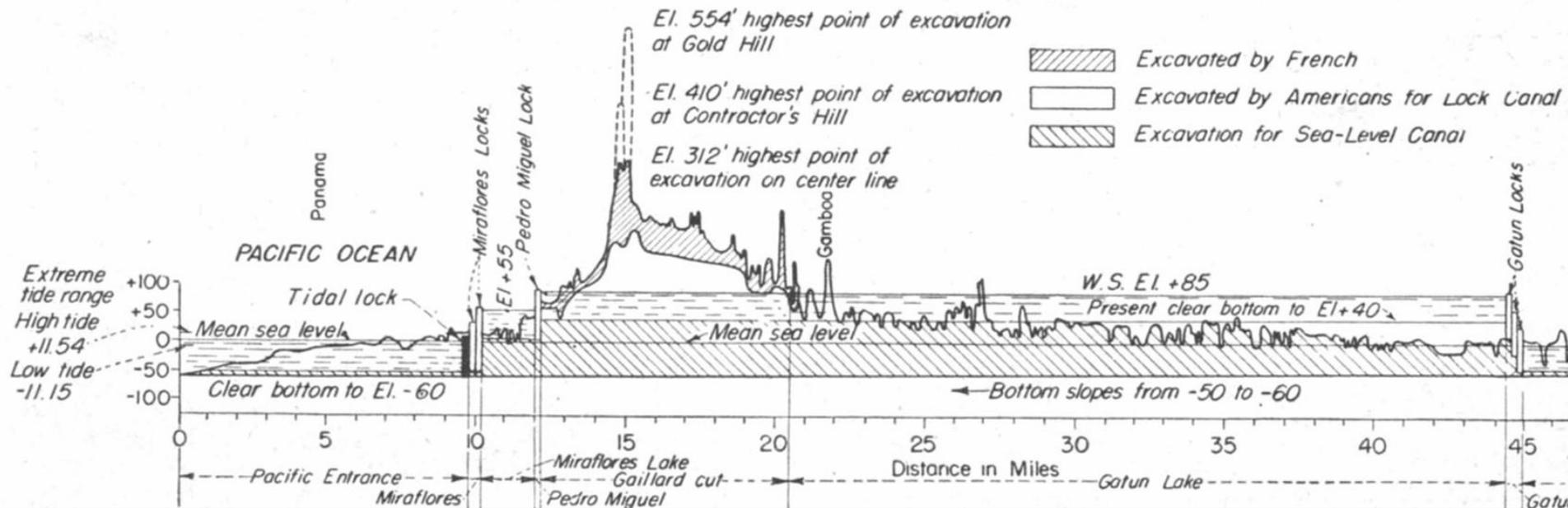


- **Closing in on the finish line.** Looking into the gapping hole at the Continental Divide on May 17, 1913. Note 1/2:1 side slopes.

The earth starts moving



Longitudinal Section Along Canal



- The deepest excavations for the Panama Canal were concentrated near the Continental Divide, as shown in this vertically exaggerated section.



- Block glide day-lighting into canal excavation in May 1910. This is one of the earliest slides that was scientifically evaluated by Army Engineers.



- One of the early landslides at Cucaracha, on the south side of Gold Hill, near the Continental Divide, on July 5, 1911.



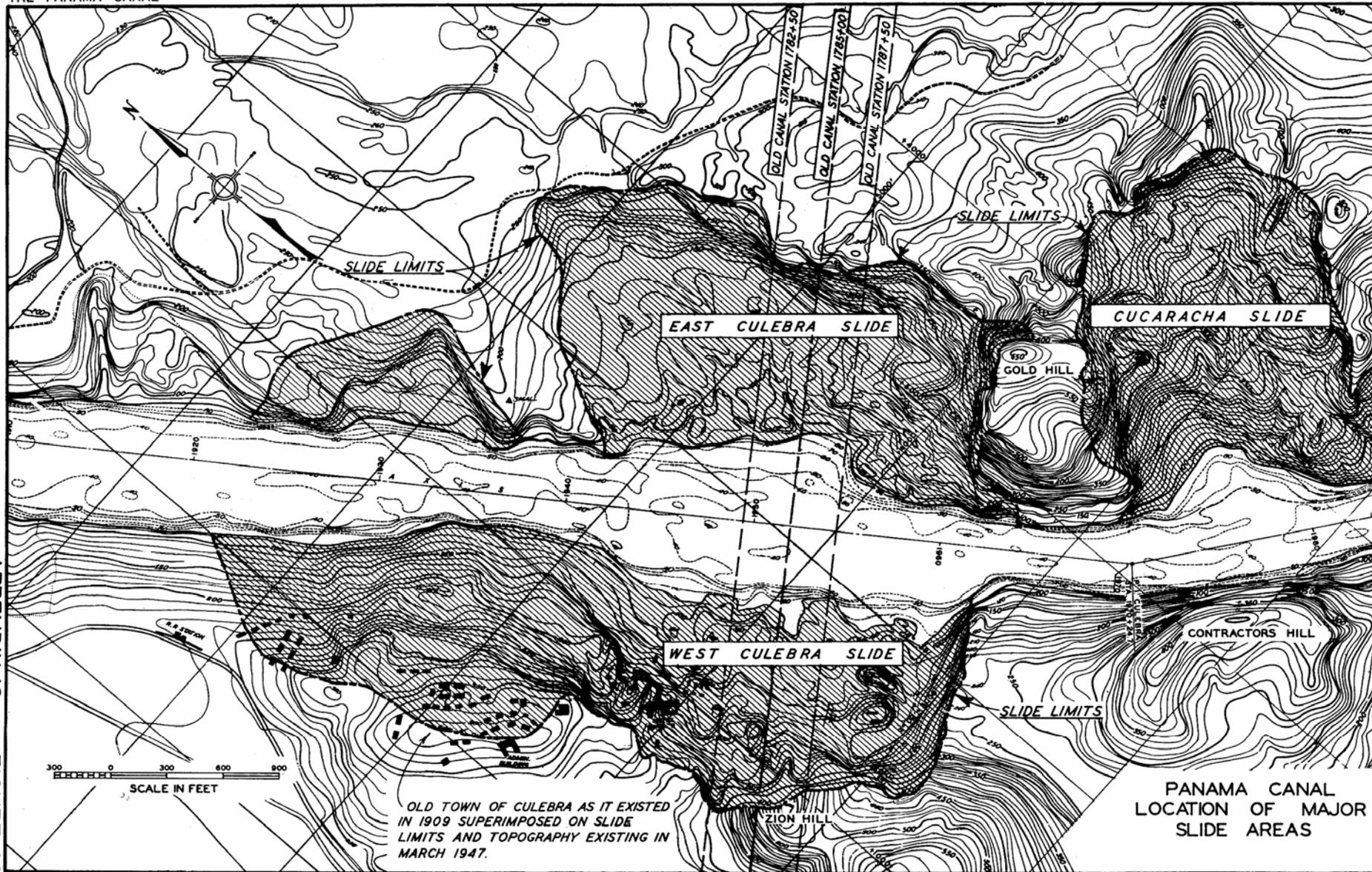
- Ground view of the same slide of July 5, 1911 at Cucaracha, showing buried steam shovel.



- **Cut slope failure on the Obispo Division on August 21, 1912. Note ponded water.**

**Engineer's attempts to
arrest landslippage
prove futile**

Like a bad dream...



- Map showing the principal slides along the Panama Canal near the Continental Divide



- Crown scarp of the East Culebra Slide on September 19, 1912, looking south.





- Excavating the toe of the West Culebra slide with steam shovels, and allowing the slide debris to disintegrate and slide into the hole.



- The shovels work desperately to fill side-dumping gondola cars and keep pace with the onslaught of earthen debris.



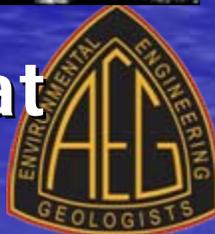
- Close-up view of the rail-mounted shovels excavating slide debris at Culebra. Side-dumping gondola cars in foreground.

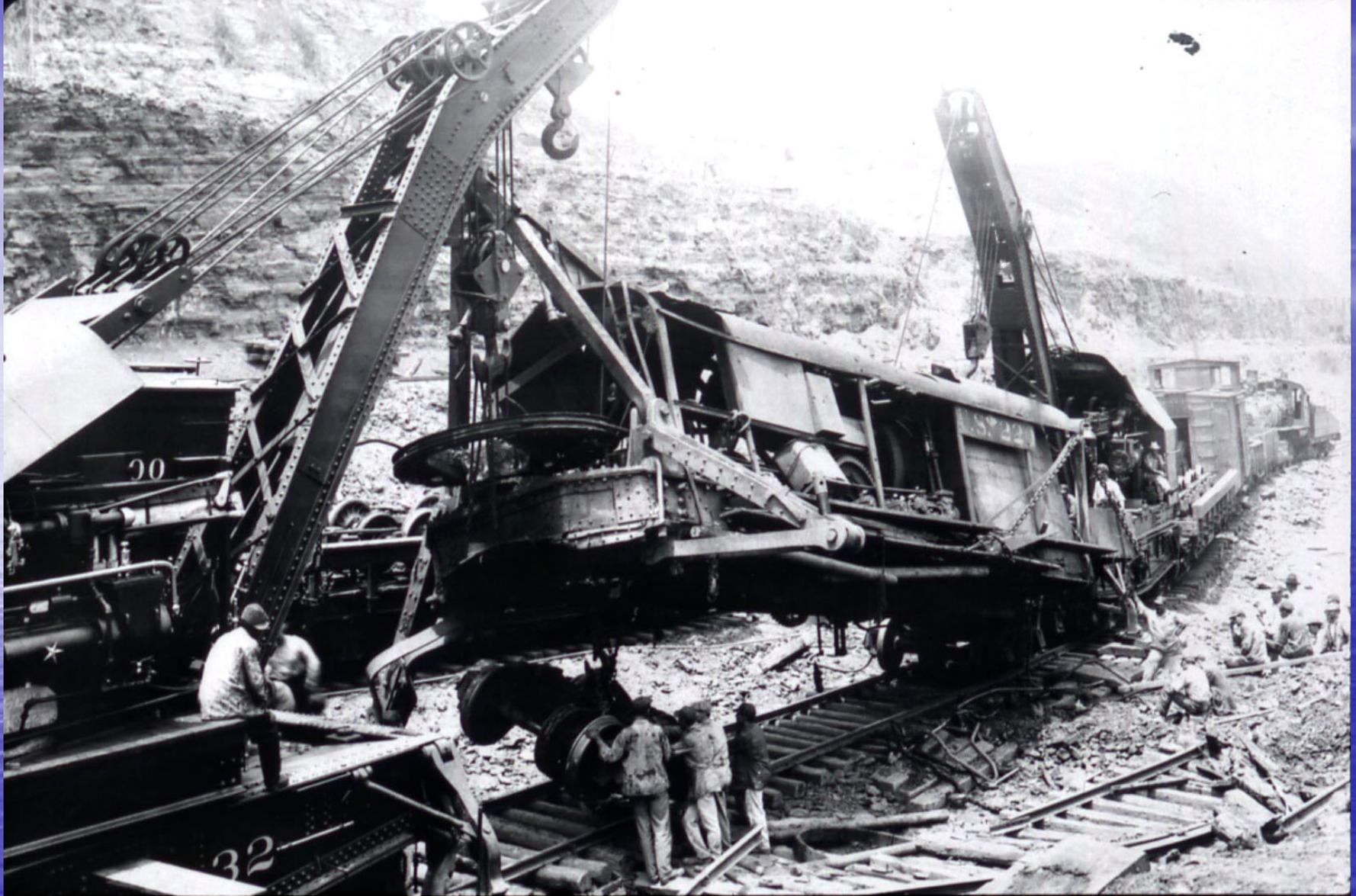


- Large deep-seated slump on the East Culebra Slide blocks the canal excavation, May 27, 1913.



- Buried steam shovel and shredded tracks at East Culebra.





- Work crews salvaging one of the buried Bucyrus-Erie rail-mounted shovels.



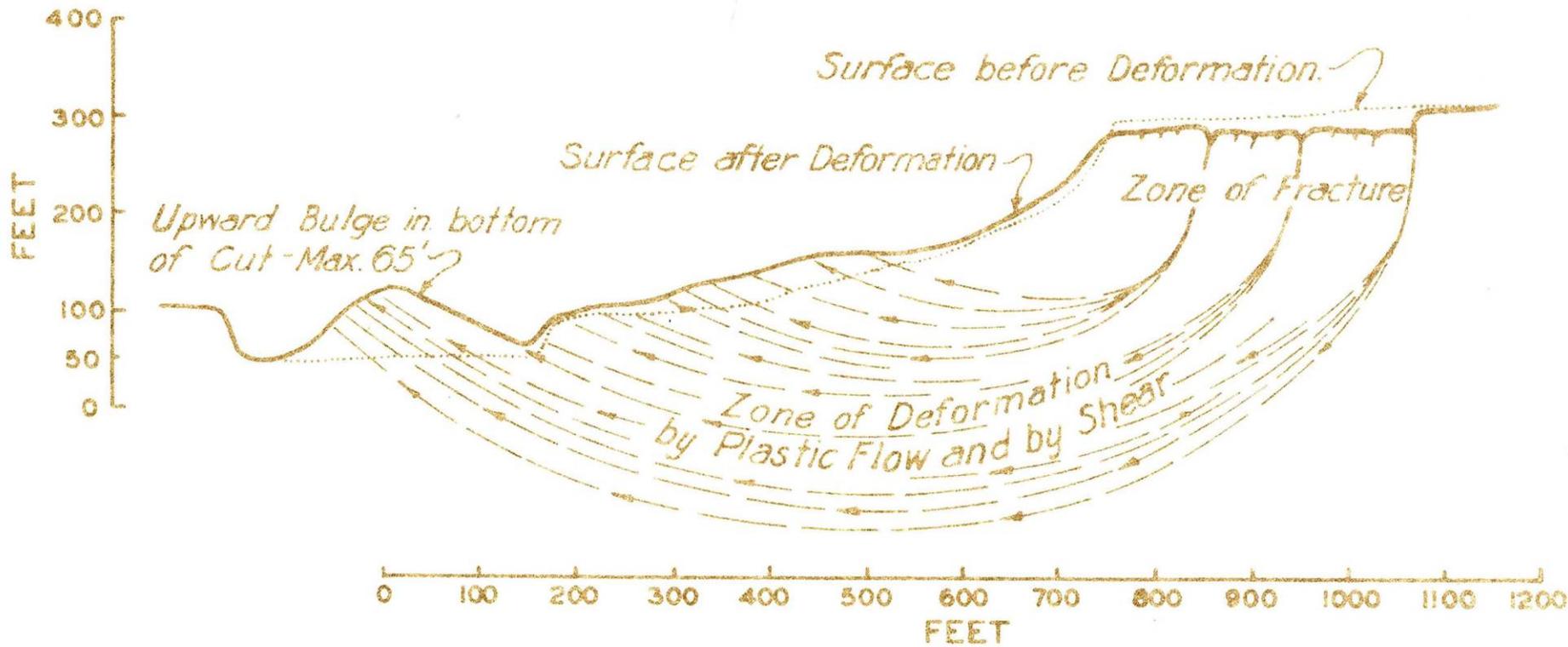
- The awesome massif of Zion Hill on the West Culebra Slide



- Zion Hill and West Culebra Slide in July 1916, taken from Contractor's Hill, looking north.



