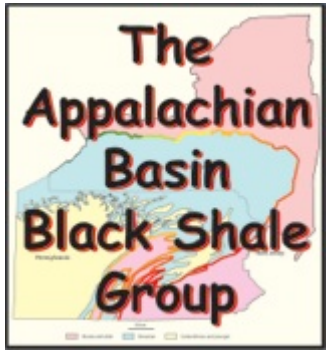
The confluence of the shale gas revolution and plate tectonics in the Appalachian Basin

<u>Subtitle</u>: A corollary for the Hubbert-Rubey (1959) solution to Escher's "colossal over-shove" problem

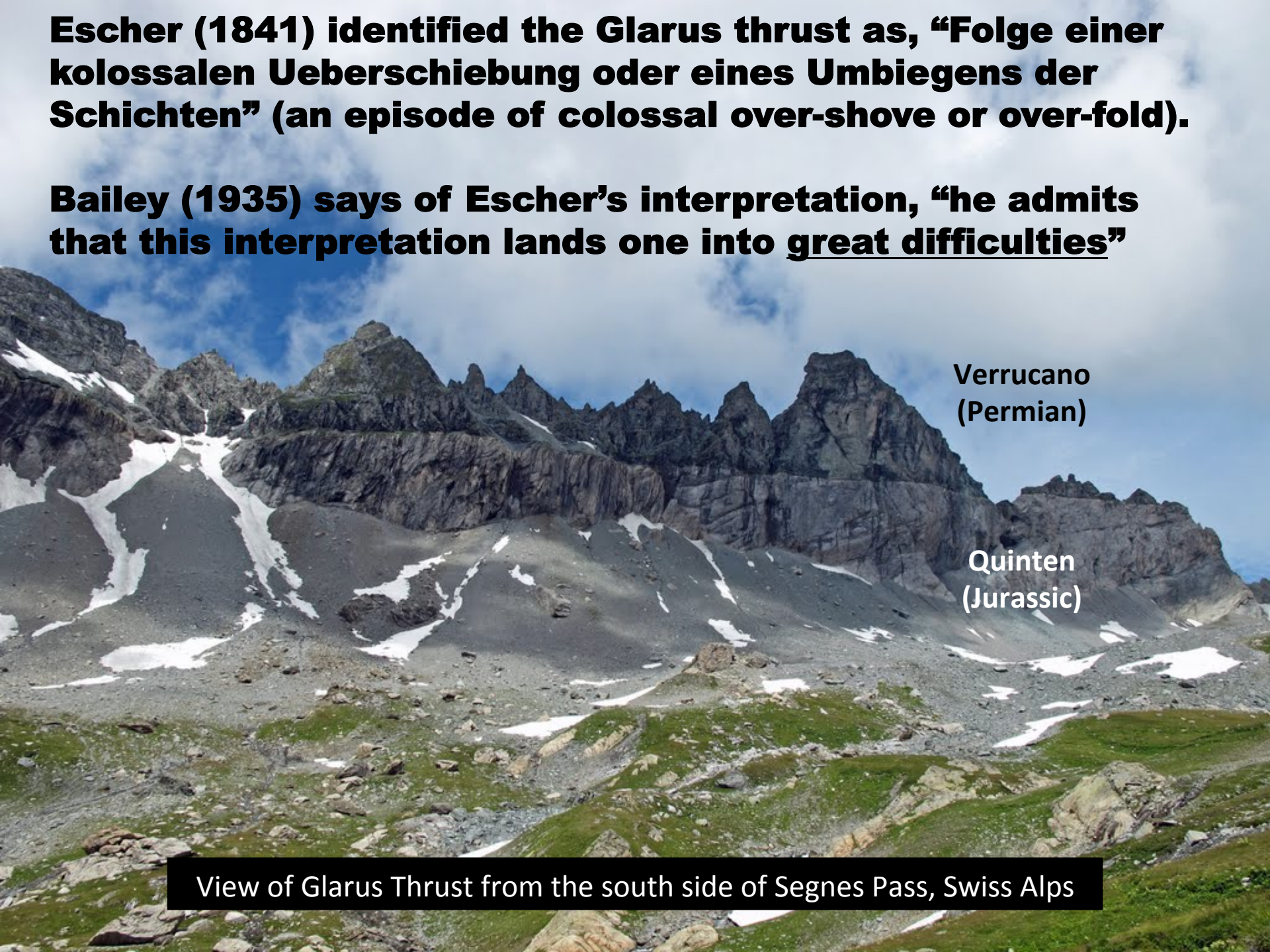
Terry Engelder

The Pennsylvania State University



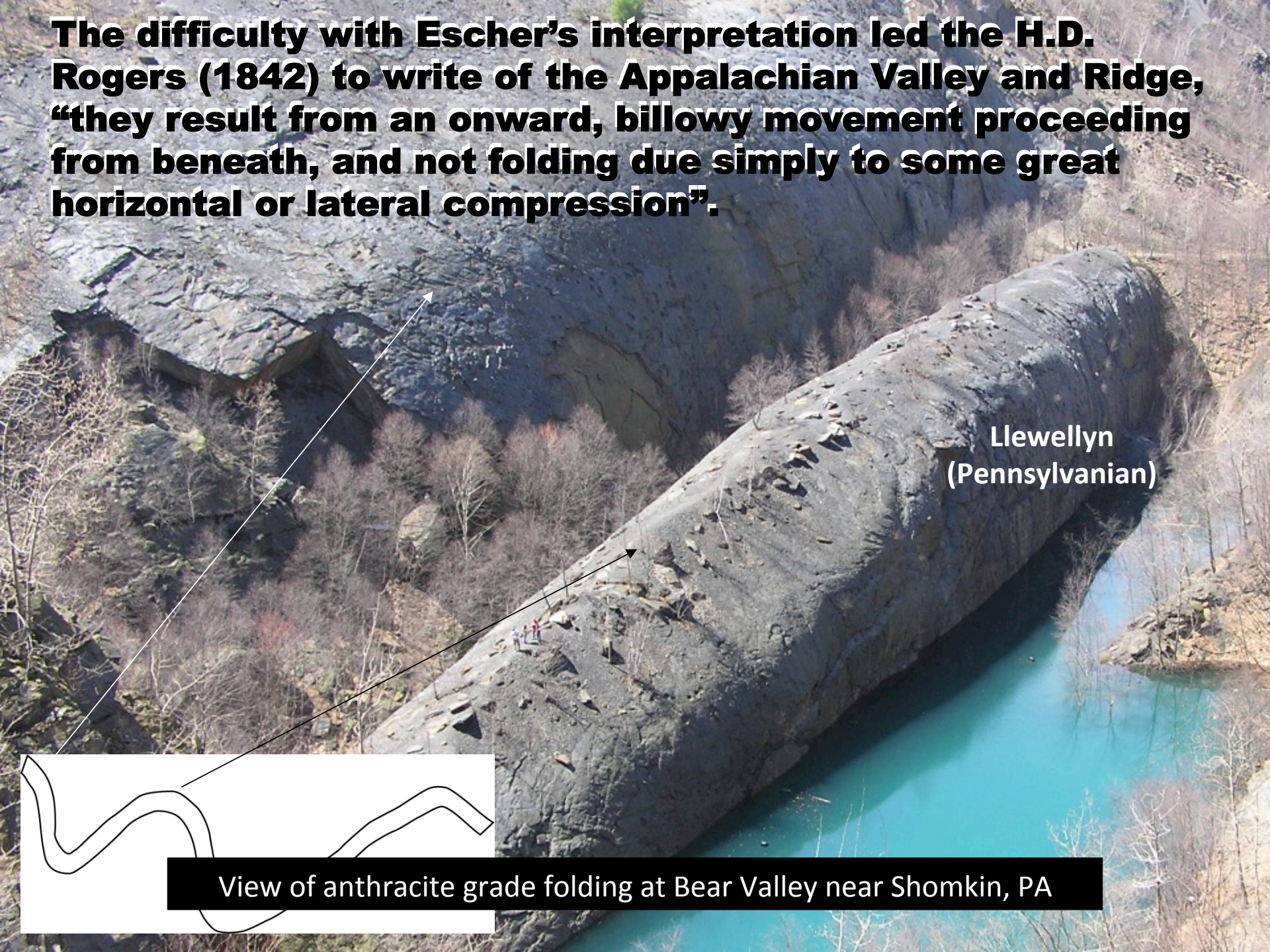
Escher (1841) identified the Glarus thrust as, "Folge einer kolossalen Ueberschiebung oder eines Umbiegens der Schichten" (an episode of colossal over-shove or over-fold).

Bailey (1935) says of Escher's interpretation, "he admits that this interpretation lands one into <u>great difficulties</u>"



View of Glarus Thrust from the south side of Segnes Pass, Swiss Alps

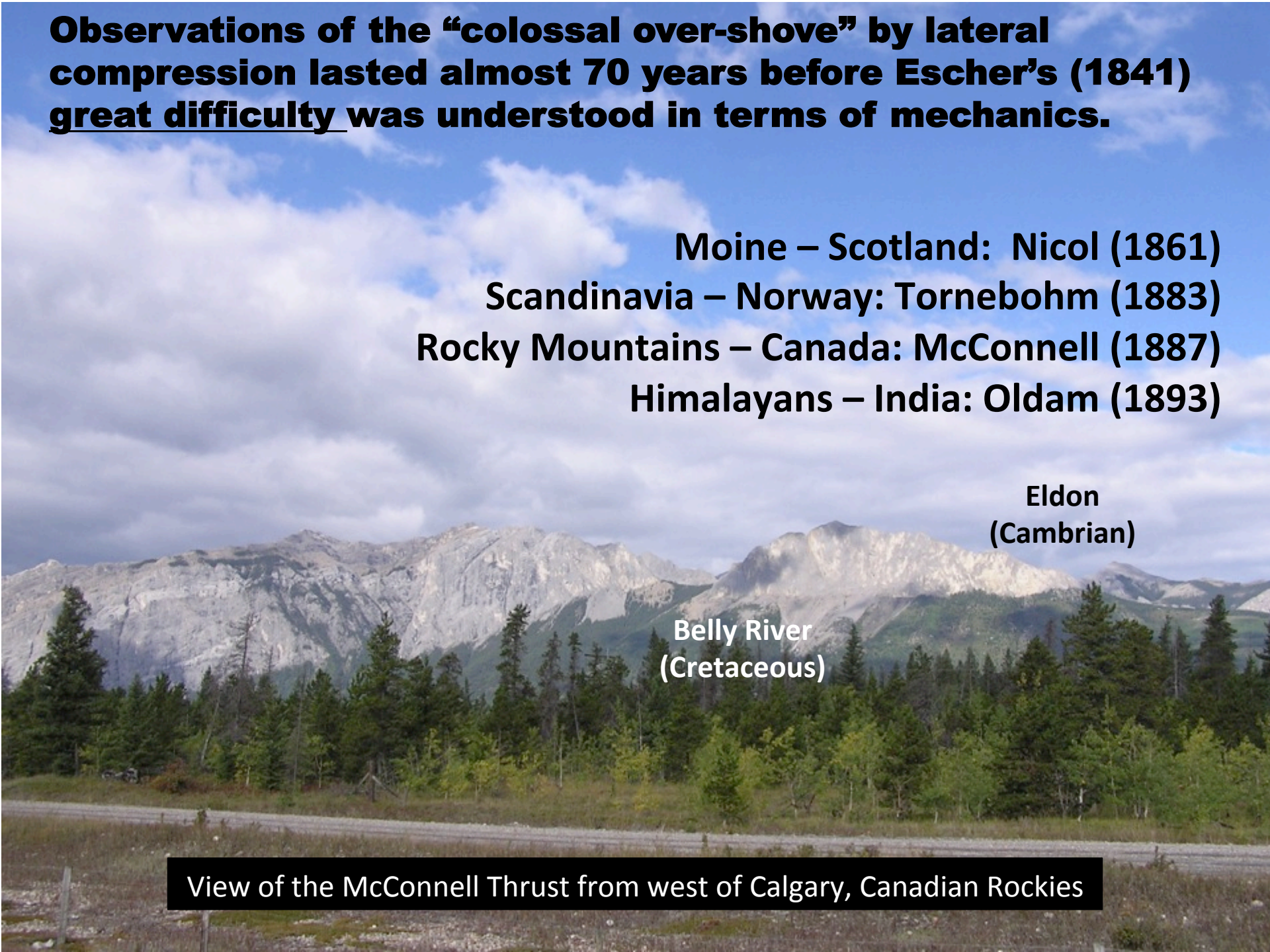
The difficulty with Escher's interpretation led the H.D. Rogers (1842) to write of the Appalachian Valley and Ridge, "they result from an onward, billowy movement proceeding from beneath, and not folding due simply to some great horizontal or lateral compression".



View of anthracite grade folding at Bear Valley near Shomkin, PA

Observations of the "colossal over-shove" by lateral compression lasted almost 70 years before Escher's (1841) <u>great difficulty</u> was understood in terms of mechanics.

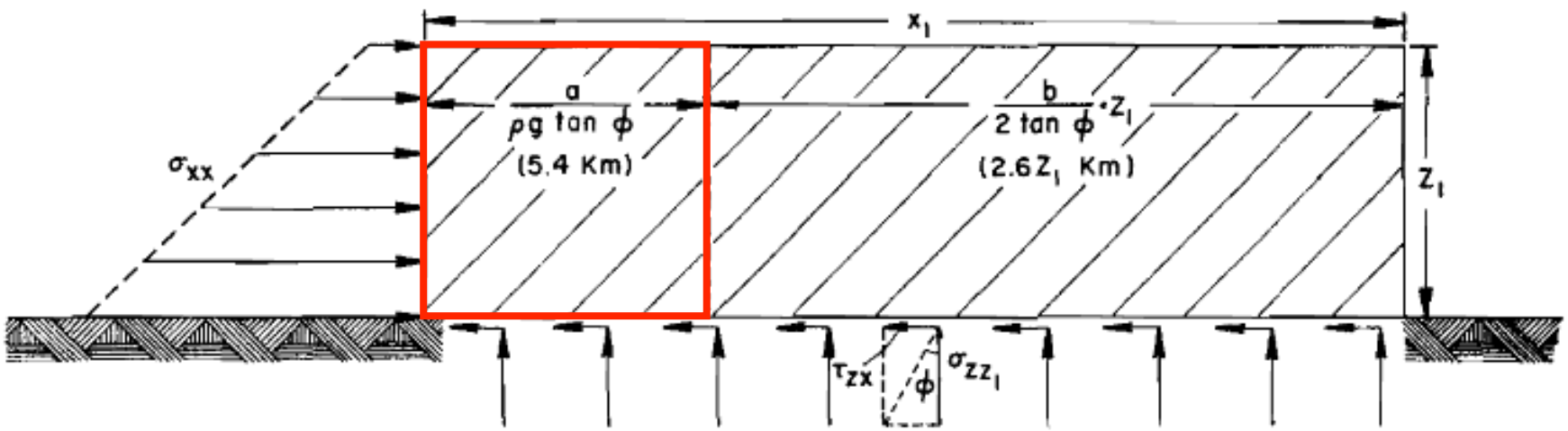
Moine – Scotland: Nicol (1861)
Scandinavia – Norway: Tornebohm (1883)
Rocky Mountains – Canada: McConnell (1887)
Himalayans – India: Oldam (1893)

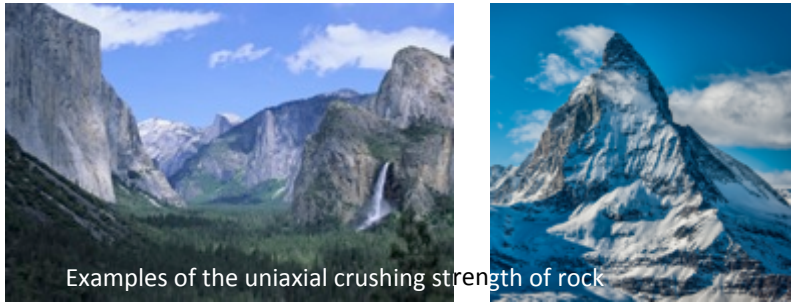


View of the McConnell Thrust from west of Calgary, Canadian Rockies

Smoluchowski' (1909) Dilemma:

Granite has the strength to support a column 3 km high. Thus, sliding on a fault with a friction of ≈ 0.6, granite has the strength support the stress necessary to slide a block ≈ 5 km long.

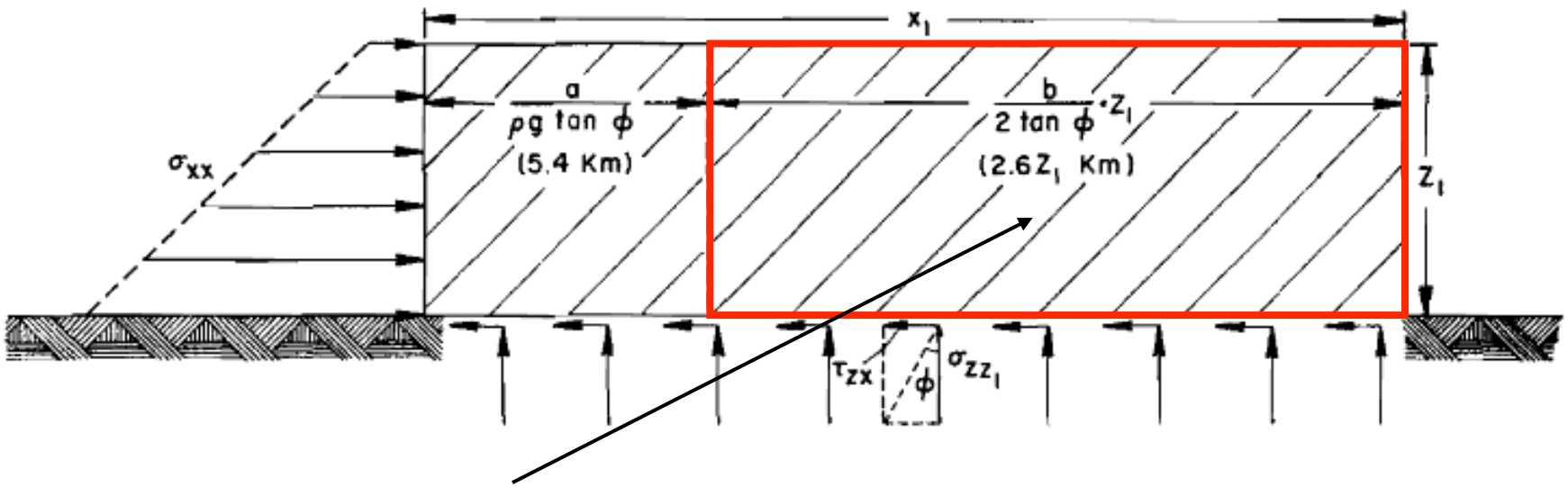




Examples of the uniaxial crushing strength of rock

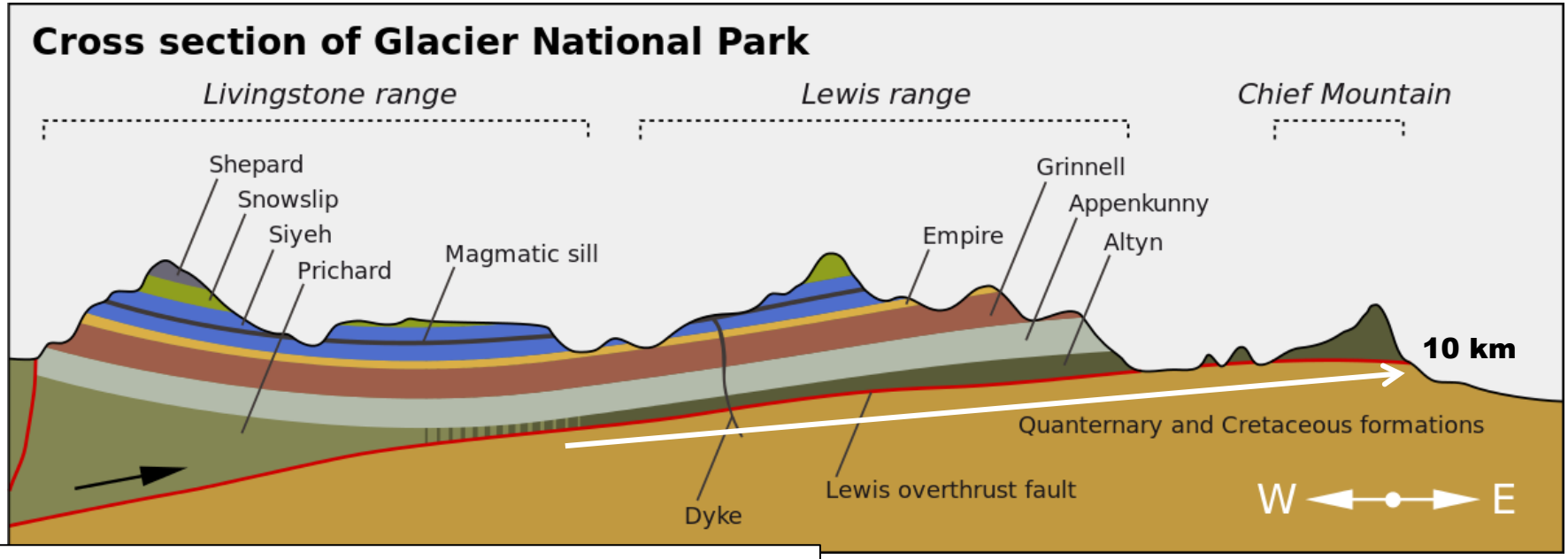
Drawing from Hubbert and Rubey (1959)

The density hoops supporting a silo is an analog for stress in the earth and depth-related increase in rock strength



Hubbert and Rubey (1959) point out that thickness of the block adds strength so that blocks may get longer by 2.6 km per km of thickness.

