Earthquake-Induced Landslides in the Western New Madrid Seismic Zone

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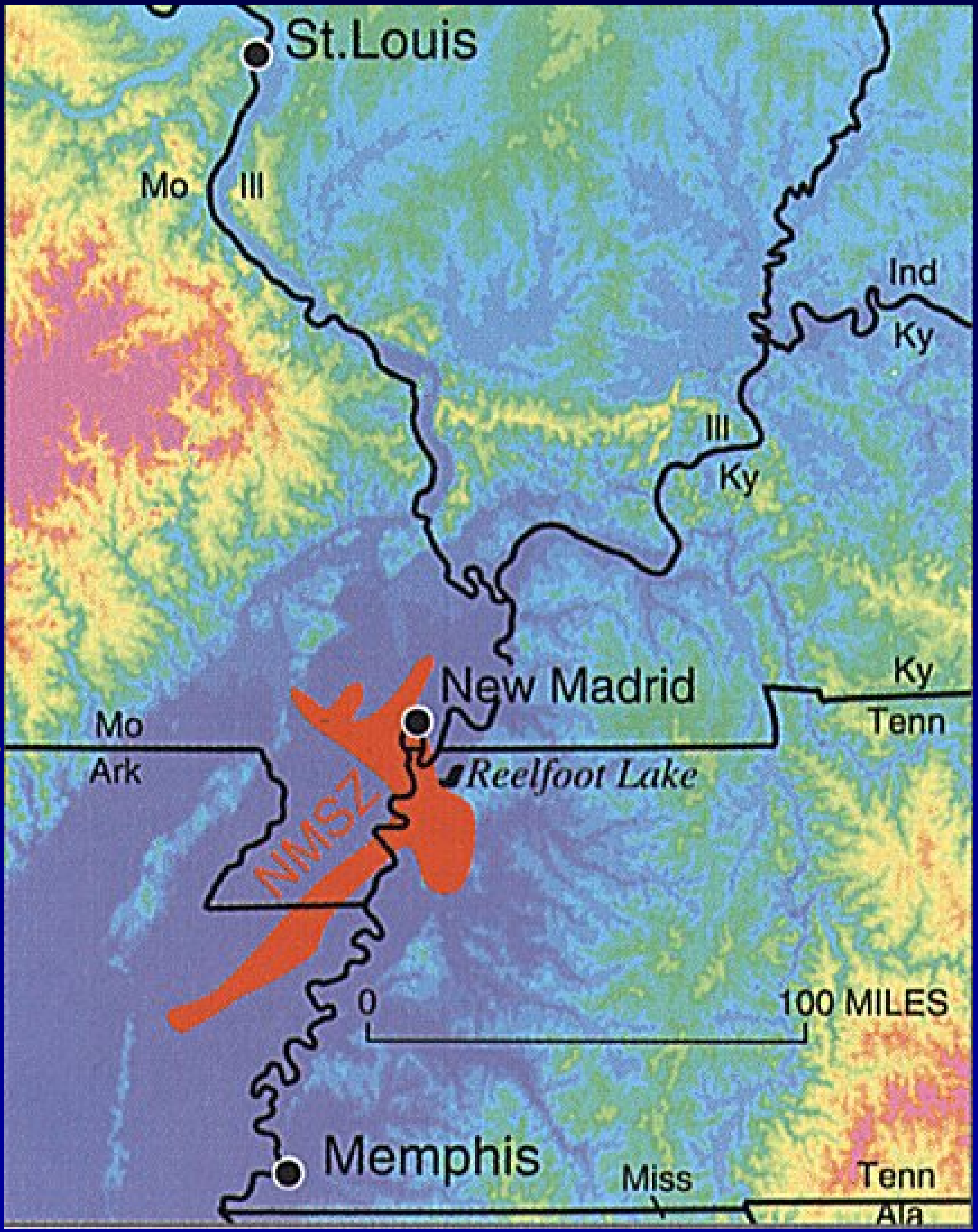
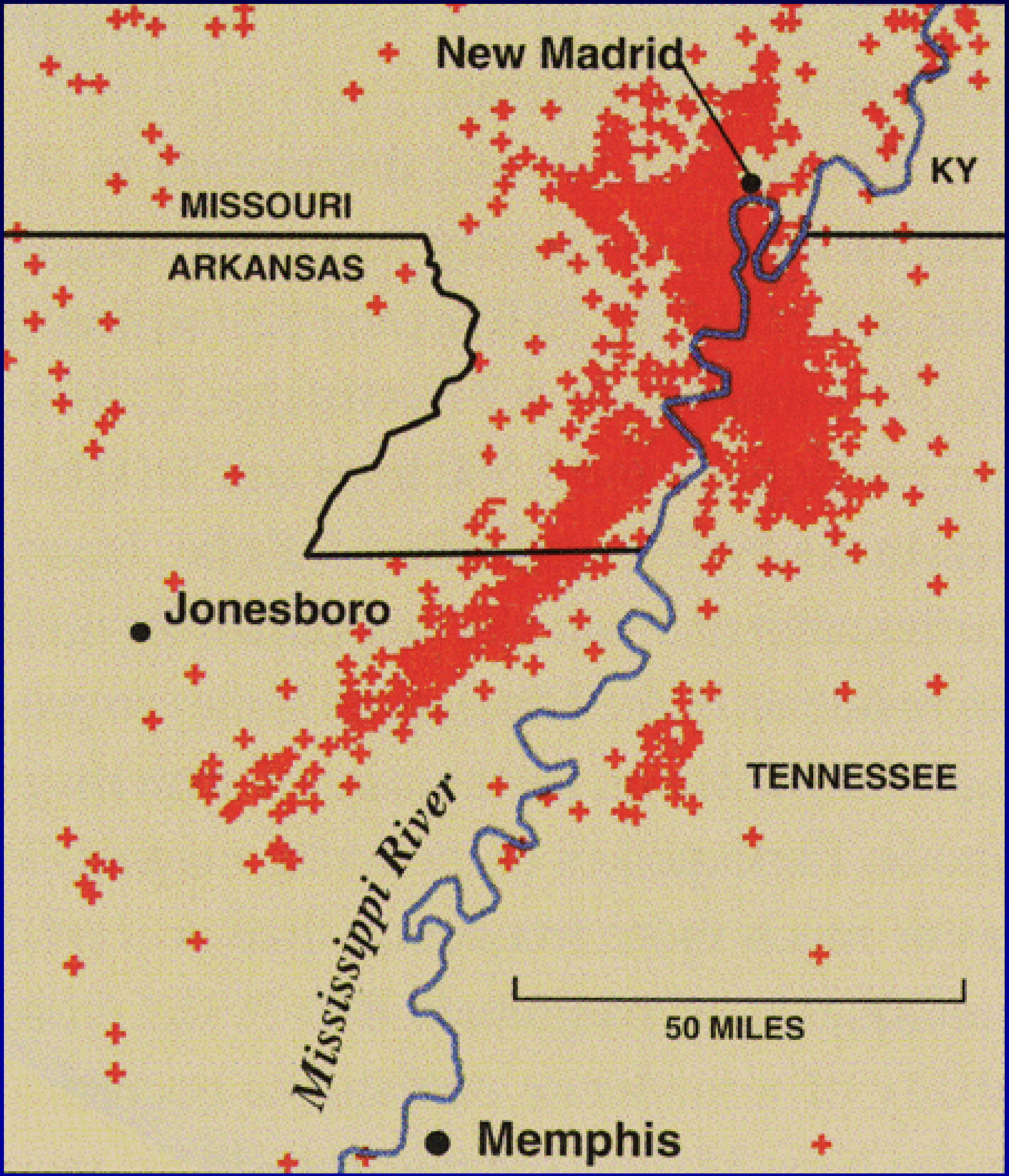
New Madrid Seismic Zone (NMSZ)

- Most seismically active area east of Rocky Mts.
  - Located within Upper Mississippi Embayment
- In 1811-1812
  - Over 2000 felt earthquakes in 4 month period
  - 4 quakes with $M_s \geq 8.0$
- Damage estimates for similar quakes today
  - $10 to $20 billion in Central U.S. (1994)

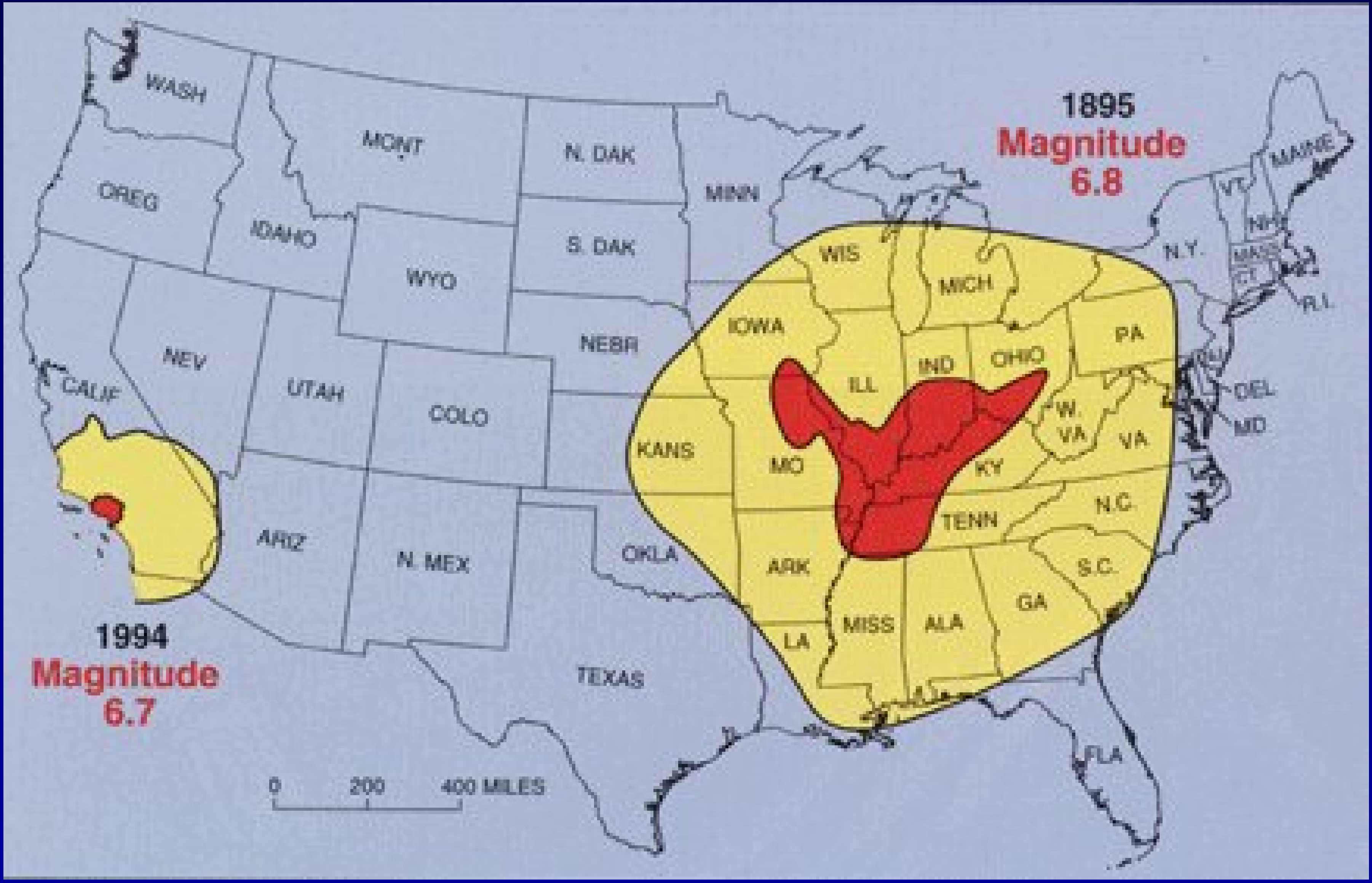


Distribution of Recent Seismicity

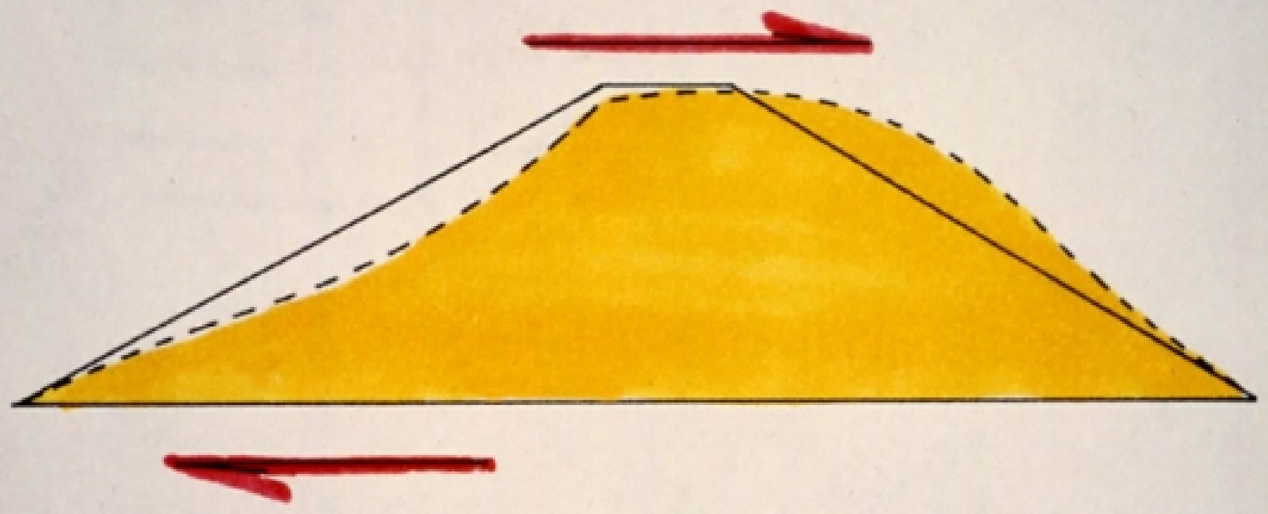
- Funding to investigate initiated in the mid-1970s when a nuclear power plant was being considered in the Memphis area
- Locations of earthquakes recorded in the NMSZ from 1974 to 1995



Area affected by a M_s 6.8 Earthquake

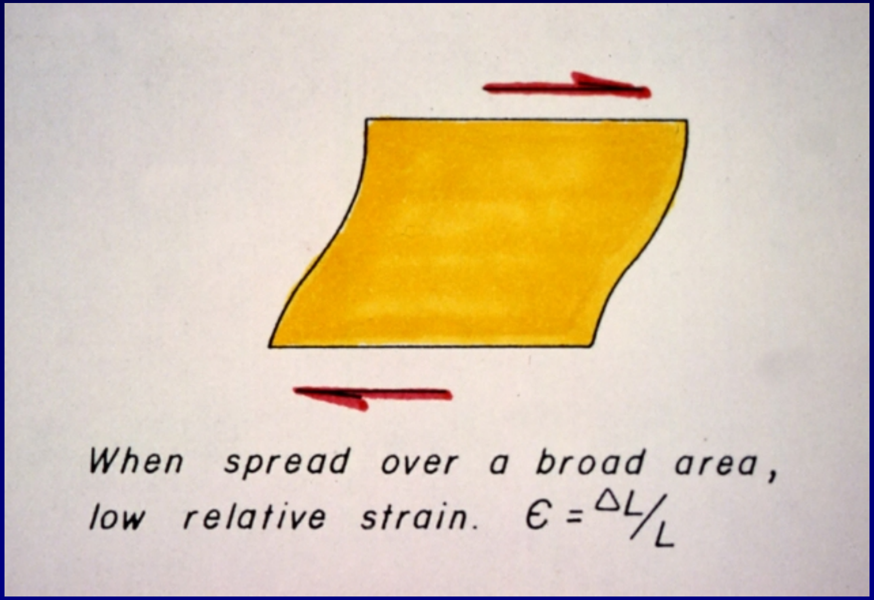


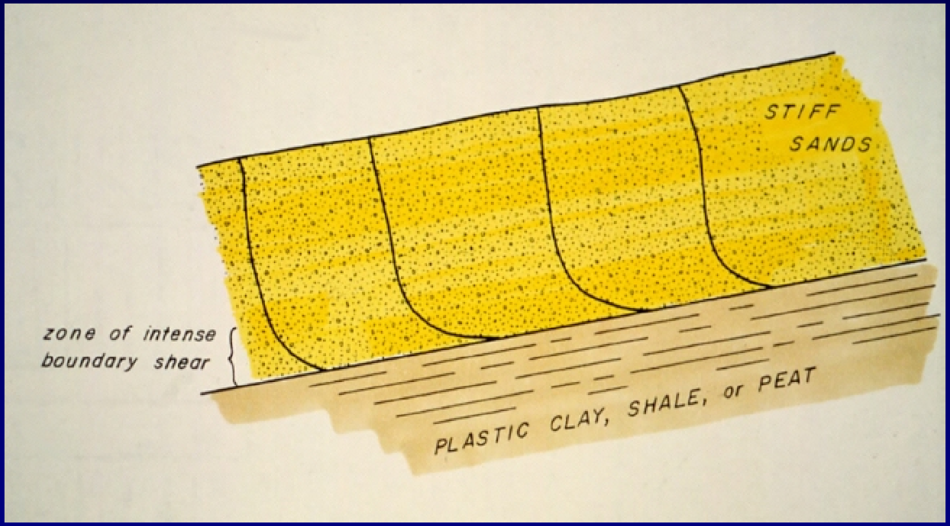
DISTRIBUTION OF ENERGY DELIVERED BY A SEISMIC WAVE TRAIN



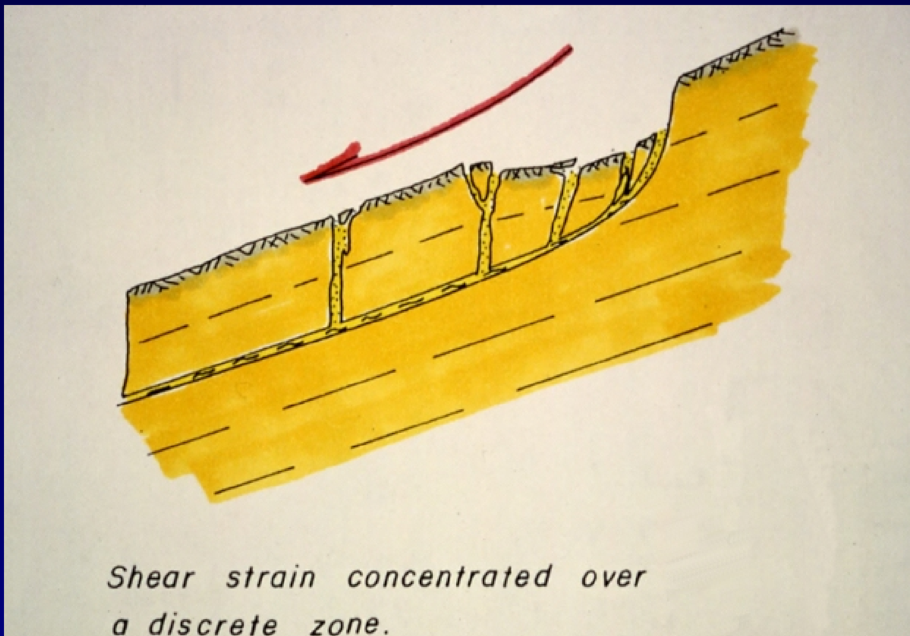
Semi-homogeneous clay embankment flexes with motion, thereby dispersing shear strain.