- The headscarp of the West Culebra Landslide swallowed up part of the town of Culebra



IDEAL CROSS-SECTION WEST SIDE GAILLARD CUT, NEAR CULEBRA, TO SHOW DEVELOPMENT OF DEEP DEFORMATION TYPE OF SLIDE IN CUCARACHA ROCKS.

- Concept of zone of flowage in West Culebra Slide, as hypothesized in 1912

DEPARTMENT OF THE INTERIOR
FRANKLIN K. LANE, Secretary
UNITED STATES GEOLOGICAL SURVEY
GEORGE OTIS SMITH, Director

PROFESSIONAL PAPER 98—N

MECHANICS OF THE PANAMA CANAL SLIDES

BY

GEORGE F. BECKER

Published July 25, 1916

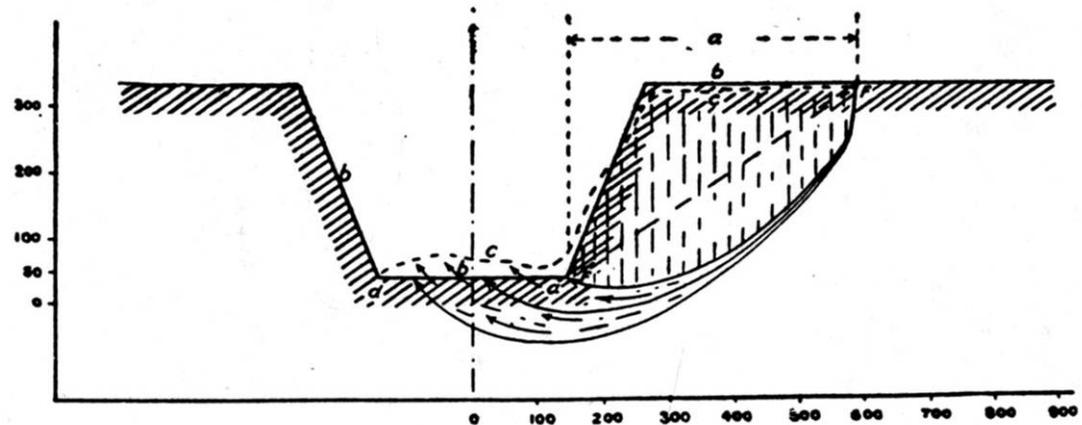
Shorter contributions to general geology, 1916

(Pages 253-261)



WASHINGTON
GOVERNMENT PRINTING OFFICE
1916

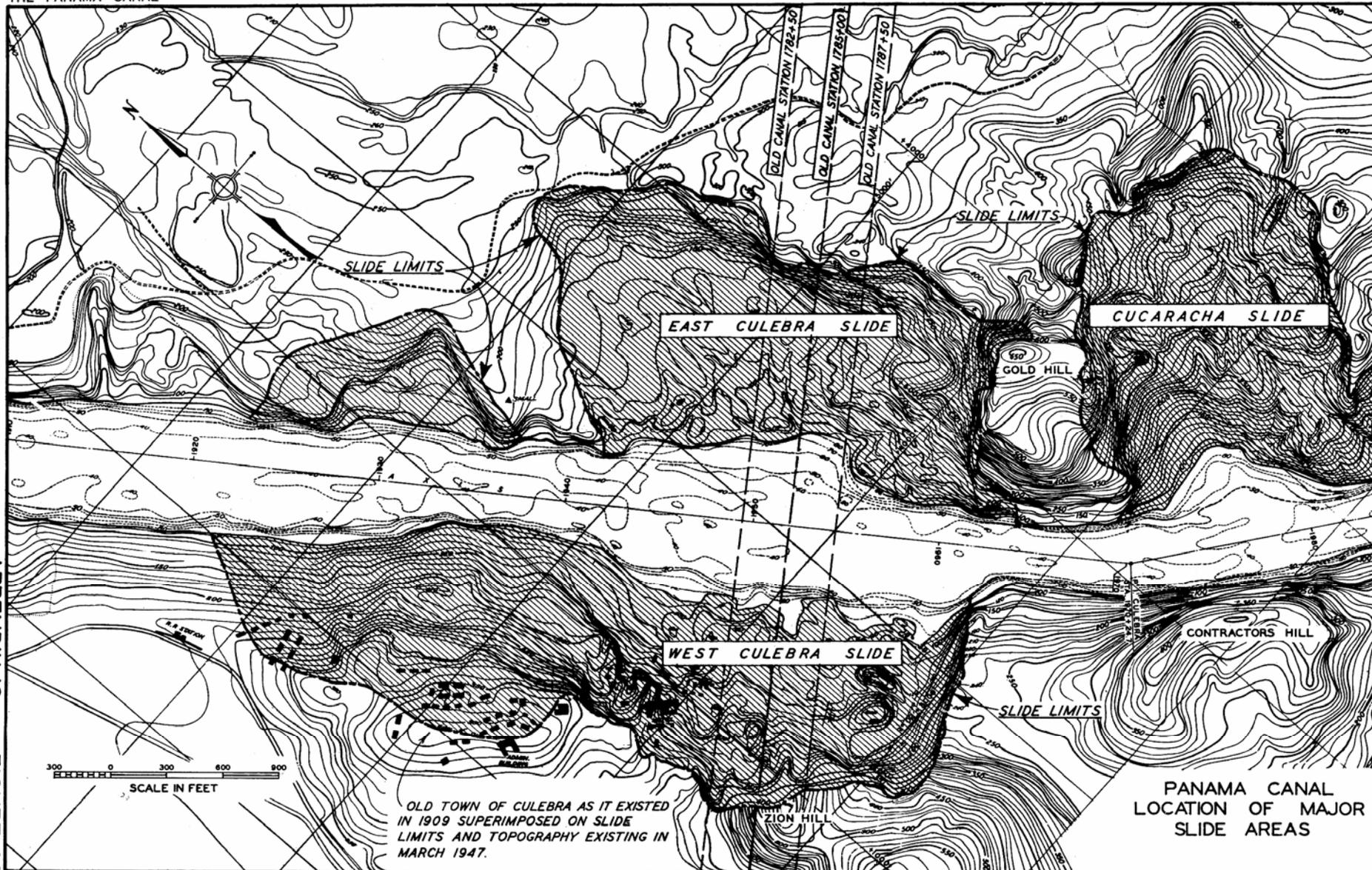
Mechanics of the Panama Canal Slides – 1916 USGS PP-98N



- The U.S. Geological Survey sent George F. Becker to study the Panama Canal slides in 1913

Cucaracha Landslide

The vexing nemesis of the
American Engineers, which
could never be stopped, only
slowed



- Map showing the principal slides near the Continental Divide



- The massive cut at Gold Hill and Cucaracha, just before the first big slide



- Excavating debris at the toe in the wake of the first massive slide at Cucaracha, on August 20, 1913.



- Flowage off the Cucaracha Landslide on February 2, 1913. A harbinger of what was to come...

Goethals floods the channel and steps up the dredging

“This will take years...”



- The south end of the canal is flooded as far as Cucaracha, October 28, 1913



- Colonel Goethals flooded the canal excavation across the Continental Divide to facilitate dredging and subsequent excavation by shovels.



- Shovel dredge working the face of the East Culebra Slide after the canal was flooded.



- Fleet of suction dredges working the toe of the Cucaracha Slide - February 8, 1914