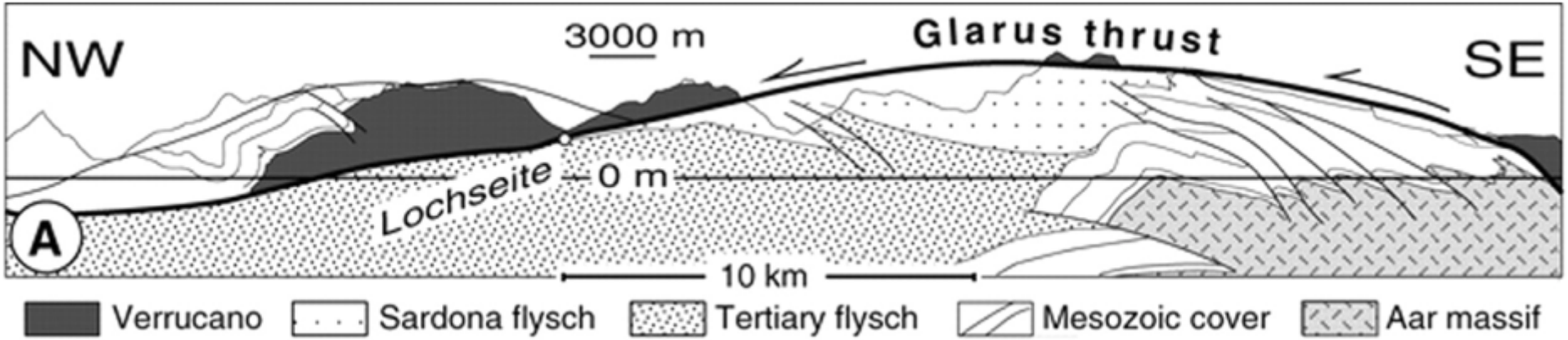
Reasonable crustal thicknesses can account for up to 10 to 15 km of over-shove on a detachment of normal friction!



http://www.nps.gov/history/history/online_books/glac/3/images/fig3.jpg

The Glarus thrust has a minimum displacement of 40 km and the Scandinavian over thrusts have a displacement of 130 km.

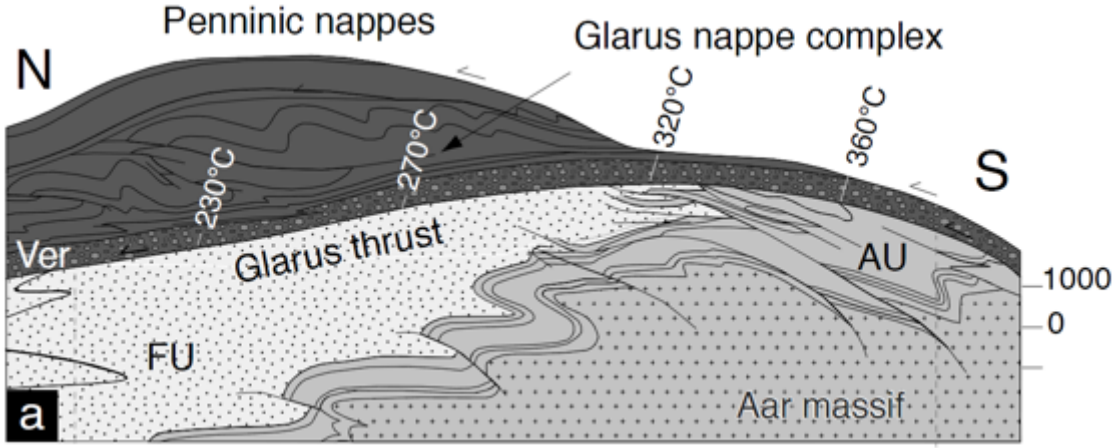
View of Glarus Thrust from the south side of Segnes Pass, Swiss Alps



Three solutions to Escher's colossal over-shove

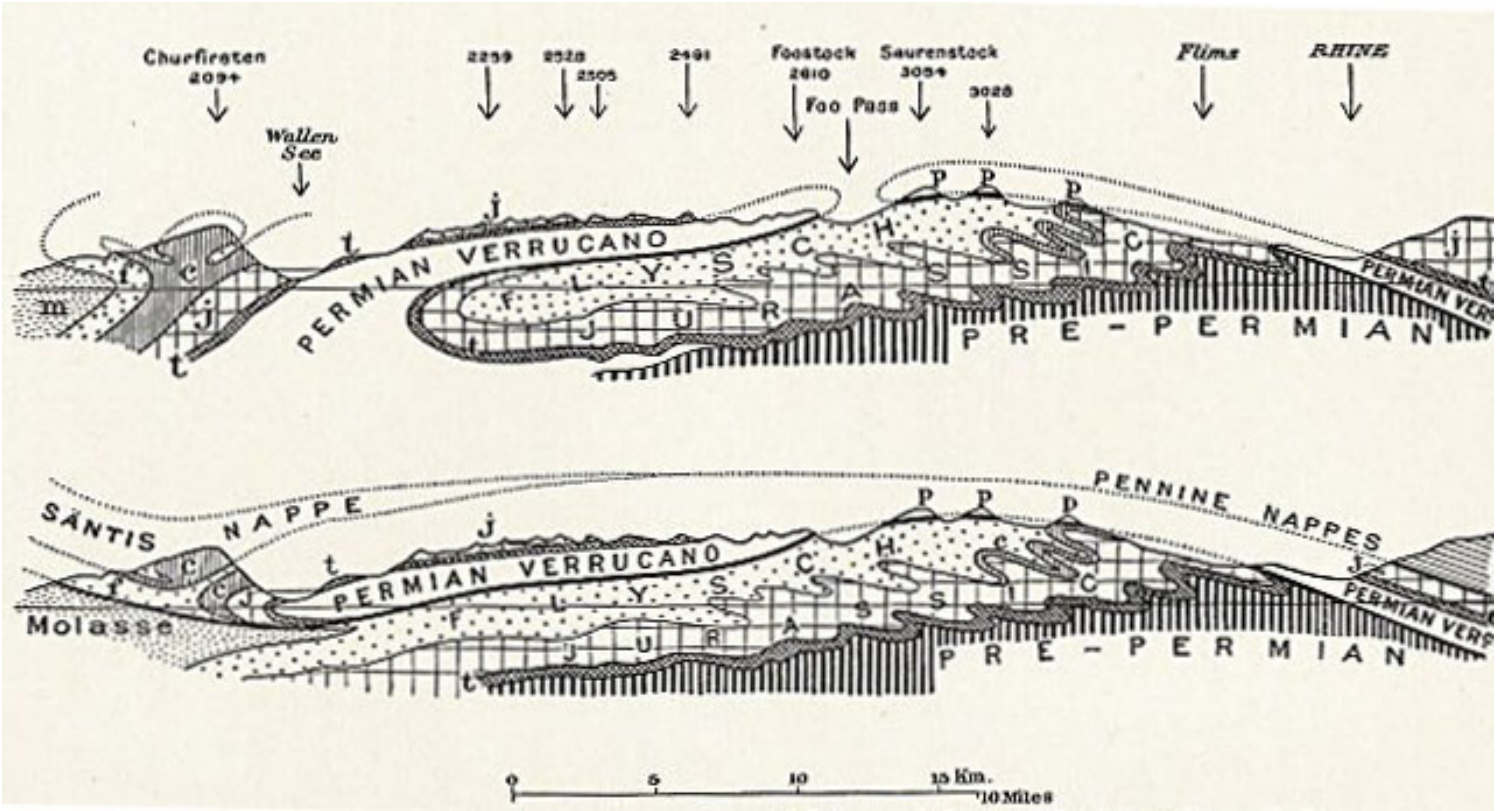
1. A high temperature detachment
2. A strong tectonic wedge
3. A low-strength detachment

Under the heading of "Swiss Tectonic Arena Sardona", Switzerland asks UNESCO support for the "Glarus overthrust" World Heritage site.



High Temperature Detachment

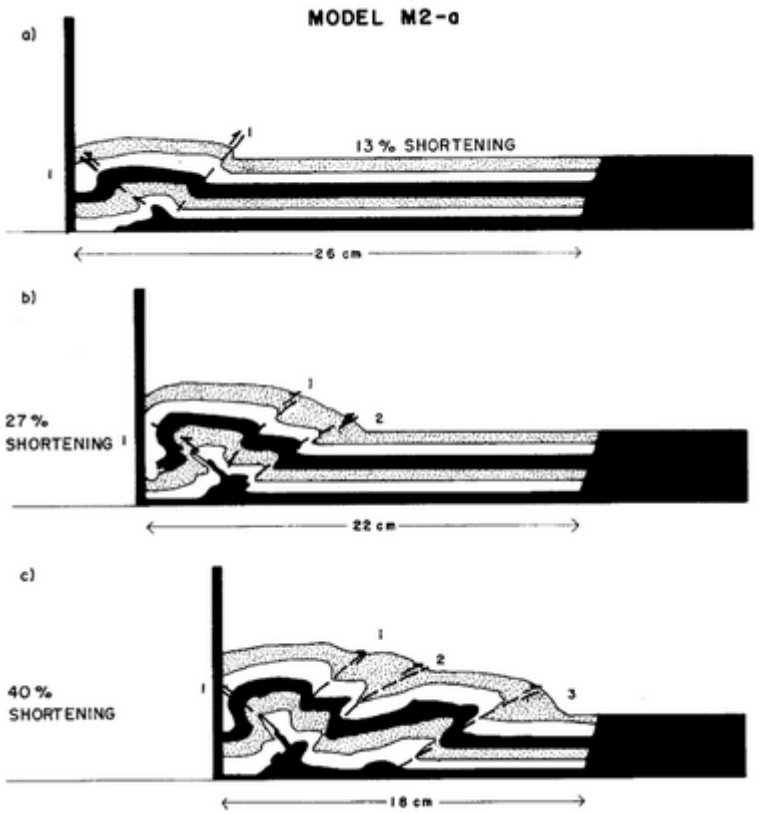
Herwegh et al., (2008)



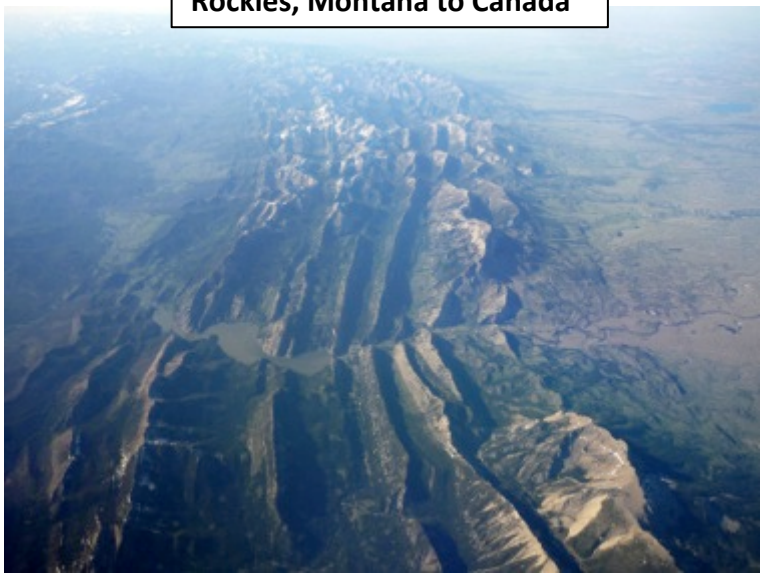
The contrasting "double-fold" of Escher and Heim with the single Glarus thrust sheet proposed by Bertrand (E.B. Bailey, 1935).