SHEAR STRAIN





- If the shear stress induced by EQ motion is distributed vided over a wide area, the resulting shear strain will be lower than if it is confined to a discrete zone or horizon.



- Earthquakes tend to trigger shallow block failures on steep-sided bedrock ridges.
- These can be modeled easily using Newmark's Method, which is a rigid block analysis that uses either PGA or time histories to simulate the EQ, then back-calculates a yield acceleration, k_y.

Rock detached by earthquake of June 17, 1929, at Murchison, New Zealand.

- In some earthquakes the duration of strong shaking can be of sufficient duration to trigger movement of very large blocks.

Pseudostaic Slope Stability Analysis

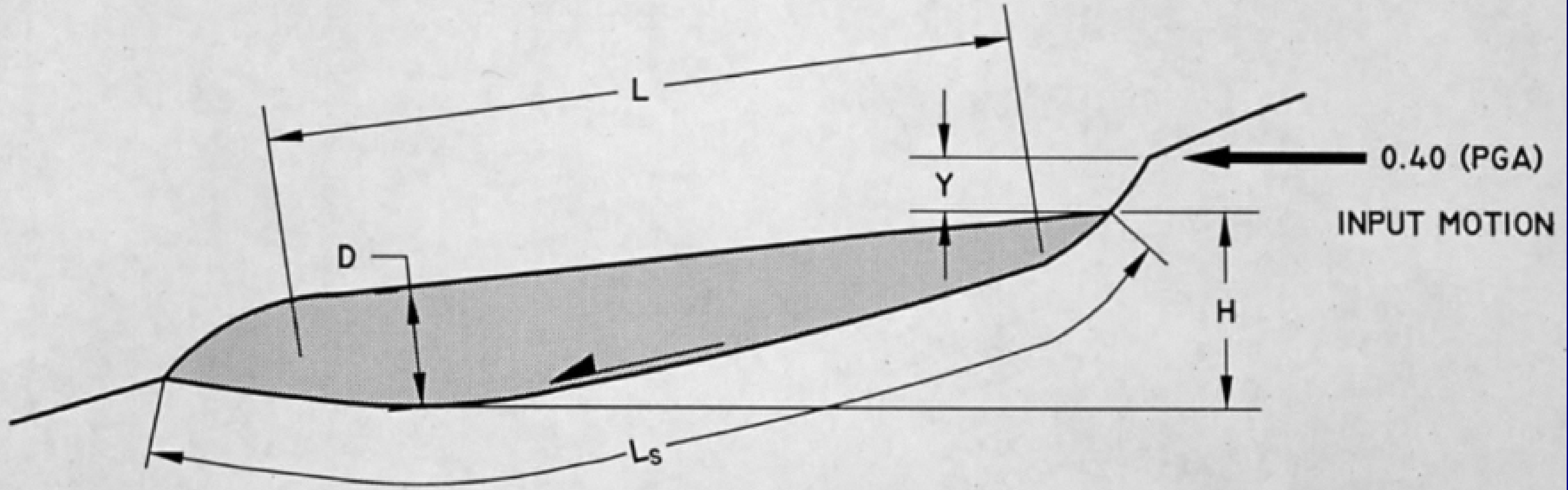
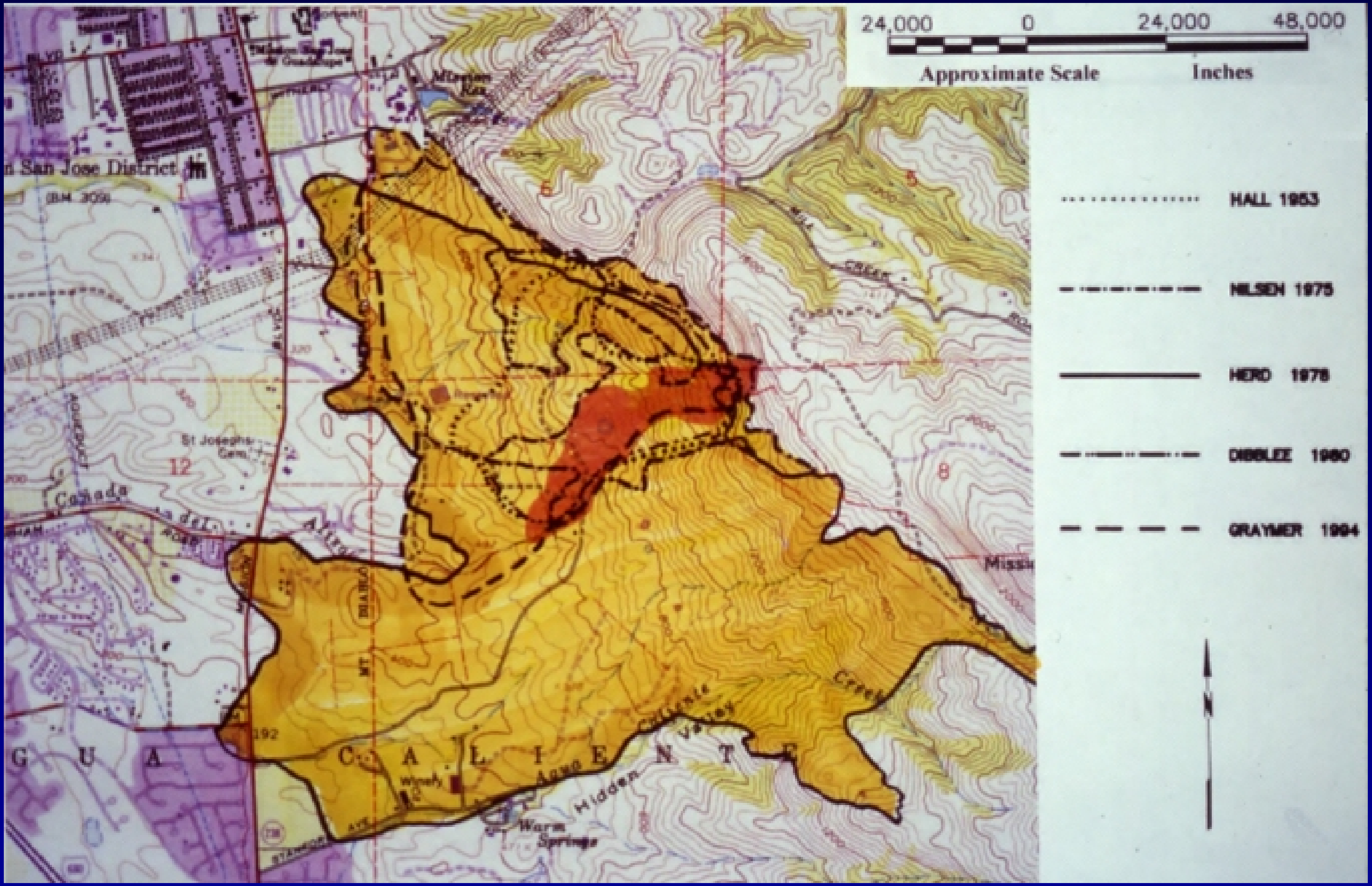


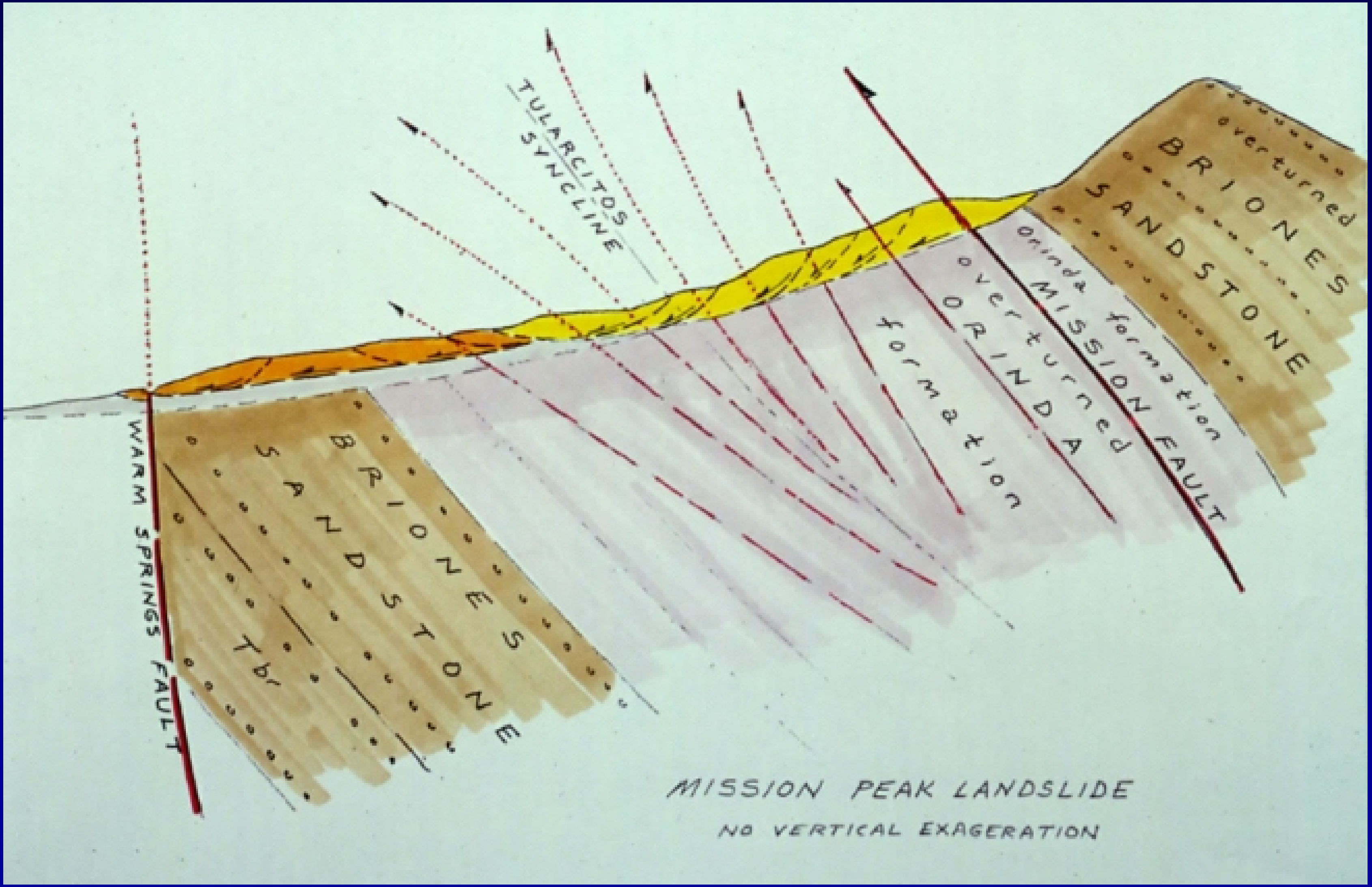
FIG 2 - GEOMETRY OF A DORMENT LANDSLIDE SUBJECT TO SEISMIC LOADING.
L = LENGTH OF SLOPE-PARALLEL PORTION OF SLIDE; L_S = THE LENGTH OF THE LANDSLIDE SLIP SURFACE; D = THE MAXIMUM DEPTH OF SLIDING; H = THE OVERALL HEIGHT OF THE SLIDING MASS; Y = THE SEISMICALLY - INDUCED DISPLACEMENT. THE EQUIVALENT ACCELERATION DESIRED FOR INPUT MOTION IS THAT PERCENTAGE OF THE PGA THAT PREDICTS THE CORRECT DYNAMIC SHEAR STRESS ON THE FAILURE PLANE. A MAXIMUM VALUE OF 40% PGA IS COMMONLY APPLIED TO LARGE DEEP-SEATED LANDSLIDES.

- Mission Peak Landslide in Fremont, CA on Mission fault
- Partially reactivated in March 1998
- 5,450 feet long, dropping 1,310 feet
- 17,000,000 yds^3
- 85.5 acres
- Threatening homes
- How much movement could occur in an earthquake



- The slide was recognized in five different geologic studies between 1958 and 1994. Orange area is March 1998 Mission Peak Landslide.

GEOLOGIC CROSS SECTION

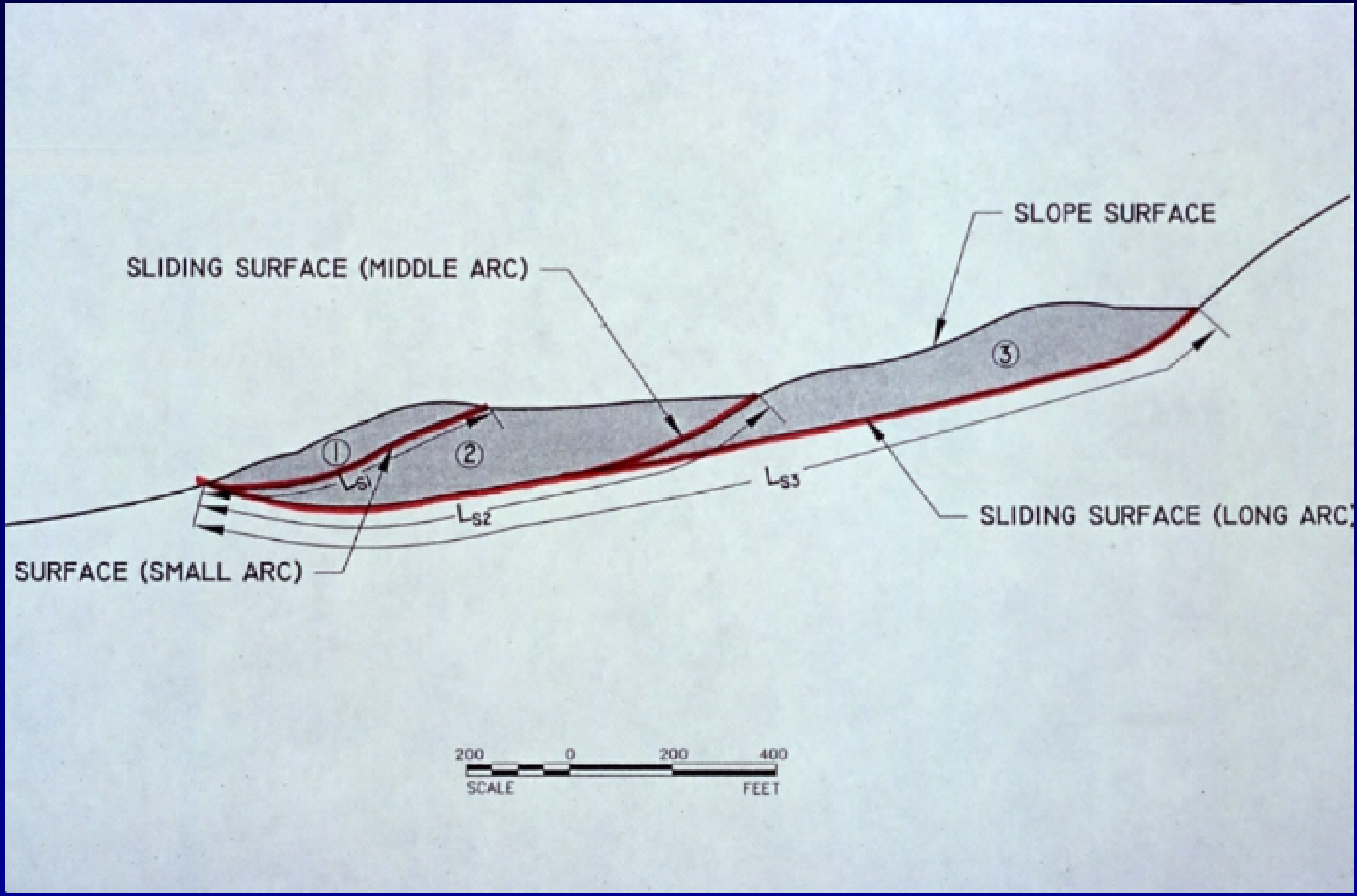


COALESCING EARTHFLOWS

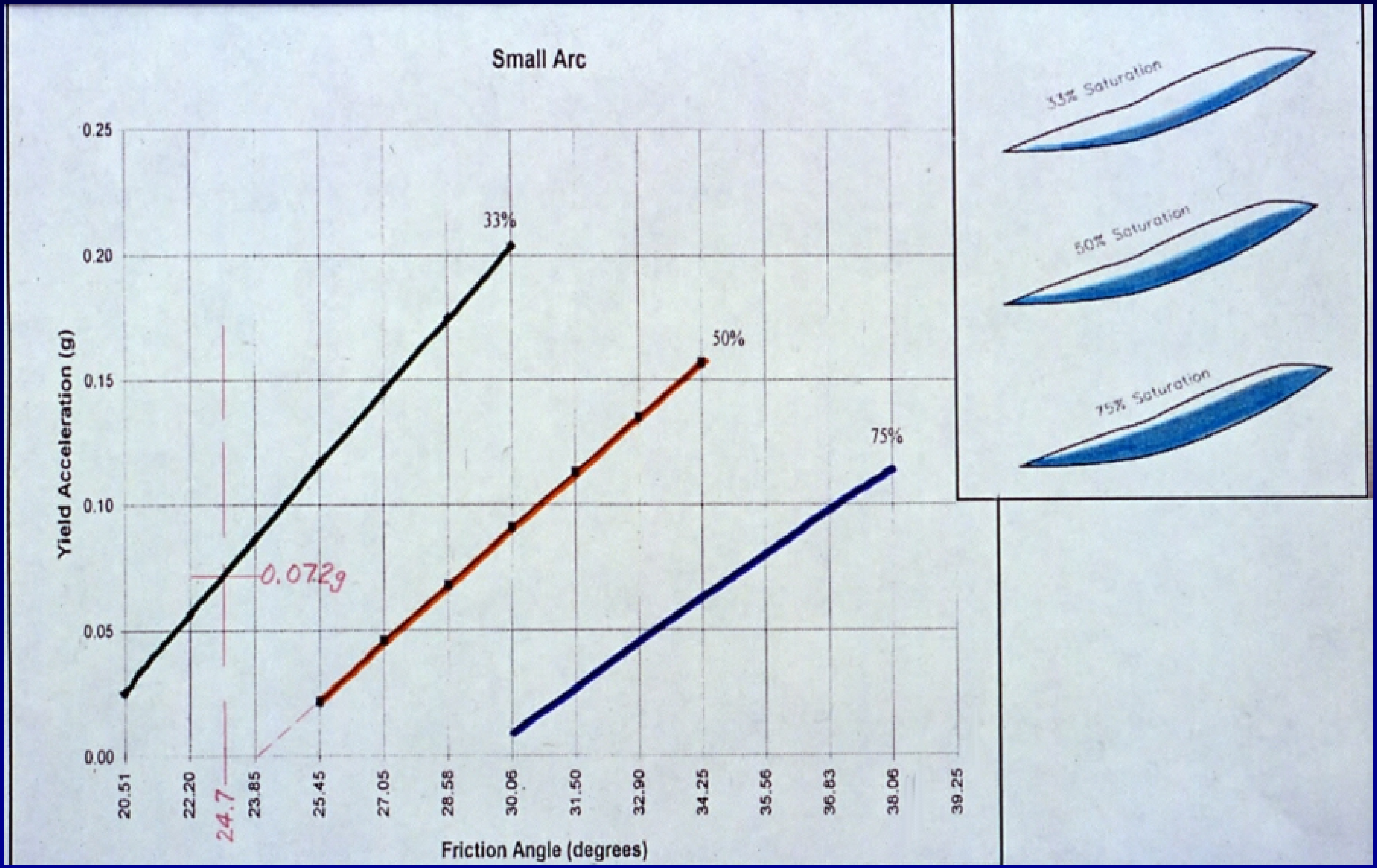
- The Mission Peak Landslide is a series of intercalating earthflows. Individual flow lobes are up to 900 feet long and up to 180 feet deep.
- Very clayey source materials, mostly from the Pliocene-age Orinda formation