- Goethals increased the number of dredges five-fold

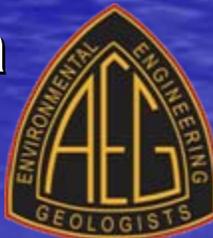


- Dredging the gap closed by landslides on October 5, 1915



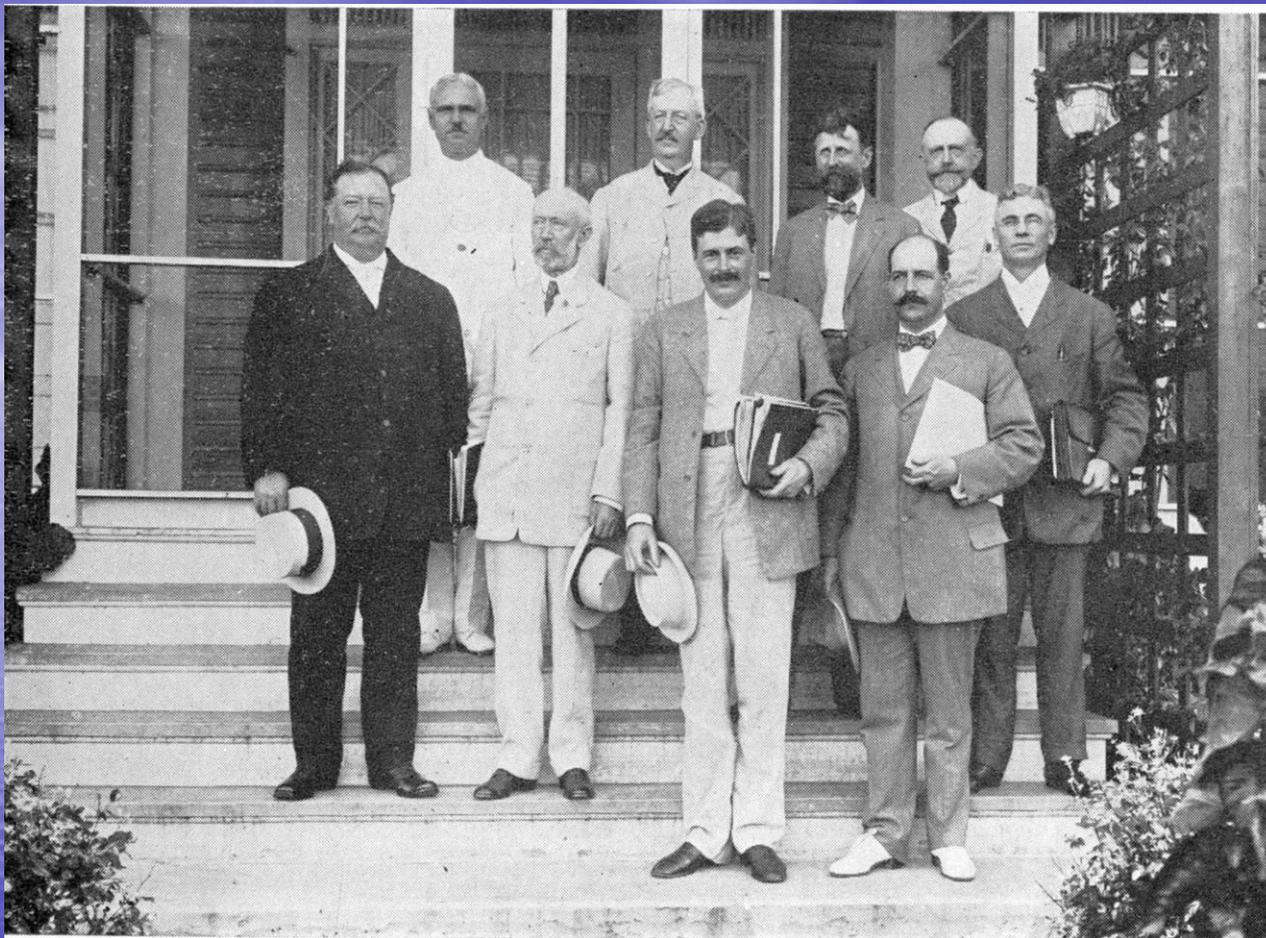


- Dredges battling with the slides at Culebra on November 8, 1915





- Still dredging at Culebra on December 20, 1915

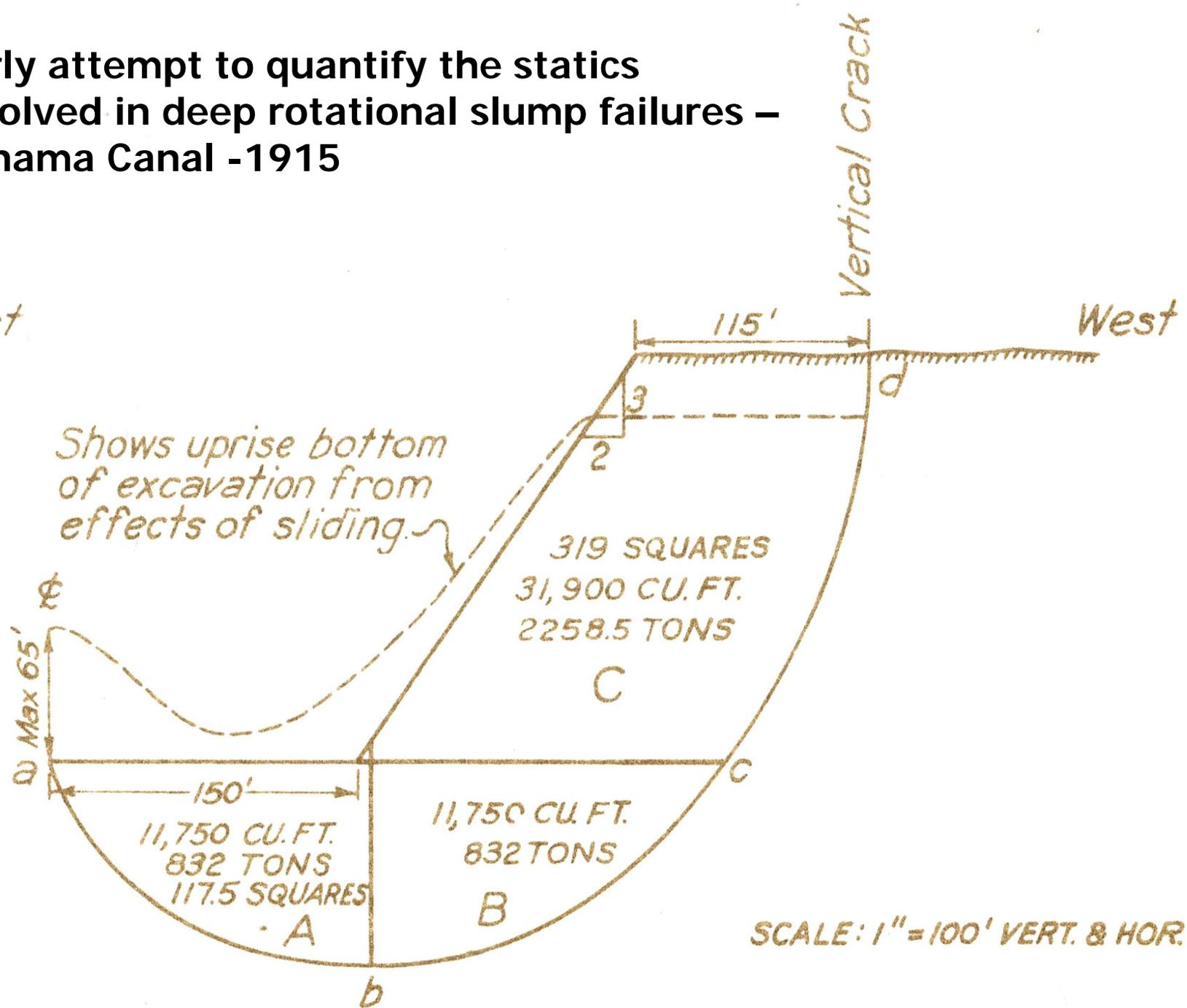


- The Corps looked to their Special Board of Consulting Engineers for help on the landslide issues. In 1913 they hired Canadian Professor Dr. Donald F. MacDonald to be the first resident geologist working on the canal.

Early attempt to quantify the statics involved in deep rotational slump failures – Panama Canal -1915

East

West



Sample No. 11113-Y
 Ultimate load, 490 lbs. per sq. in.
 Elastic limit, 380 " " " "
 Modulus of elasticity 165000.

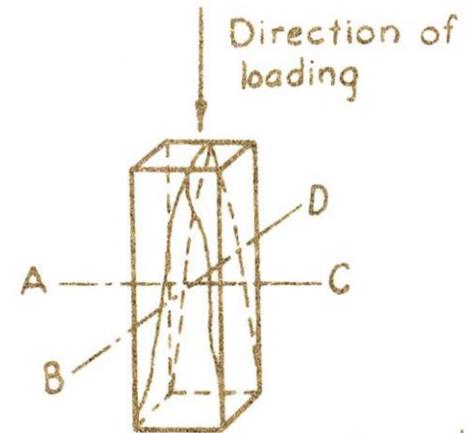
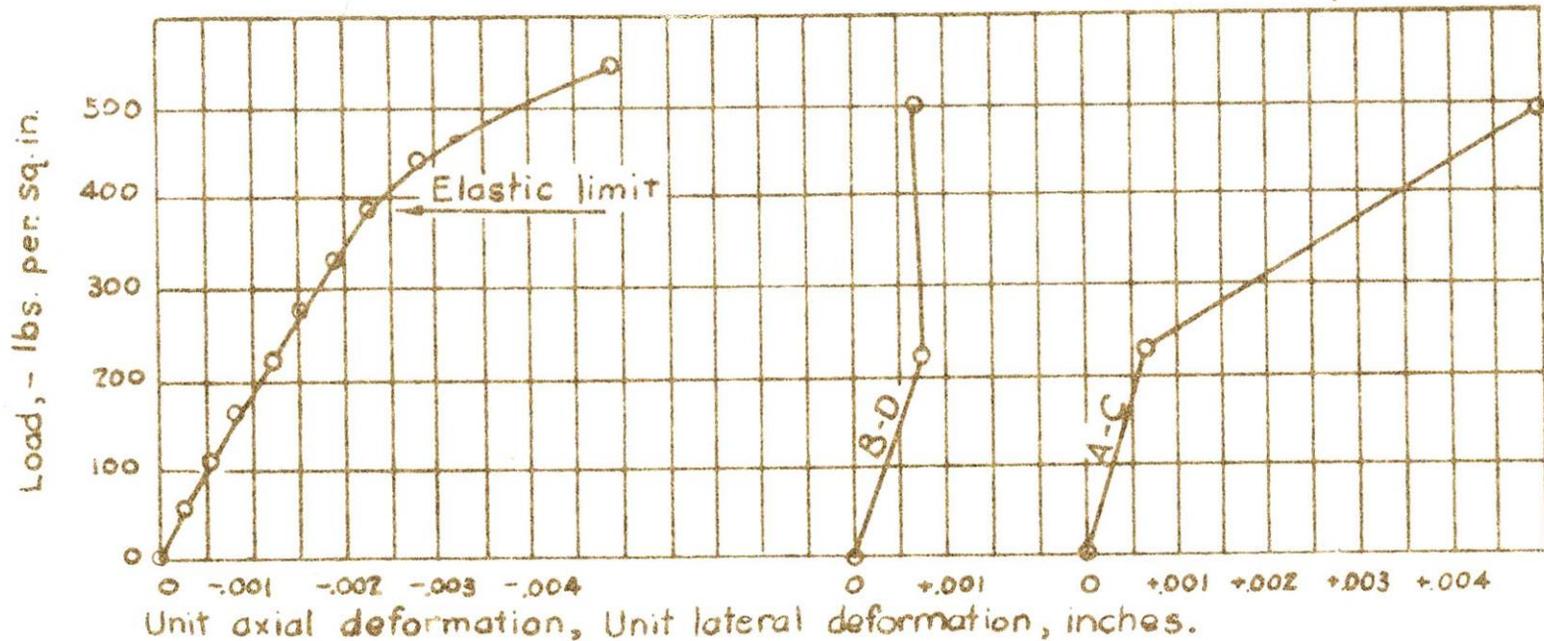


Diagram showing principal lines of rupture



- Early compressive strength tests on the Culebra formation

August 1914
The Canal Opens for
Business

**Trumpeted as an American
Triumph**



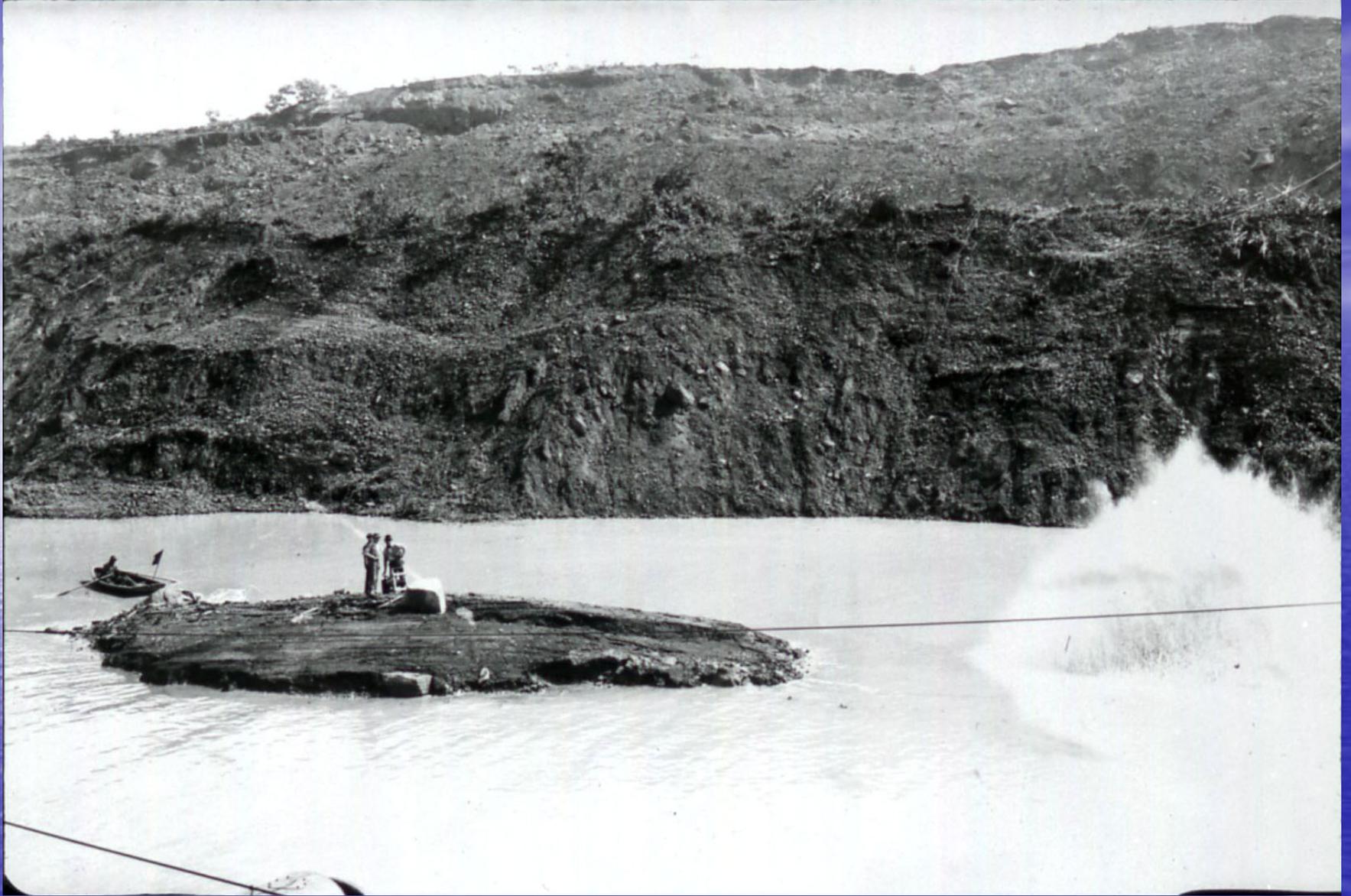
- The S.S. Ancon makes the historic first passage through the canal, from the Atlantic to the Pacific on August 15, 1914. Note dredges.



- **Barge shovels and suction dredges working the toe of the East Culebra Slide on July 3, 1916**



**Landslippage
continues
after the canal opens**



- Toe heave that protruded upward through 30 feet of water on September 19, 1915.



- **Zion Hill and the West Culebra Slide on October 24, 1915**



- **West Culebra slide activity viewed on July 3, 1916. Note emergence of 'Culebra Heights' in background.**



- Landslides shut down the canal on 26 occasions between 1914 and 1986. This shows a tug assisting a coastal freighter passing through the canal in 1917.



- Ship transiting canal around the East Culebra Slide. Note dredges and muck barges



- **When landslides partially blocked the channel, ships were queued up on either side of the construction and escorted through the gap.**



- Still running one-way traffic on June 13, 1933—passing the dormant East Culebra Slide

Evolving the Concept of Residual Strength

**Materials that get weaker
as they shear**



- East Culebra Slide as seen from the crest of Gold Hill on June 19, 1923. The shear strength of the slide debris had obviously been transformed to a much lower value.



- Dredges continue to work the zone between Obispo and East Culebra on April 25, 1924, ten years after the canal opened



Tensile scarps

- Massive tension crack opening above the West Culebra Landslide on October 22, 1936