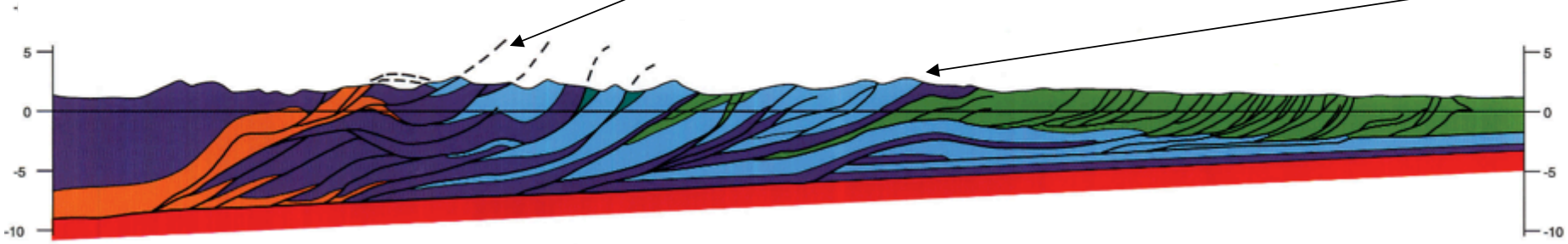
Strong Tectonic Wedge

Davis et al, 1985



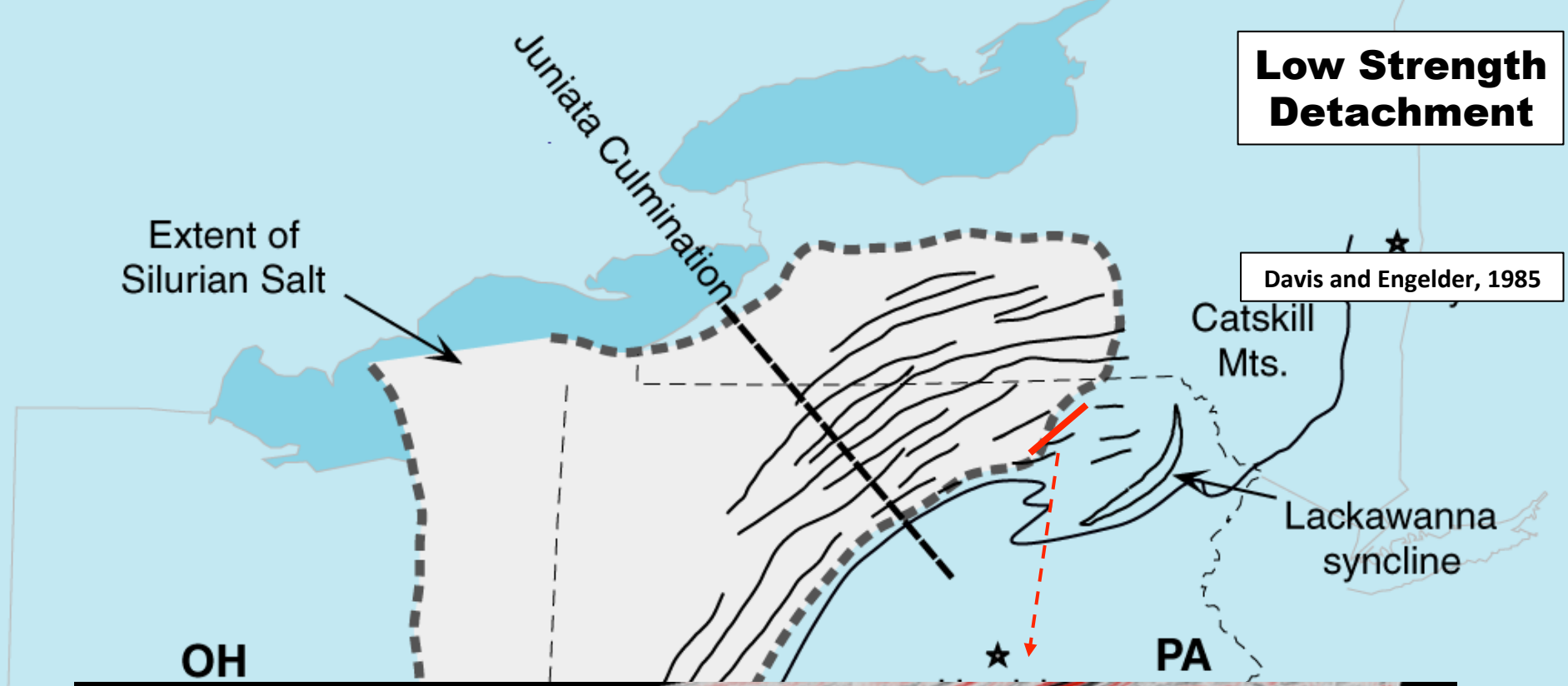
Rockies, Montana to Canada

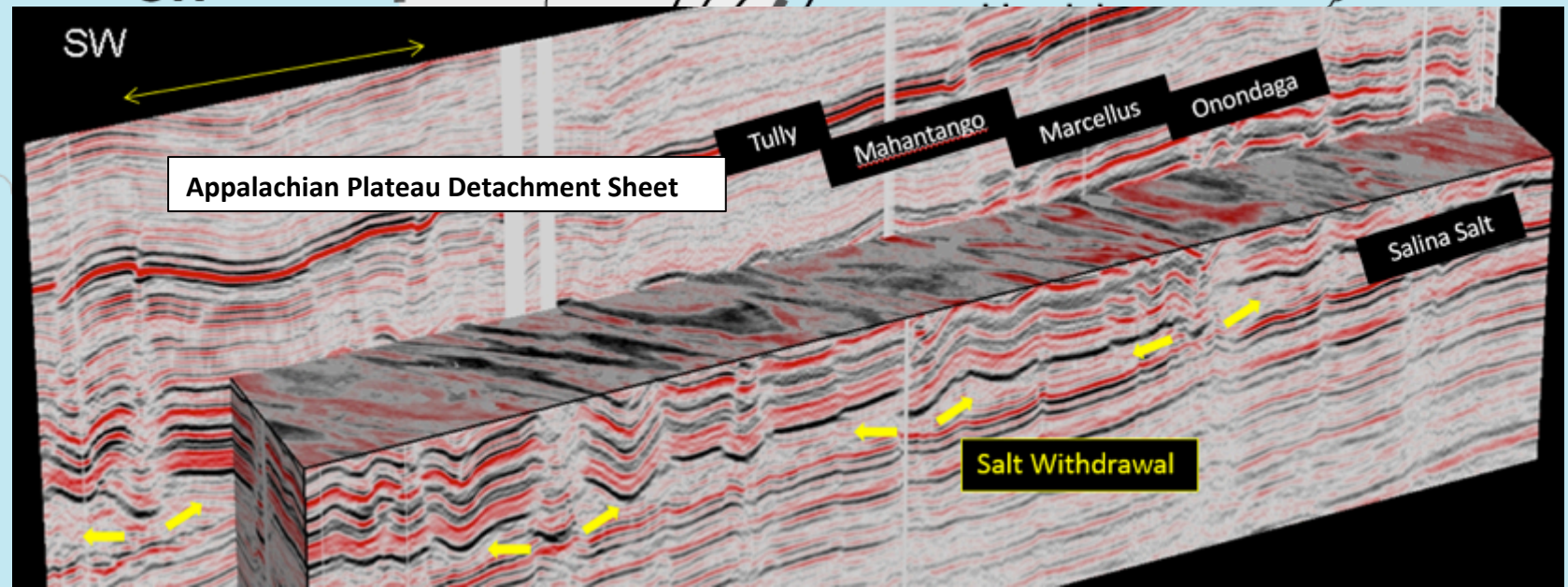


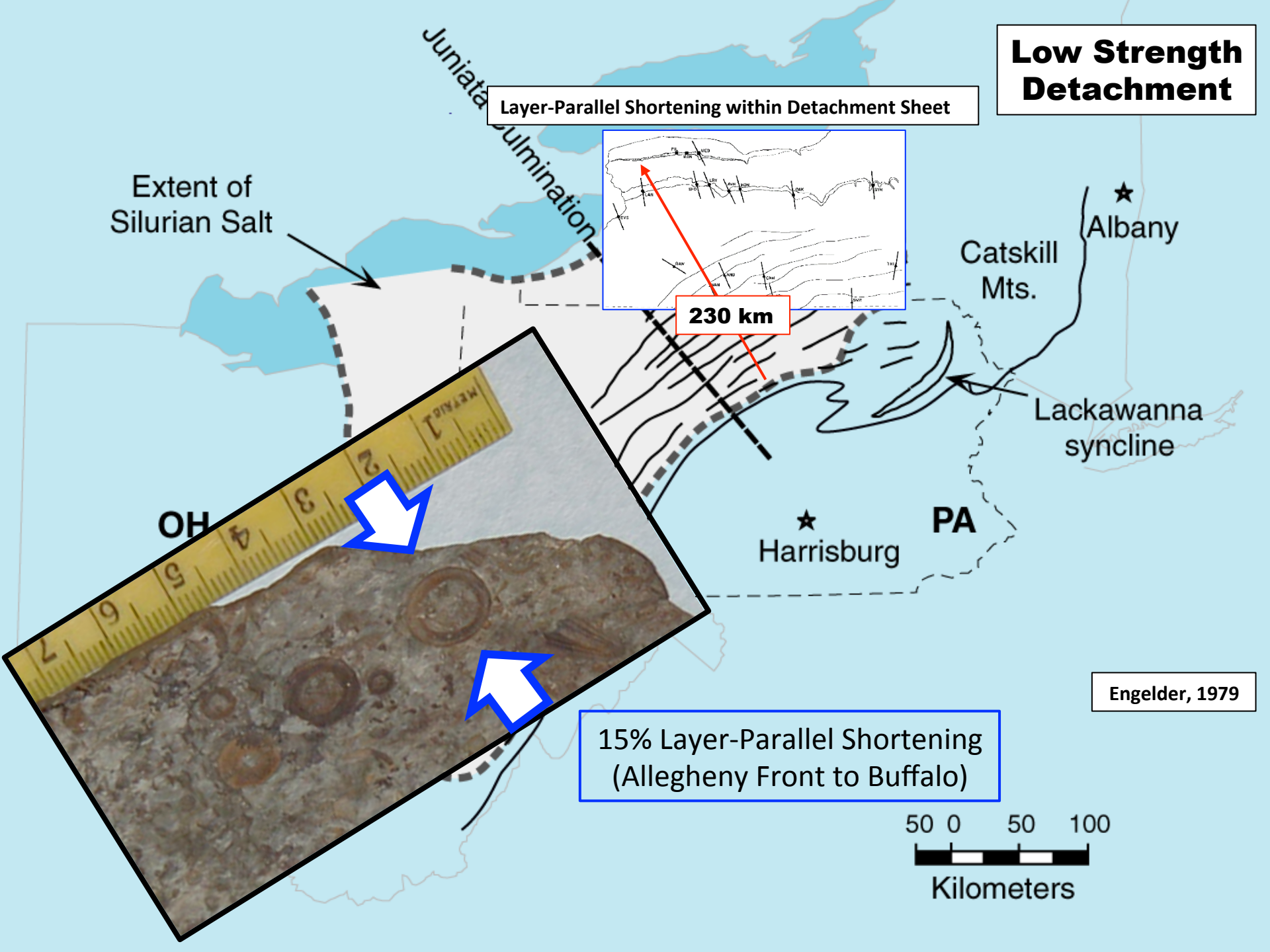


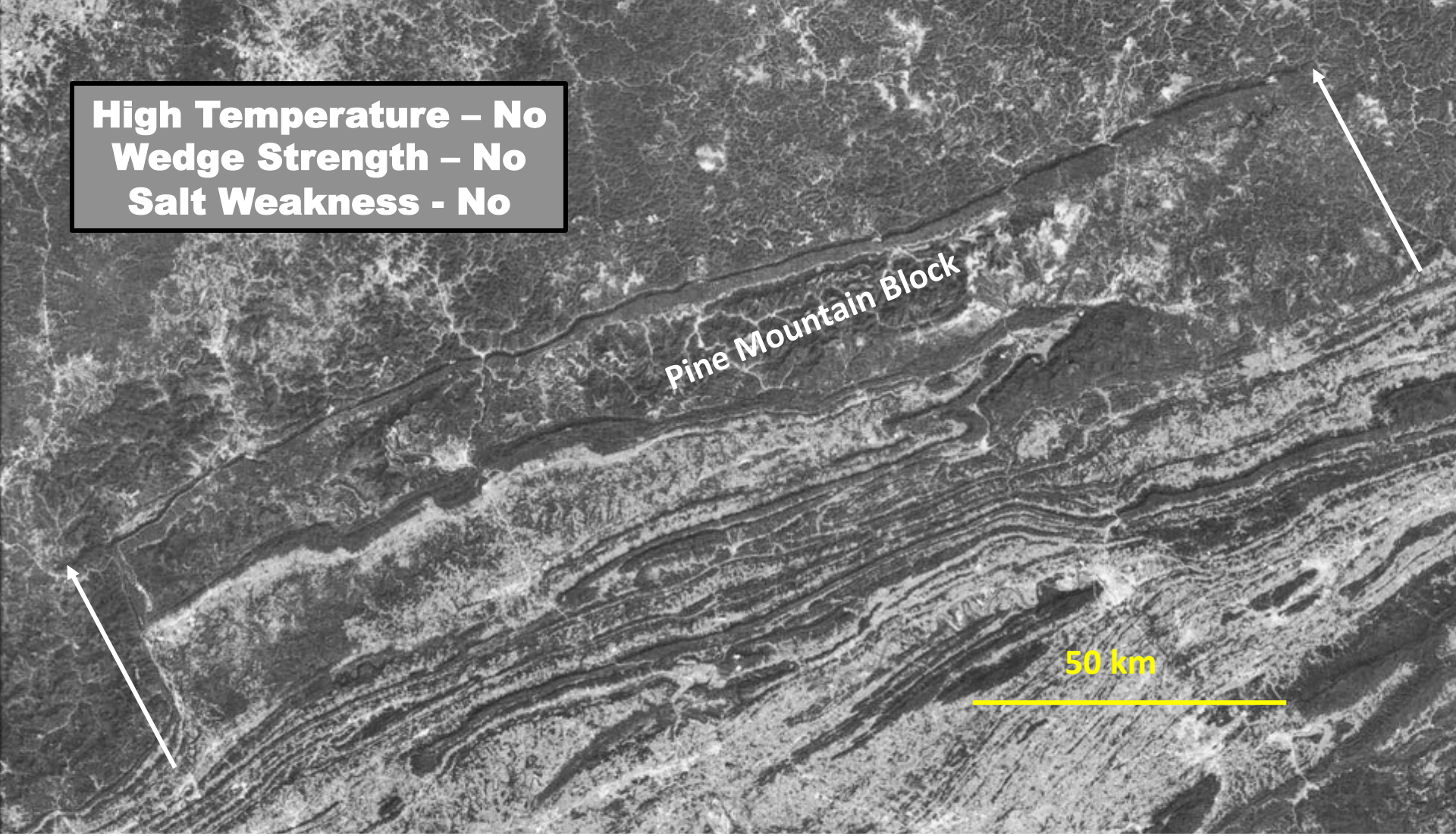
Low Strength Detachment

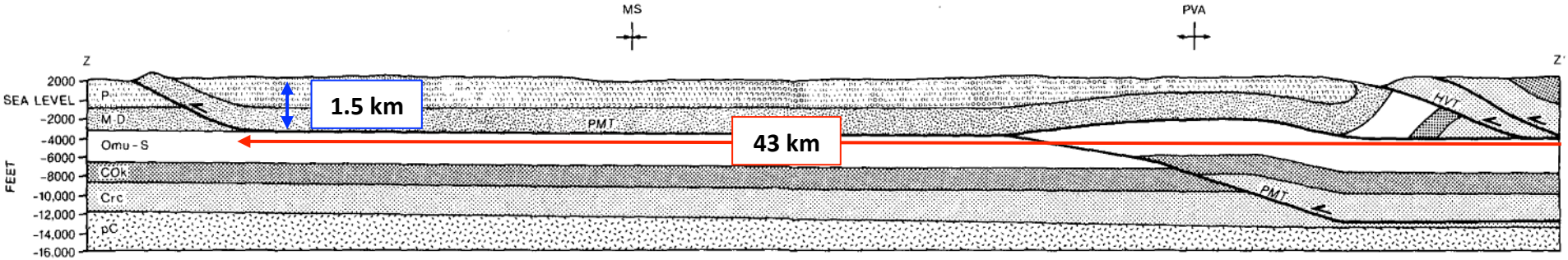
Davis and Engelder, 1985

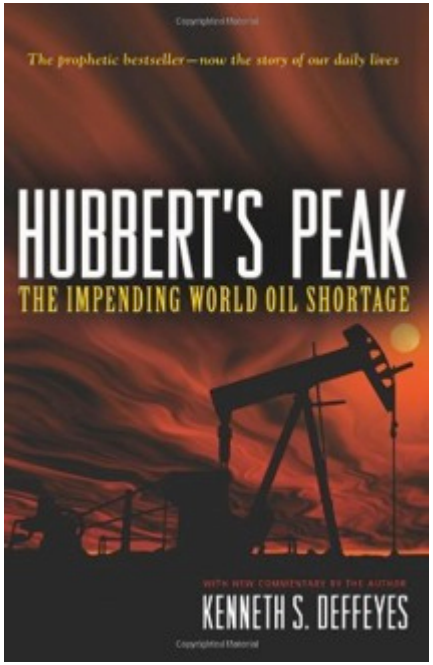


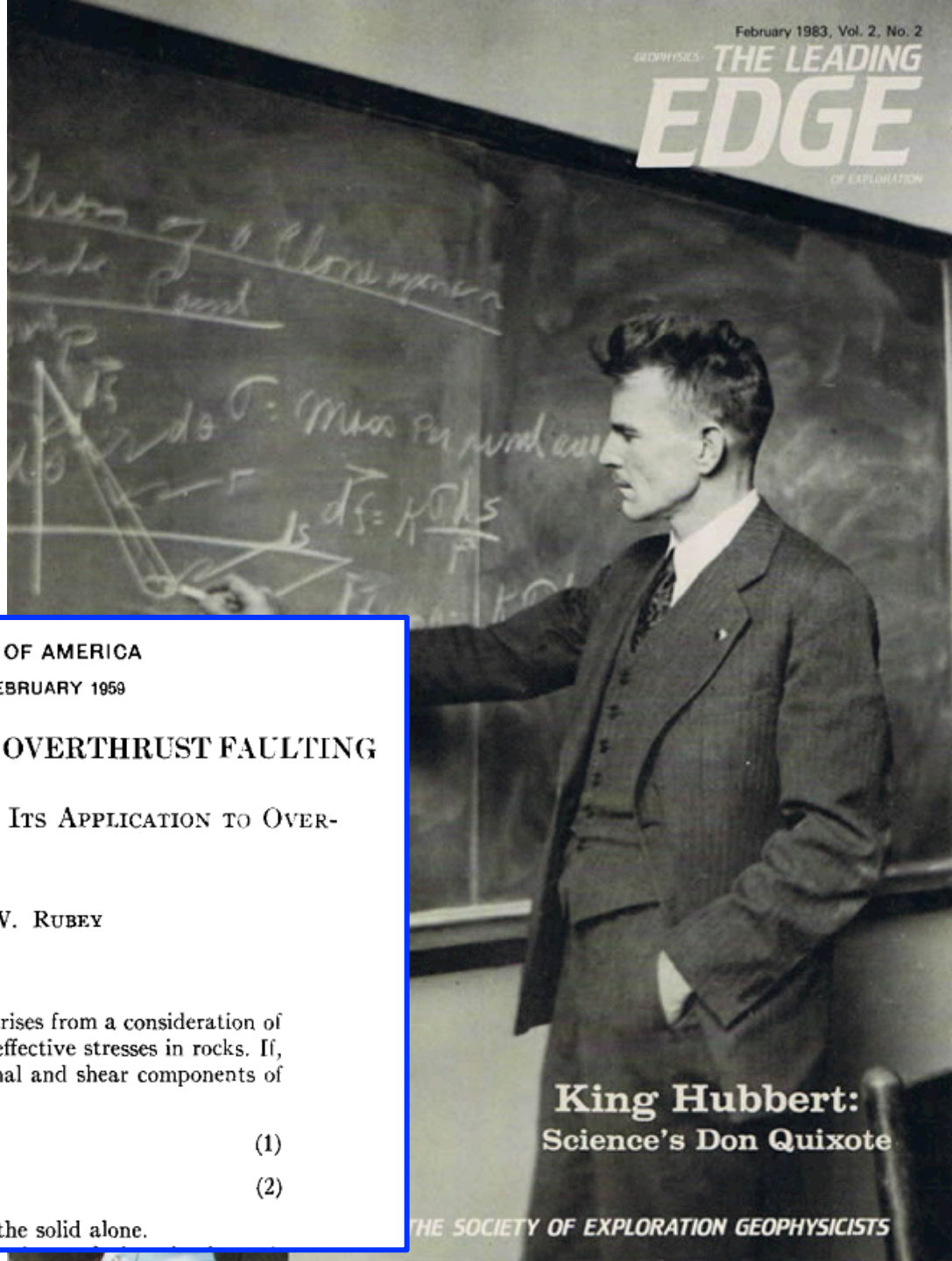



Low Strength Detachment
Layer-Parallel Shortening within Detachment Sheet
230 km
Juniata culmination
Extent of Silurian Salt
Albany
Catskill Mts.
Lackawanna syncline
OH
PA
Harrisburg
Engelder, 1979
15% Layer-Parallel Shortening (Allegheny Front to Buffalo)
50 0 50 100
Kilometers


High Temperature – No
Wedge Strength – No
Salt Weakness - No
Pine Mountain Block
50 km


MS
PVA
Z
Z'
2000
SEA LEVEL
-2000
-4000
-6000
-8000
-10,000
-12,000
-14,000
-16,000
FEET
P
M D
Omu - S
COk
Crc
pC
PMT
HVT
1.5 km
43 km





BULLETIN OF THE GEOLOGICAL SOCIETY OF AMERICA
VOL. 70, PP. 115-166, 32 FIGS. FEBRUARY 1959

ROLE OF FLUID PRESSURE IN MECHANICS OF OVERTHRUST FAULTING

I. Mechanics of Fluid-Filled Porous Solids and Its Application to Overthrust Faulting

By M. King Hubbert and William W. Rubey

Abstract

Promise of resolving the paradox of overthrust faulting arises from a consideration of the influence of the pressure of interstitial fluids upon the effective stresses in rocks. If, in a porous rock filled with a fluid at pressure p, the normal and shear components of total stress across any given plane are S and T, then

$$\sigma = S - p, \quad (1)$$

$$\tau = T, \quad (2)$$

are the corresponding components of the *effective* stress in the solid alone.

Three necessary geological conditions for the Hubbert-Rubey mechanism for overthrust faulting:

Biot actually suggested this experiment to Hubbert

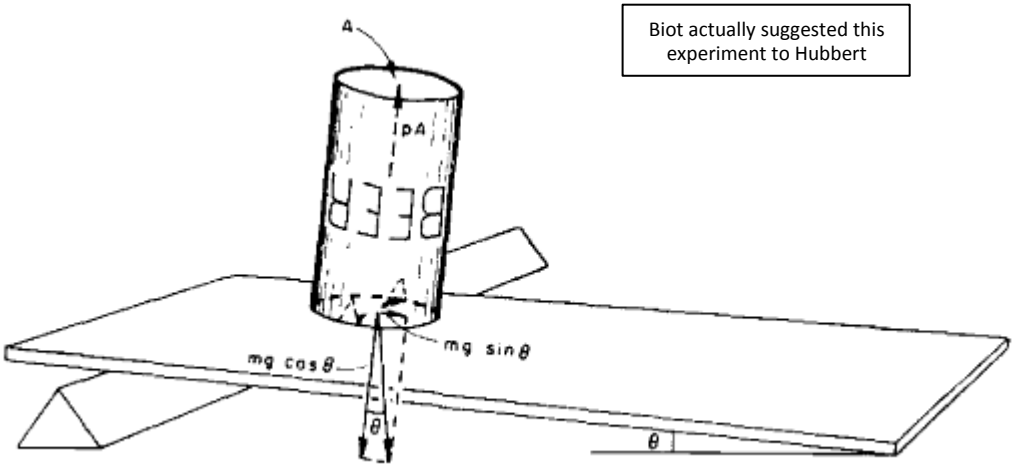


FIGURE 32.—BEER-CAN EXPERIMENT

1. Requires a mechanism(s) for generating abnormal pore pressure.

   Expansion of cold air

2. Requires a mechanism(s) for delivering abnormal pressure to the slip surface.
   1. High permeability rock

   The popped top

3. Requires a mechanism(s) for maintaining pressure even when leakage occurs.
   1. Low permeability rock

   Time-dependent expansion

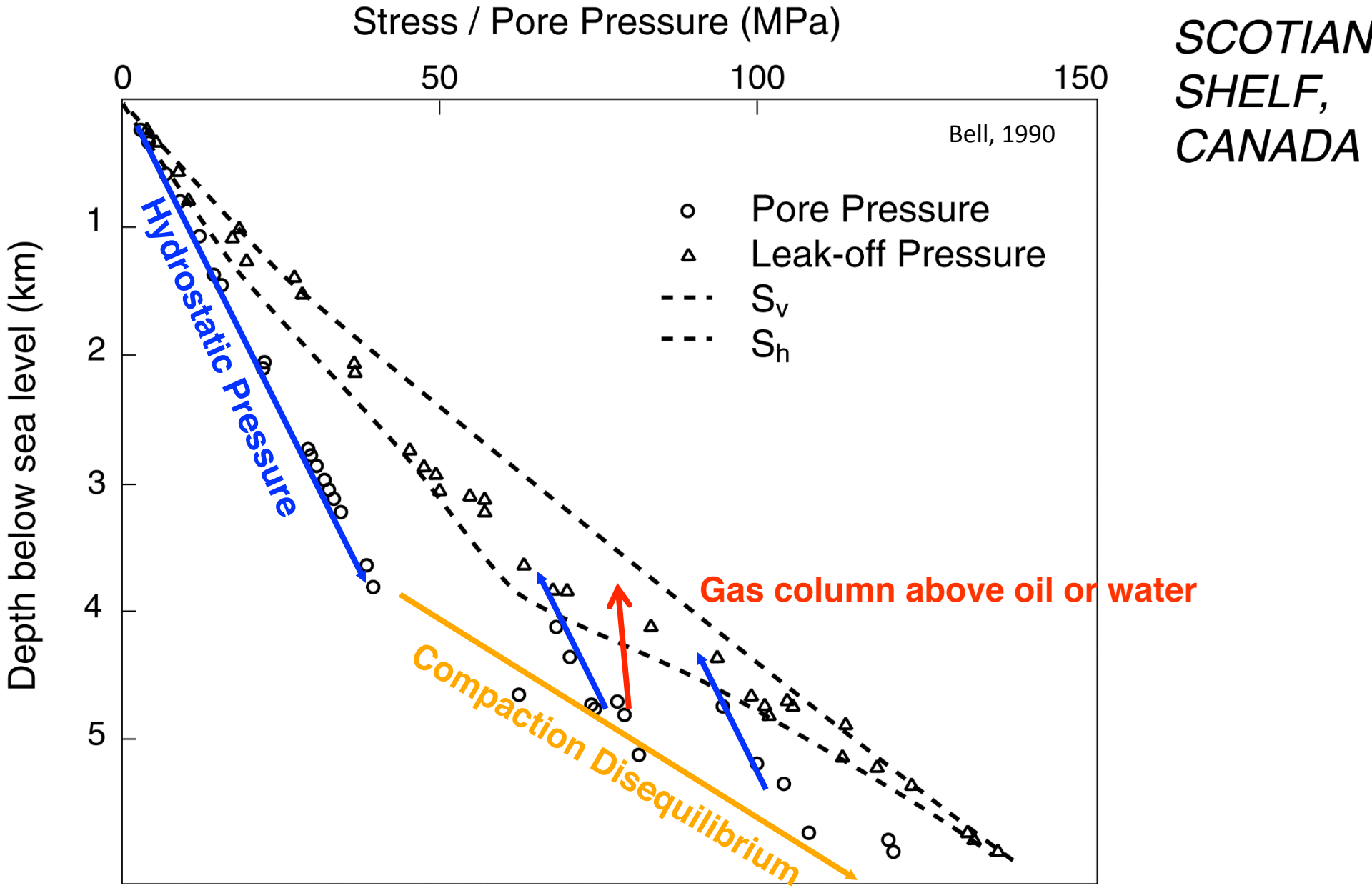
Mechanisms for Generating Overpressure

Most effective generation mechanisms

- Stress-Related Mechanisms ★
  - Disequilibrium Compaction
  - Tectonic Compaction
- Fluid Volume Increase Mechanisms
  - Aquathermal Expansion
  - Water release during mineral diagenesis
  - Hydrocarbon generation ⇦
- Fluid Dynamic Mechanisms ★ ⇦
  - Potentiometric head
  - Hydrocarbon buoyancy

★ Hubbert-Rubey focus
⇦ Engelder focus

Swarbrick & Osborne, 1998



Two (2) Hubbert-Rubey (1959) mechanisms for abnormal pore pressure (mechanical compaction = stress mechanism - **Orange**) and (buoyancy = fluid dynamic mechanism - **Red**)

M King Hubbert (1903-1989)

Signed at a 1980 AAPG Hedberg Conference when Hubbert was 77 years old.

With appreciation to Terry Engelder for working on such an important problem

M. King Hubbert

Deformation associated with the movement of the Muddy Mountain overthrust in the Buffington window, southeastern Nevada

WILLIAM G. BROCK *AMOCO Production Company, Security Life Building, Denver, Colorado 80202*
TERRY ENGELDER *Lamont-Doherty Geological Observatory, Palisades, New York 10964*

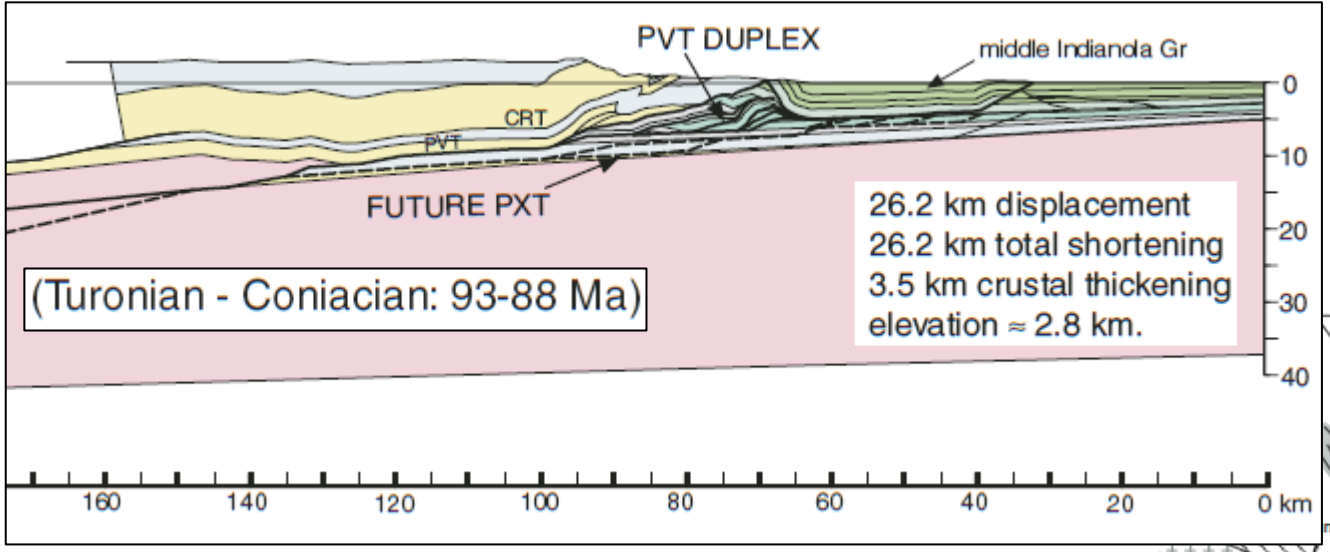
ABSTRACT

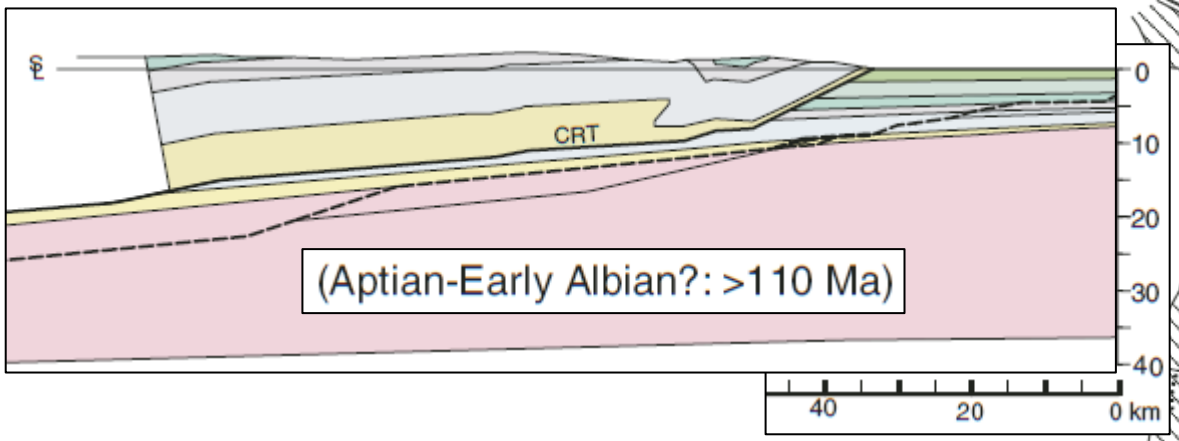
The Muddy Mountain overthrust, exposed in the Buffington window, southeastern Nevada, consists of a Paleozoic carbonate sheet thrust over Mesozoic Aztec Sandstone, with a molasse filling topographic lows. Evidence suggests that the thrust sheet moved across an erosional surface and that the molasse may have been a

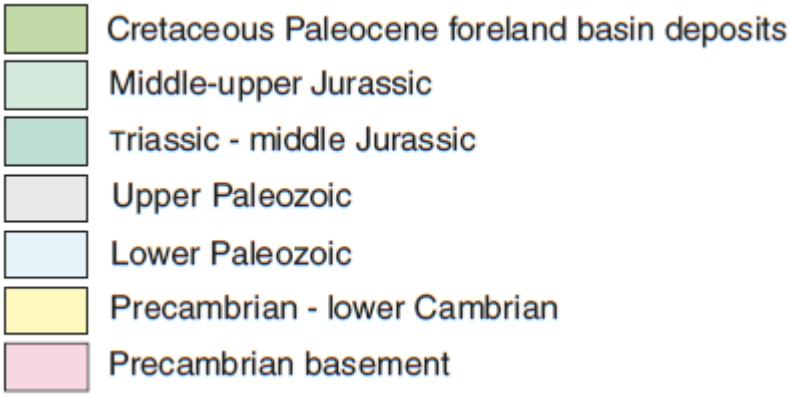
on a fault when the shear stress on this plane exceeds the sum of the cohesive strength and the product of the coefficient of friction and the effective normal stress. The Hubbert-Rubey hypothesis suggests a mechanism for reducing the effective normal stress, whereas the Wilson hypothesis suggests a way to reduce the coefficient of friction.