MAXIMUM CROSS SECTION

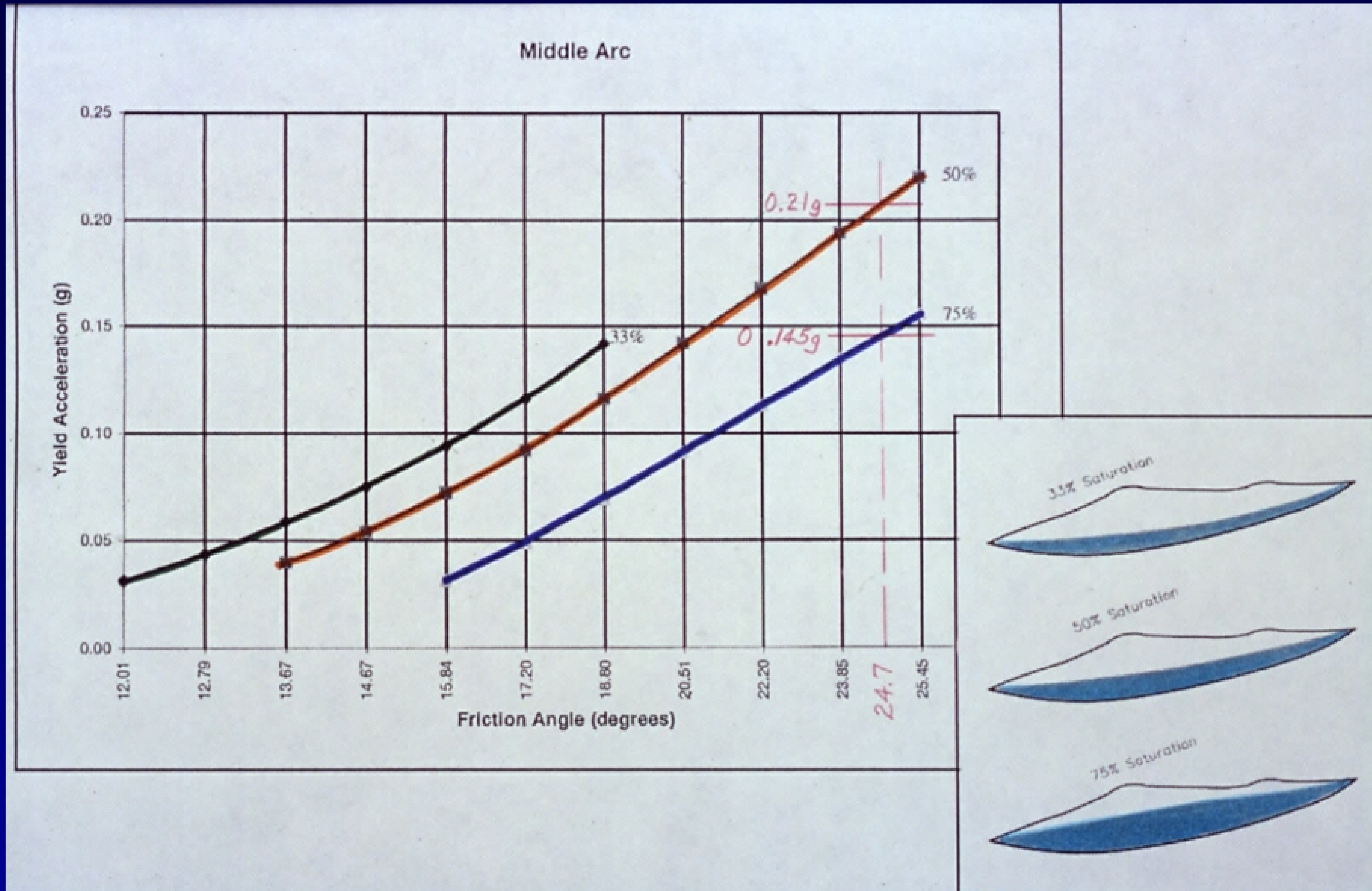
- Cross section through the Mission Peak Landslide, taken from headscarp to distal toe. Portion that moved most (300 ft) was in the middle slope.



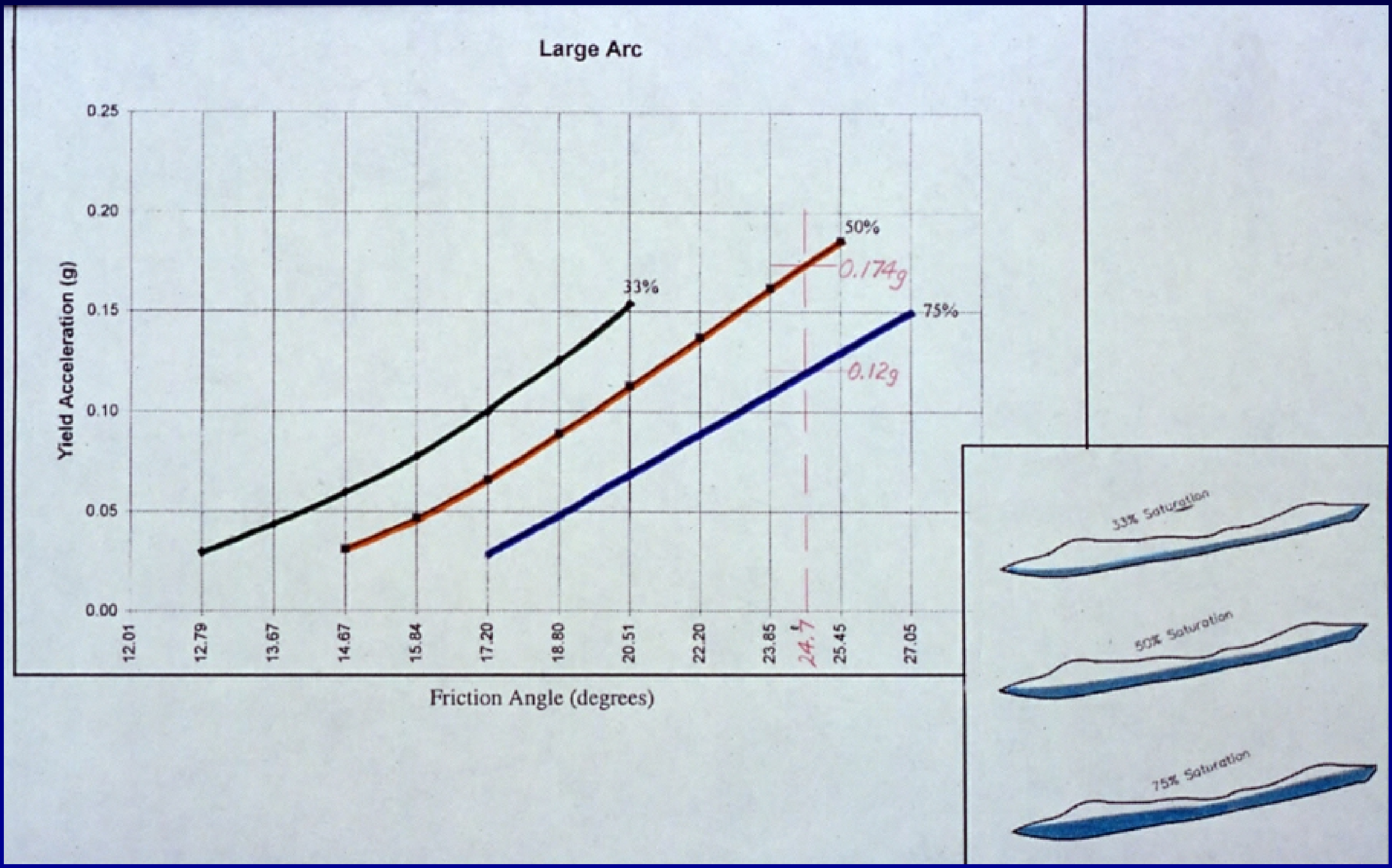
- Any dynamic analysis should evaluate small, medium and large portions of the dynamic system being modeled. L_1 = 550’; L_2 = 1100’; L_3 = 2000’



- A series of rigid block analyses allows yield accelerations to be determined for a range of water contents within the smallest earthflow. For friction angle 24.7°, k_y = 0.072g

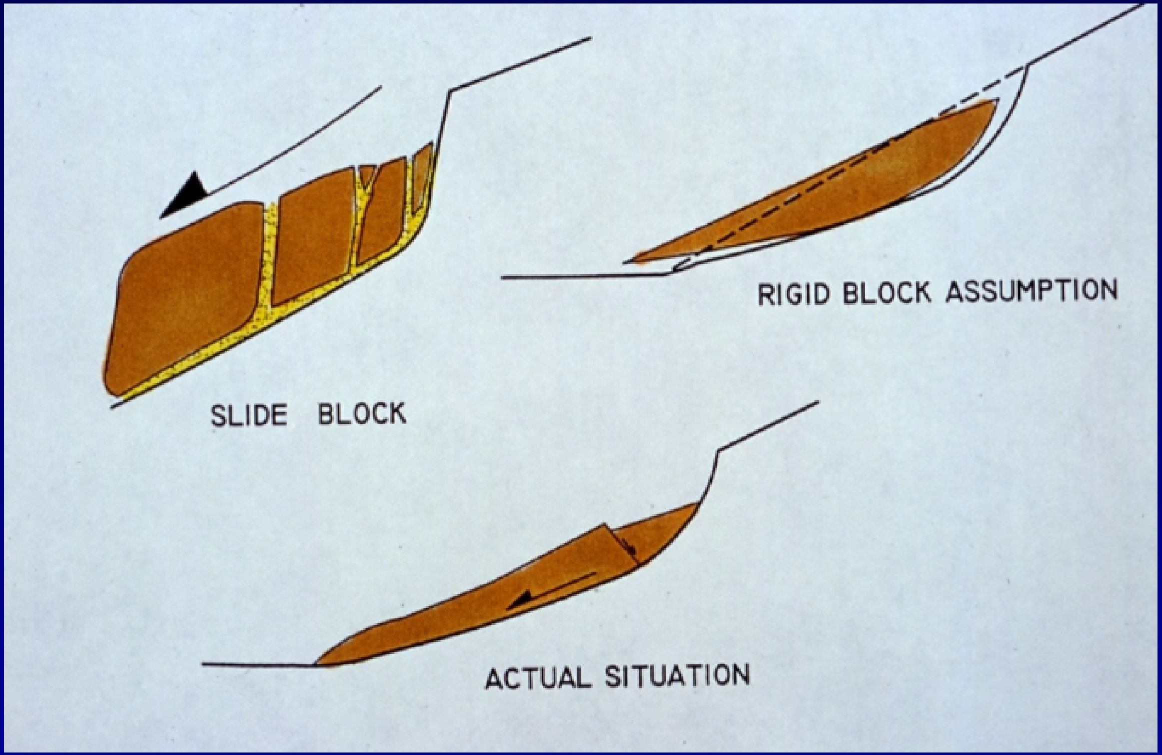


- Rigid block analyses for the medium sized earthflow, having a base length of 1100 feet. The yield acceleration for phi of 24.7^o was k_y = 0.210g



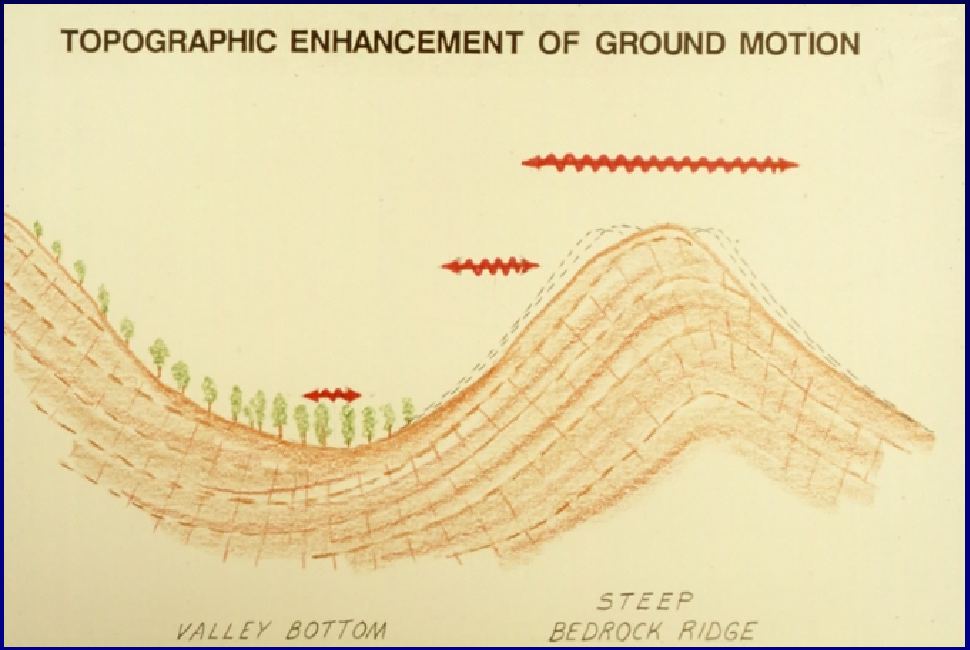
- Rigid block analyses for the largest earthflow lobe, having a base length of 2000 feet. The yield acceleration for phi of 24.7° was k_y = 0.174g

Appropriateness of Pseudostatic Methods



- Rigid block assumptions should not be used to model EQ-induced movements of large dormant landslide complexes

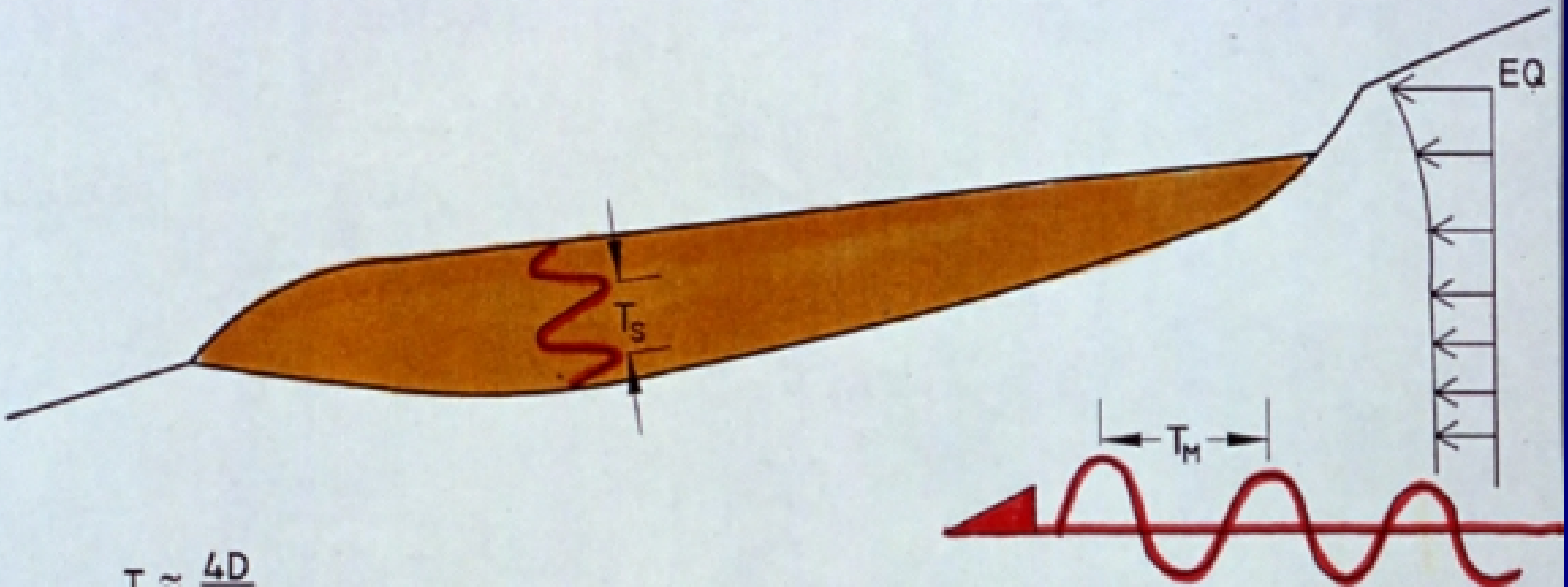
TOPOGRAPHIC ENHANCEMENT



- Steep-sided bedrock ridges tend to amplify ground motions, causing greater structural damage and triggering shallow block slides.