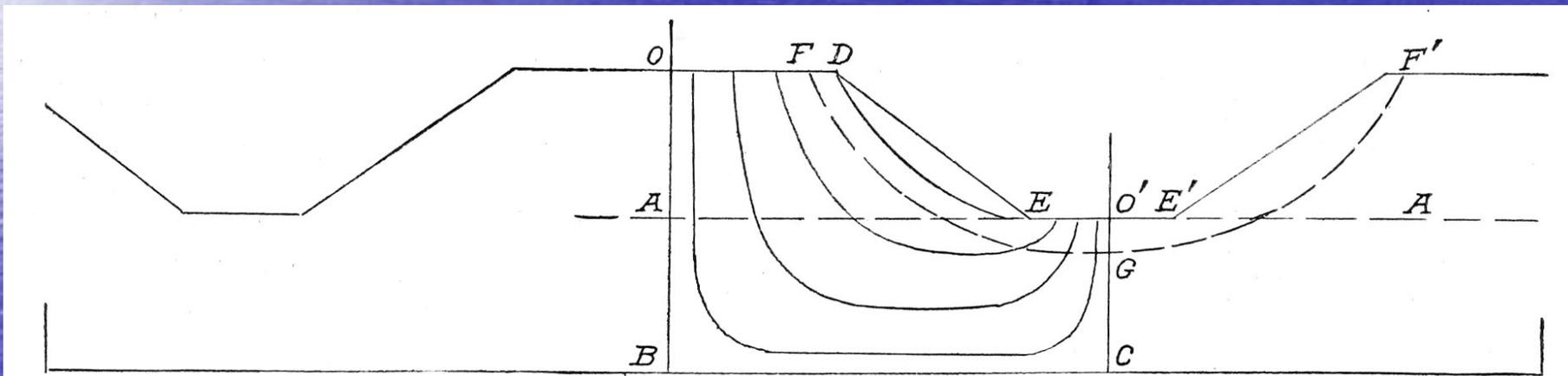
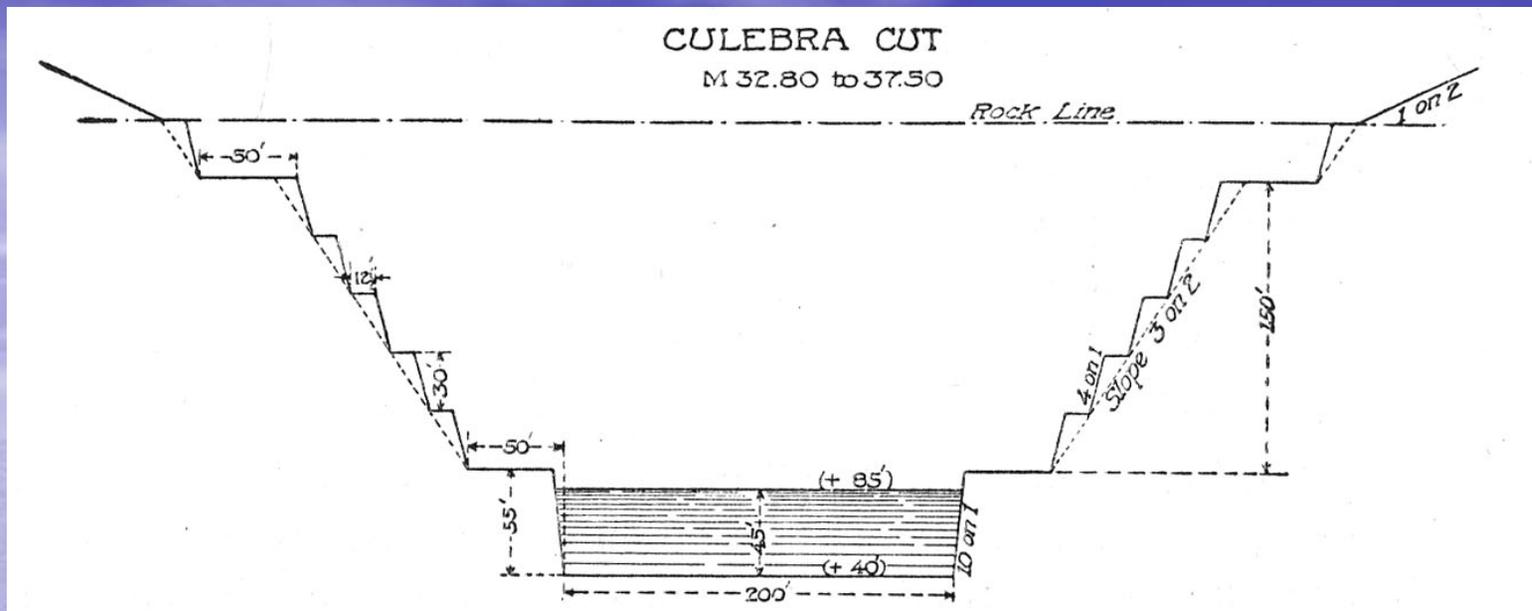
- Head scarp of the West Culebra Slide, 25 years later, on January 26, 1937



The 1924 study
Landslides Along the
Panama Canal

by the

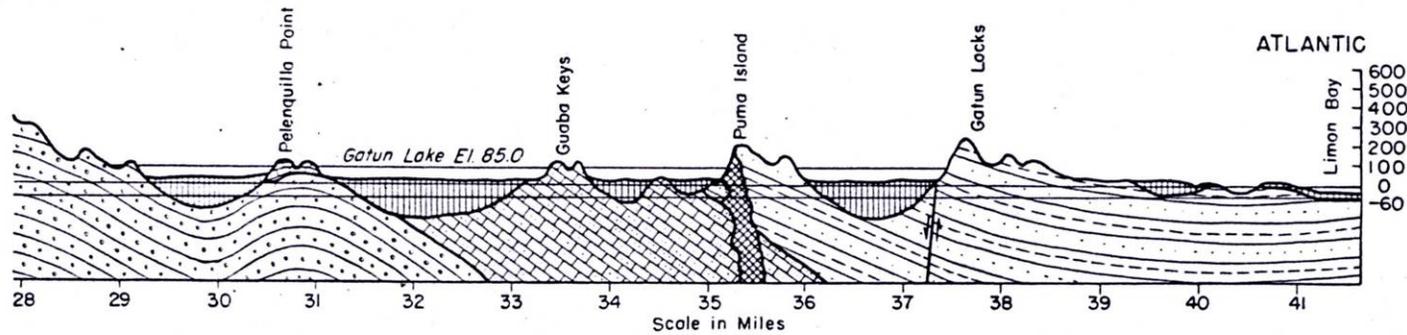
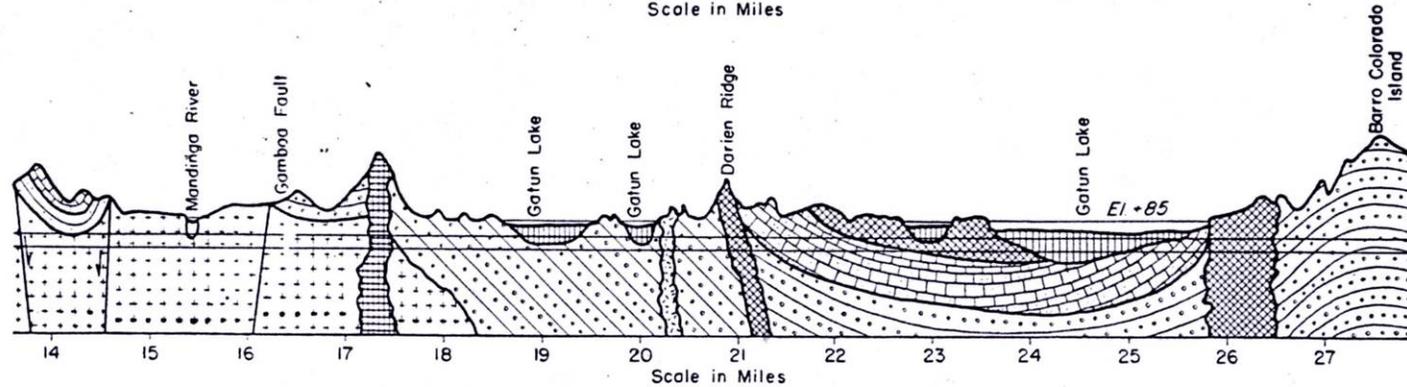
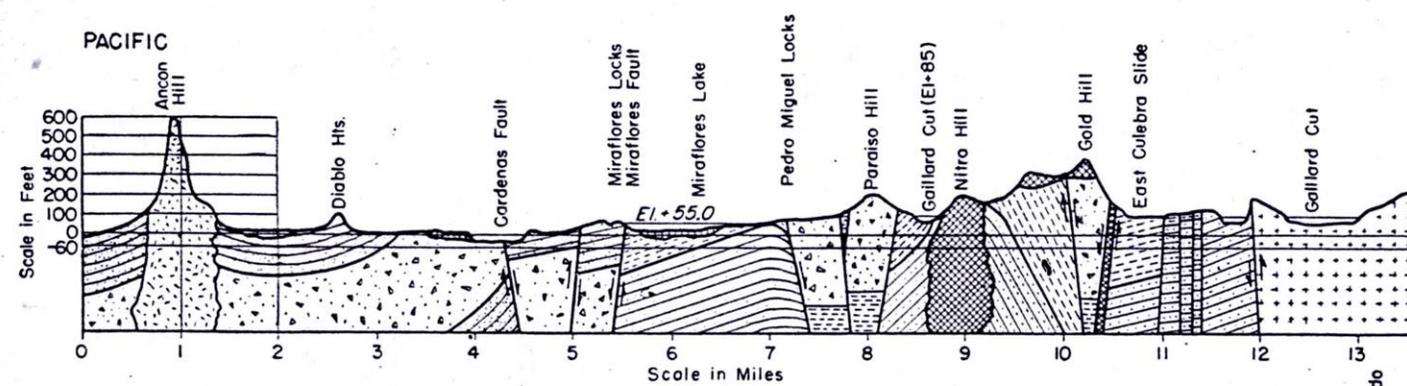
National Academy of
Sciences



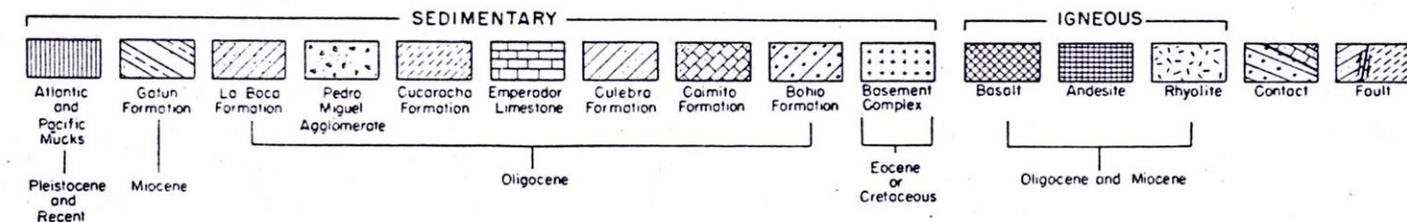
- The 1924 NAS study did a credible job of documenting the history of landslide problems along the canal excavations, but offered little in the way of meaningful analyses or solutions. Note flow net.

Geologic sections

The 1924 study presented a simple picture of the complex geologic structure



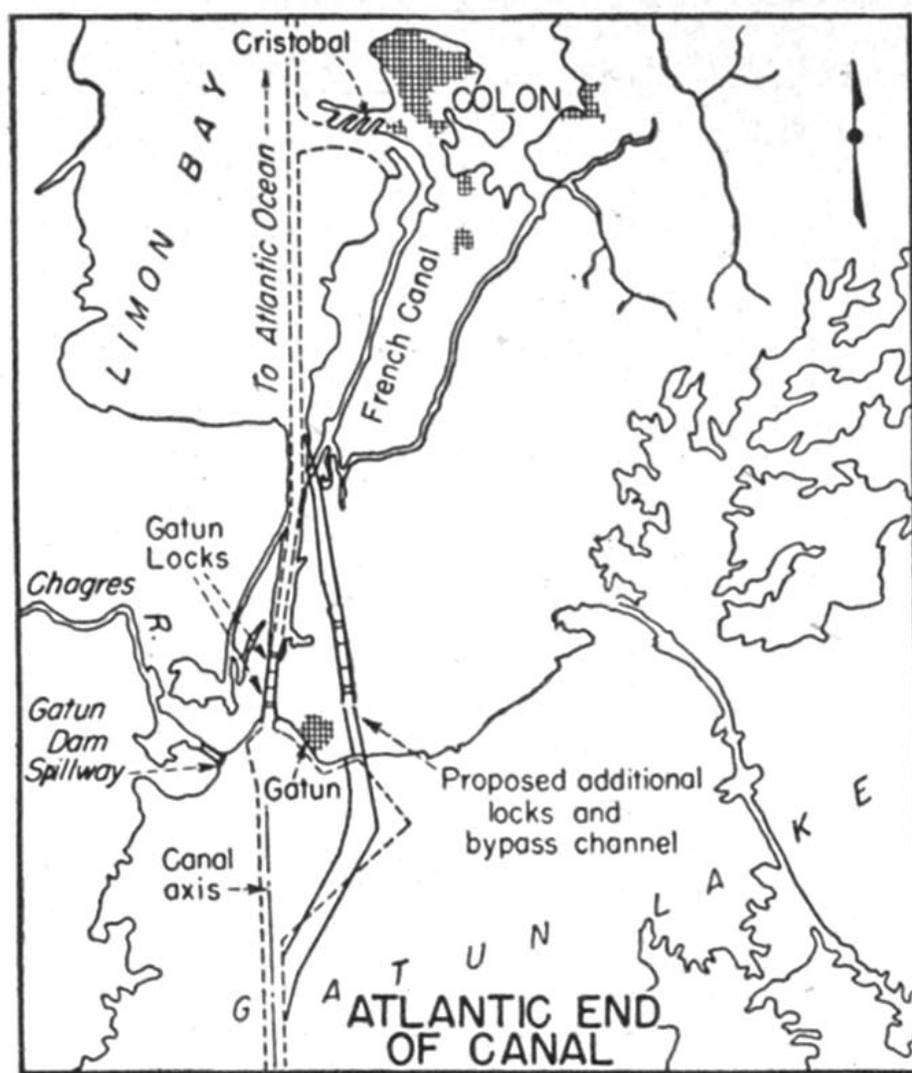
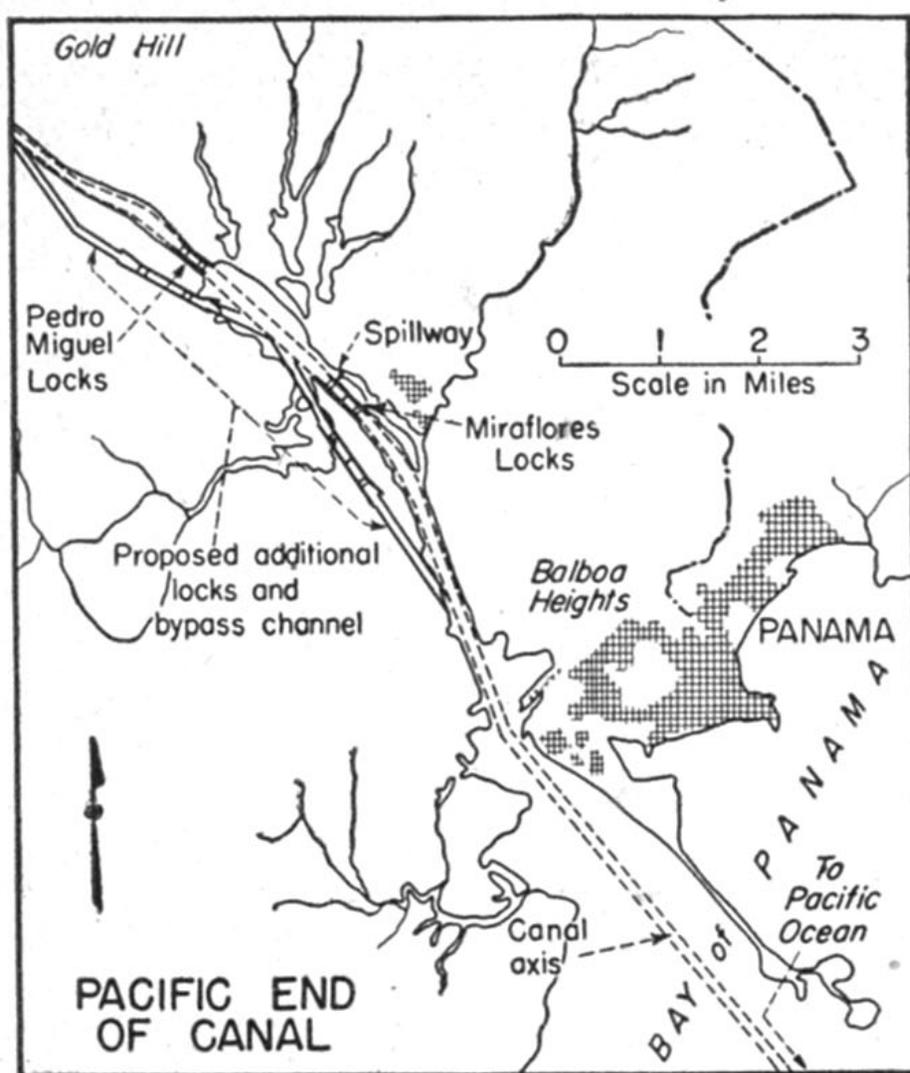
LEGEND