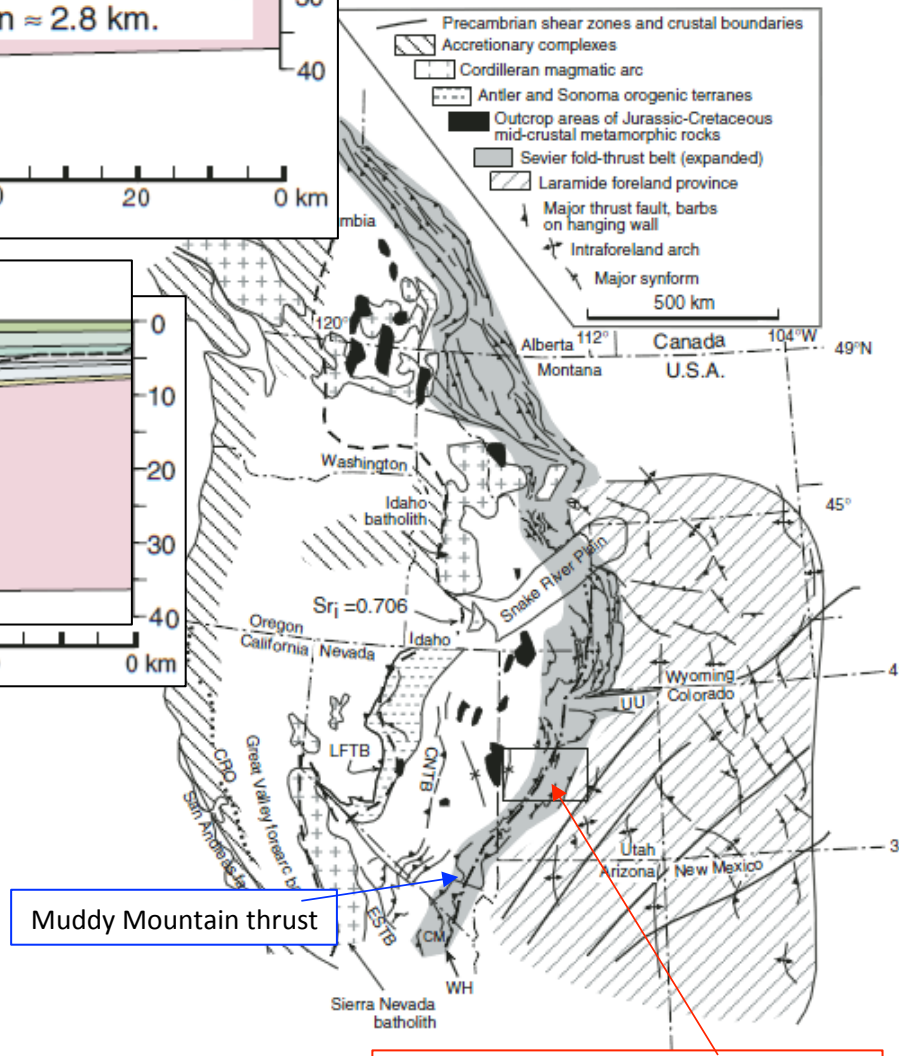
We wished to study deformation associated with overthrust

Brock and Engelder (1977) Geological Society of America Bulletin

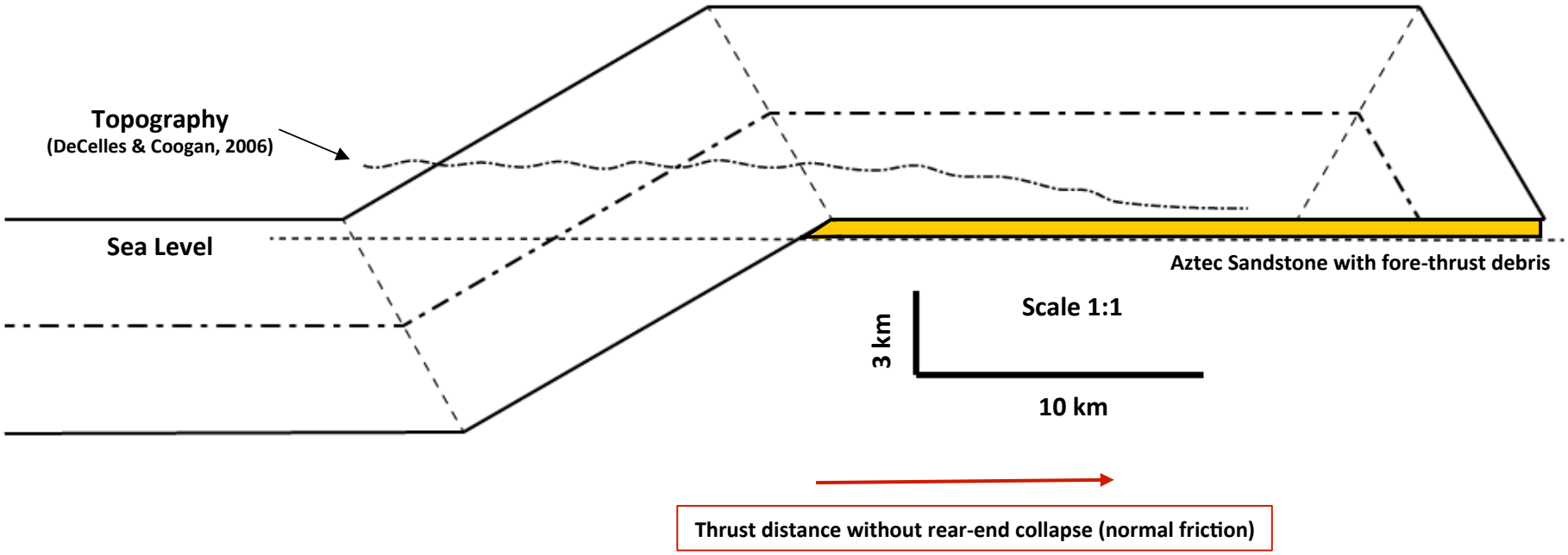

PVT DUPLEX
middle Indianola Gr
CRT
PVT
FUTURE PXT
(Turonian - Coniacian: 93-88 Ma)
26.2 km displacement
26.2 km total shortening
3.5 km crustal thickening
elevation ≈ 2.8 km.
0
10
20
30
40
160
140
120
100
80
60
40
20
0 km


CRT
(Aptian-Early Albian?: >110 Ma)
0
10
20
30
40
40
20
0 km


Cretaceous Paleocene foreland basin deposits
Middle-upper Jurassic
Triassic - middle Jurassic
Upper Paleozoic
Lower Paleozoic
Precambrian - lower Cambrian
Precambrian basement

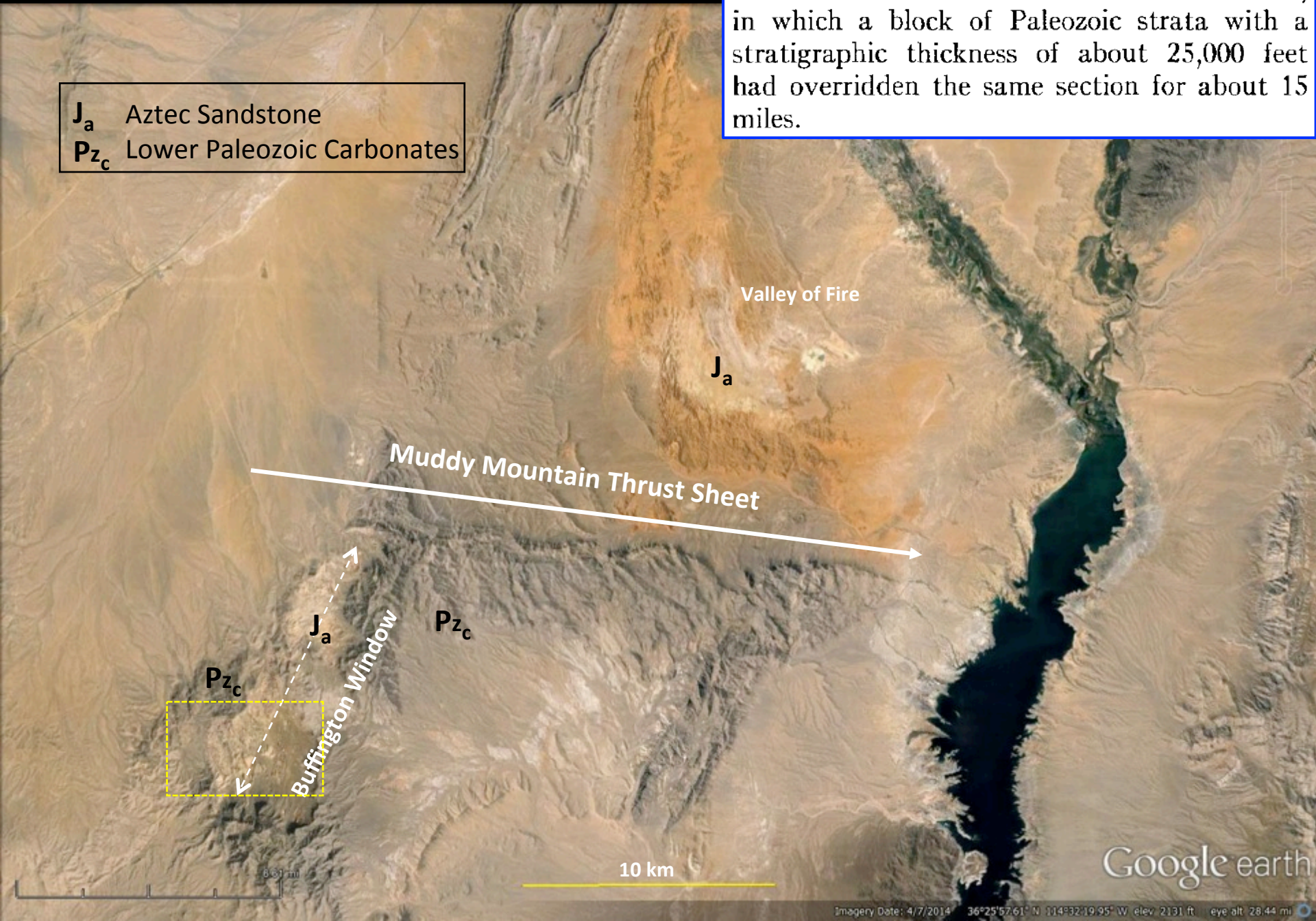

Precambrian shear zones and crustal boundaries
Accretionary complexes
Cordilleran magmatic arc
Antler and Sonoma orogenic terranes
Outcrop areas of Jurassic-Cretaceous mid-crustal metamorphic rocks
Sevier fold-thrust belt (expanded)
Laramide foreland province
Major thrust fault, barbs on hanging wall
Intraforeland arch
Major synform
500 km
Alberta
Montana
Canada
U.S.A.
Washington
Idaho batholith
Snake River Plain
Sr$_i$ =0.706
Oregon
California
Nevada
Idaho
Wyoming
Colorado
UU
LFTB
CNTB
Great Valley forearc b
CRO
San Andreas fa
ESTB
CM
WH
Sierra Nevada batholith
Utah
Arizona
New Mexico
Muddy Mountain thrust
DeCelles & Coogan (2006) cross section

The Muddy Mountain Thrust



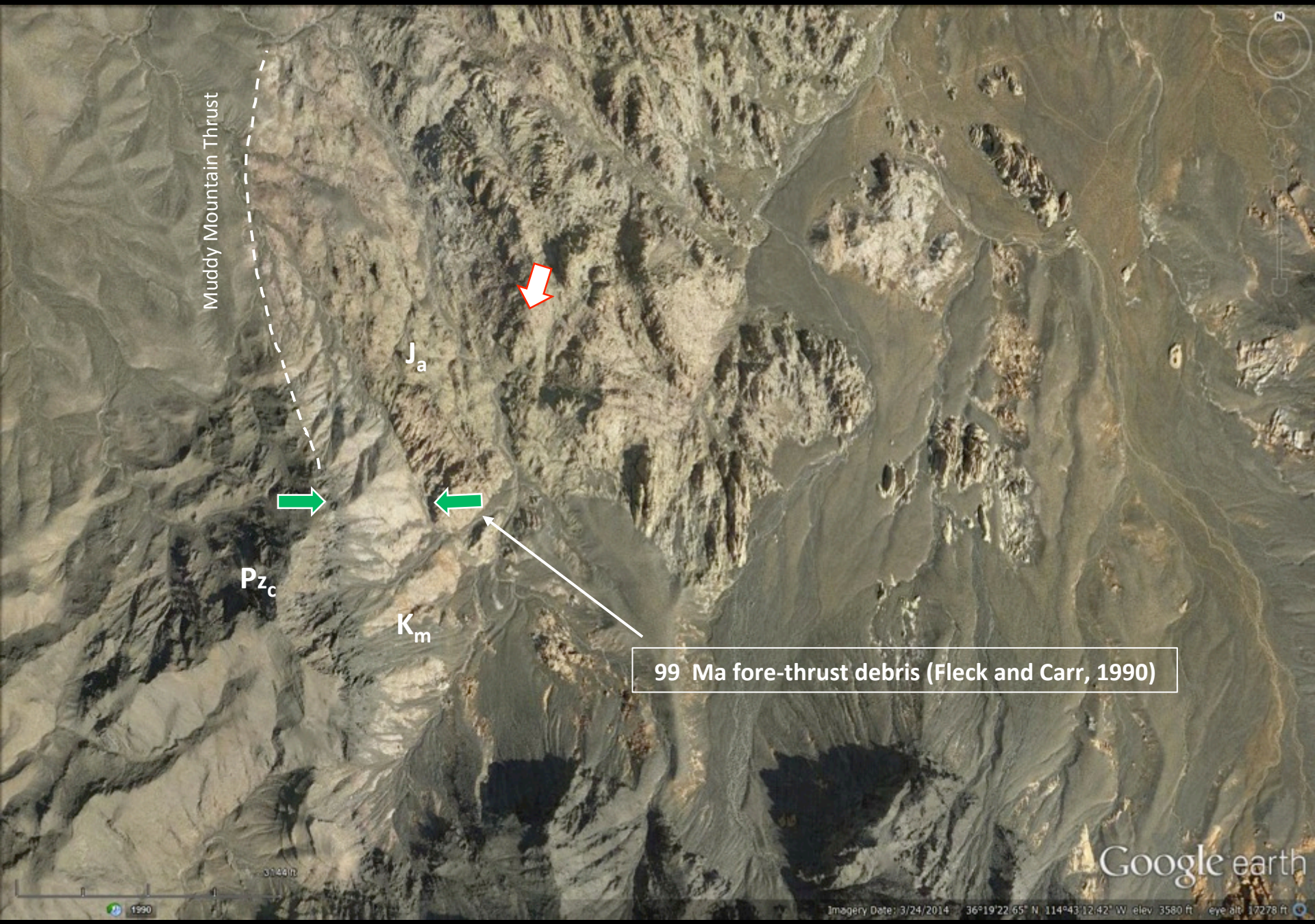
Hubbert and Rubey (1959) said:

Longwell (1922) discovered the Muddy Mountain overthrust in southeastern Nevada, in which a block of Paleozoic strata with a stratigraphic thickness of about 25,000 feet had overridden the same section for about 15 miles.



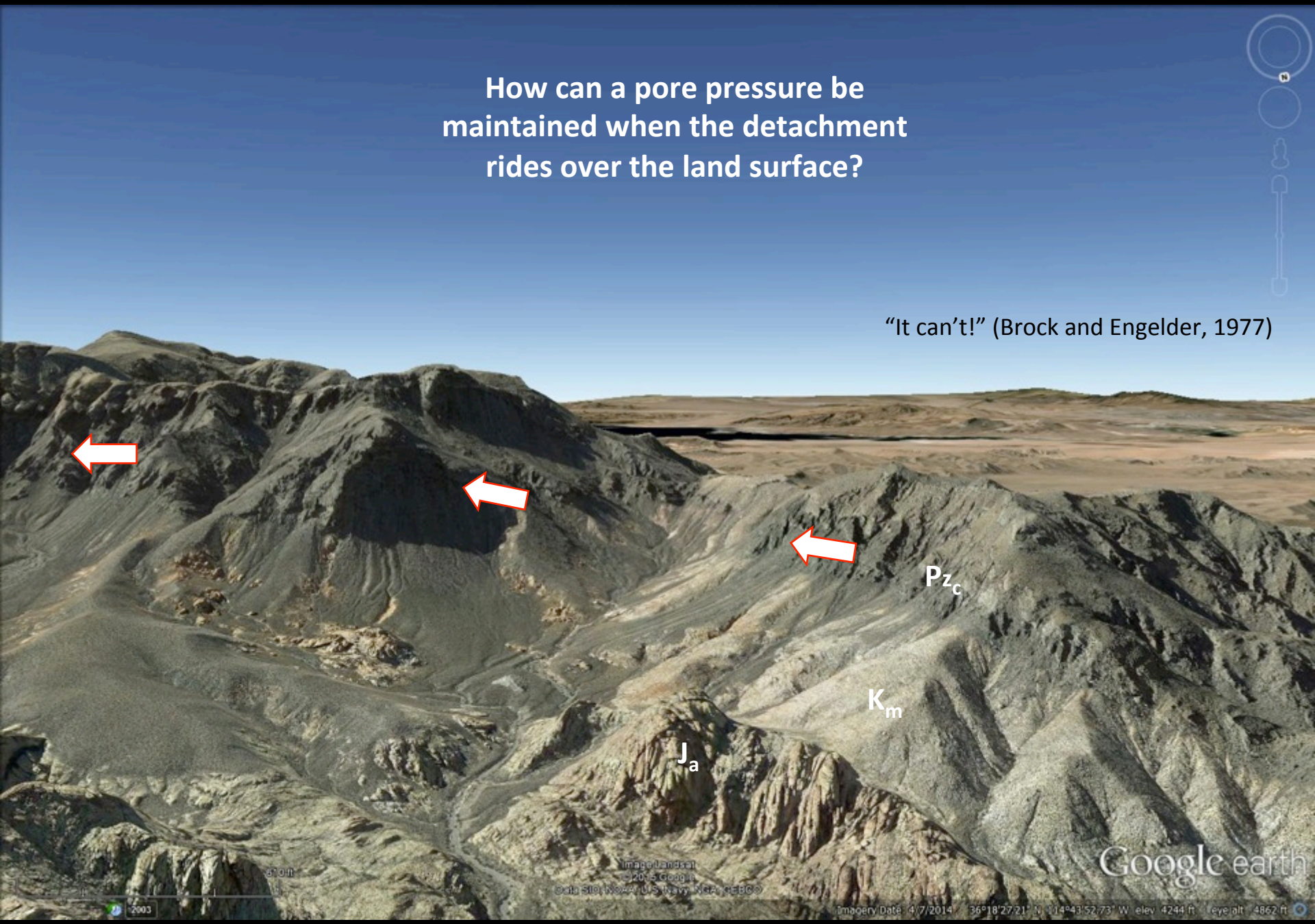
Engelder – Kodachrome Slide

Buffington Window
Looking west (1971)


Muddy Mountain Thrust
J_a
Pz_c
K_m
99 Ma fore-thrust debris (Fleck and Carr, 1990)
Google earth

How can a pore pressure be maintained when the detachment rides over the land surface?