- Earthquake-induced landslides triggered by the January 1994 Northridge Earthquake
- These surficial slides can be analyzed using the Newmark sliding block method
- Note the preferential orientation of the sliding

FUNDAMENTAL PERIOD OF THE SLIDE MASS, T_S

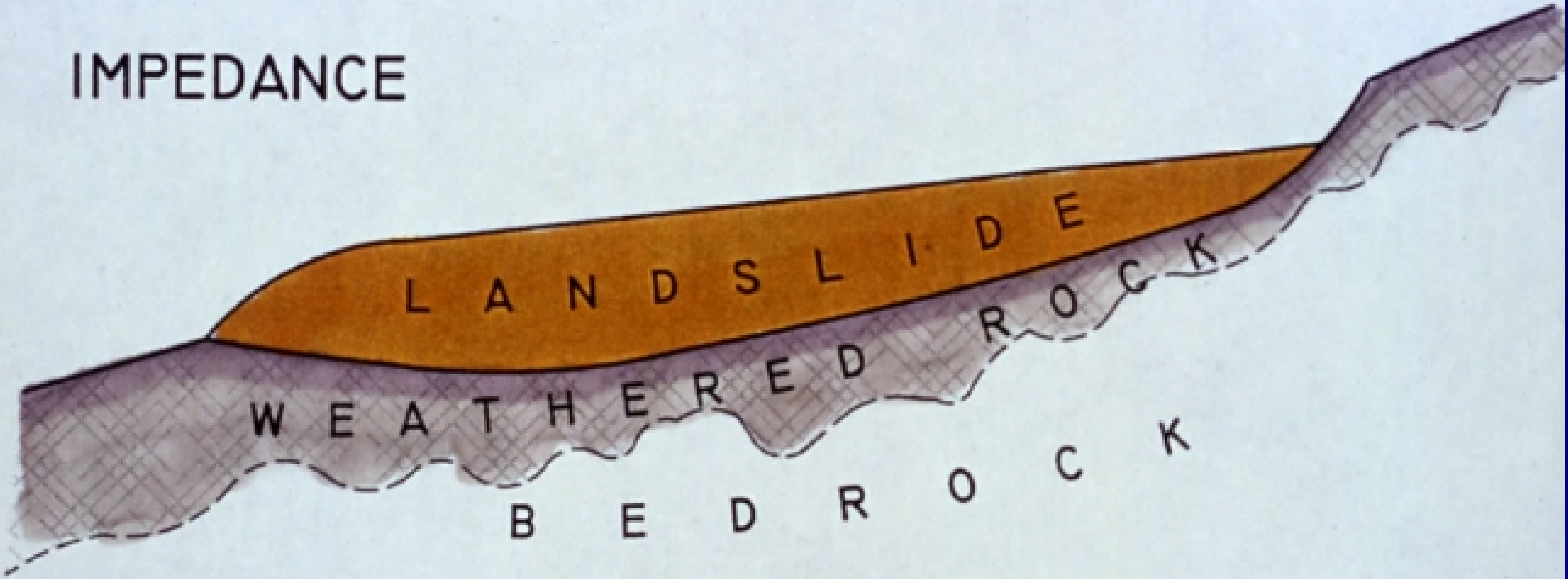


$$T_S \approx \frac{4D}{V_S}$$

T_M = INPUT FOUNDATION MOTION

FIG 5 - ANY DYNAMIC ANALYSIS BEGINS BY CONSIDERING THE FUNDAMENTAL PERIOD OF THE SLIDE MASS AND THE PREDOMINANT PERIOD OF THE INPUT GROUND MOTION. IF INPUT MOTION IS NEAR RESONANCE, MASSIVE GROUND AMPLIFICATION WOULD RESULT. D = DEPTH OF THE SLIDE MASS.

IMPEDANCE



IMPEDANCE RATIO

$$IR = \frac{\rho_{FOUNDATION} \, (V_S)_{BEDROCK}}{\rho_{LANDSLIDE} \, (V_S)_{LANDSLIDE}}$$

FIG 6 - IF THICK SEQUENCES OF SOFT MATERIAL OVERLIE STIFF MATERIAL, SOME DYNAMIC AMPLIFICATION OF THE EARTHQUAKE ENERGY CAN BE EXPECTED IN THE SOFT MATERIAL.

VERTICAL INCOHERENCE

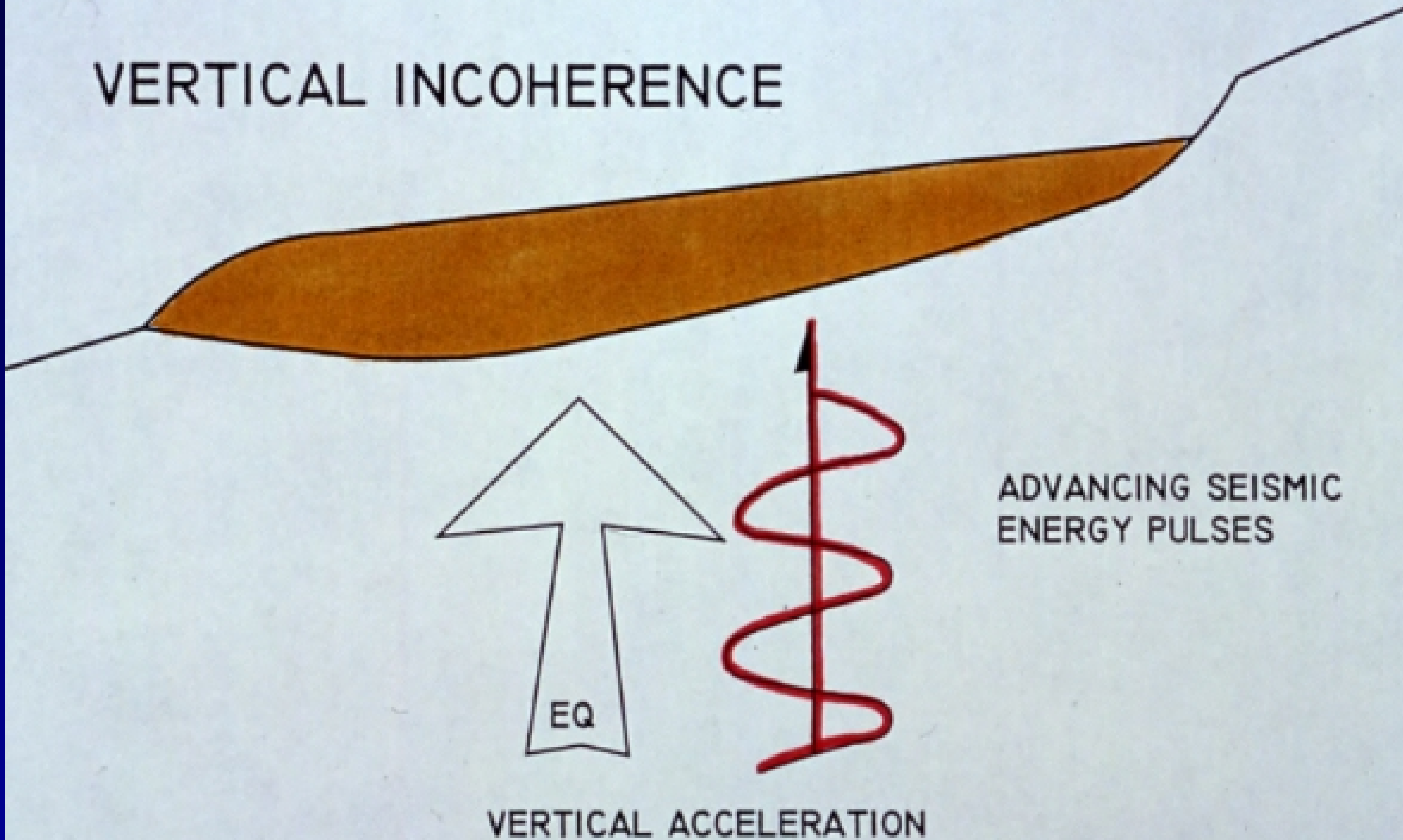


FIG 3 - VERTICAL INCOHERENCE DESCRIBES THE (UPWARD) COMPONENT OF SEISMIC ENERGY AS IT TRAVELS THROUGH THE SLIDE MASS, ALTERNATIVELY COMPRESSING AND STRETCHING THE SOIL/ROCK IN A VERTICAL PLANE.

LATERAL INCOHERENCE

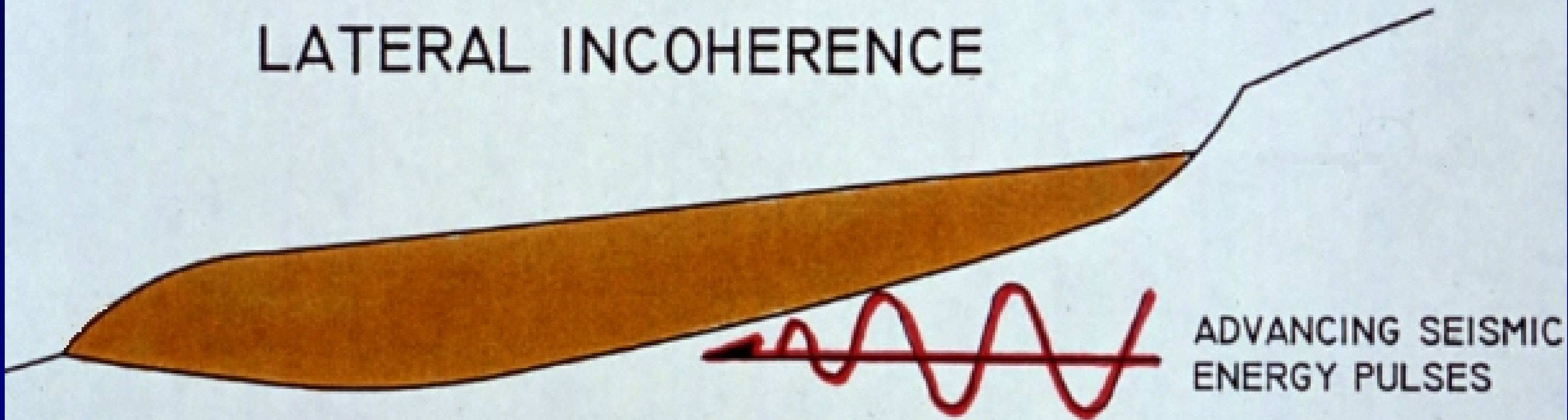
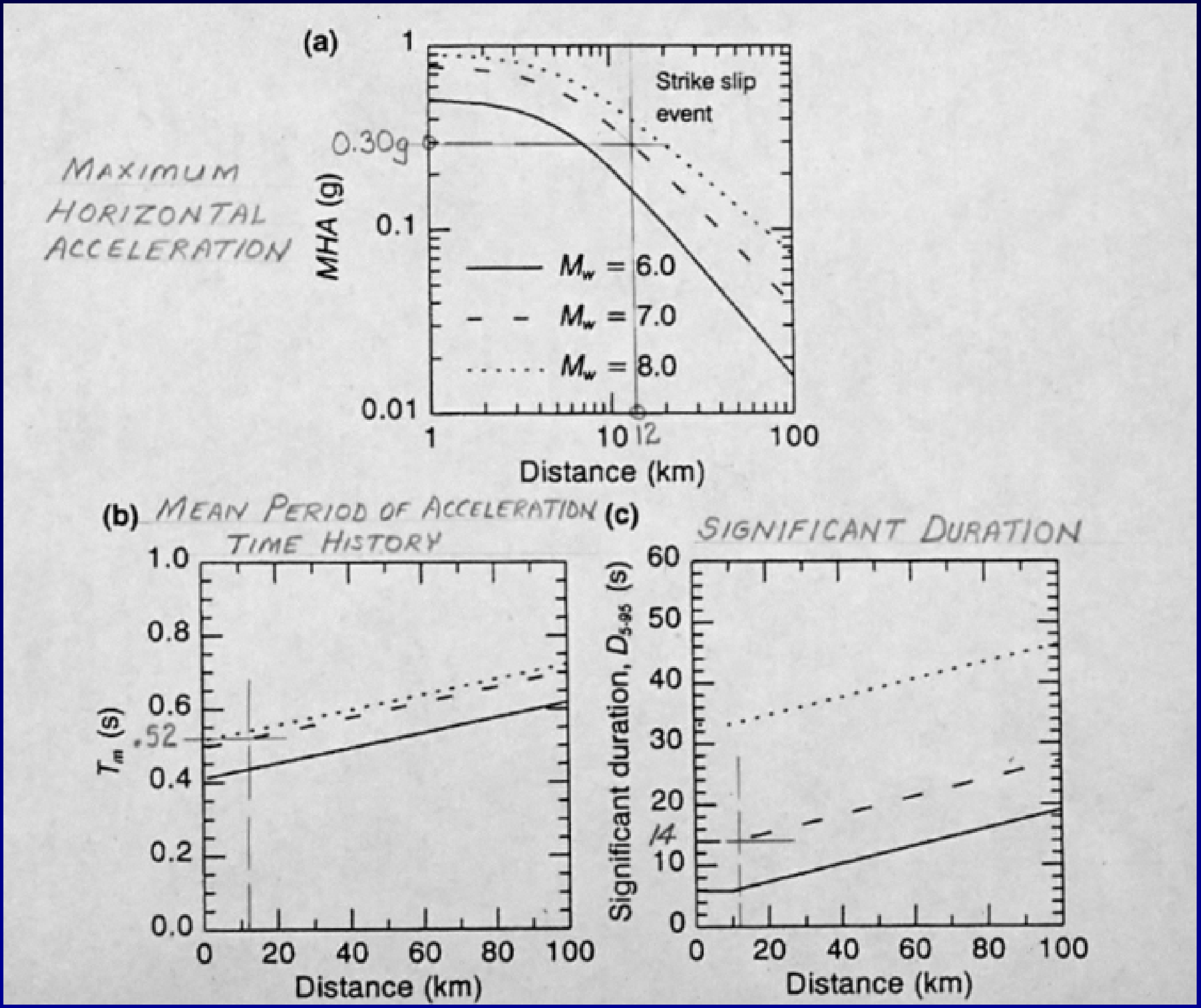
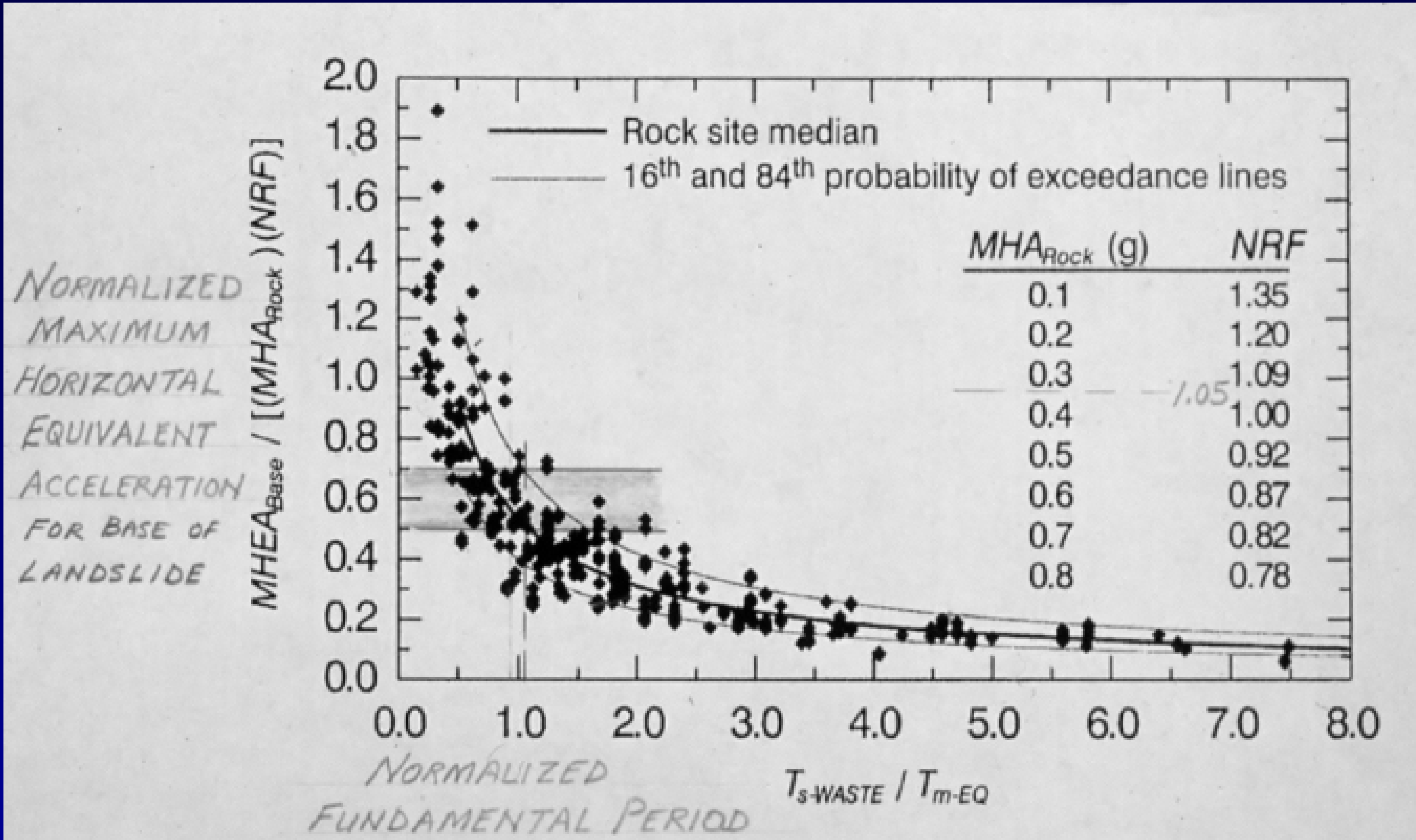


FIG 4 - AS SEISMIC ENERGY PULSES THROUGH THE SLIDE, IT ALTERNATIVELY STRETCHES AND COMPRESSES THE GROUND MASS. IF THE SLIP SURFACE IS LONG, THE MAXIMUM SEISMIC FORCE CANNOT BE EXERTED ALONG THE ENTIRE BOUNDARY AT ANY GIVEN INSTANT. AN EQUIVALENT ACCELERATION MUST BE USED TO DESCRIBE THE OVERALL IMPACT OF SEISMIC LOADING.