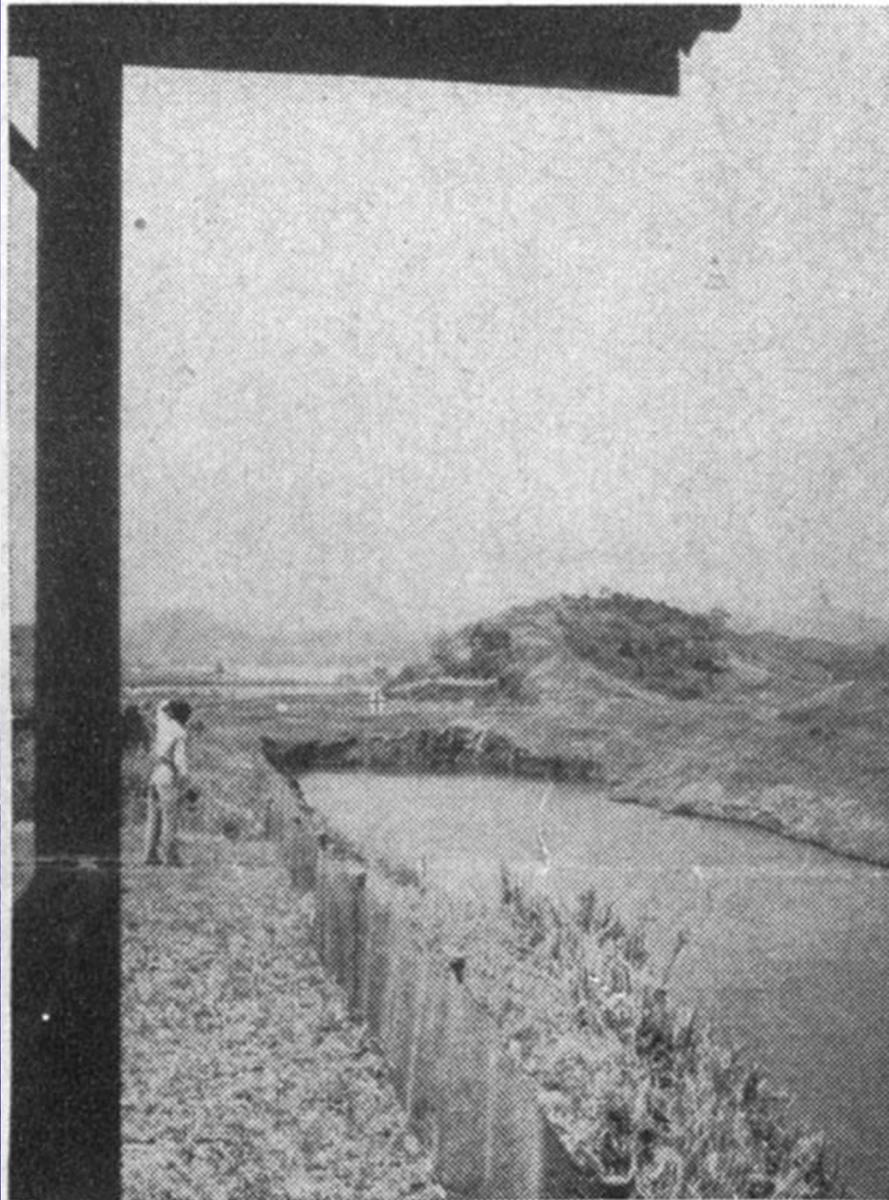
**The Third Locks
Project
During World War II
1940-47**

and

**Modern Slope Stability
Analyses
1947**

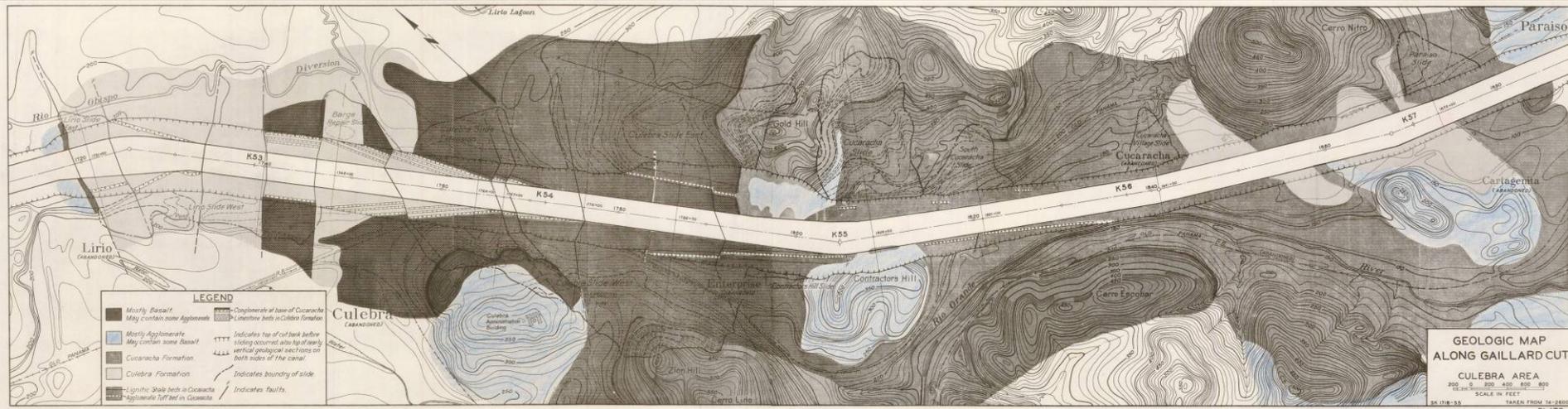


- The Third Locks project was undertaken during World War II to accommodate the Montana Class battleships and Midway Class aircraft carriers.

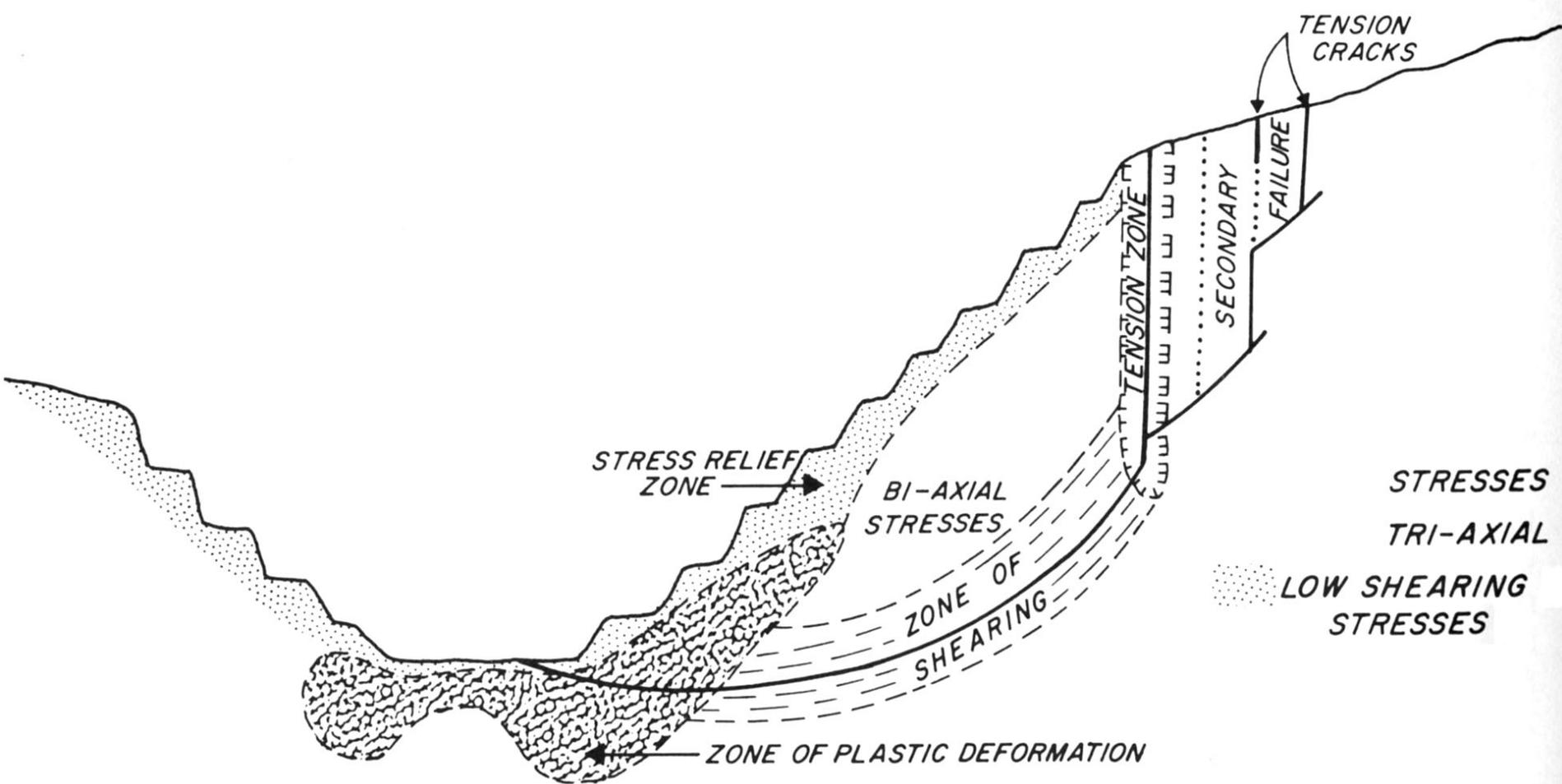


- Excavations for the Third Locks at either end of the canal, made on the eve of World War II, in 1939.

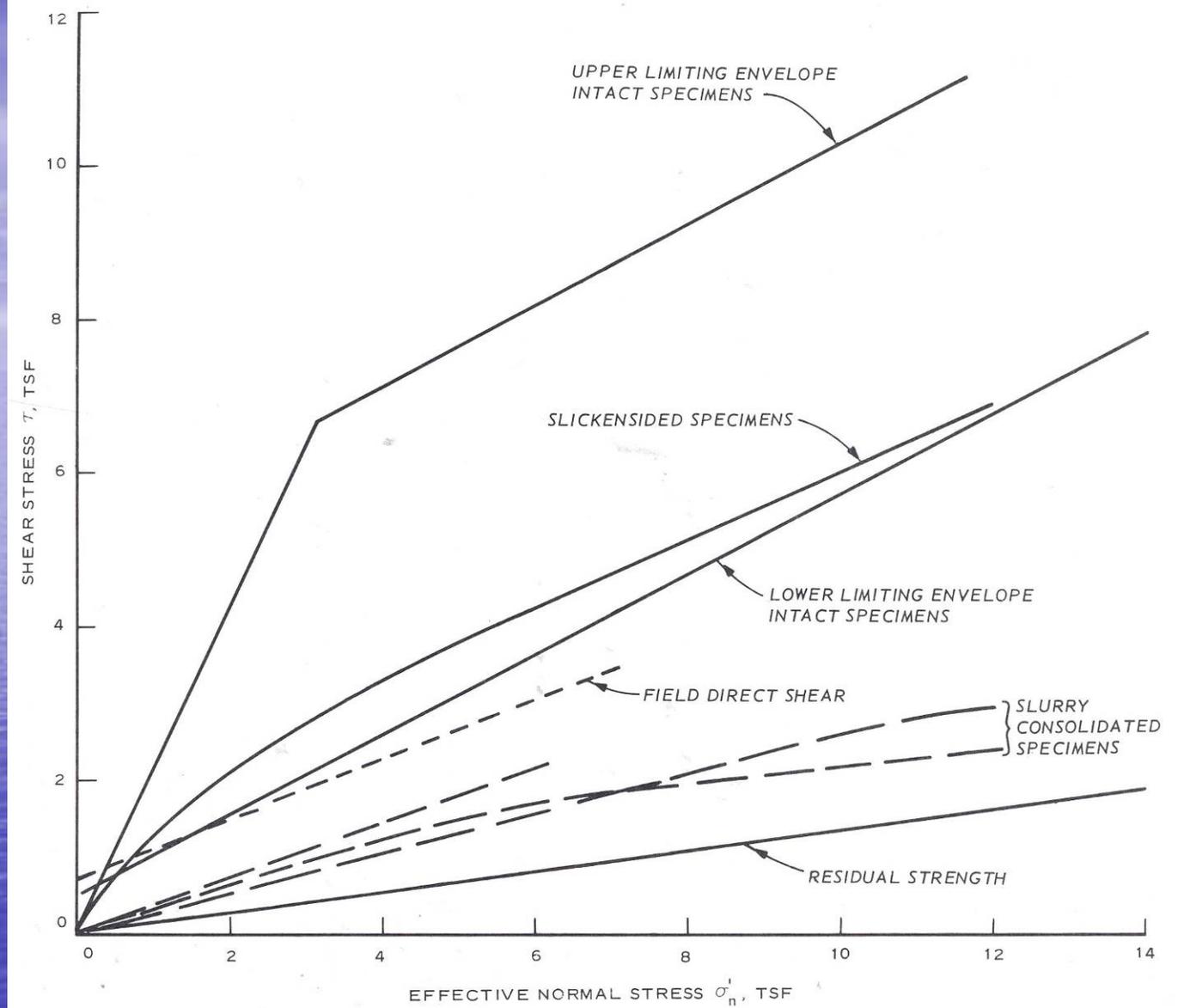
Geologic Strip Map



- The Panama Canal Commission brought Donald F. MacDonal back to work on the Third Locks Project during World War II. He supervised the compilation of a new geologic map, shown here.