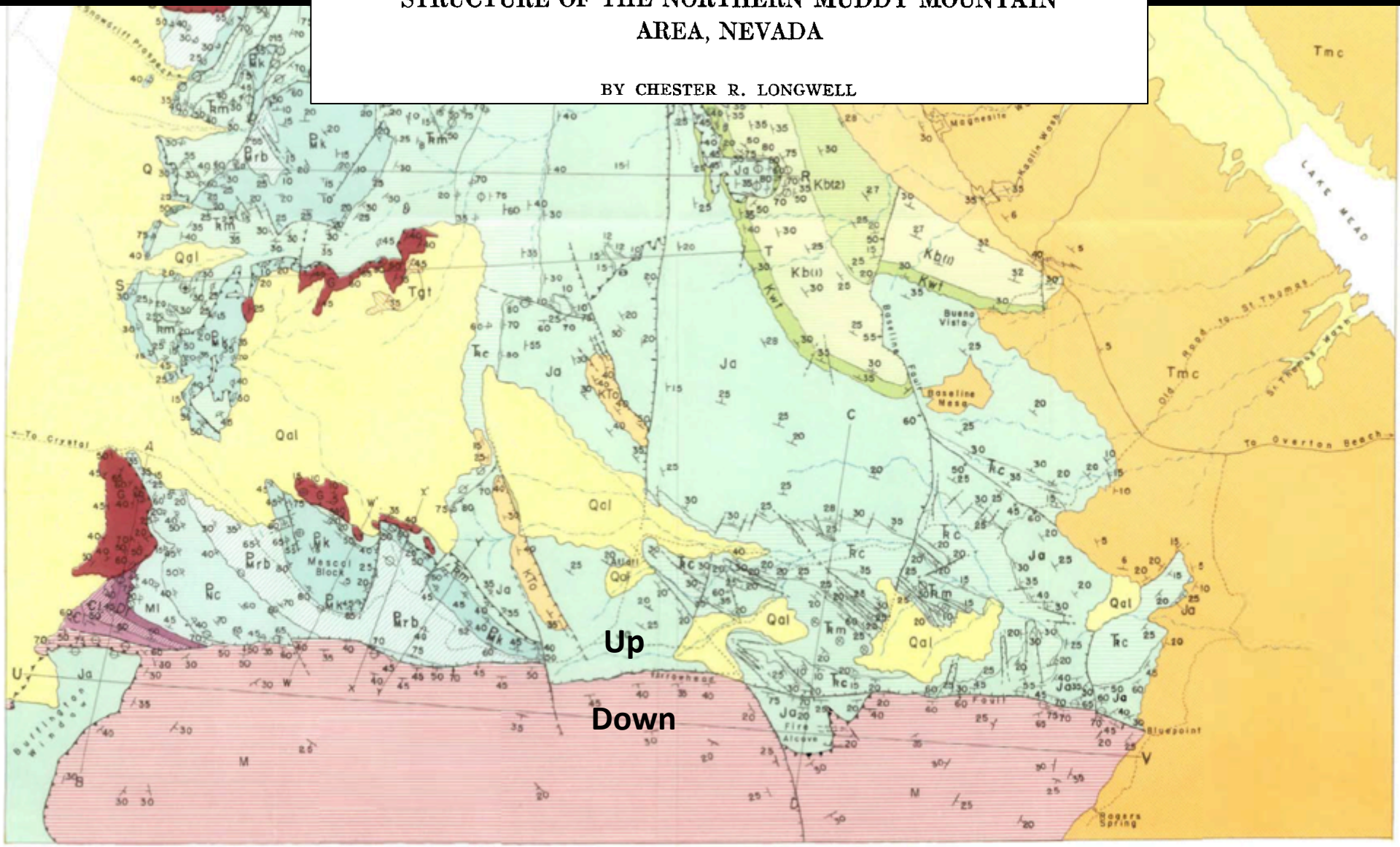
"It can't!" (Brock and Engelder, 1977)



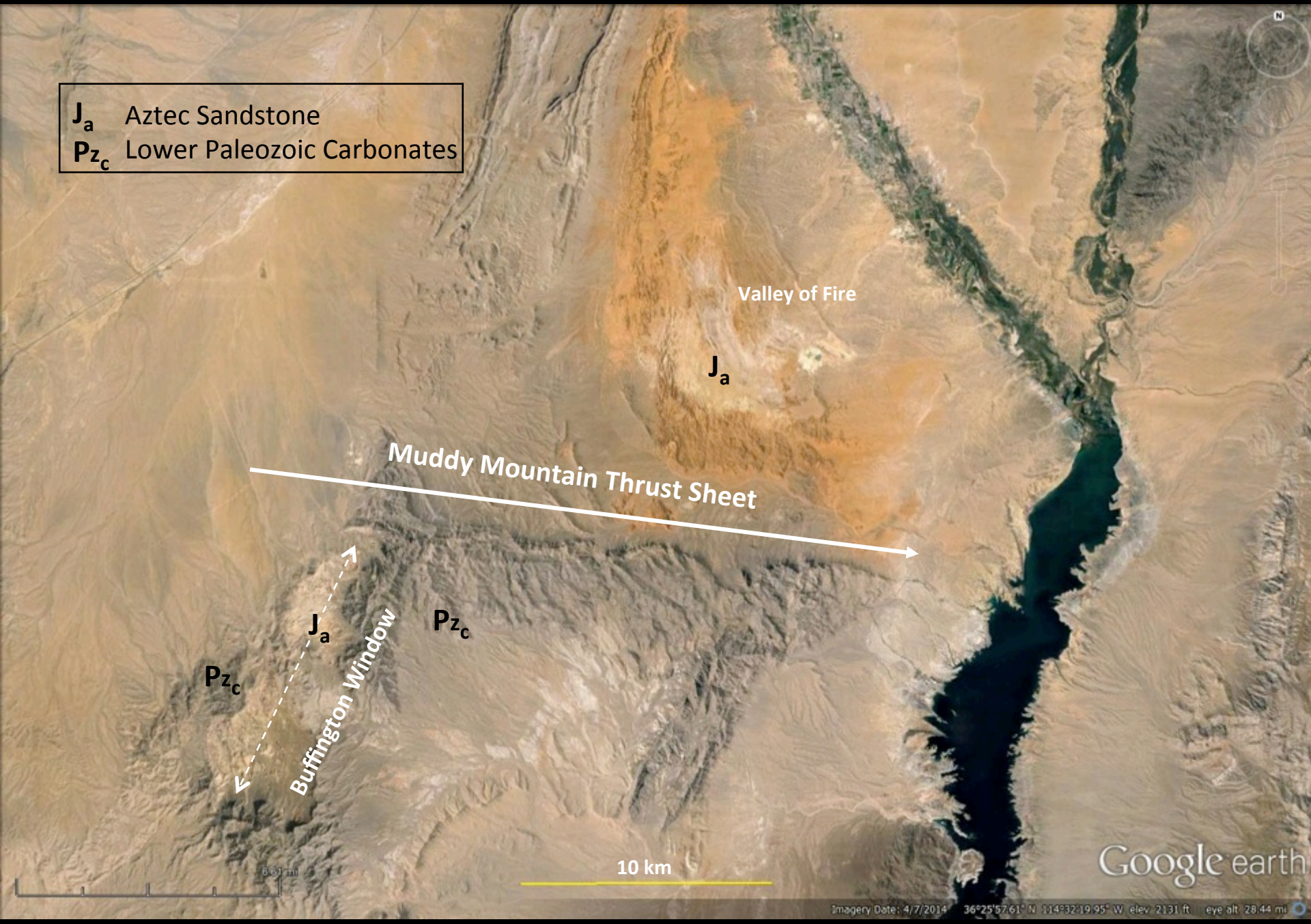
BULLETIN OF THE GEOLOGICAL SOCIETY OF AMERICA
VOL. 60, PP. 923-968, 14 FIGS, 11 PLS. MAY 1949

STRUCTURE OF THE NORTHERN MUDDY MOUNTAIN AREA, NEVADA

BY CHESTER R. LONGWELL

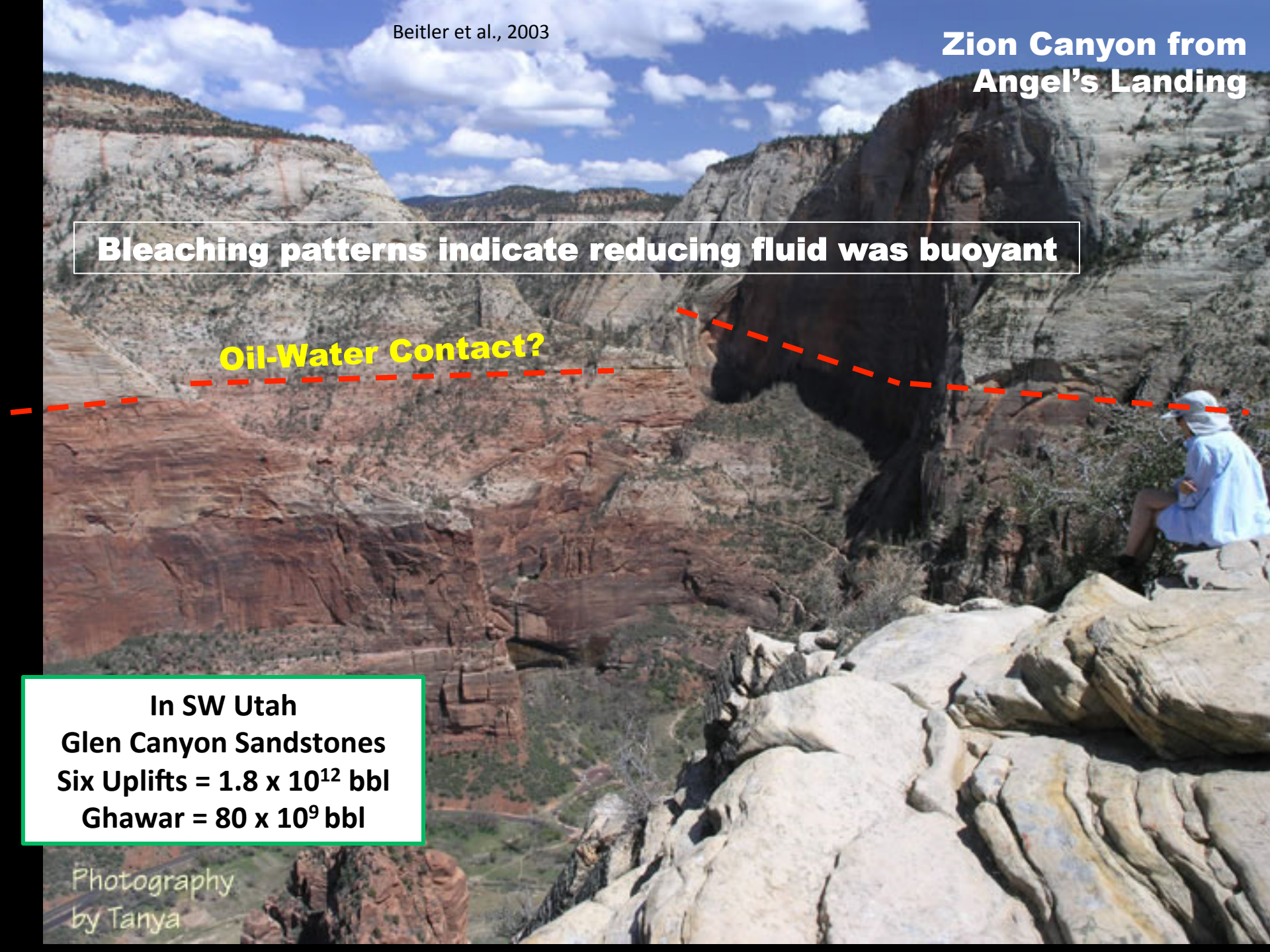


GEOLOGIC AND TECTONIC MAP OF THE NORTHERN MUDDY MOUNTAIN AREA


J_a Aztec Sandstone
Pz_c Lower Paleozoic Carbonates
Valley of Fire
J_a
Muddy Mountain Thrust Sheet
J_a
Pz_c
Pz_c
Buffington Window
10 km
Google earth

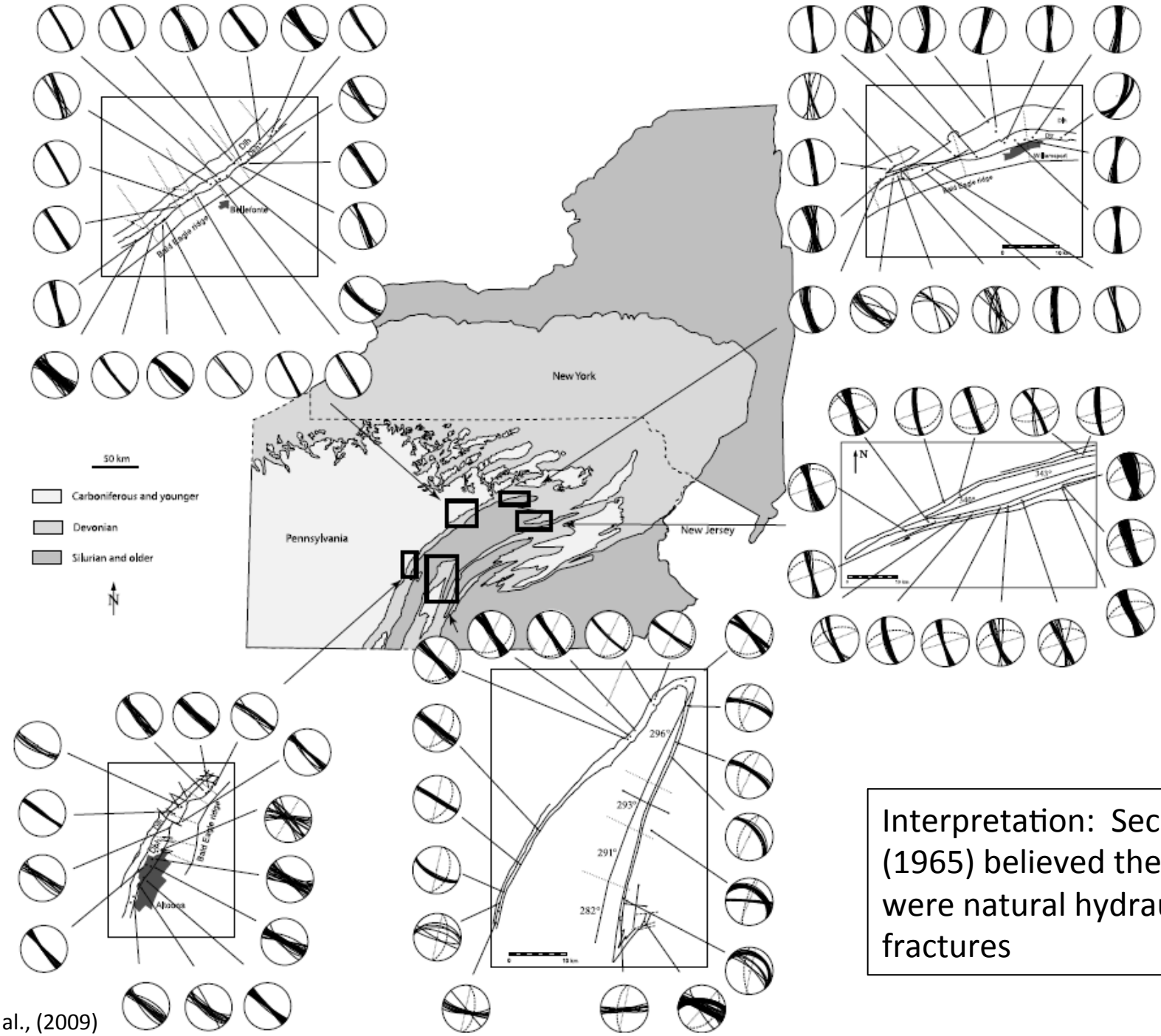
Beitler et al., 2003

Zion National Park from Checkerboard Mesa


Beitler et al., 2003
Zion Canyon from
Angel's Landing
Bleaching patterns indicate reducing fluid was buoyant
Oil-Water Contact?
In SW Utah
Glen Canyon Sandstones
Six Uplifts = 1.8 x 10^{12} bbl
Ghawar = 80 x 10^{9} bbl
Photography
by Tanya

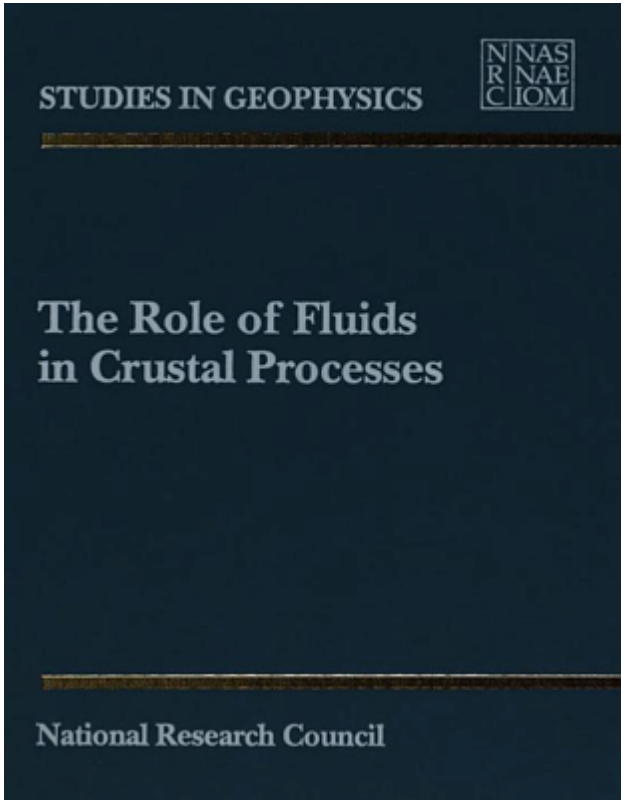

Angel's Landing
5 km
9
Checkerboard Mesa
Oil-water contact
© 2015 Google
2.44 mi
Imagery Date: 4/22/2013 37°13'29.71" N 112°53'26.25" W elev 5533 ft

Valley of Fire



Interpretation: Secor (1965) believed these were natural hydraulic fractures

Engelder et al., (2009)



Smoluchowski's Dilemma Revisited: A Note on the Fluid Pressure History of the Central Appalachian Fold-Thrust Belt

9

TERRY ENGELDER
The Pennsylvania State University

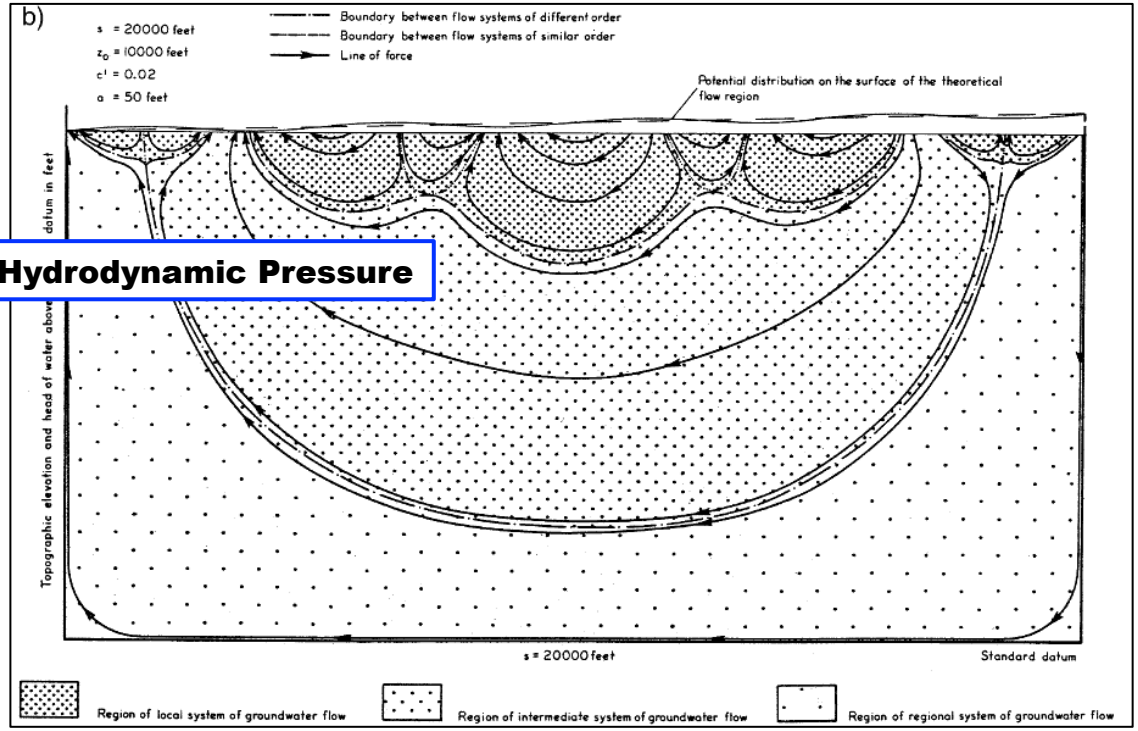
Not every scientific paper is a smash hit!

Smoluchowski's Dilemma Revisited: A Note on the Fluid Pressure History of the Central Appalachian Fold-Thrust Belt

T **ENGELDER** - The Role of Fluids in Crustal Processes, 1990 - books.google.com

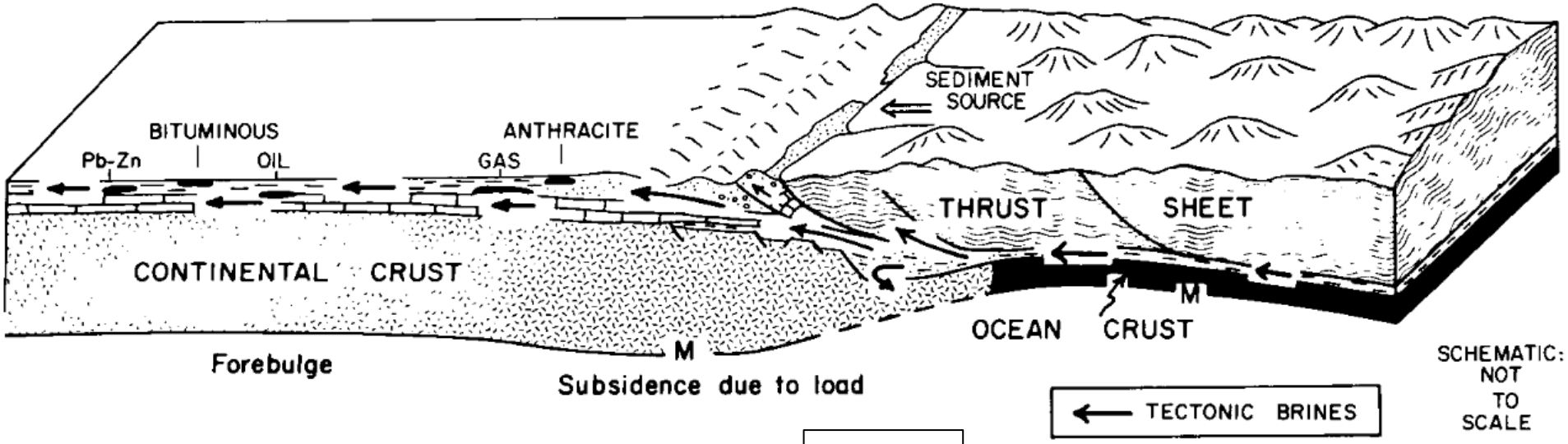
ABSTRACT Cross-fold joints in the Central Appalachian fold-thrust belt propagated during periods of abnormally high fluid pressure prior to tectonic compaction and the development of first-order Alleghanian structures in the valley and ridge. These early joints, found in ...