- We can perform a screening analysis of the dynamic system by evaluating fundamental dynamic parameters and comparing these with existing data from earthquakes



- We need to know the Maximum Horizontal Equivalent Acceleration at the base of the landslide, known as the $MHEA_{base}$

The procedure can then be manipulated to estimate the *maximum horizontal equivalent acceleration at the base of the slide* ($MHEA_{Base}$), as:

MHA ↓ Non Linear Response Factor ↓

$$MHEA_{Base} = 0.33g \times 1.05 \times [0.5 \text{ to } 0.7]$$ ← RANGE of Normalized MHEA

$$= 0.17g \text{ to } 0.24\, g \text{ (a range)}$$

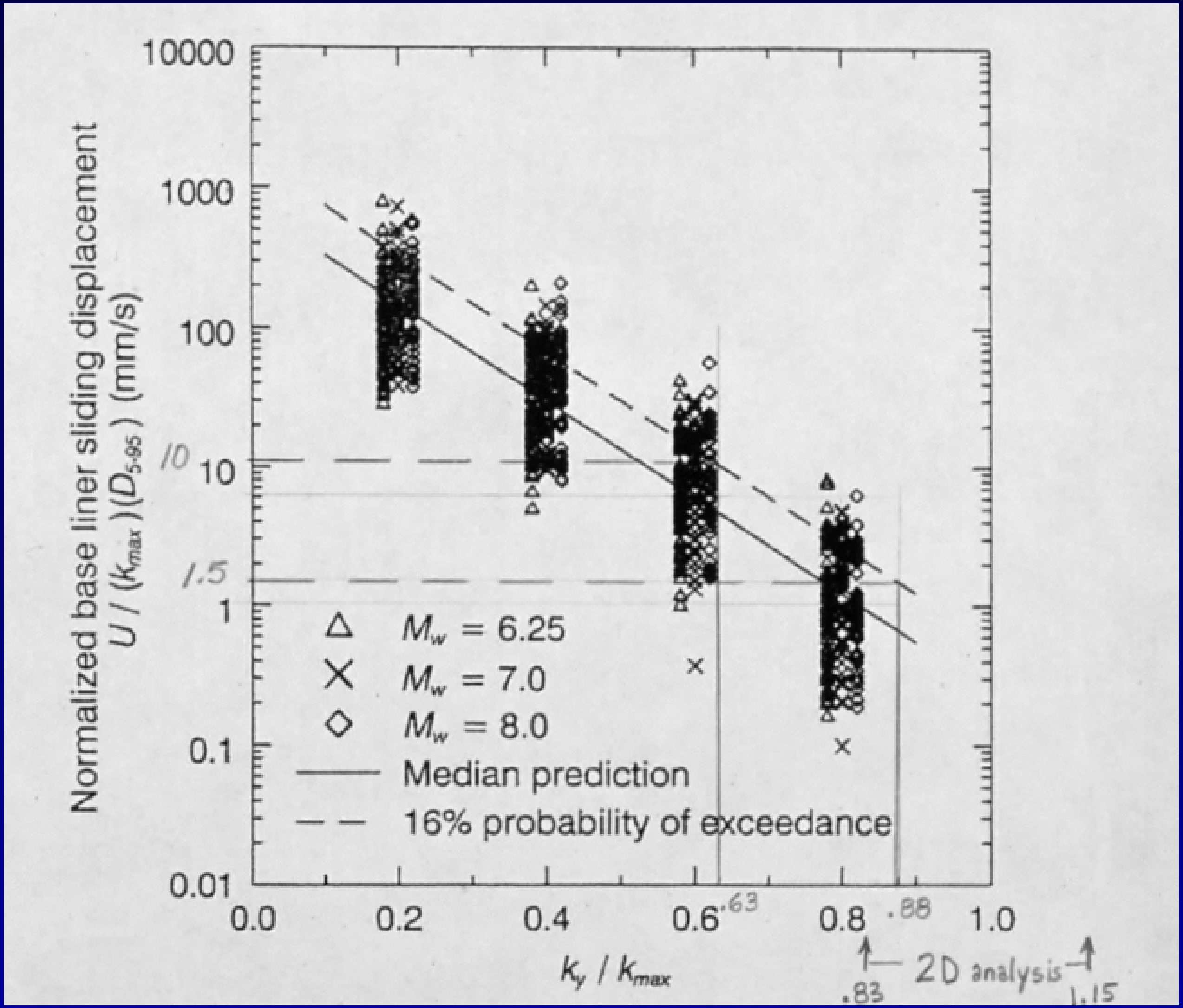
and the *maximum seismic acceleration coefficient* (k_{max})

$$k_{max} = MHEA/g = 0.17 \text{ to } 0.24$$

Given that the *dimensionless yield acceleration*, $k_y = 0.15g$,

The ratio $k_y/k_{max} = 0.88 \text{ to } 0.63 < 1$

- The range of k_y /k_{max} allows us to the normalized base sliding displacement for a large range of earthquake motions



- For the Mission Peak earthflows, the range of normalized base sliding displacement was between 1.5 and 10.

The ratio k_y/k_{max} = 0.88 to 0.63 < 1

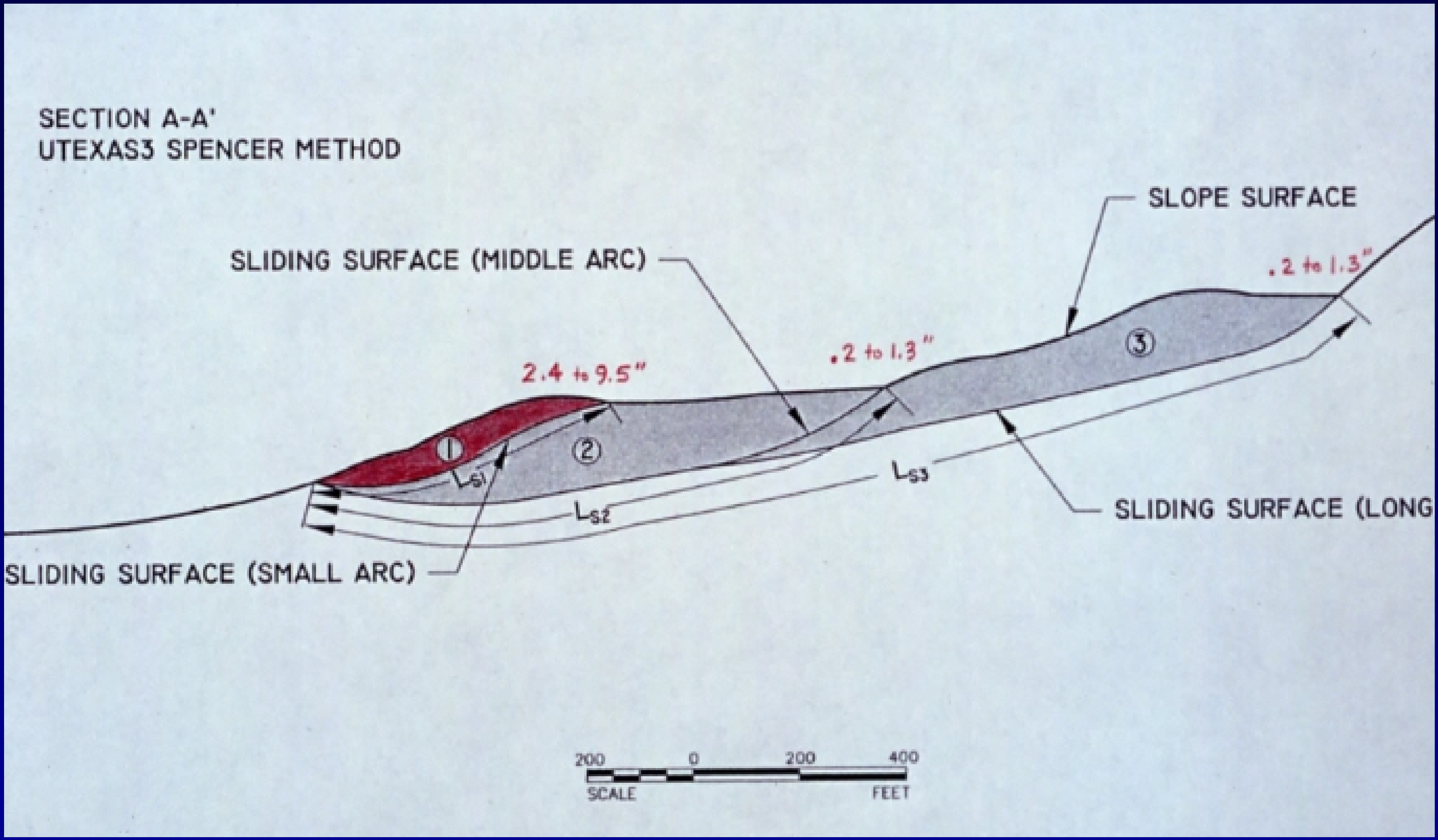
From Fig. 11 in Bray, et al (1988), the normalized base liner sliding displacement $[U/(k_{max})(D_{5\text{-}95})(mm/s)]$ from the ratio k_y/k_{max} These seismic coefficients were calibrated for seismically-induced displacements generally less than 150 mm for basal slip surfaces and <300 mm for surface displacement.

This reduces to a normalized base (liner) sliding displacement between 1.5 and 10 mm/s, considering 50% of the 16^{th} probability of exceedance.

The *permanent ground deformation*, U, was then estimated by:

$$U = (1.5 \text{ to } 10)\ (0.17 \text{ to } 0.24)\ (14\ s) = \underline{3.6 \text{ to } 33.6\ mm}$$

- For this case, the expected range of permanent ground deformation is between 3.6 and 33.6 mm



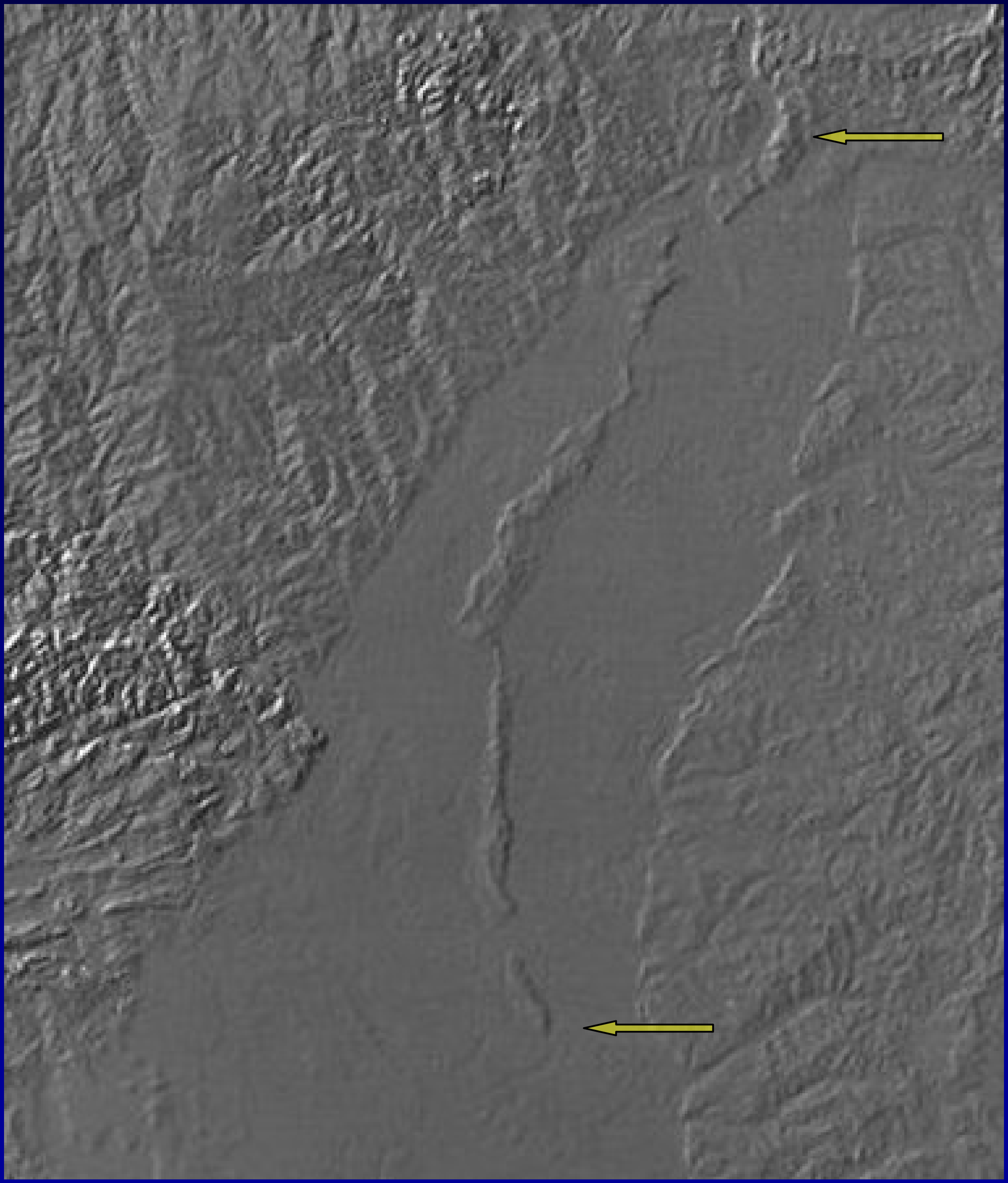
- Permanent ground deformations increase with decreasing size of the earthflow, because of lateral incoherence.

Little Previous Work Evaluating Landslides in the Western NMSZ

- Eastern NMSZ
  - – Jibson (1985); Jibson and Keefer (1988,1994)
- Western NMSZ
  - – Ding (1991)
    - Mapped at 1:124,000 scale (~1inch to 2 miles)
  - – McFarland (1992)
    - Arkansas Geological Commission
- **Previous studies have not identified lateral spreads in the NMSZ**

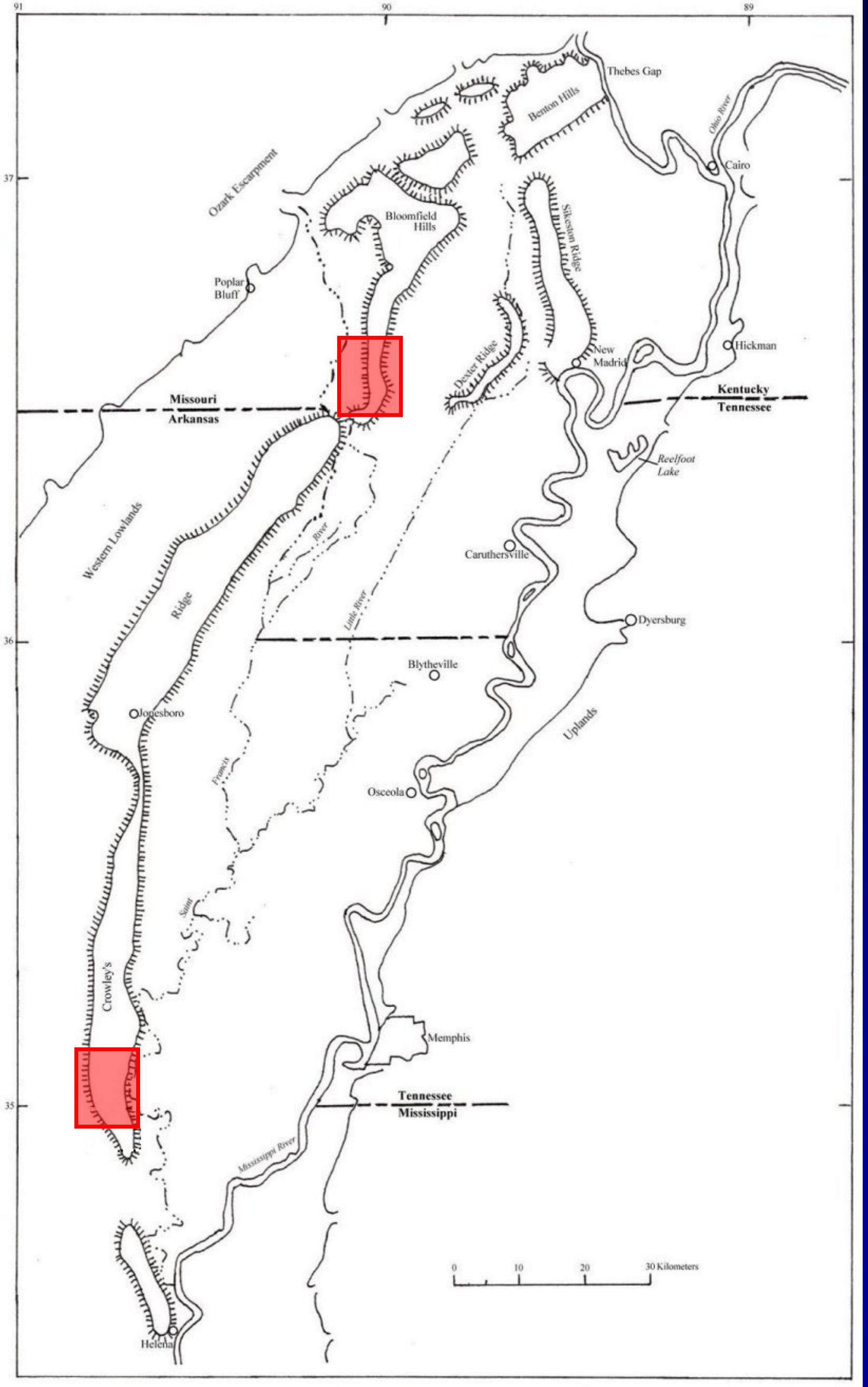
Crowley's Ridge

- Elevated upland within the Mississippi River Embayment, along the NMSZ
- Over 380 km long
- 32 km wide at widest point
- Up to 90 m of relief