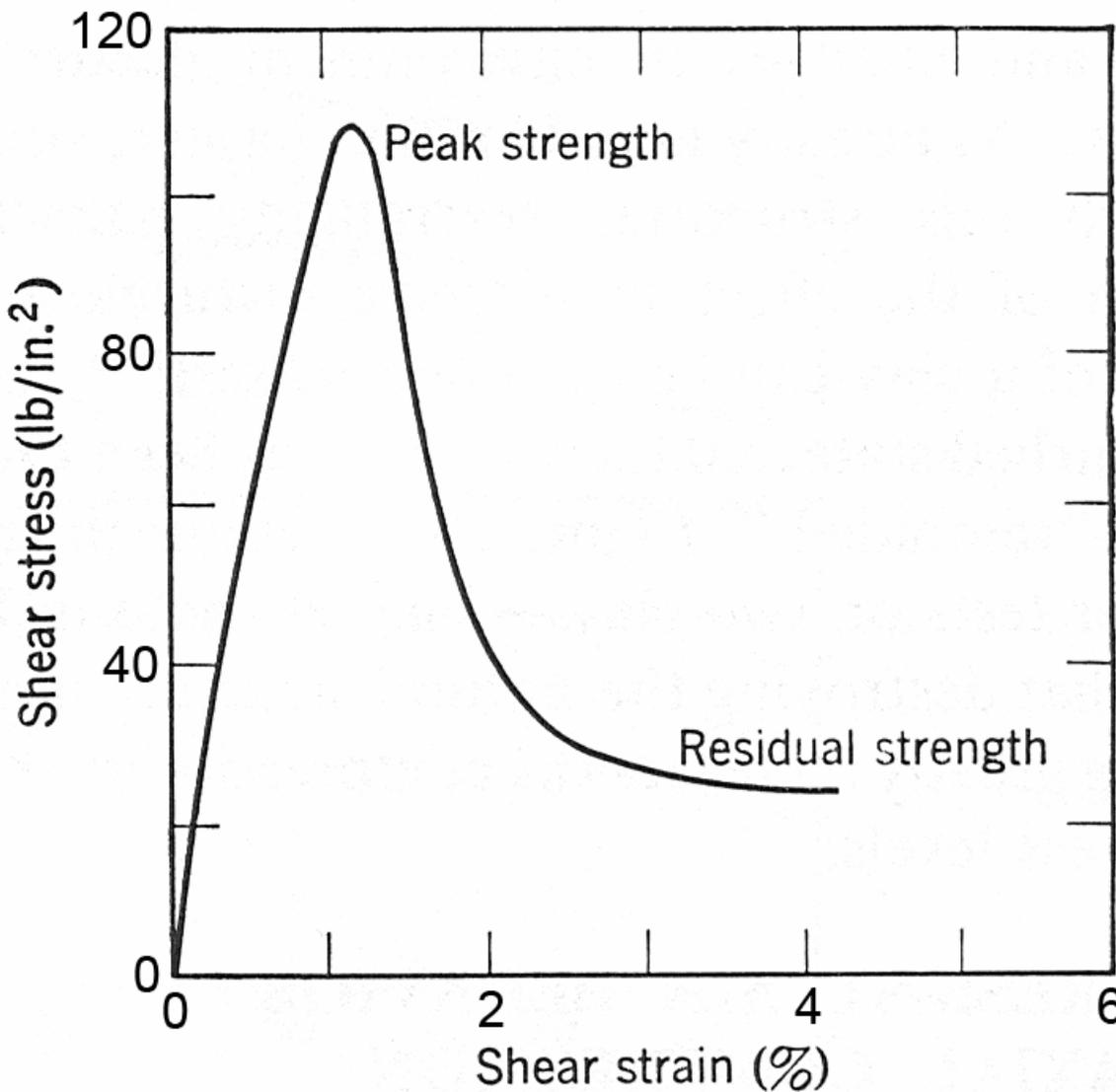
- By the mid 1940s Corps of Engineers researchers were beginning to appreciate the significance of stress regimes and strain on soil strength parameters, as sketched here.



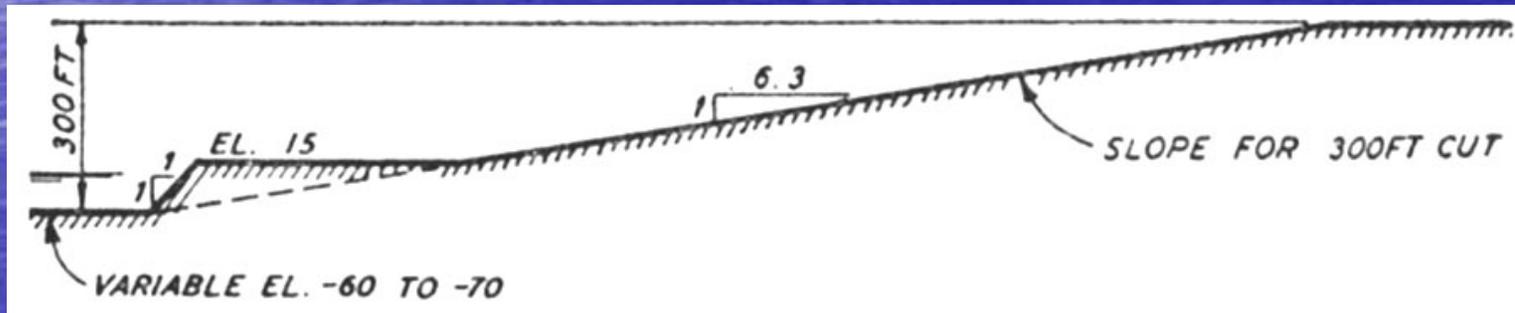
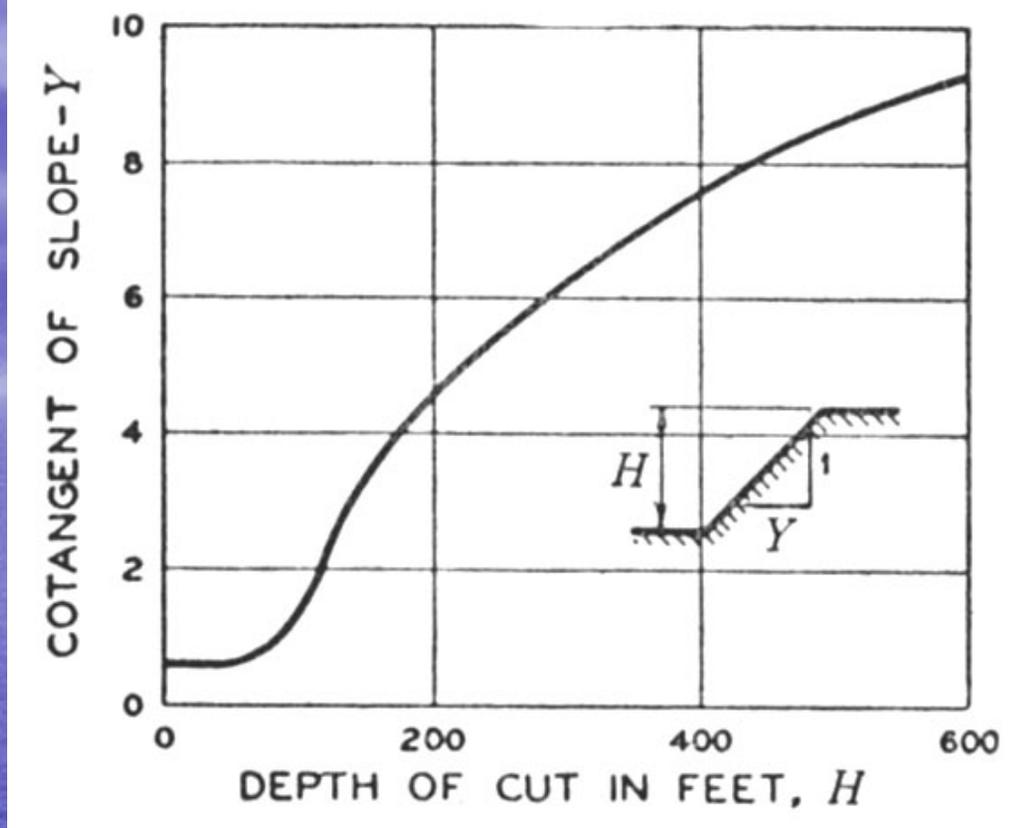
- Shear vs effective normal stress plots. Note impact of disturbance, or plastic strain, on mobilized shear strength.

Residual Strength

- The concept of residual strength came out of tests on the Cucaracha Shale in the late 1940s for the Corps of Engineers, shown here.



Overconsolidated shales tend to exhibit strain softening behavior



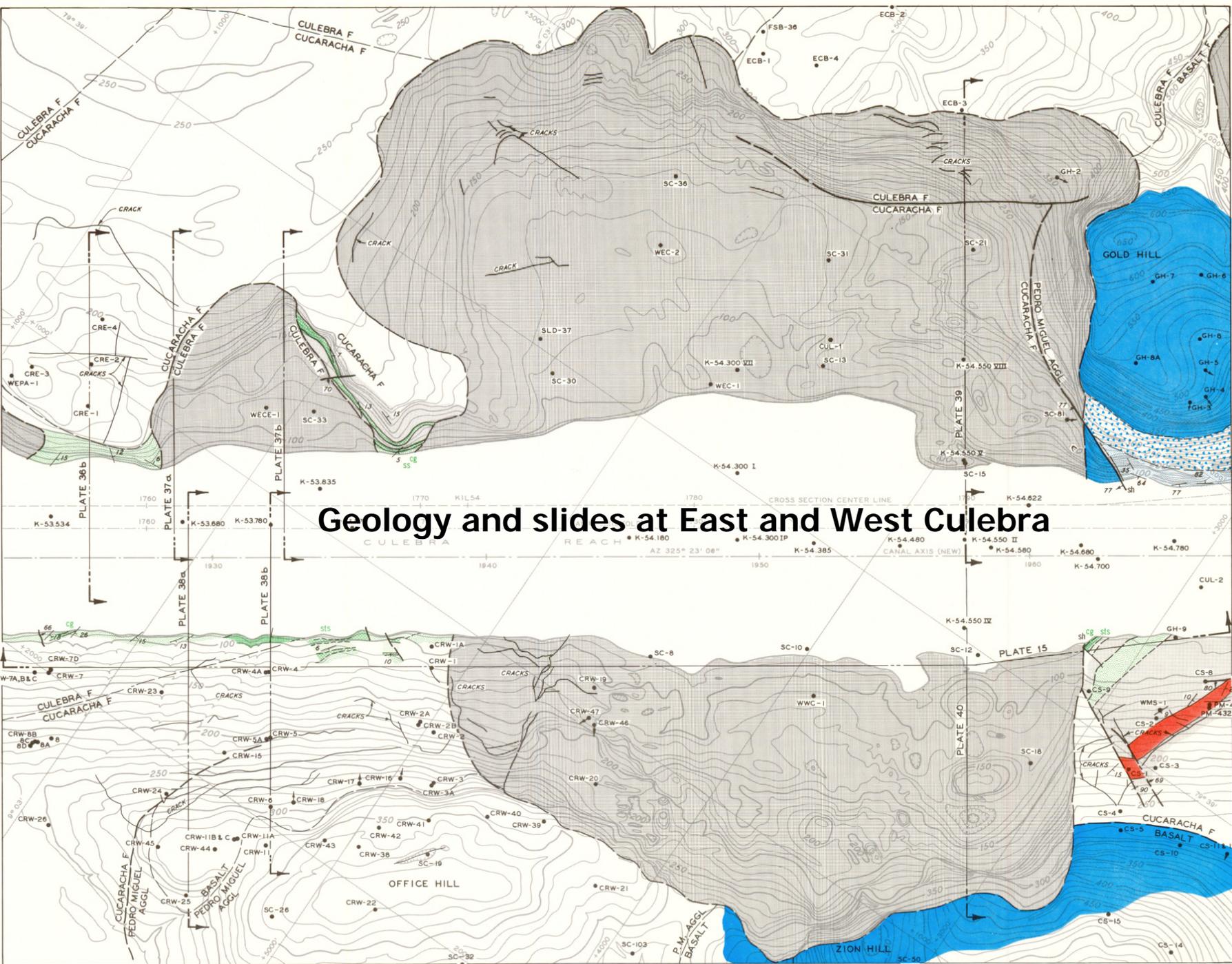
- In 1947 the Corps evolved the first design charts for the most problematic units along the canal; these are for the Cucaracha Shale