Cited by 2 Related articles All 2 versions Cite Save

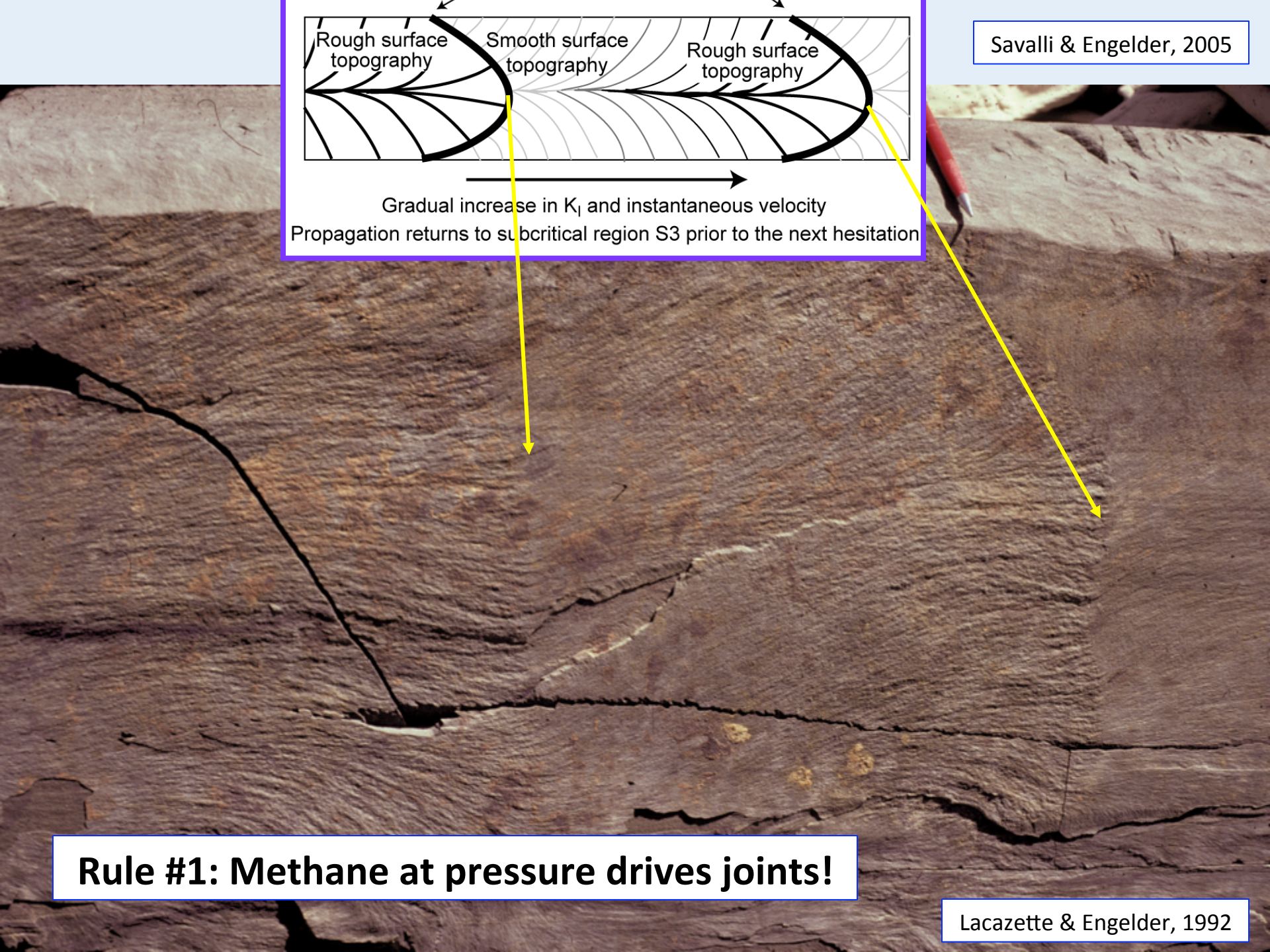


Hydrodynamic Pressure

Toth, 1962



Oliver, 1986

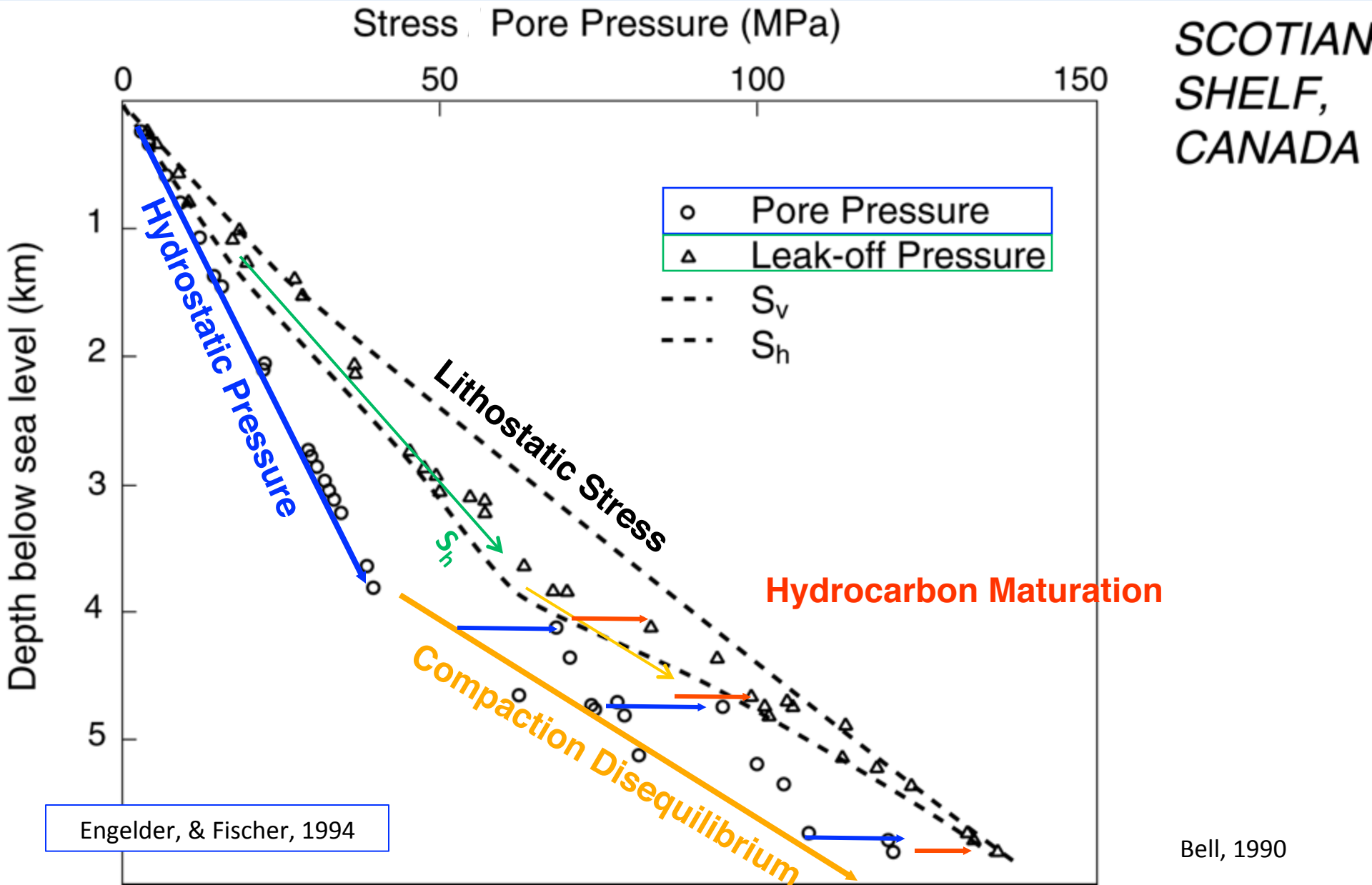


Savalli & Engelder, 2005

Rule #1: Methane at pressure drives joints!

Lacazette & Engelder, 1992

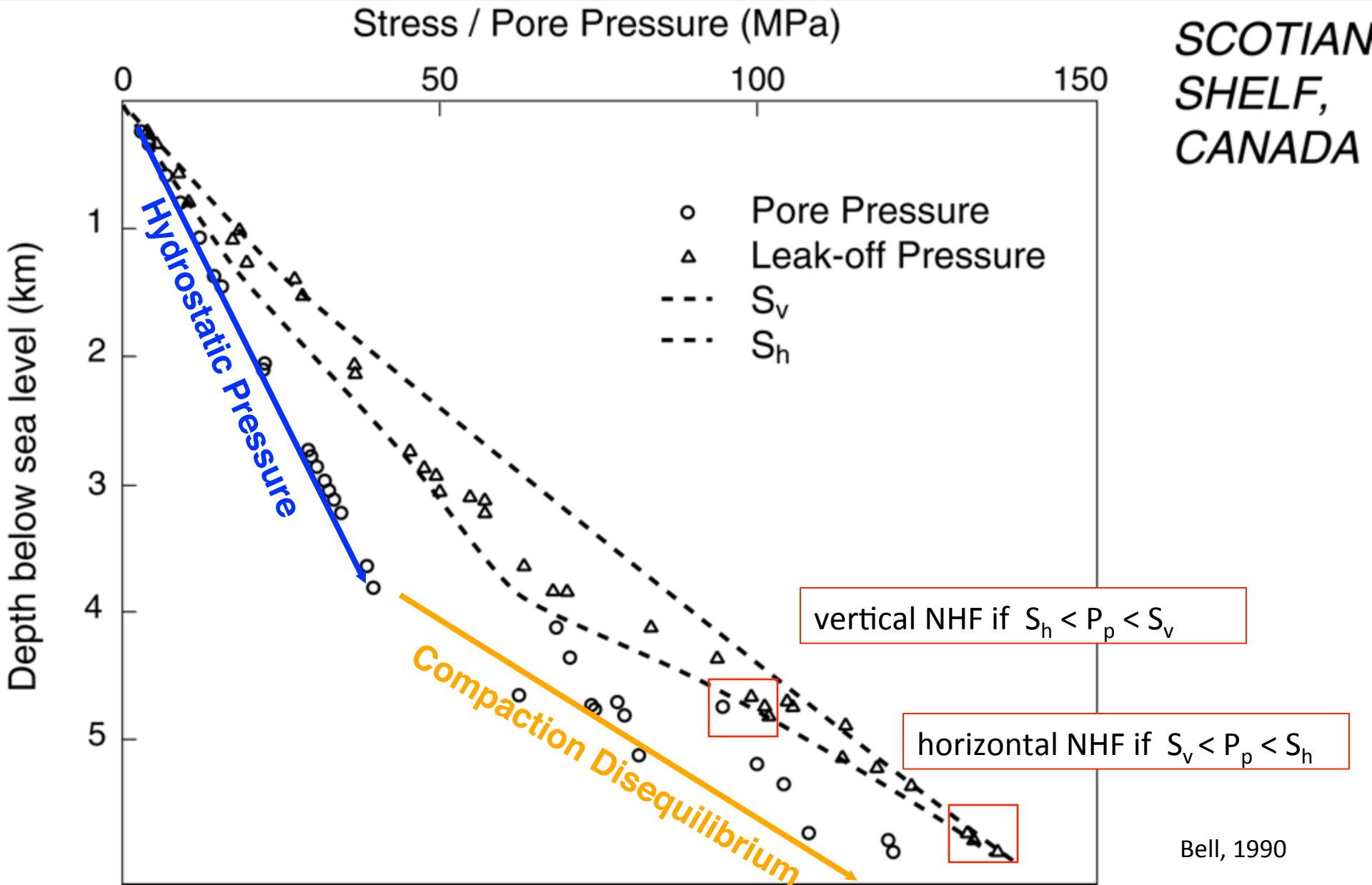
Rule #2: Orientation of NHF controlled by superposition of gravity-related stress and tectonic stress yoked to pore pressure!



Engelder, & Fischer, 1994

Bell, 1990

Rule #2: Orientation of NHF controlled by superposition of gravity-related stress and tectonic stress yoked to pore pressure!

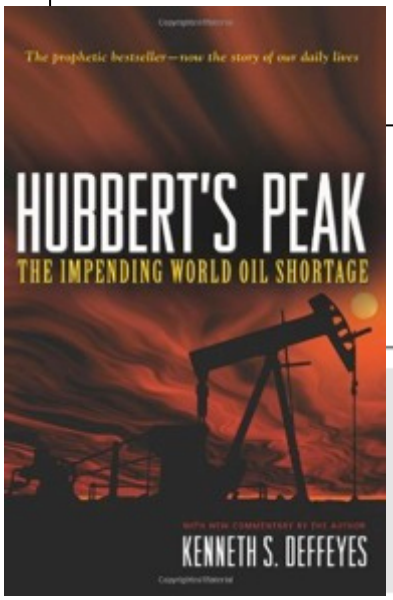


BULLETIN OF THE GEOLOGICAL SOCIETY OF AMERICA
VOL. 70, PP. 115-166, 32 FIGS. FEBRUARY 1959

ROLE OF FLUID PRESSURE IN MECHANICS OF OVERTHRUST FAULTING

I. Mechanics of Fluid-Filled Porous Solids and Its Application to Overthrust Faulting

By M. King Hubbert and William W. Rubey



Journal of Structural Geology 69 (2014) 519–537

Journal of Structural Geology

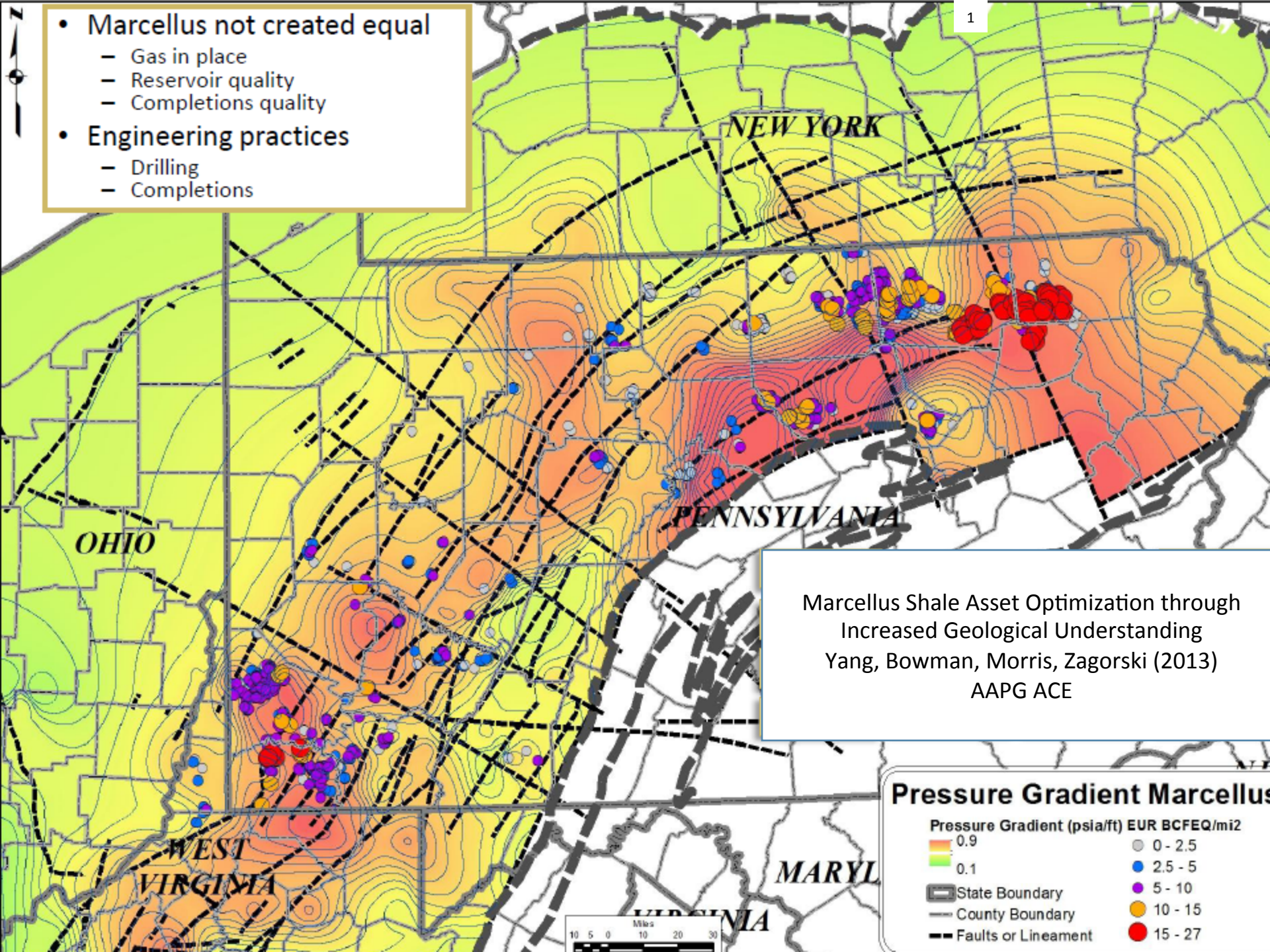
journal homepage: www.elsevier.com/locate/jsg

Revisiting the Hubbert–Rubey pore pressure model for overthrust faulting: Inferences from bedding-parallel detachment surfaces within Middle Devonian gas shale, the Appalachian Basin, USA

Murat G. Aydin [1], Terry Engelder*

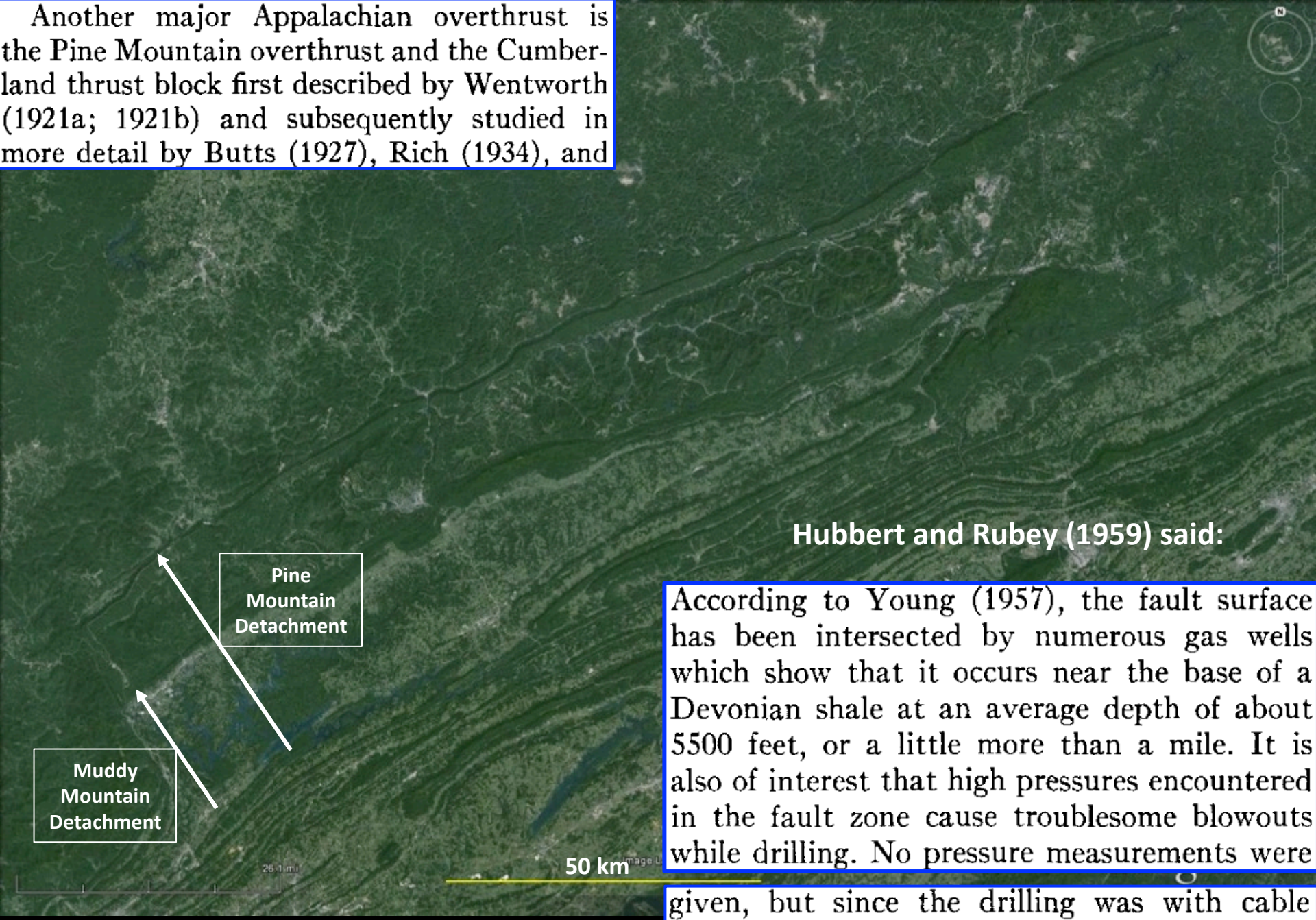
Department of Geosciences, The Pennsylvania State University, University Park, PA 16802, USA

- Marcellus not created equal
  - Gas in place
  - Reservoir quality
  - Completions quality
- Engineering practices
  - Drilling
  - Completions



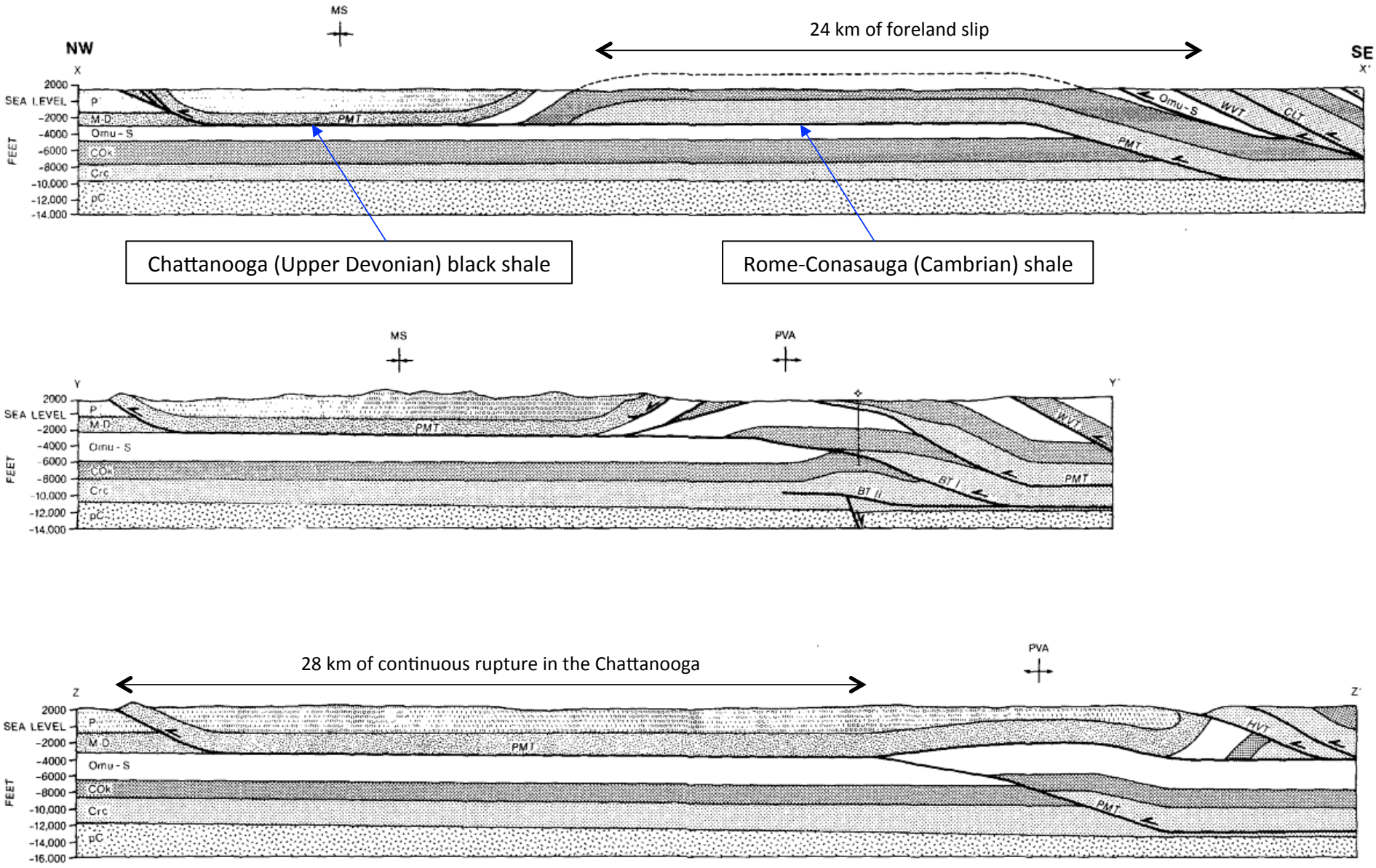
Marcellus Shale Asset Optimization through Increased Geological Understanding
Yang, Bowman, Morris, Zagorski (2013)
AAPG ACE