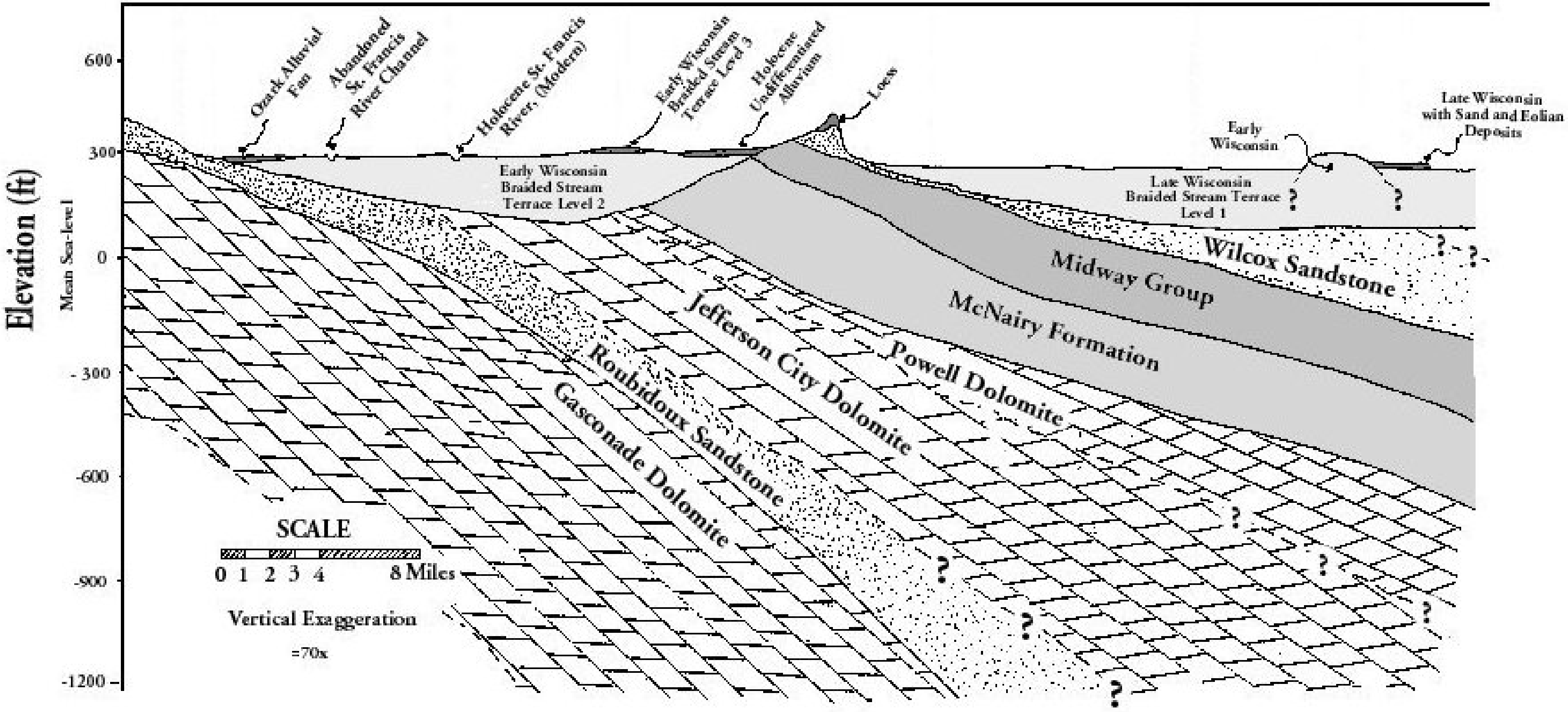


Crowley's Ridge

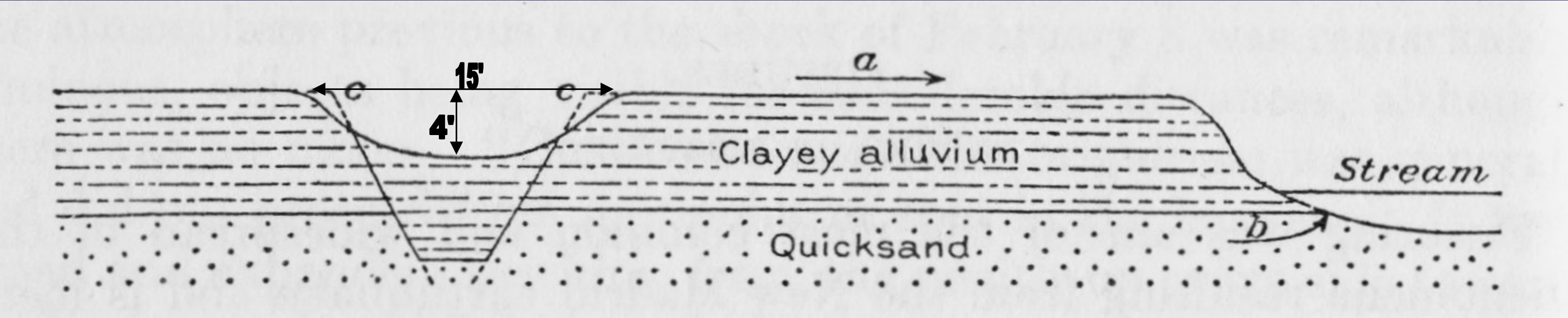
- Likely formed by:
  - erosive processes
  - tectonic processes
    - related to the NMSZ
- 52 quadrangles cover the ridge
- Landslide mapping demonstration quadrangles
  - LaGrange, AR
  - Valley Ridge, MO



Geology Northern Crowley's Ridge



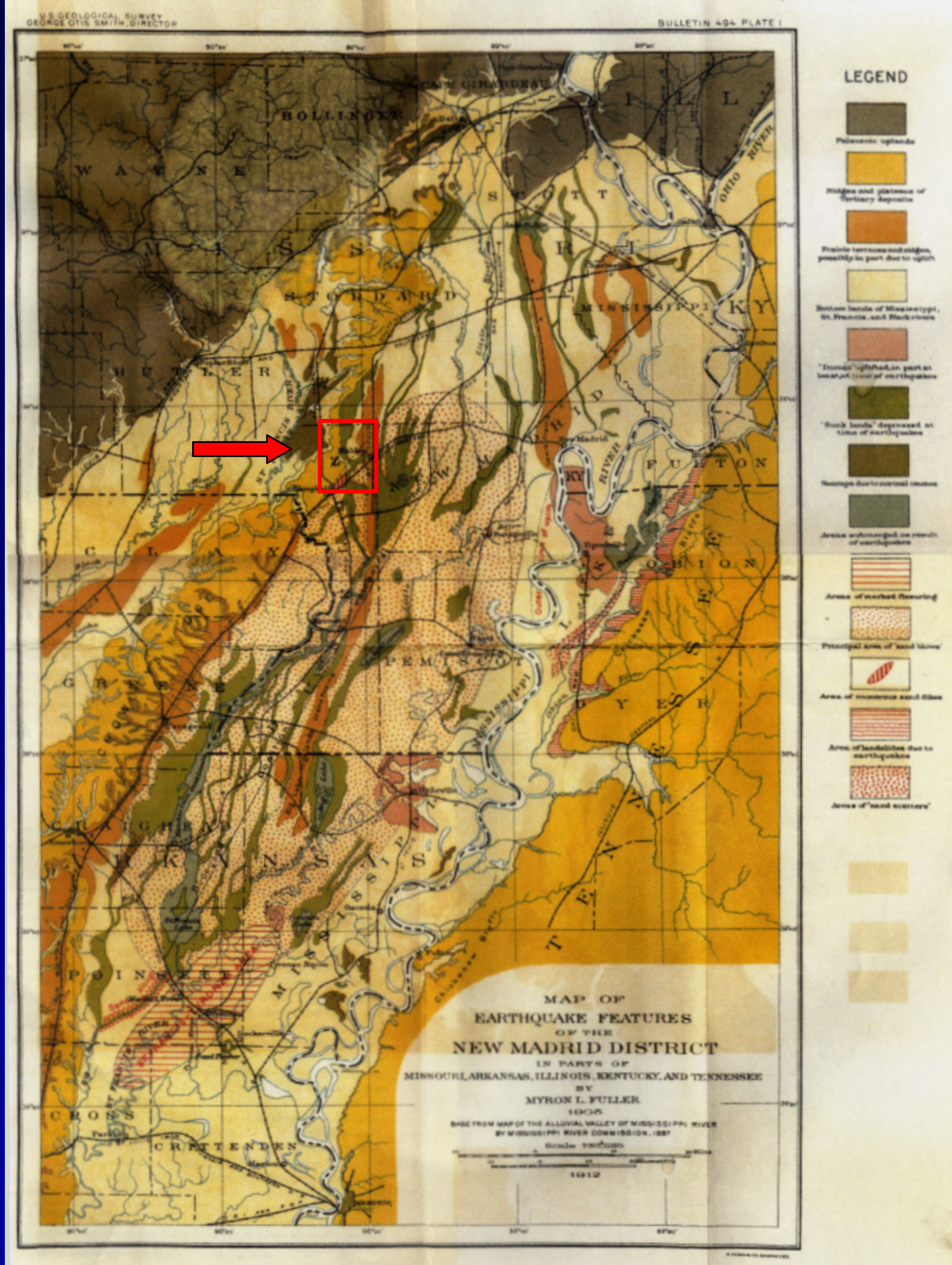
Liquefaction of Discrete Horizons Causes Lateral Spreads



- In 1912 Myron Fuller wrote: "The depth of the openings was not usually very great, probably being in most cases limited to the hard clayey zone extending from the surface down to the **quicksand which usually underlies the surface soil at depths of from 10 to 20 feet**. Few openings probably extended much below the water level, which is apparently nowhere much over 25 feet from the surface."

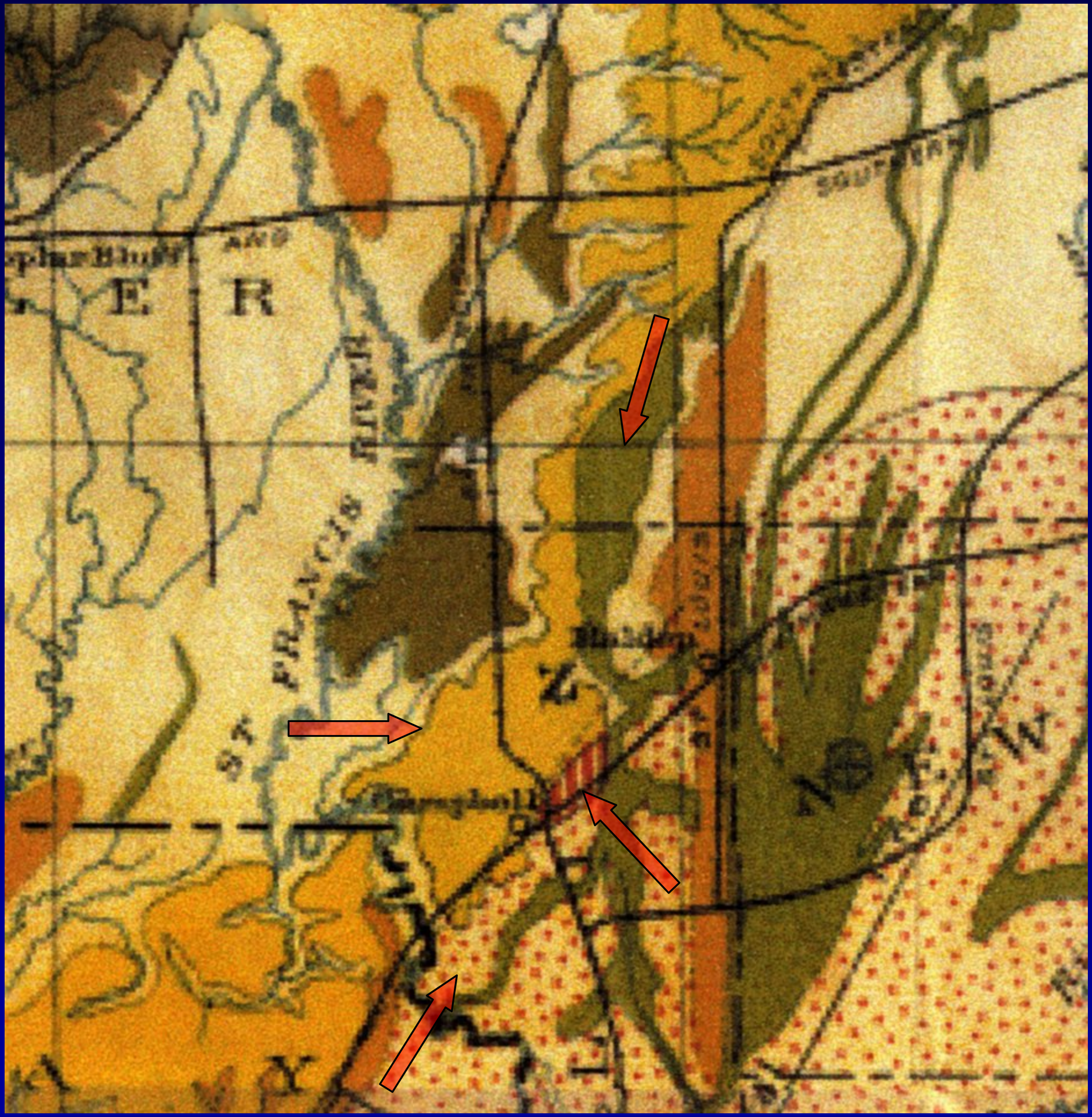
Geomorphic Features Associated with the 1811-1812 New Madrid Earthquakes

- Mapped by Myron Fuller in 1905
- Published by the USGS for the 100th anniversary in 1912

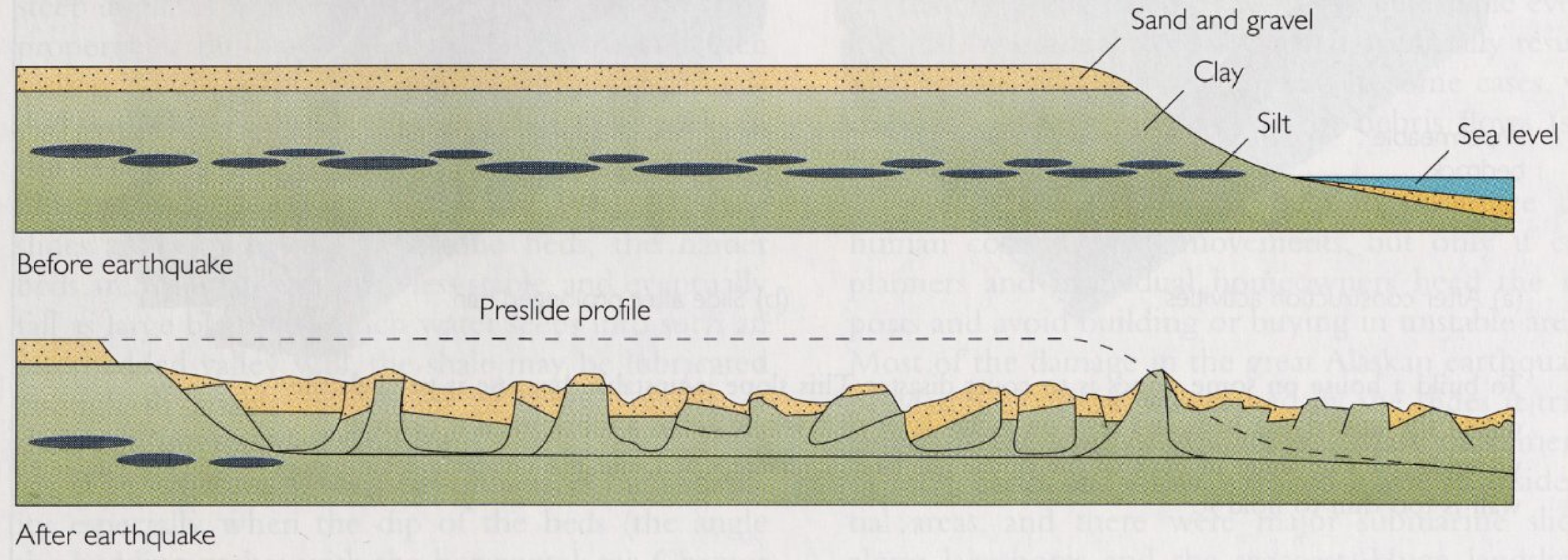


Geomorphic Features of 1811-12 Earthquakes around Valley Ridge quadrangle

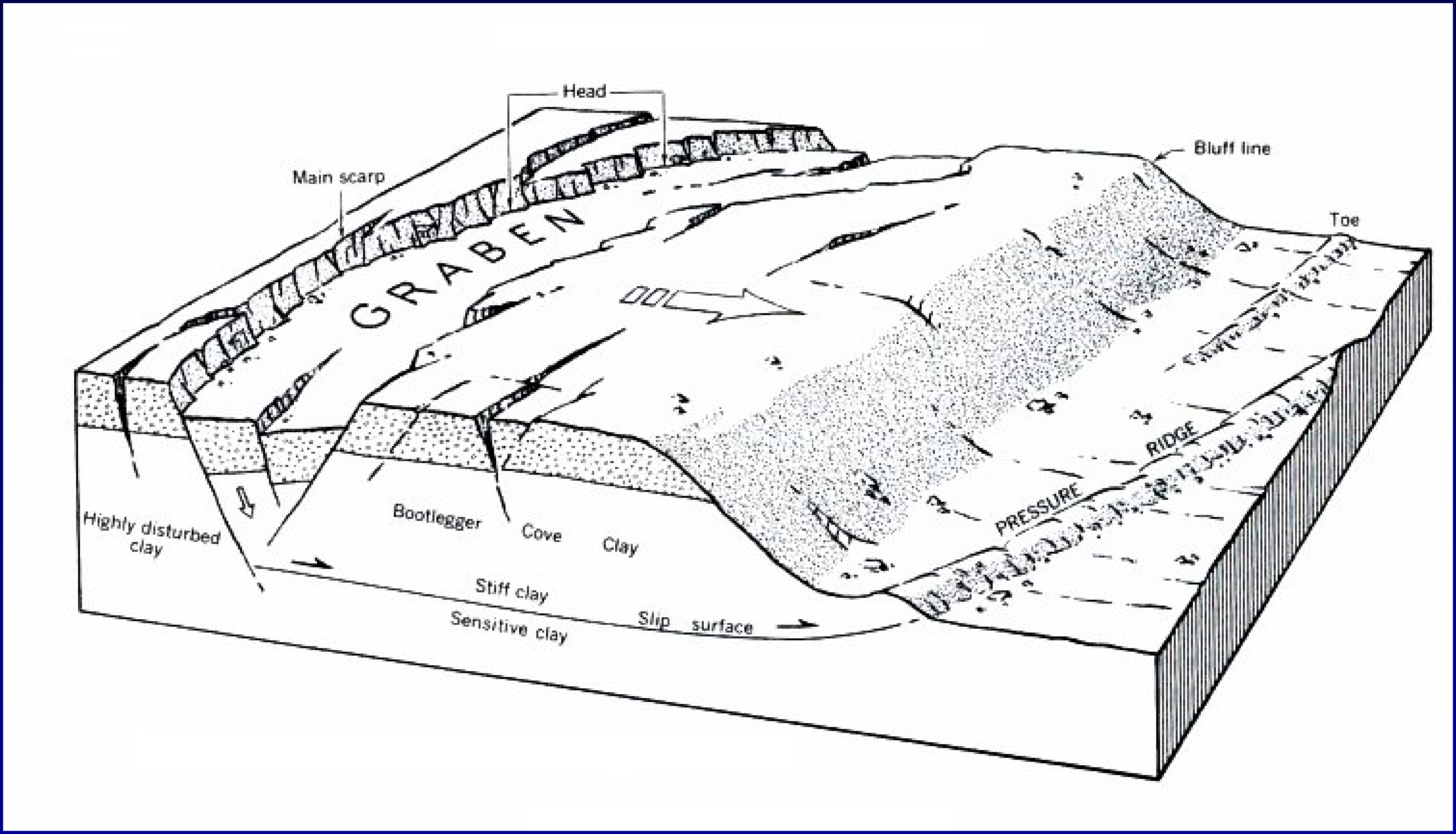
- Elevated terraces
  - Sand blows
  - “Sunk lands”
  - Areas of numerous sand dikes