Applying Everything We Know....in the computer age

**The Corps of Engineers work
in the early 1970s**

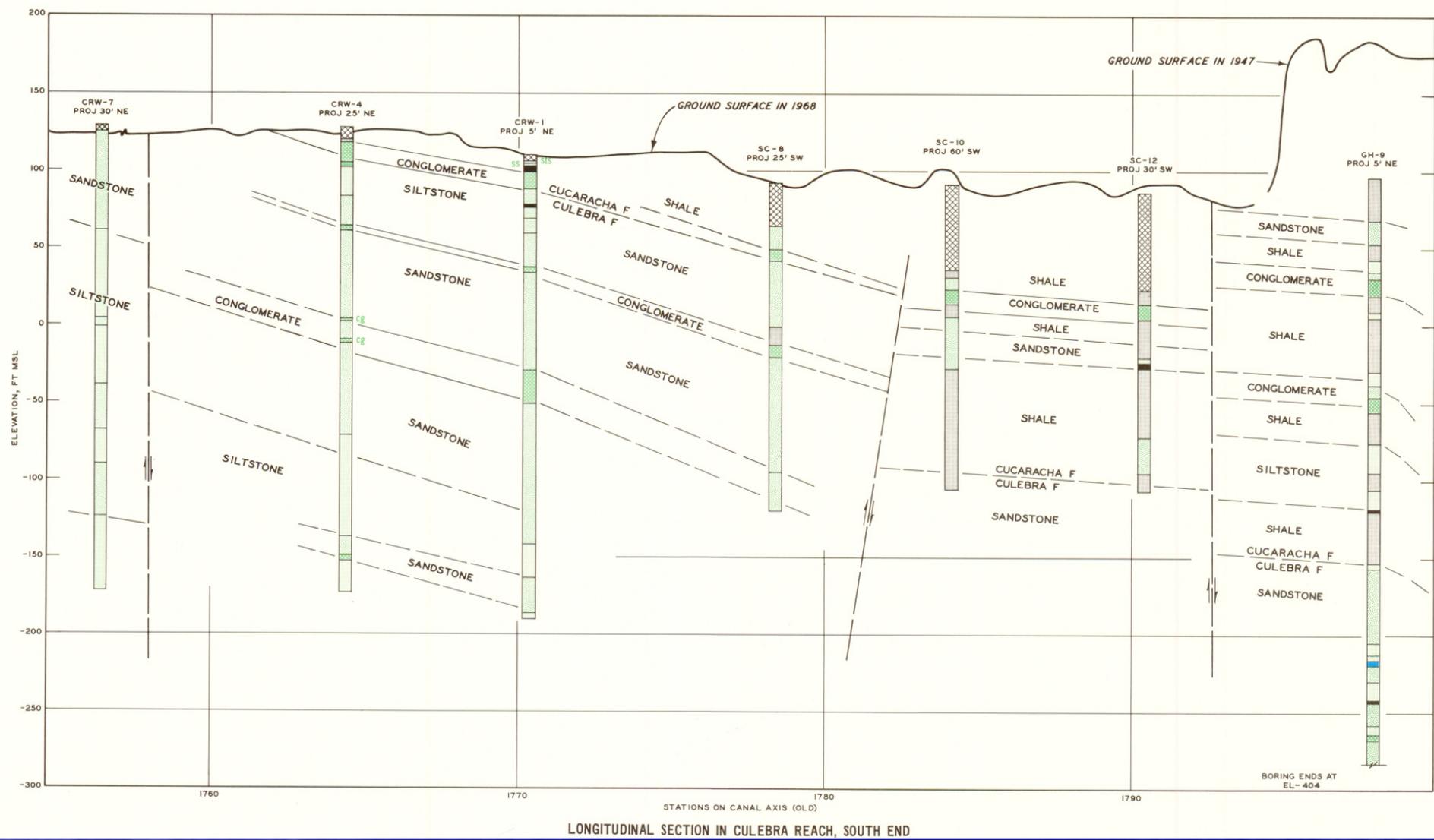
Some Statistics

- More than 60 landslides, up to $17.6 \times 10^6 \text{ m}^3$ have occurred since 1912.
- These slides required additional excavations of $> 45 \times 10^6 \text{ m}^3$ to construct and maintain the Canal before it was turned over to the Panamanian government in 1979.



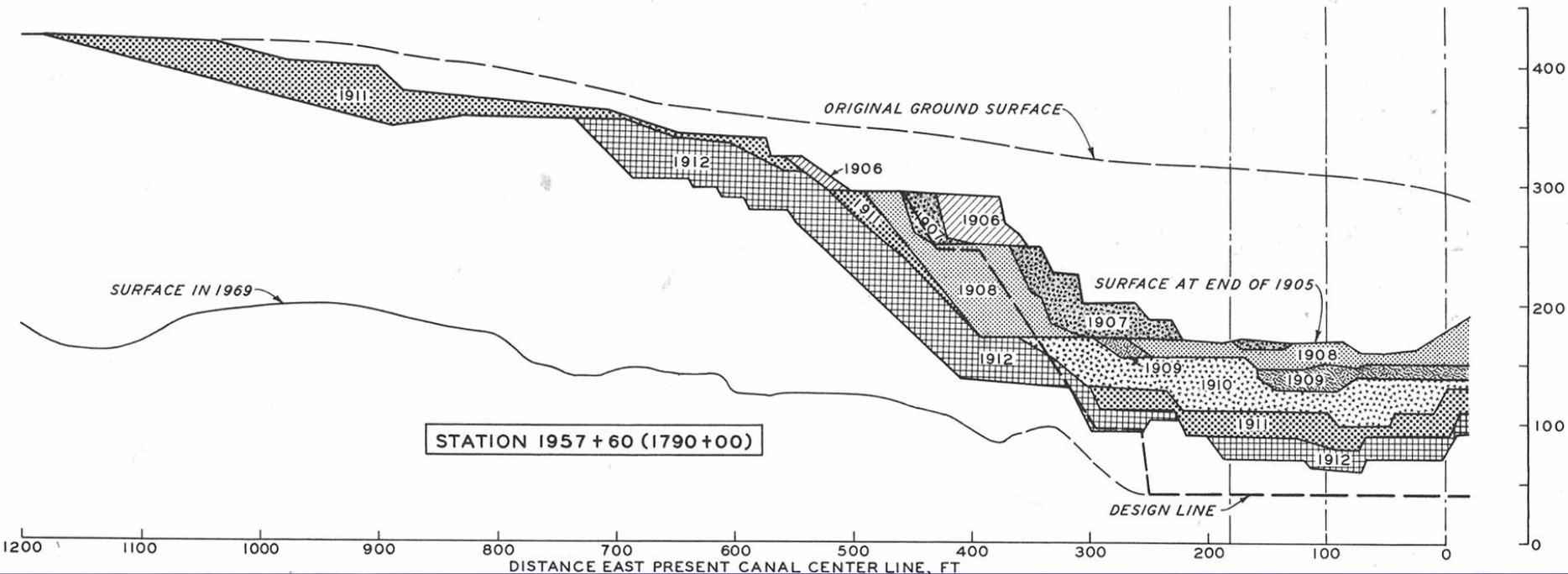
Geology and slides at East and West Culebra

GEOLOGY OF CULEBRA REACH SOUTH END

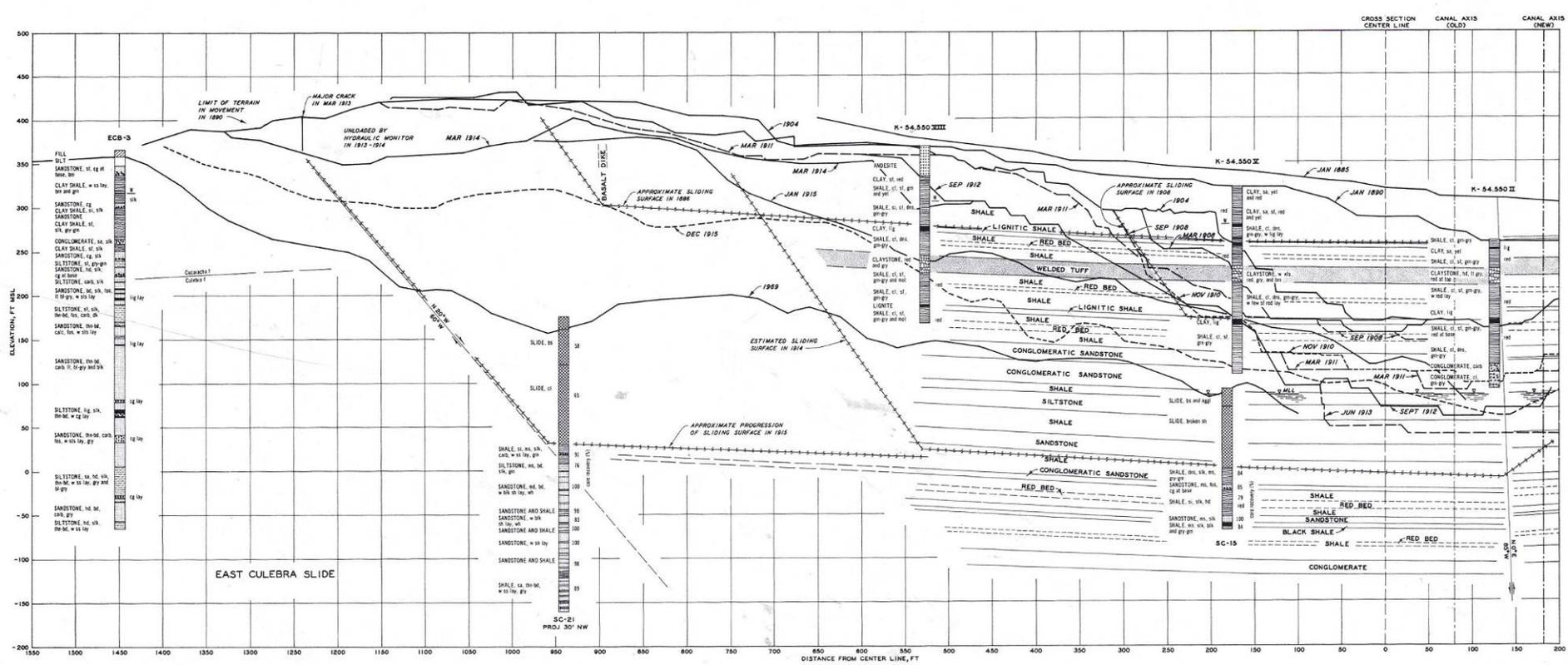


- Longitudinal section at south end of Culebra, where slides encroach both sides of the canal.

60+ years of data

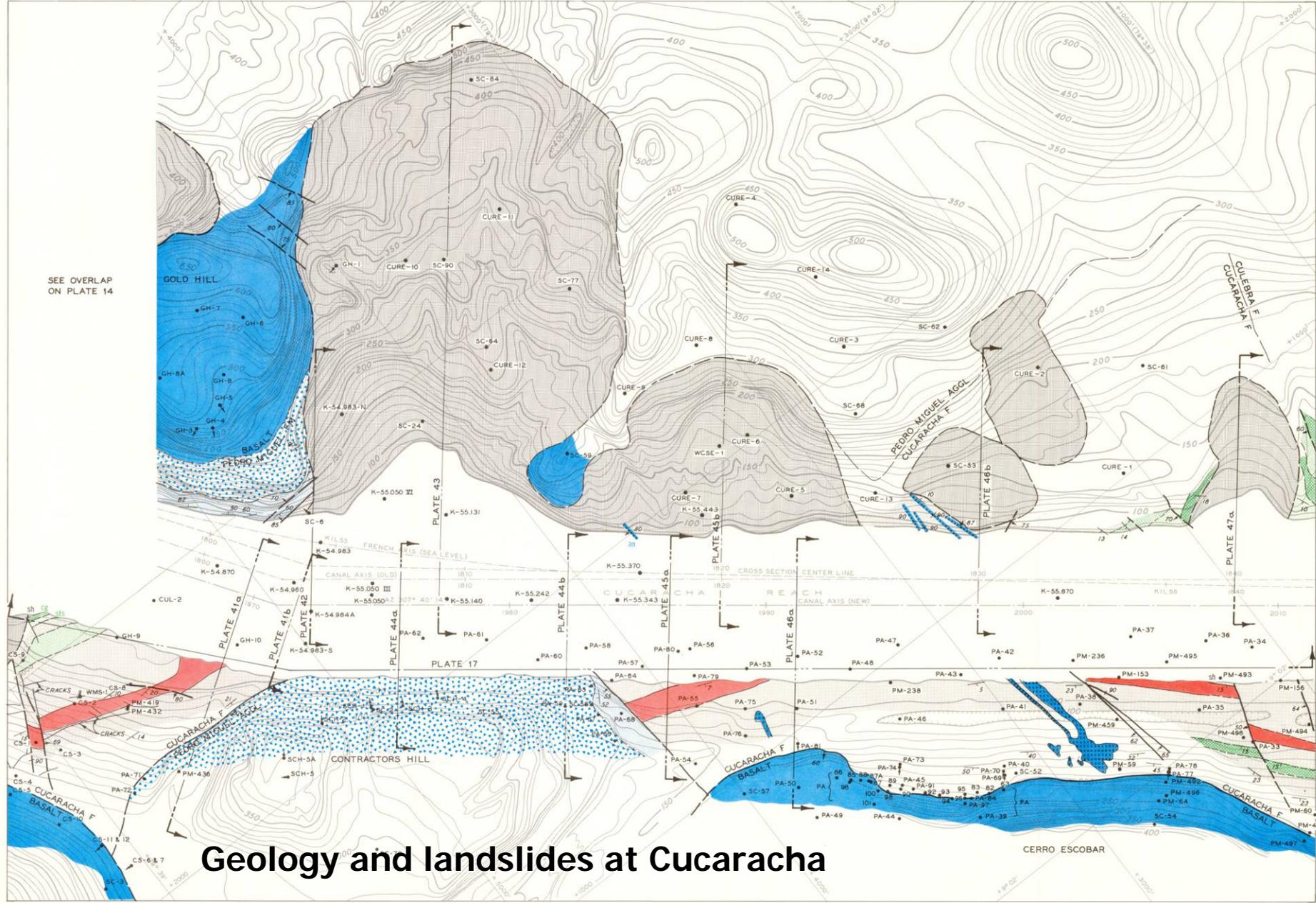


- Successive sections through the East Culebra Slide. Note original ground surface and surface in 1969.