Another major Appalachian overthrust is the Pine Mountain overthrust and the Cumberland thrust block first described by Wentworth (1921a; 1921b) and subsequently studied in more detail by Butts (1927), Rich (1934), and

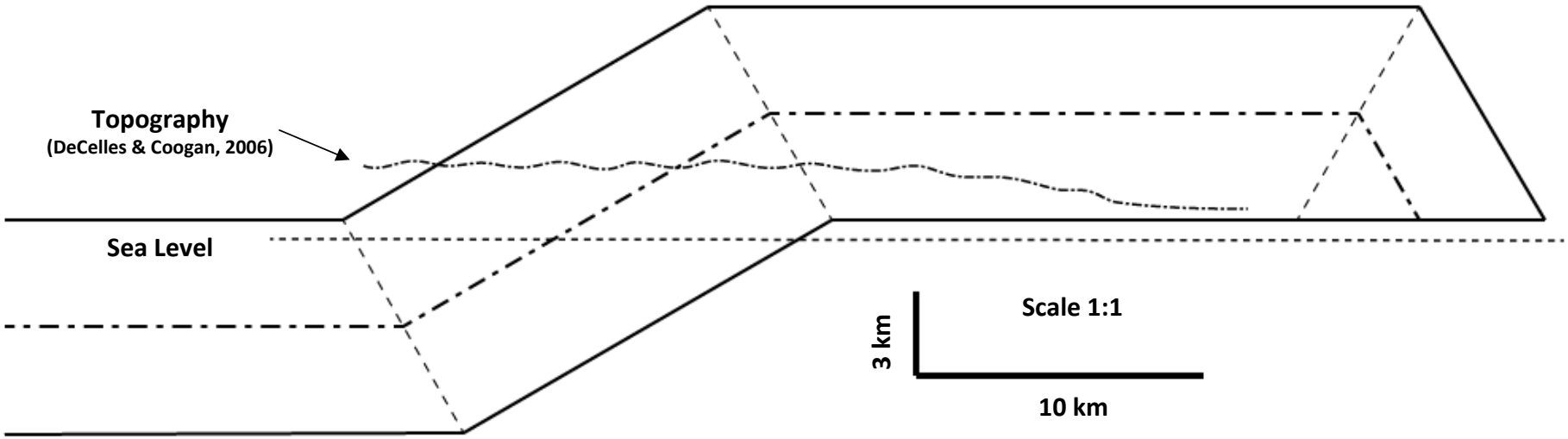


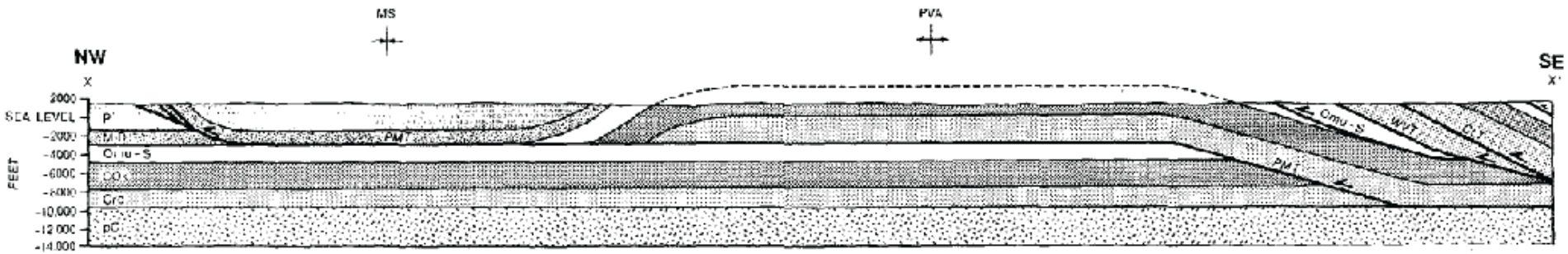
Hubbert and Rubey (1959) said:

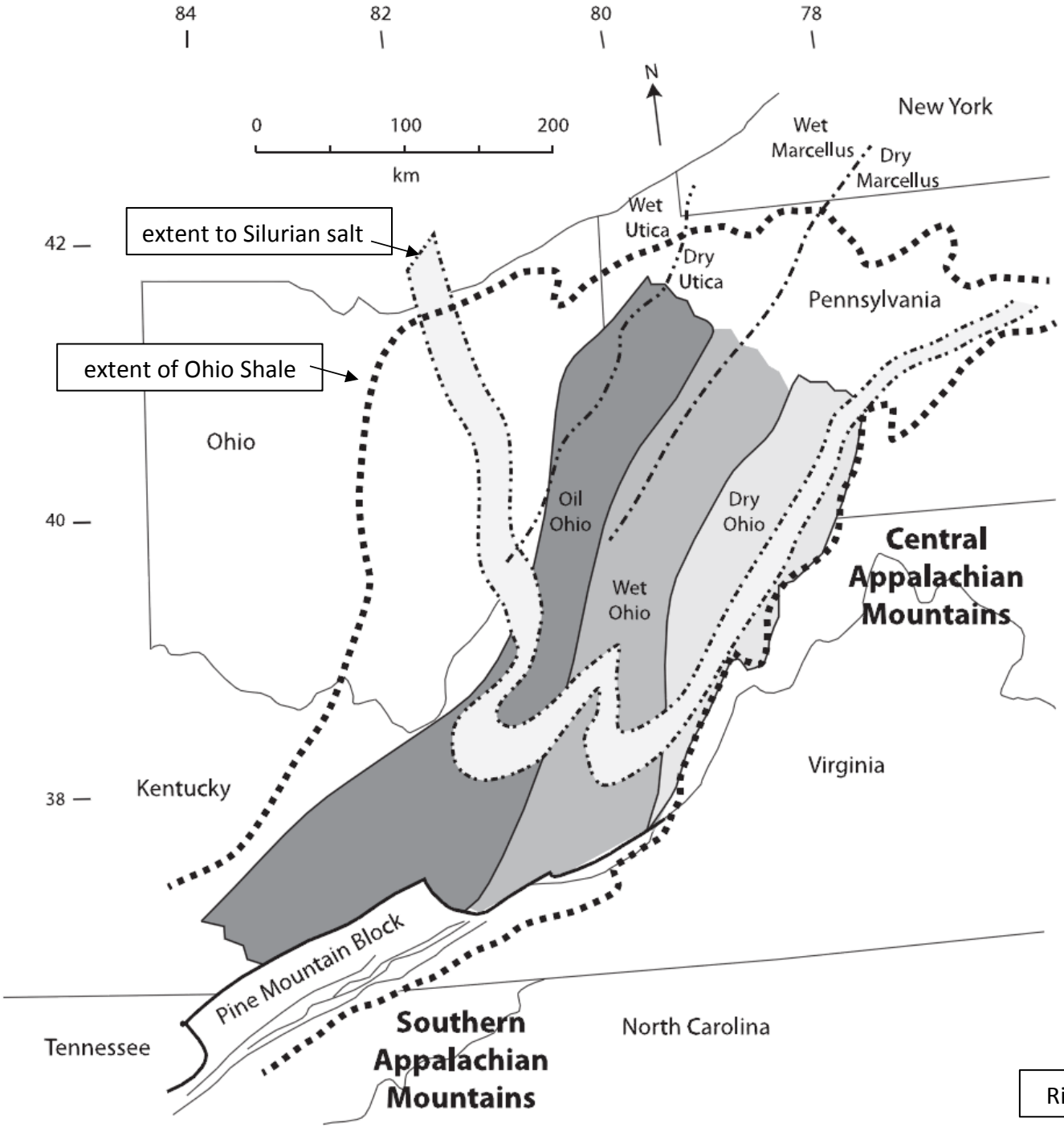
According to Young (1957), the fault surface has been intersected by numerous gas wells which show that it occurs near the base of a Devonian shale at an average depth of about 5500 feet, or a little more than a mile. It is also of interest that high pressures encountered in the fault zone cause troublesome blowouts while drilling. No pressure measurements were given, but since the drilling was with cable tools this does not necessarily imply that the pressure was abnormally high.



Mitra, 1988, GSAB

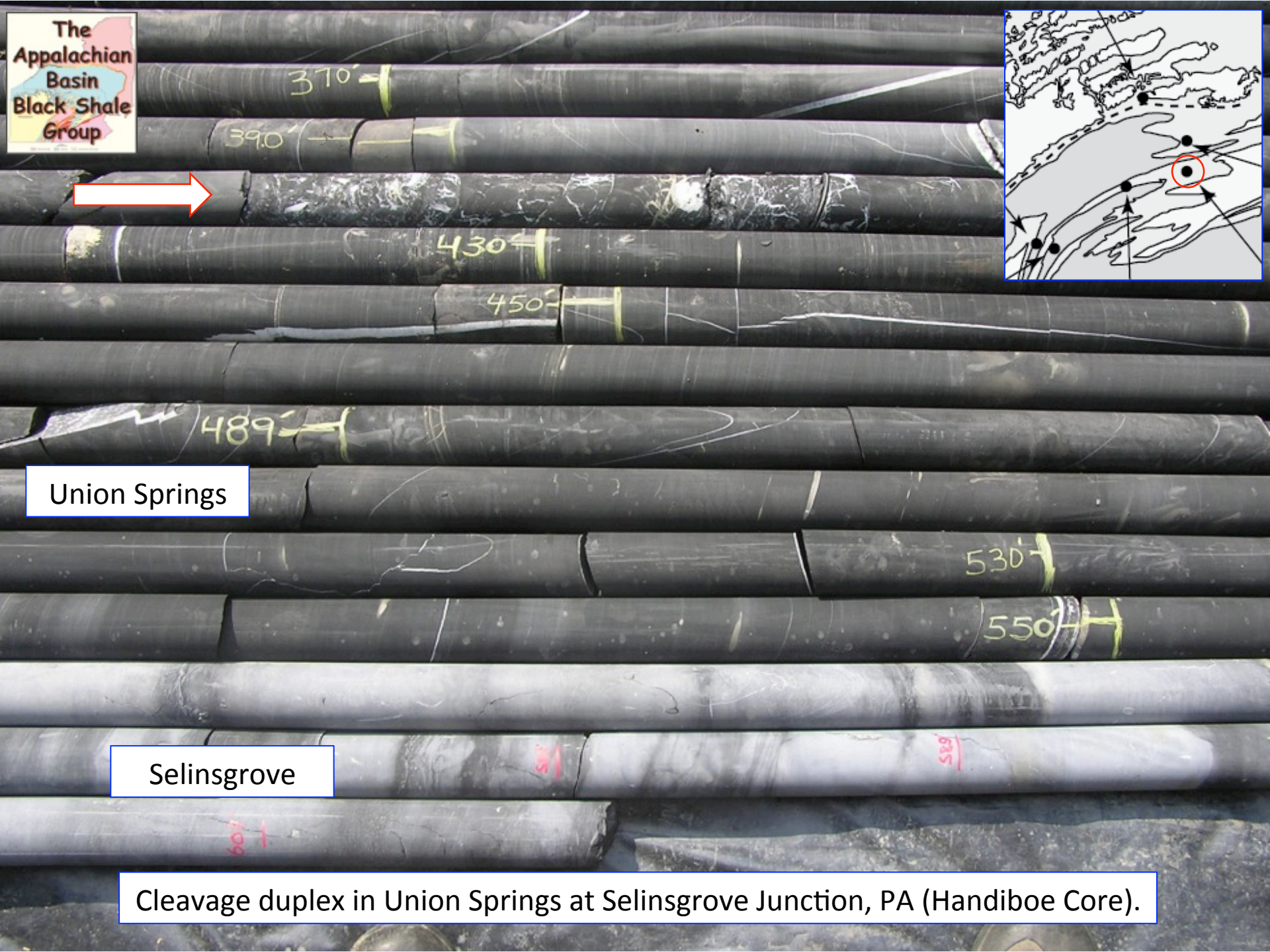

Topography
(DeCelles & Coogan, 2006)
Sea Level
Scale 1:1
3 km
10 km


MS
PVA
NW
X
SE
X'
2000
SEA LEVEL
-2000
-4000
-6000
-8000
-10,000
-12,000
-14,000
FEET
P
PM
Cmu-S
Cr
pC

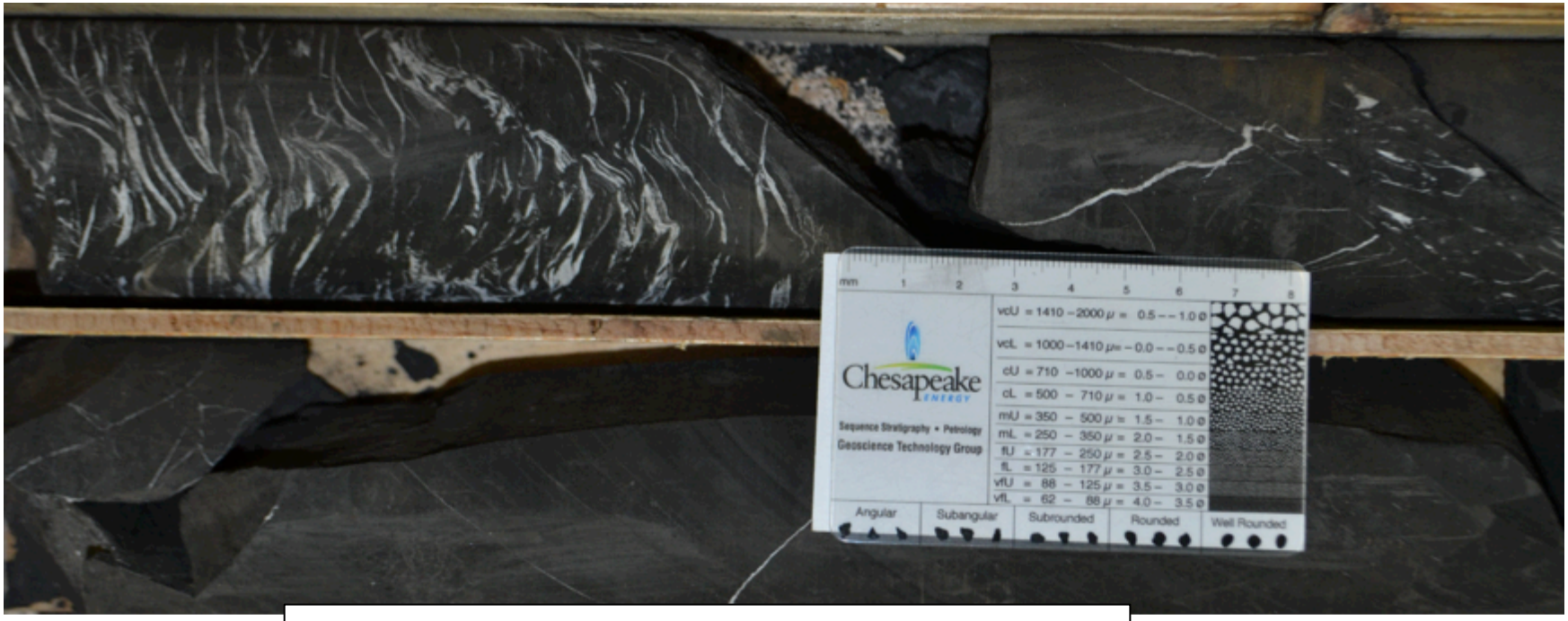


Rimmer et al., 1993

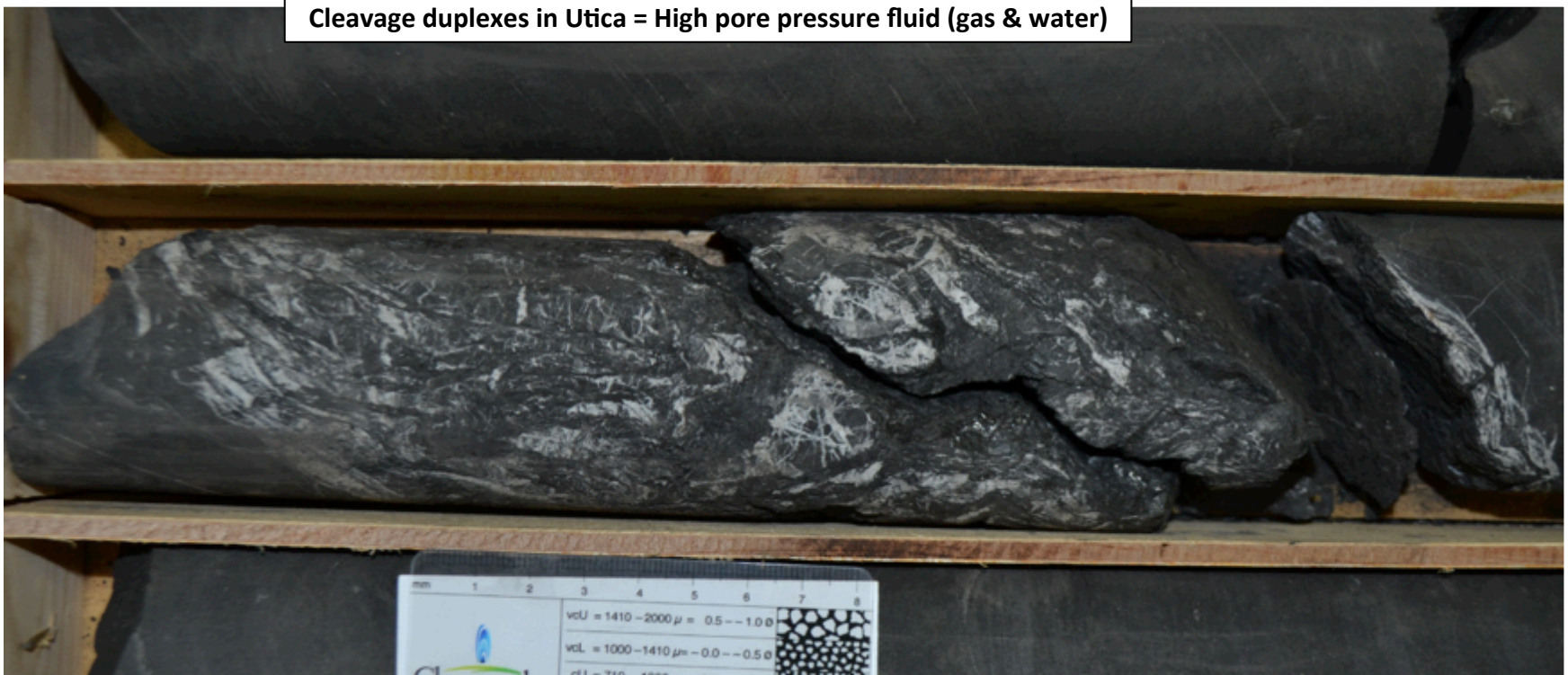
53 cm thick cleavage duplex 2 m above the Selinsgrove Limestone in the Marcellus Formation at Newtown Hamilton.