Lateral Spreading Initially Analyzed after the 1964 Alaska Earthquake



- Stan Wilson and Harry Seed studied the Turnagain Heights Landslide in considerable detail and discovered that discontinuous seams of silt were responsible for the liquefaction that allowed large parcels of ground to be rafted

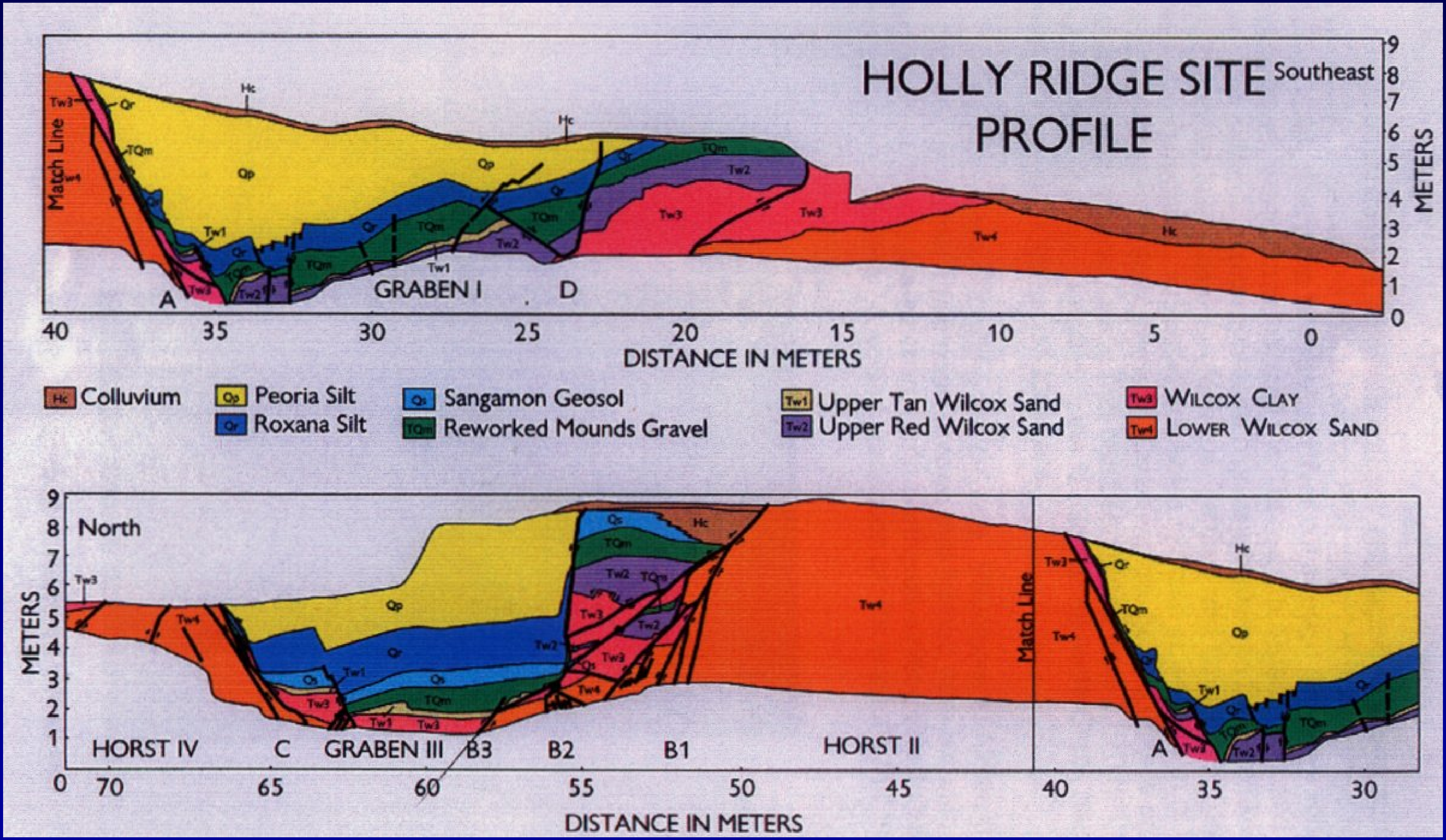


Block diagram of lateral spread which evolved from post-1964 earthquake evaluations in Alaska by Walt Hansen in USGS Professional Paper 542-A (1966)

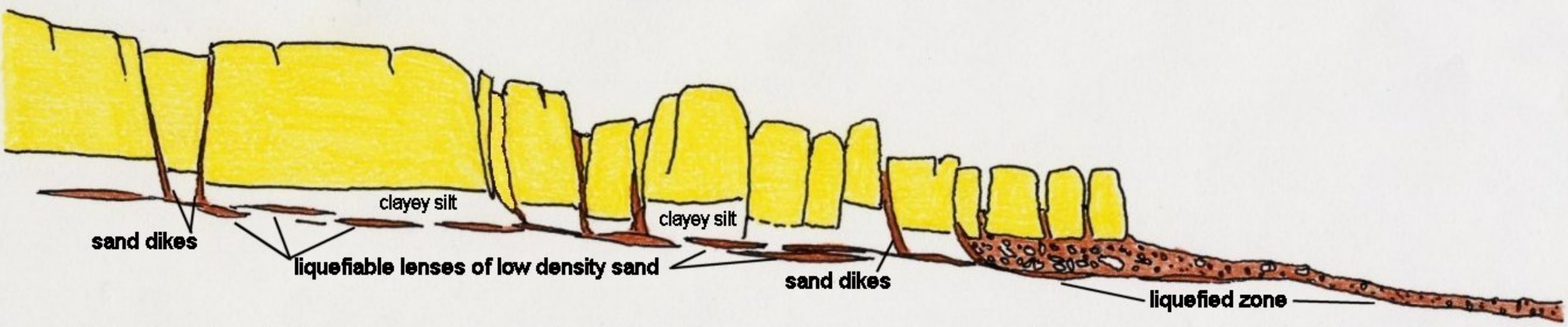
Potential for Lateral Spreads in the NMSZ

- Confined horizons of saturated sands, silty sand and non-cohesive silt, adjacent to channels or other natural depressions:
  - Margins of Crowley’s Ridge where river channels come within 3/8 mile
  - Adjacent to sweeping turns of the major river channels
  - Levees and banks of drainage ditches

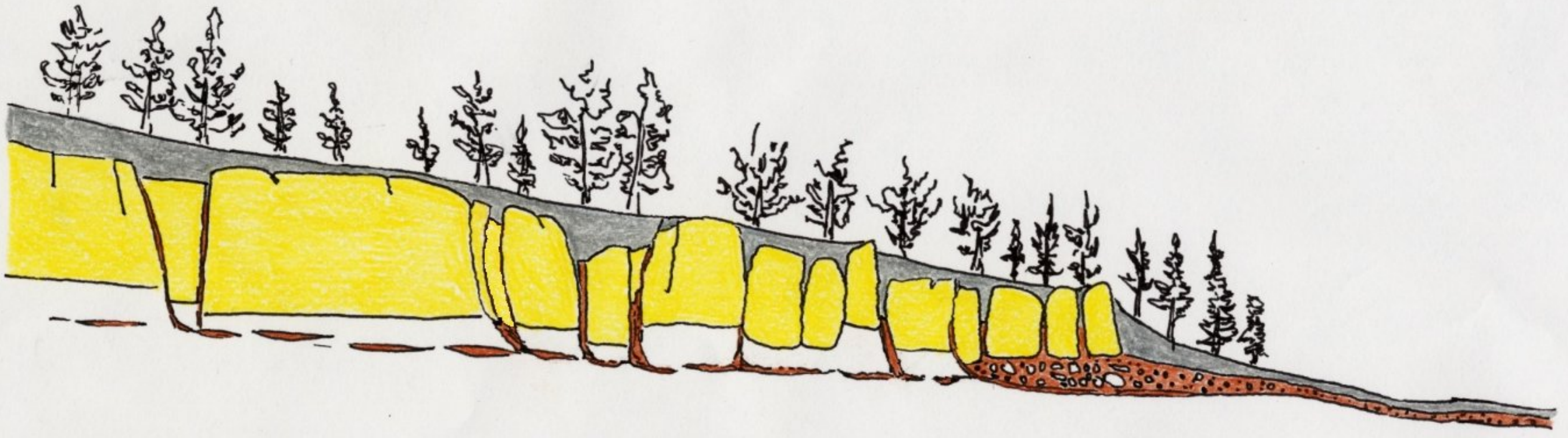
Faulting Recently Observed at Holly Ridge



Lateral Spreads Can Cause Horst and Graben Structures to Form in Their Headscarps

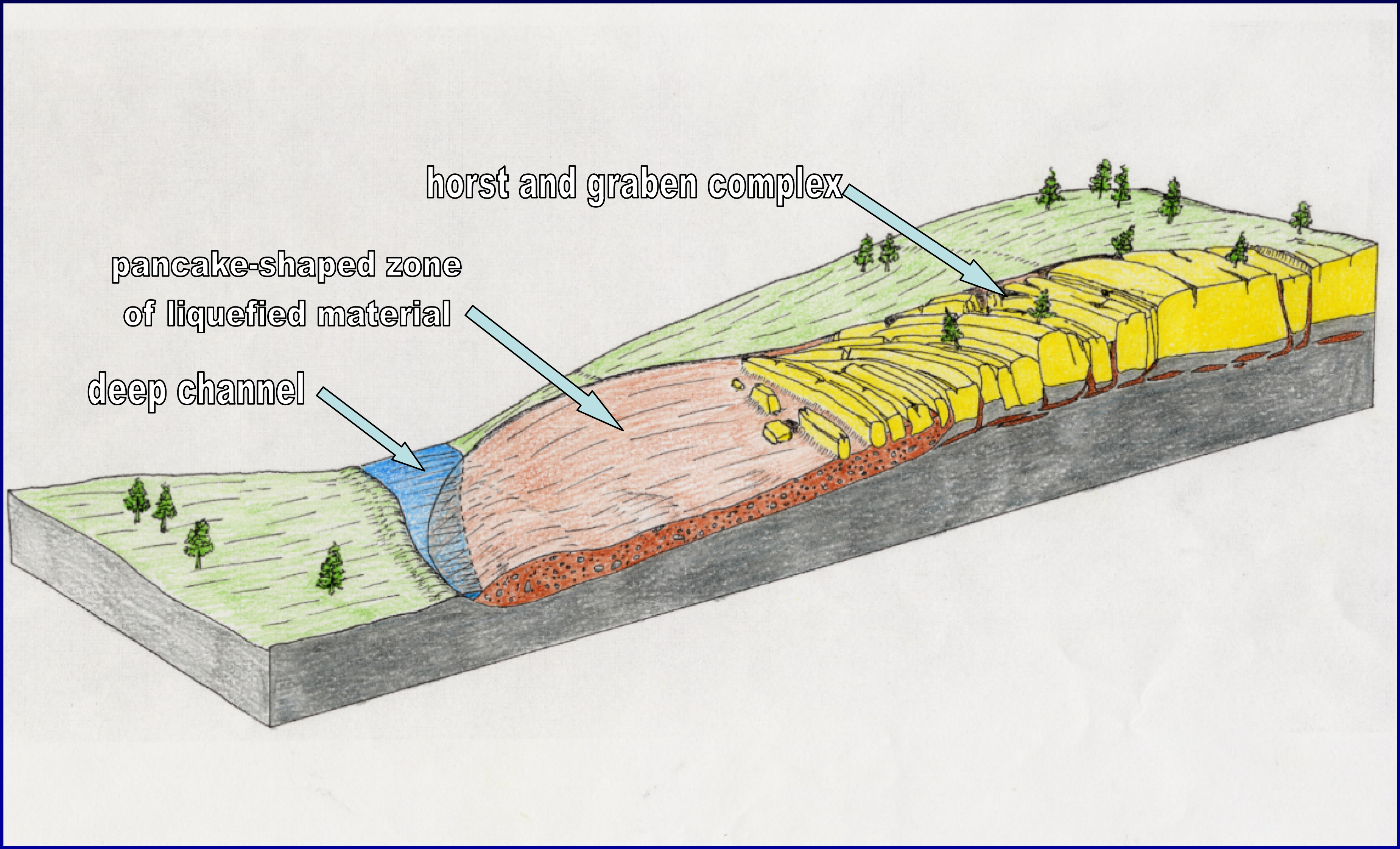


Retrogressive Graben Complex formed by partial liquefaction at shallow depth above a lateral spread



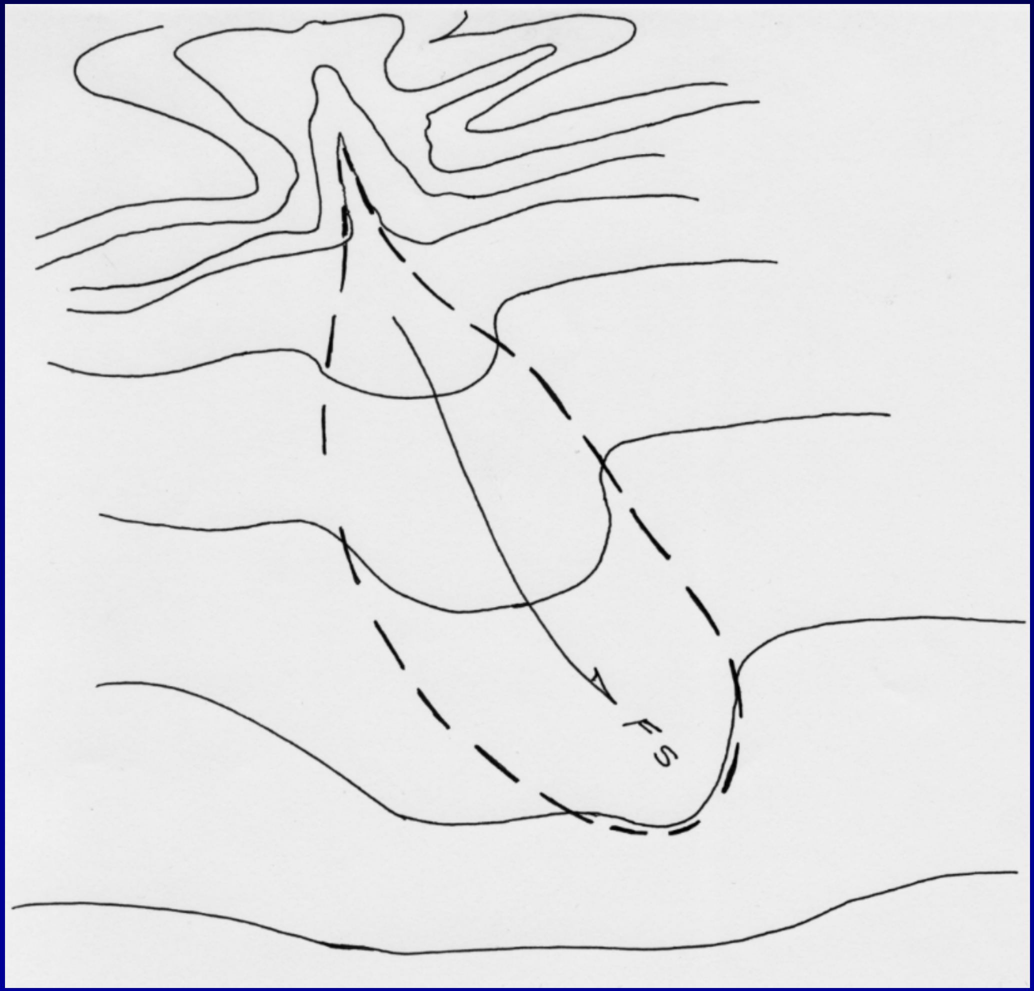
Same graben complex after deposition of Peoria Loess and establishment of vegetation