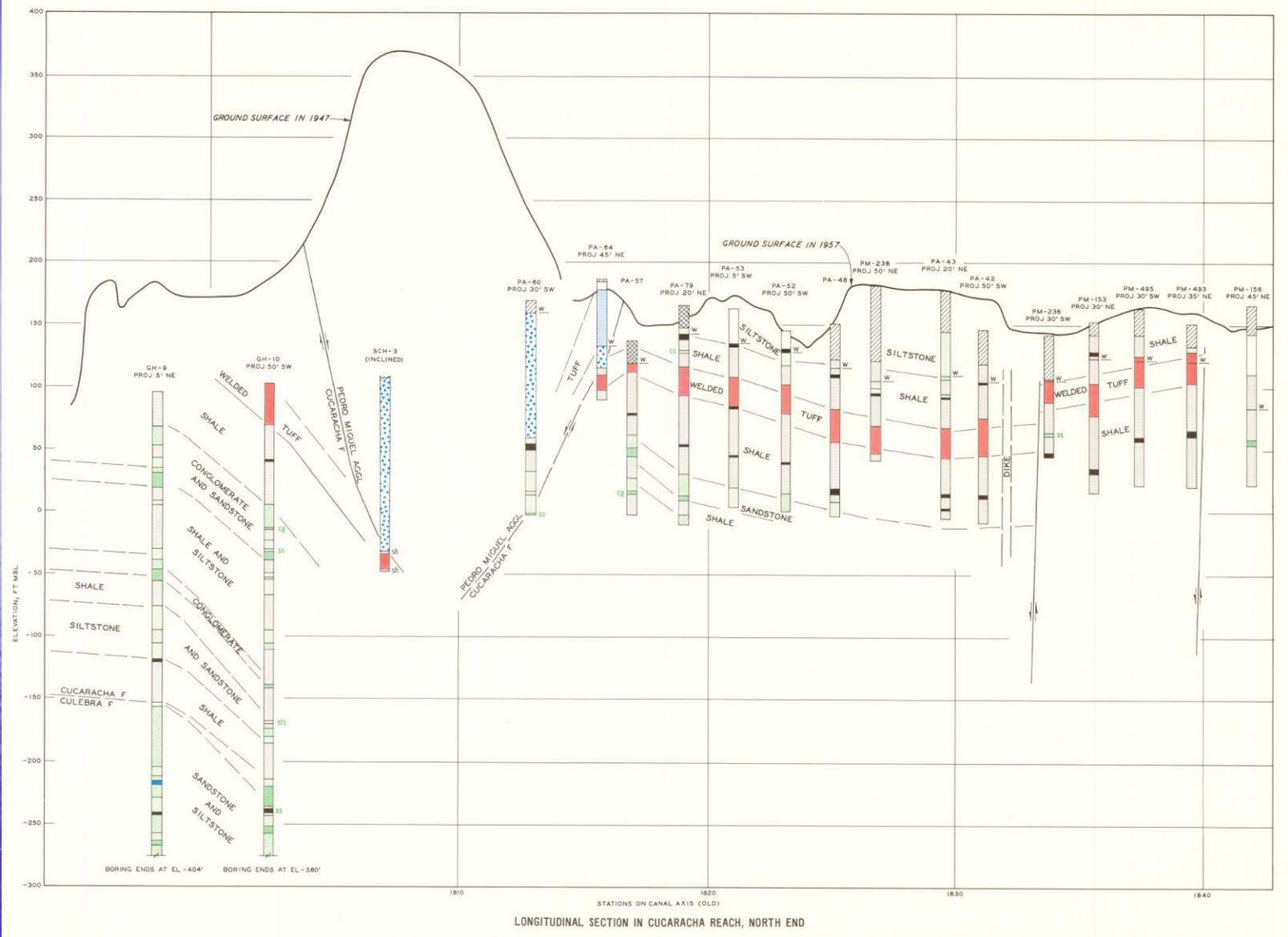


- By the early 1970s the Corps had amassed 60 years of data. This shows a section through the East Culebra Landslide, showing retrogression of the head scarp, progressive deflation, and controlling stratigraphy.

SEE OVERLAP
ON PLATE 14

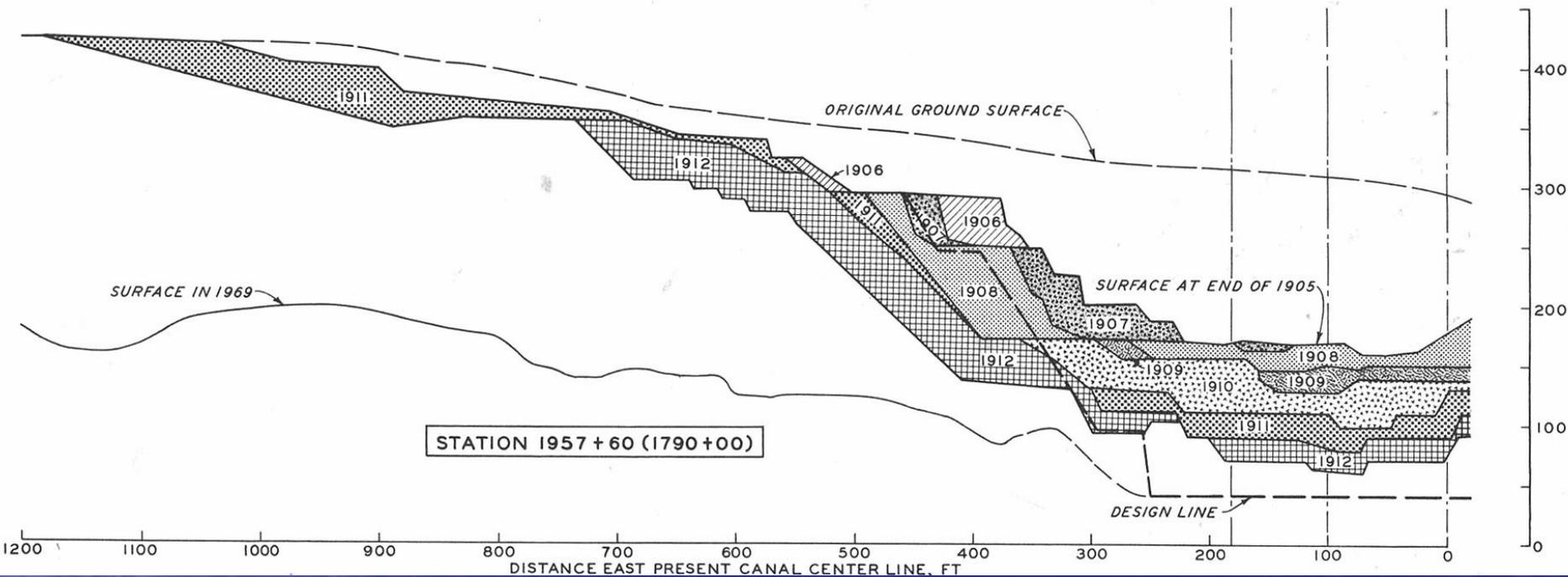


Geology and landslides at Cucaracha

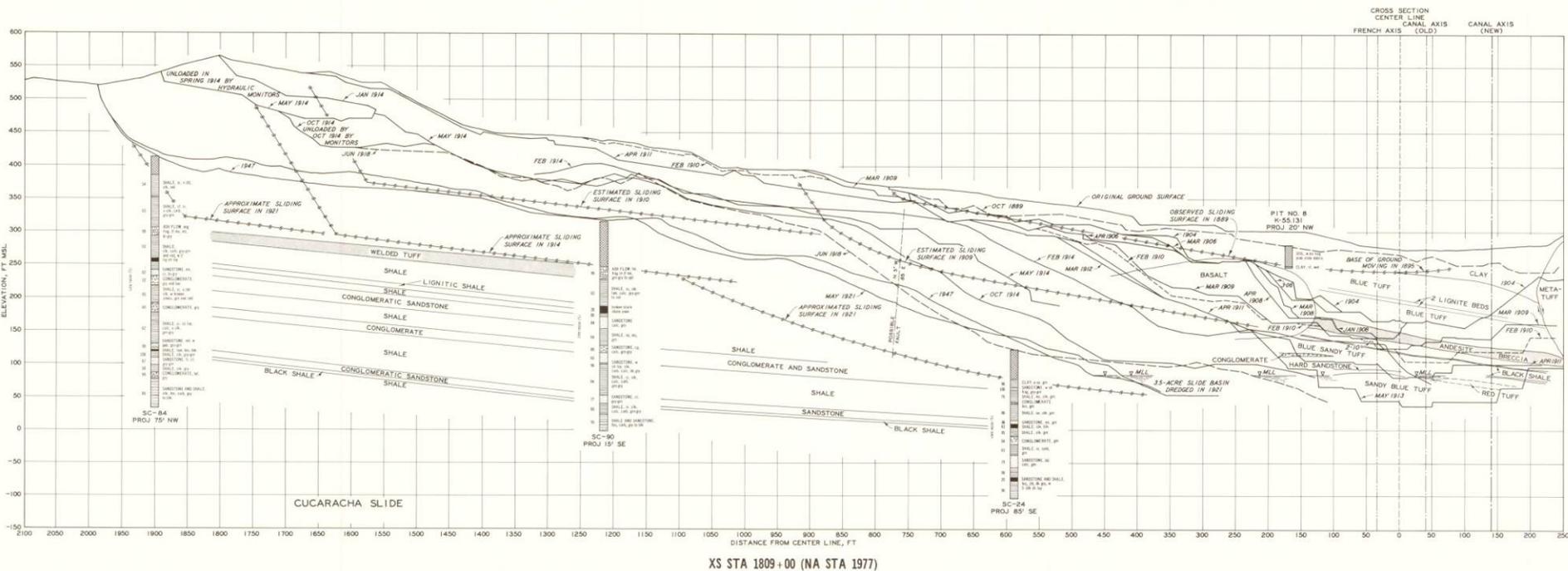


- Longitudinal section through Cucaracha, showing floating nature of Gold Hill.

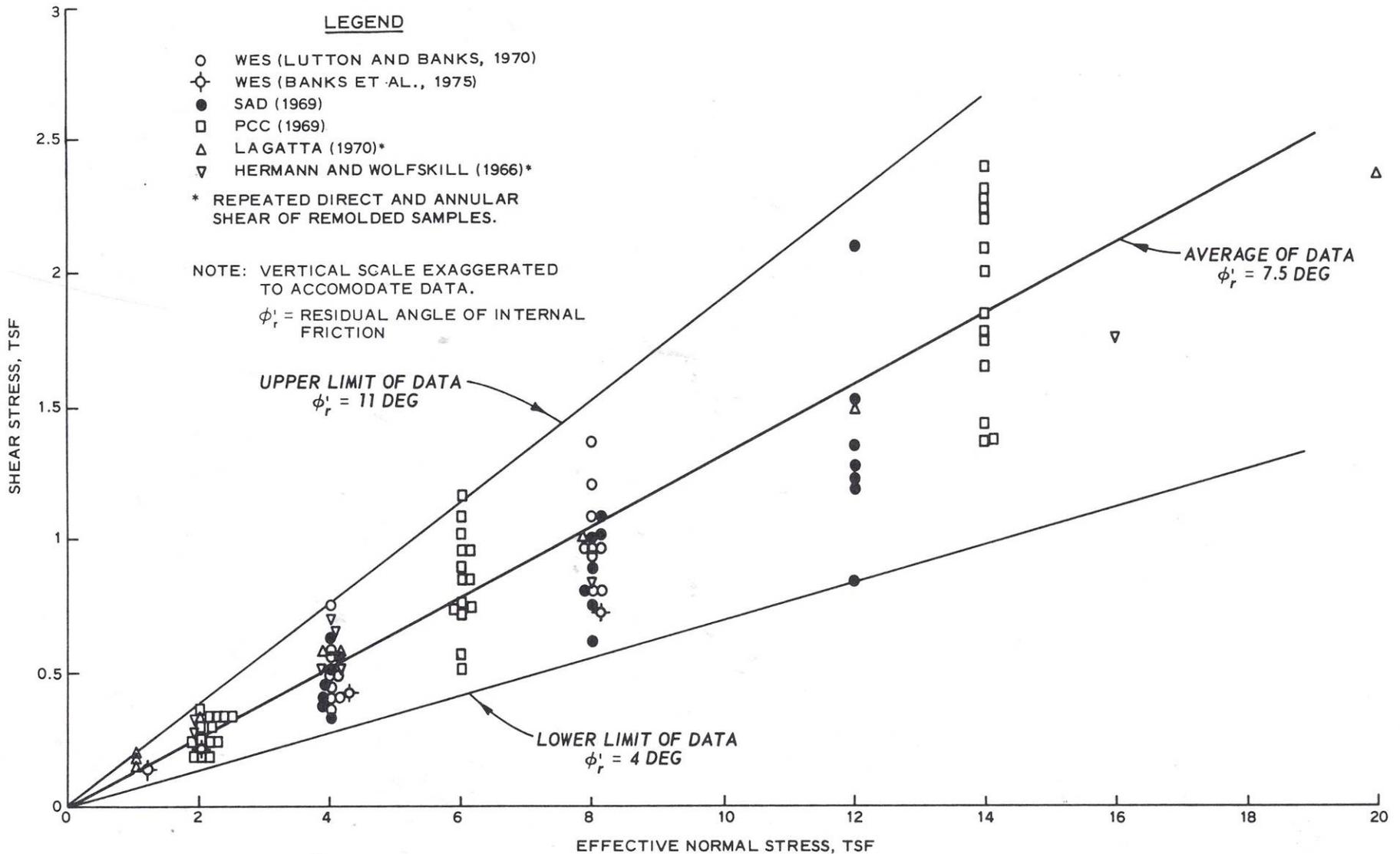
60+ years of data



- Successive sections through the Cucaracha Slide. Note original ground surface and surface in 1969.



- This shows a section through the troublesome Cucaracha Landslide, showing retrogression of the head scarp, progressive deflation, and controlling stratigraphy.



- By 1974, the Corps of Engineers decided that the best graphical method to describe strain softened materials was to use a fan plot, showing the upper and lower limits of strength.

Geologic materials subject to strain softening

- Tertiary volcanic sedimentary rocks, mostly shales, siltstones, and agglomerates. All of these contain smectite clays
- Cucaracha Formation
- Culebra Formation
- LaBoca Formation



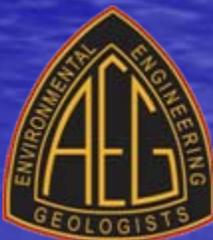
Strain Softening

- For initial unloading/relaxation of cut slopes, the effective strength parameters are close to peak shear strength.
- For reactivated slides, the effective strength parameters degrade to residual values, about 75% less than peak strength.



Strain Incompatibility

- Relative strain, and the rate of strain, appear to be important triggers in strain softening materials.
- Strain tends to concentrate at interfaces of materials with dissimilar stiffness and modulus, such as the interface between sandstone and clay
- Strain can also be caused by: 1) loss of lateral support; 2) simple unloading (relaxation); 3) incremental slope creep; and 4) weathering.



Mitigation Measures

- Most slope movements are driven by increased pore pressure. Drainage is essential to limiting incremental movements triggered by pore pressure conductance.
- Strain-softening materials lose strength when some limiting strain threshold is exceeded.
- Our focus must be upon limiting movements by whatever means possible.