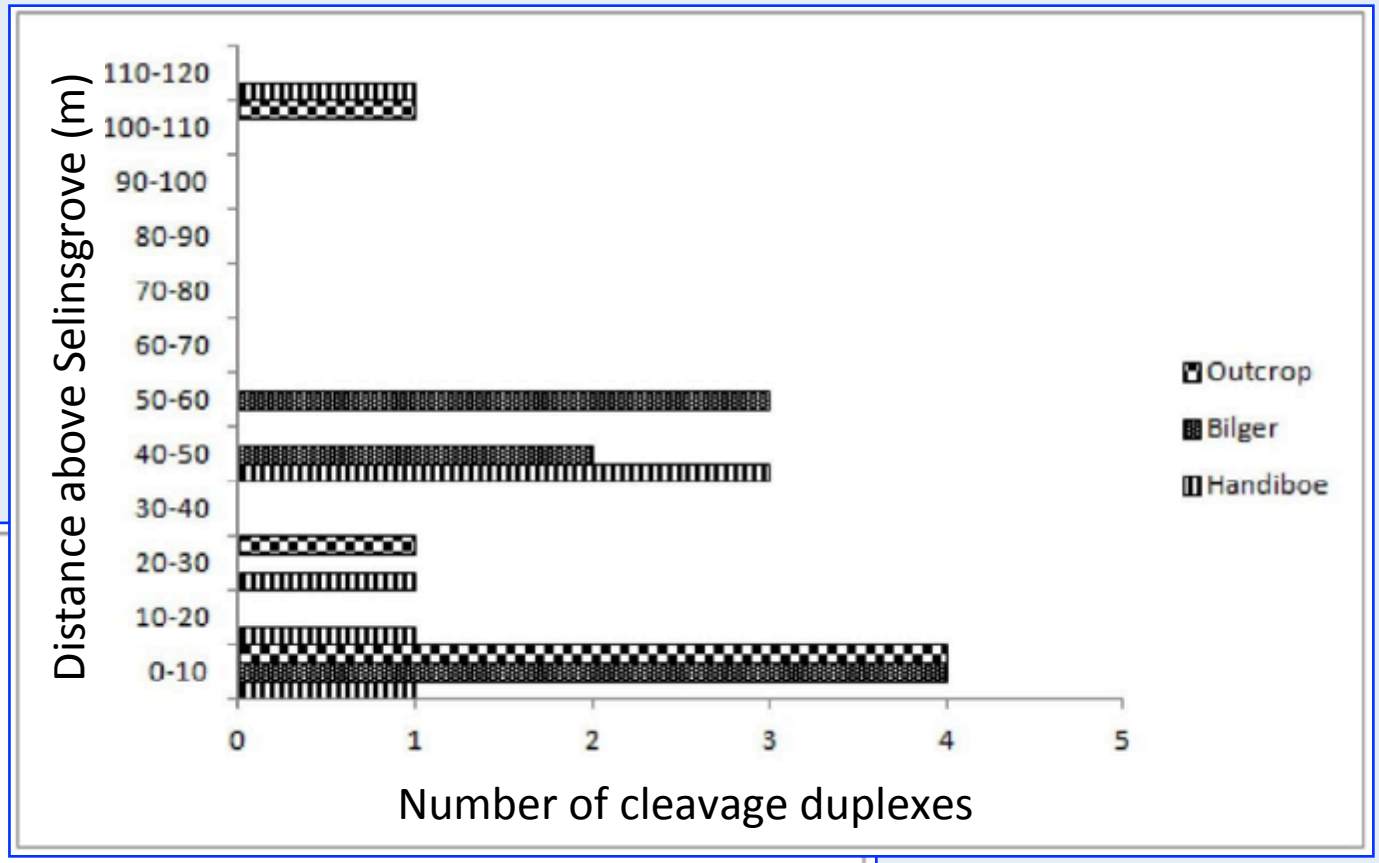


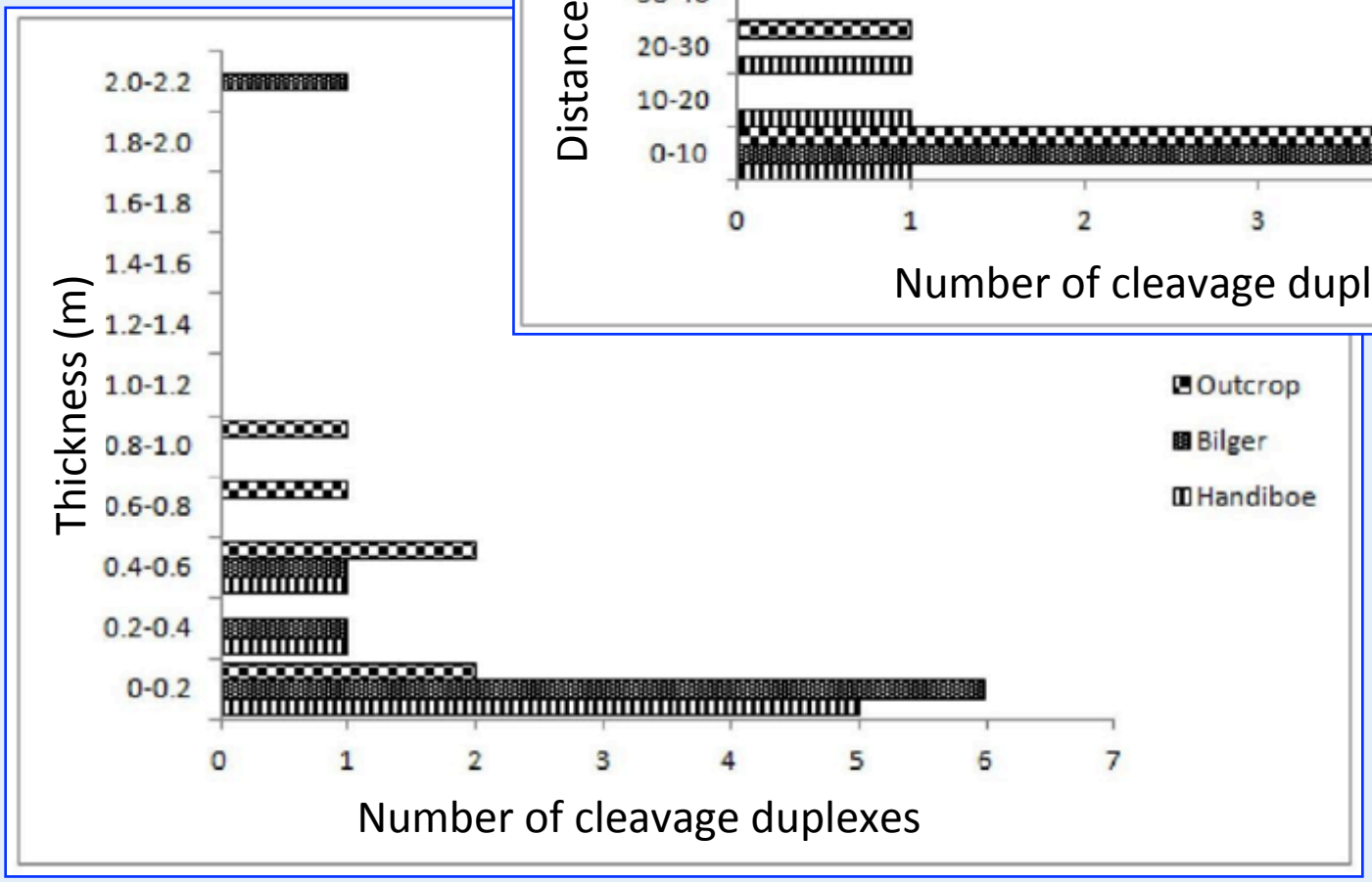
Cleavage duplex in Union Springs at Selinsgrove Junction, PA (Handiboe Core).

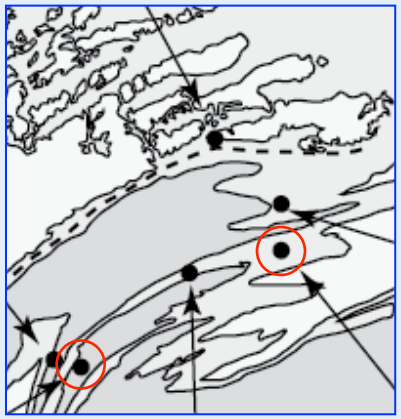


Cleavage duplexes in Utica = High pore pressure fluid (gas & water)

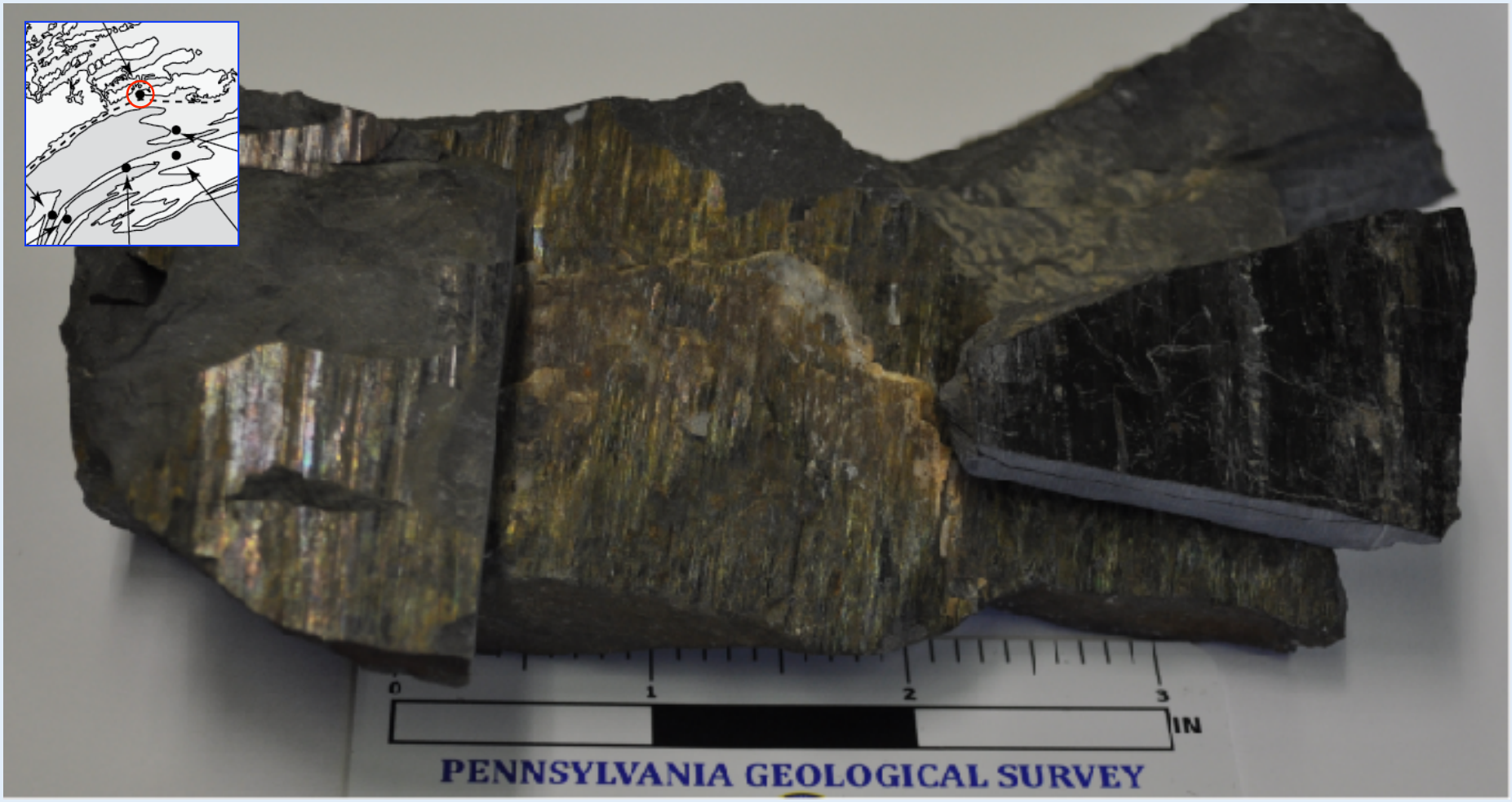



Distance above Selinsgrove (m)
110-120
100-110
90-100
80-90
70-80
60-70
50-60
40-50
30-40
20-30
10-20
0-10
0
1
2
3
4
5
Number of cleavage duplexes
Outcrop
Bilger
Handiboe


Thickness (m)
2.0-2.2
1.8-2.0
1.6-1.8
1.4-1.6
1.2-1.4
1.0-1.2
0.8-1.0
0.6-0.8
0.4-0.6
0.2-0.4
0-0.2
0
1
2
3
4
5
6
7
Number of cleavage duplexes
Outcrop
Bilger
Handiboe



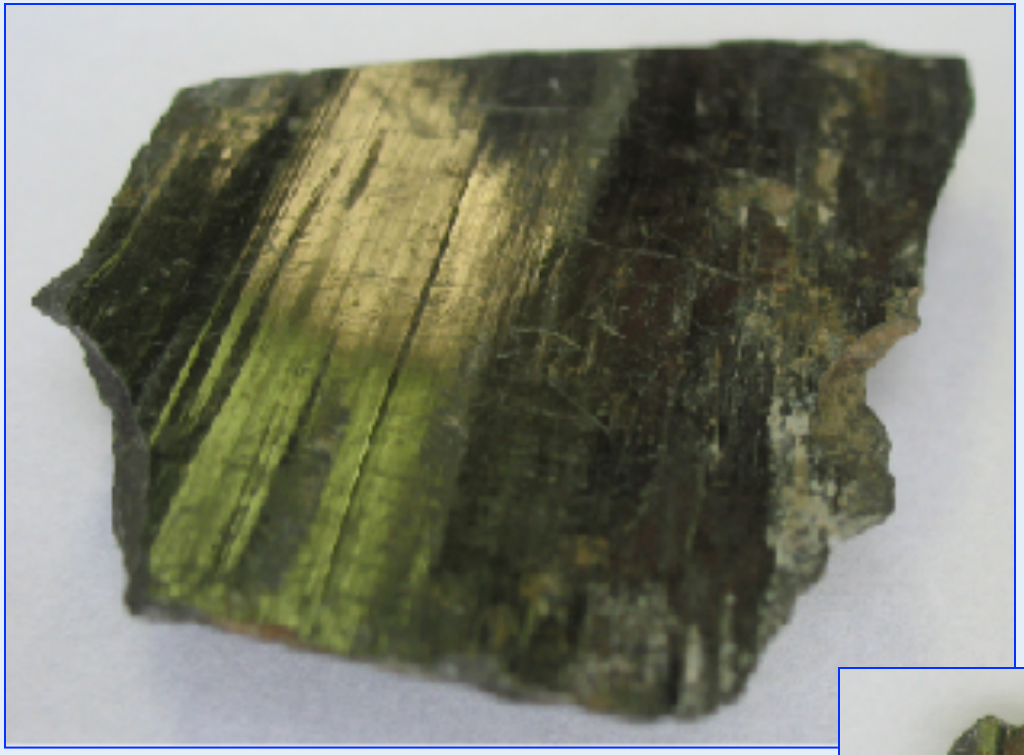
Bedding-parallel slip surfaces in the Lock Haven Formation north of Williamsport, PA.

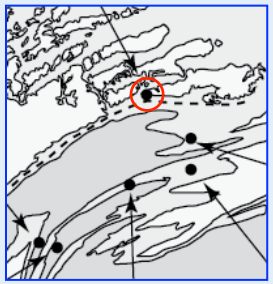


A mirror slip surface.

Green chlorite over white quartz over 'black' graywacke with ridge-in-groove striation.

A mirror slip surface that appears black when green chlorite sits directly on 'black' graywacke.





(Left) Mirror slip surface of a chlorite film on a greywacke matrix. Olive green light refracts from the mirror.

(Right) Ridge-in-groove striation on bedding slip surface in Lock Haven Formation showing the olive green color of a chlorite film on white quartz fibers.

The morphology of intraformational slip surfaces (ISS) in the Mahantango-Marcellus section

slip fibers

ridge-in-groove striations

Mahantango (Bilger 117.49 m)

Oatka Creek (Handiboe 145.57 m)

Union Springs (Handiboe 2.36 m)

Union Springs (Erb 4.30 m)

Progressive mineral development on slip surfaces.

Pyrite and quartz entrained in fibers.

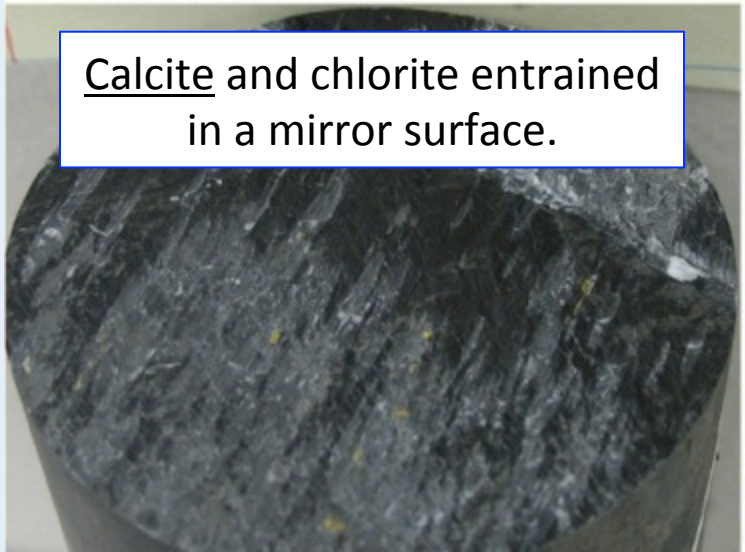
Mahantango (Bilger, 108.81 m)

Pyrite entrained in a ridge-in-grove striations of chlorite .

Union Springs (Erb, 4.63 m)

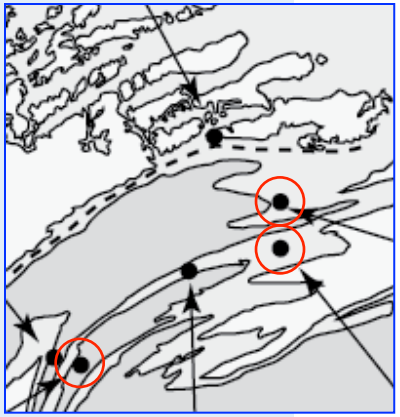
Union Springs (Handiboe, 10.57 m)

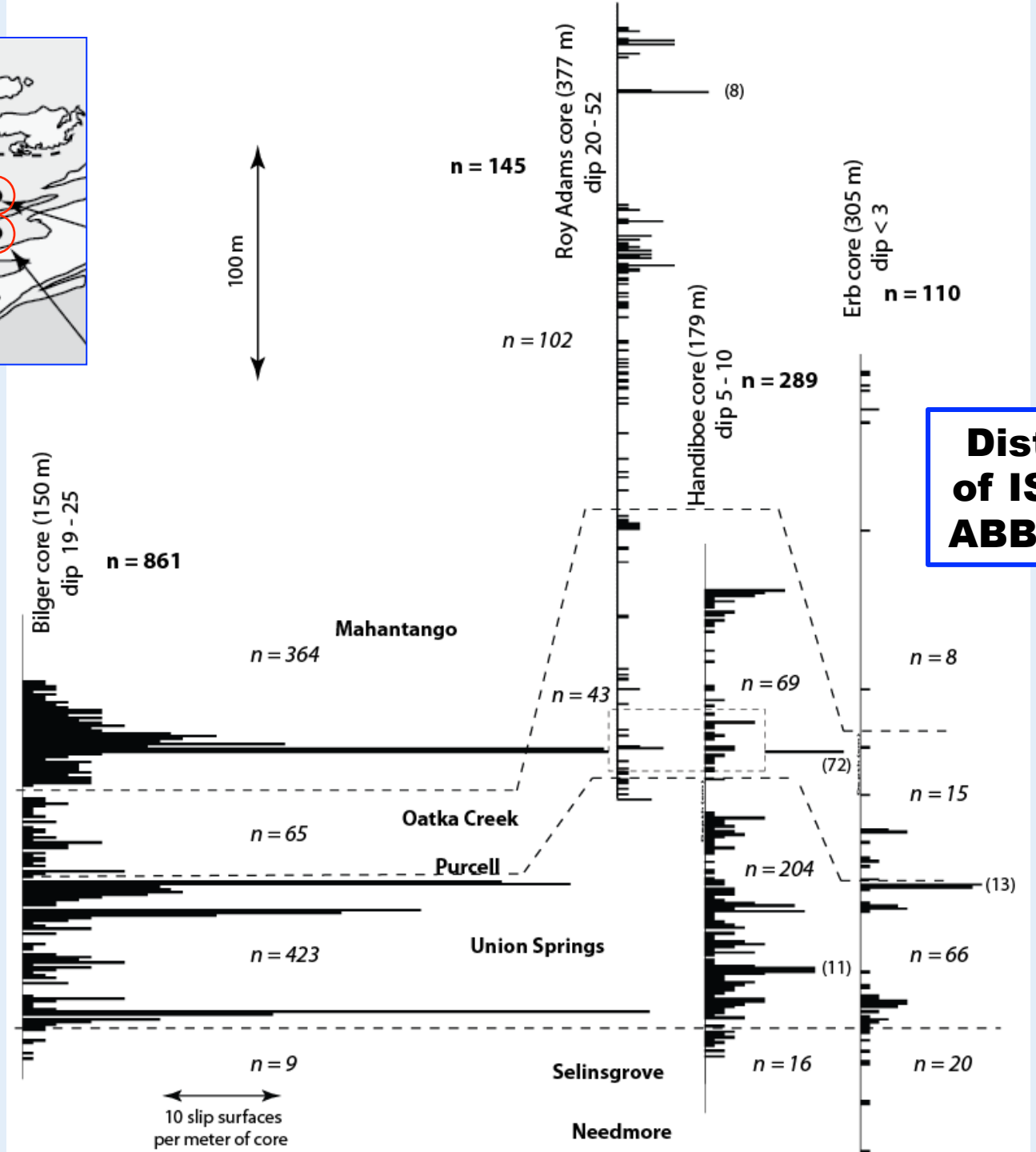
Union Springs (Handiboe, 31.84 m)



Calcite and chlorite entrained in a mirror surface.

A matrix breccia entrained in calcite fibers.





Distribution of ISS in four ABBSG cores

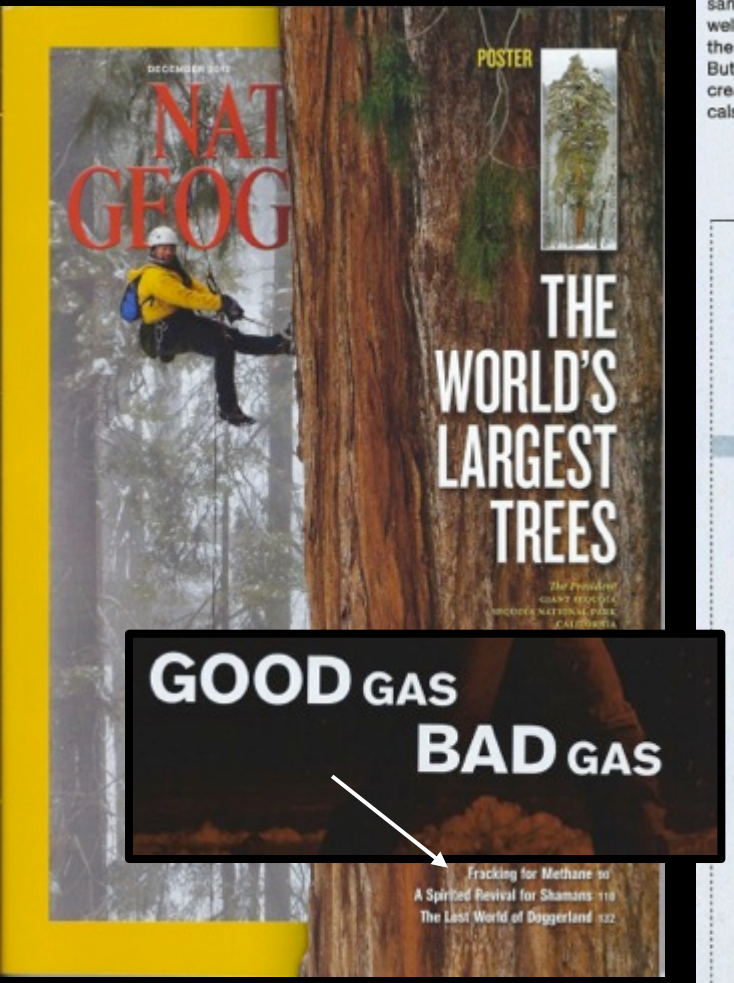
Fracking: Science and the Media

Christopher Joyce

Correspondent: Science Desk
National Public Radio (NPR)

- I have been in science journalism for more than 30 years and I have never seen more **scientific disinformation** on any topic as **fracking**. I am amazed at the level of both inadvertent and purposeful disinformation.

http://www.youtube.com/watch?v=giCRpuI-YBA



FEAR OF FRACKING

A key technique in shale drilling is hydraulic fracturing, aka fracking. A fluid mix of water, sand, and chemicals is pumped down the well at high pressure, creating fissures in the shale that let gas flow into the well. But the whole drilling process may also create pathways that allow gas or chemicals to pollute drinking water.

GRAPHICS: LAWSON PARKER AND MATTHEW TWOMBLY, NGM STAFF
SOURCES: U.S. EPA (EMISSIONS); ANTHONY INGRAFFEA, CORNELL UNIVERSITY (DRILLING)

The fracking debate: Terry Engelder at TEDxPSU

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