Classic Features of a Lateral Spread



Topographic Algorithms to Identify Anomalous Geomorphic Features

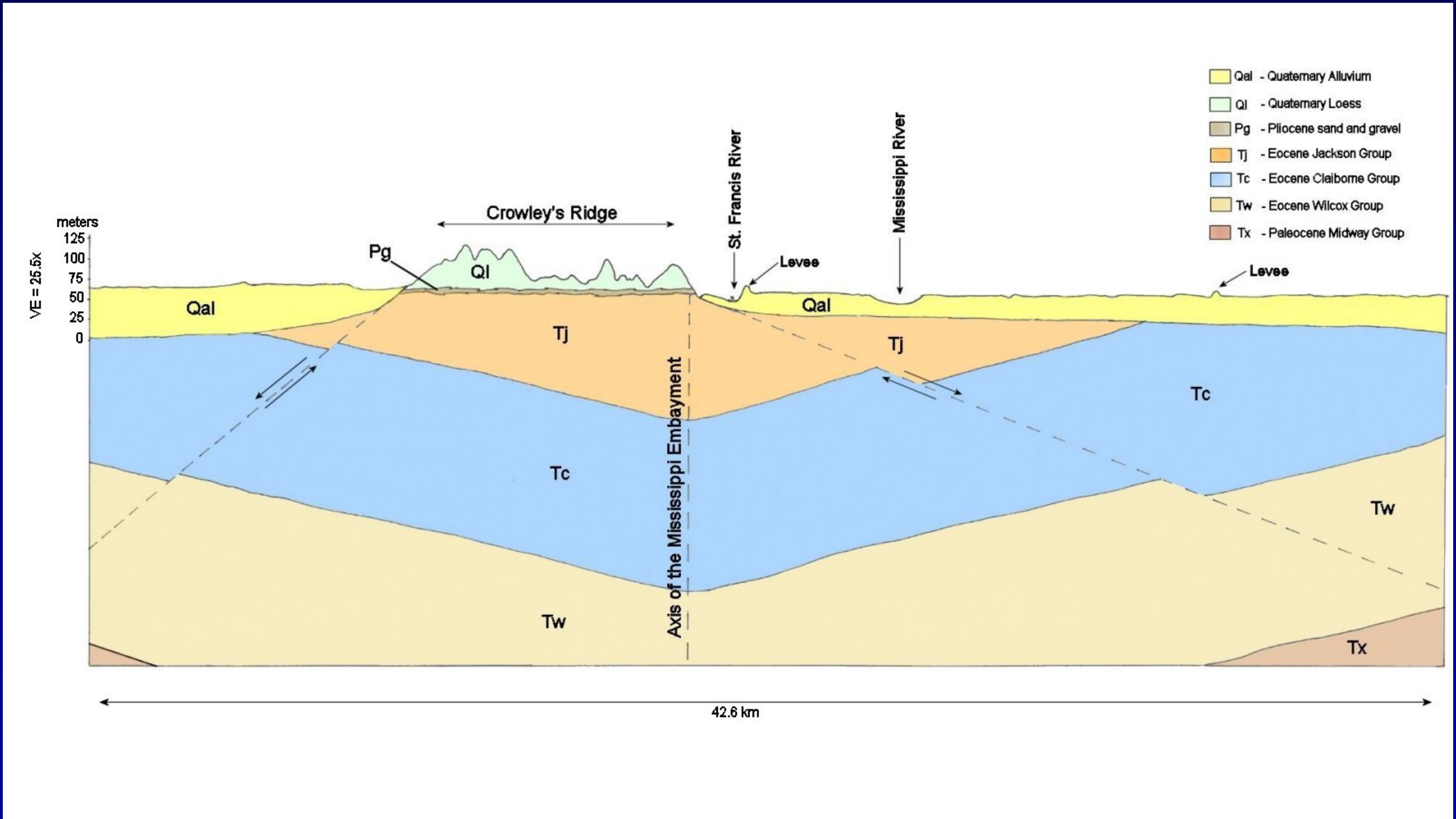
- Drainage patterns and topographic keys useful in identifying anomalous site characteristics typical of landslides
  - Divergent contours
  - Fan-to-drainage area ratios
  - Stepped fan surfaces
  - Theater-shaped headscarps



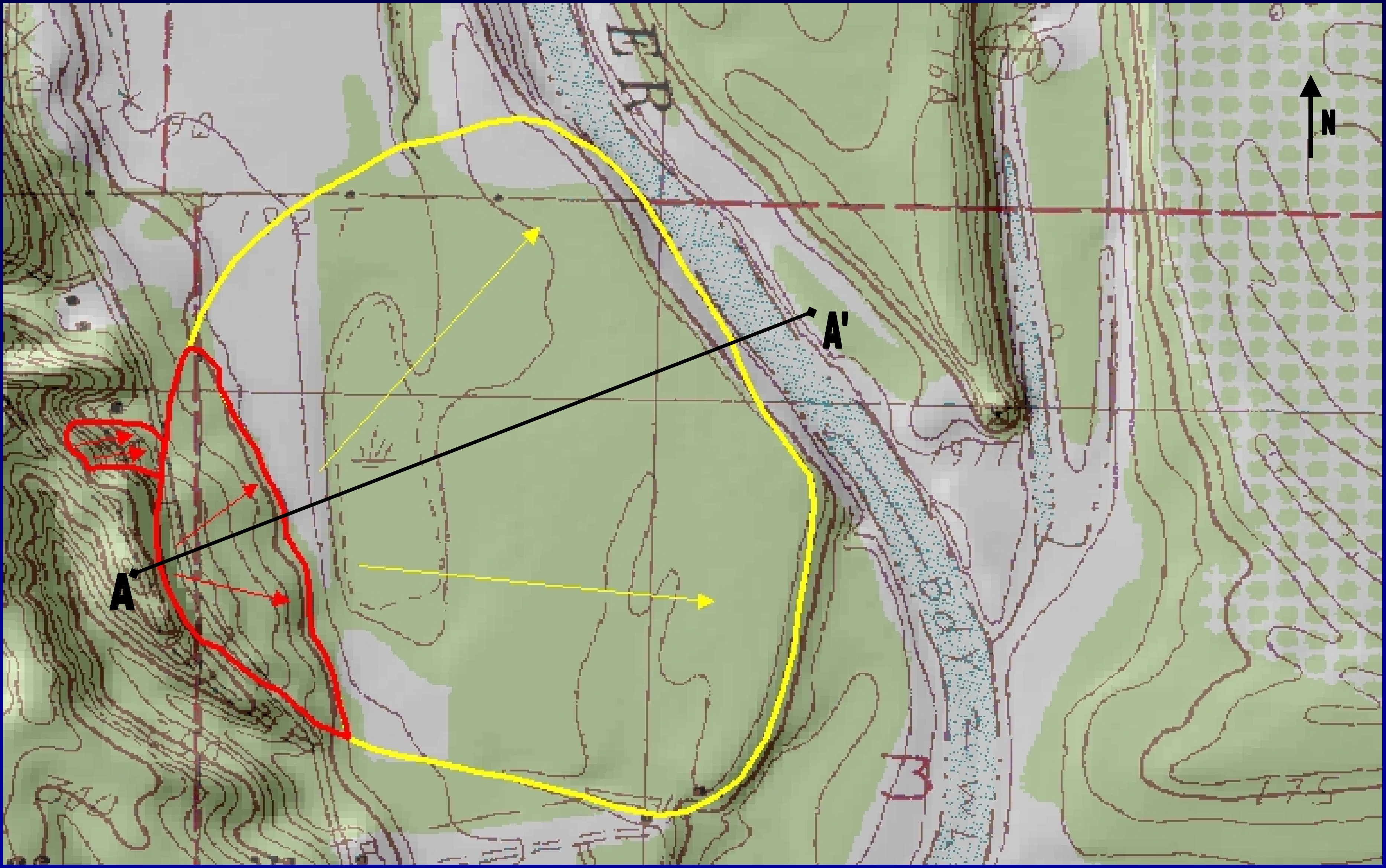
Topographic Algorithms

- Tool of tomorrow for rapid screening of large land areas
- Accuracy depends on quality and scale of topographic maps
- Will likely supplant stereopair aerial photographic methods for reconnaissance mapping of potential landslide hazards
- Following initial identification, detailed field mapping and analyses are used to determine if past landslippage actually occurred and whether or not it was seismically-induced

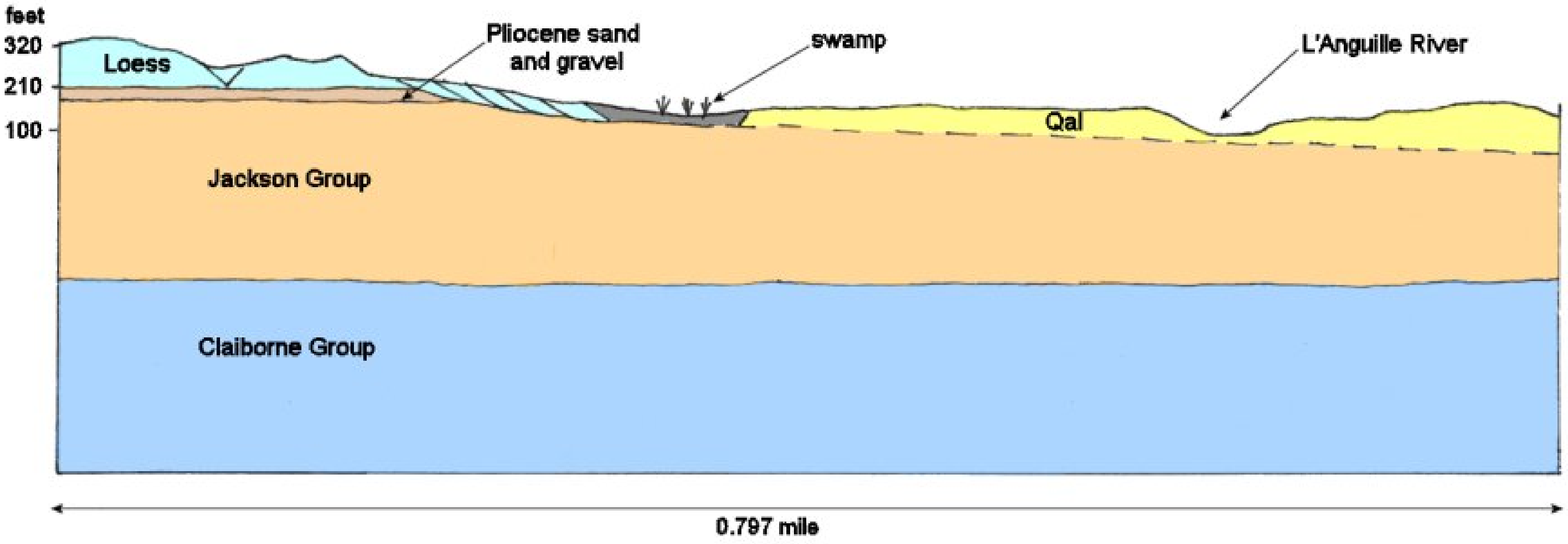
GEOLOGY OF SOUTHERN CROWLEY'S RIDGE

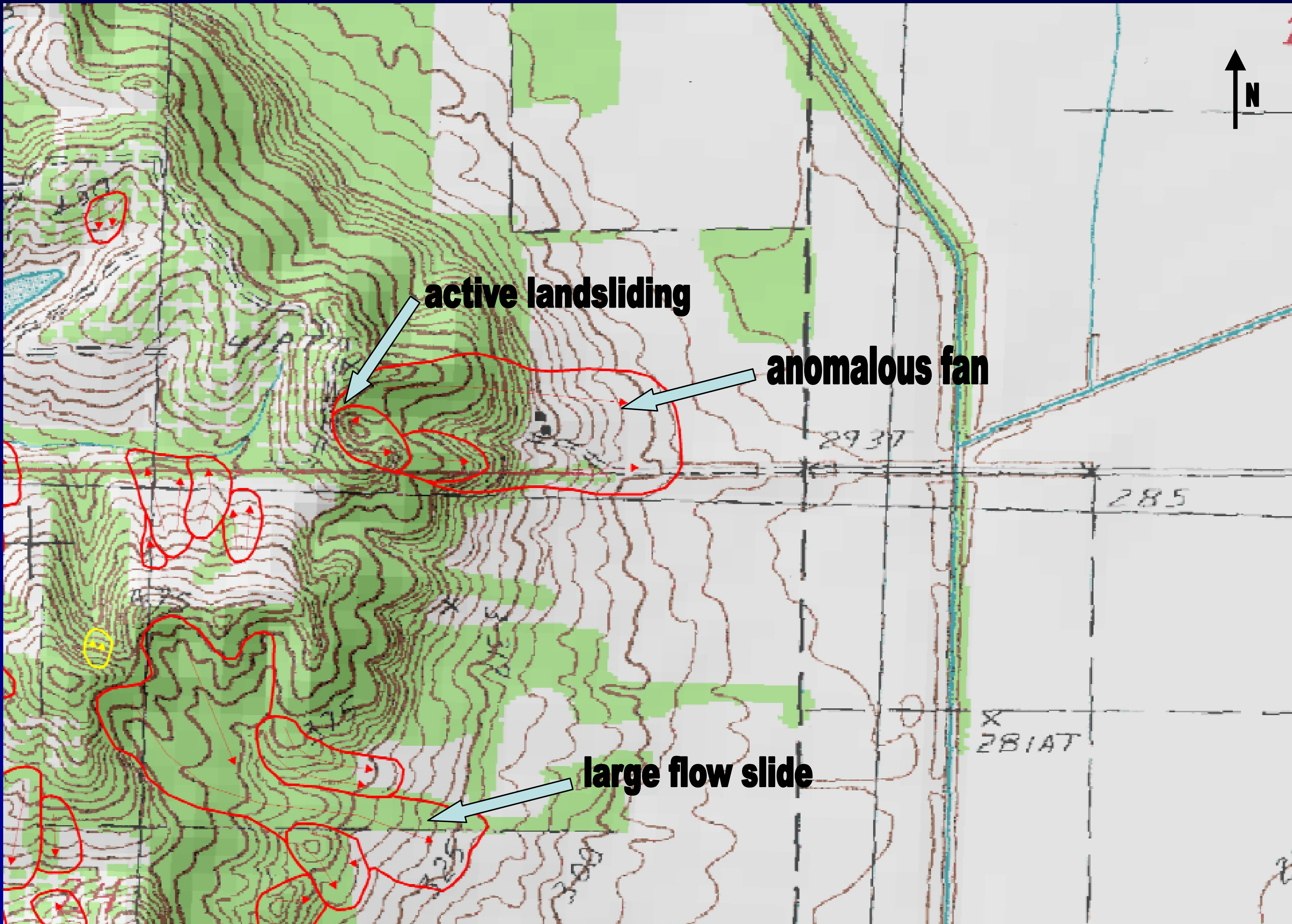


Lateral Spread Mapped Along Crowley's Ridge on LaGrange, Arkansas Quadrangle

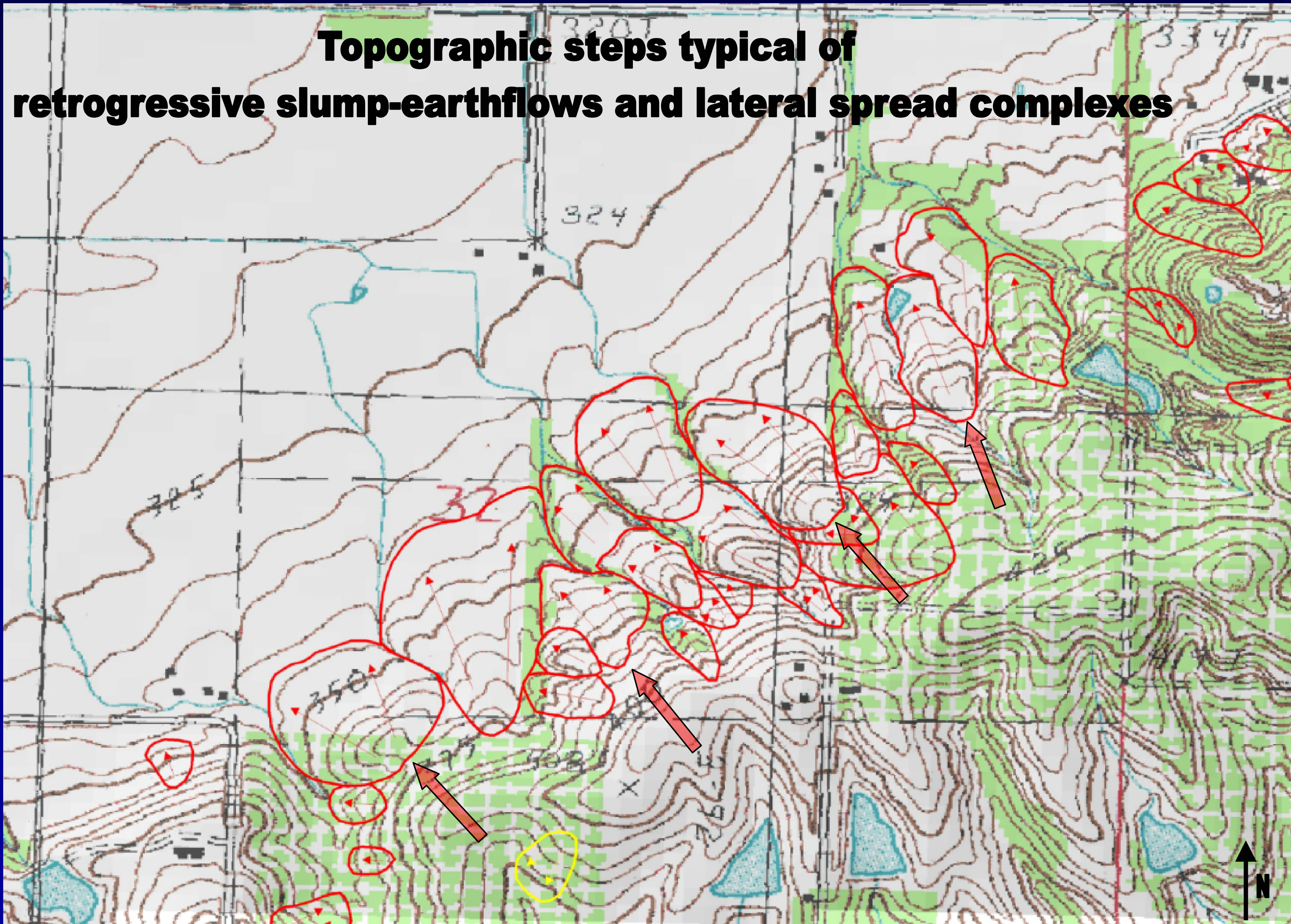


Cross Section Through Lateral Spread Feature Mapped on LaGrange, Arkansas Quadrangle




active landsliding
anomalous fan
large flow slide
N
2937
285
281AT

Topographic steps typical of retrogressive slump-earthflows and lateral spread complexes



Field Identification of Lateral Spreads

- Saturated cohesionless soils capped by low permeability materials
- Proximity to adjacent channels or depressions
- Prominent evacuation grabens because of block movement. These grabens can be infilled
- Stepped topography typical of repeated events causing lurching of selected zones
- Sand dikes filled with liquefied material are most common distinguishing feature, but
- Not all sand dikes are caused by earthquakes

Field Methods to Confirm Lateral Spreads

- Ground Inspection under tree and brush canopy
- Drainage pattern analysis
- Backhoe trenches
- Geophysical techniques very useful
  - Ground Penetrating Radar (GPR)
  - Electrical Resistivity (ER)
  - Induced Polarization (IP)

CONCLUSIONS

1. A great number of seismically-induced landslides and lateral spreads appear to exist within the escarpment formed by Crowley's Ridge within the New Madrid Seismic Zone.
2. These have not previously been recognized west of the Mississippi River
3. Future evaluations of seismic hazards in the NMSZ should include these modes of ground deformation, which may cause extensive damage to transportation, utility and drainage infrastructure

Special Thanks to:

- USGS National Earthquake Hazard Reduction Program (NEHRP)
- University of Missouri Research Board
- Missouri Geological Survey and Resource Assessment Division
- Arkansas Geological Commission
- USGS Mid-Continent Mapping Center
- Kevin James, UMR GE Department