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

Subtitle: A corollary for the Hubbert-Rubey (1959) solution to Escher’s “colossal over-shove” problem

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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 great difficulties”
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) great difficulty was understood in terms of mechanics.

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

Drawing from Hubbert and Rubey (1959)

Examples of the uniaxial crushing strength of rock
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.

The density hoops supporting a silo is an analog for stress in the earth and depth-related increase in rock strength.
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.
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.
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
Davis and Engelder, 1985

Low Strength Detachment

Extant of Silurian Salt

Appalachian Plateau Detachment Sheet

Juniata Culmination

Catskill Mts.

Lackawanna syncline

Davis and Engelder, 1985

OH

PA

Salina Salt

Salt Withdrawal

Tully Mahantango Marcellus Onondaga
Engelder, 1979

Low Strength Detachment

Layer-Parallel Shortening within Detachment Sheet

230 km

15% Layer-Parallel Shortening (Allegheny Front to Buffalo)
High Temperature – No
Wedge Strength – No
Salt Weakness - No
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:

1. Requires a mechanism(s) for generating abnormal pore pressure.
   - 1. High permeability rock

2. Requires a mechanism(s) for delivering abnormal pressure to the slip surface.
   - 1. The popped top

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

Biot actually suggested this experiment to Hubbert

Expansion of cold air

Time-dependent expansion
Mechanisms for Generating Overpressure

• 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

Most effective generation mechanisms

Swarbrick & Osborne, 1998
Two (2) Hubbert-Rubey (1959) mechanisms for abnormal pore pressure (mechanical compaction = stress mechanism - Orange) and (buoyancy = fluid dynamic mechanism - Red)
Deformation associated with the movement of the Muddy Mountain overthrust in the Buffington window, southeastern Nevada.

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
DeCelles & Coogan (2006) cross section

(Turonian - Coniacian: 93-88 Ma)

26.2 km displacement
26.2 km total shortening
3.5 km crustal thickening
elevation ≈ 2.8 km.

(Aptian-Early Albian?: >110 Ma)

Muddy Mountain thrust

DeCelles & Coogan (2006) cross section

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

Topography
(DeCelles & Coogan, 2006)

Sea Level

3 km

Scale 1:1

10 km

Aztec Sandstone with fore-thrust debris

Thrust distance without rear-end collapse (normal friction)
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.
Buffington Window
Looking west (1971)
99 Ma fore-thrust debris (Fleck and Carr, 1990)
How can a pore pressure be maintained when the detachment rides over the land surface?

“It can’t!” (Brock and Engelder, 1977)
STRUCTURE OF THE NORTHERN MUDDY MOUNTAIN AREA, NEVADA

BY CHESTER R. LONGWELL
Ja  Aztec Sandstone
Pz_c  Lower Paleozoic Carbonates
Oil-Water Contact?

Zion National Park from Checkerboard Mesa

Dune cross-strata: High permeability

Hematite

No Hematite

Navajo Sandstone

Horizontal bedding: Low permeability zones that restrict fluid flow

Beitler et al., 2003
Zion Canyon from Angel’s Landing

Bleaching patterns indicate reducing fluid was buoyant

Oil-Water Contact?

Beitler et al., 2003

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

Checkerboard Mesa

Oil-water contact
Interpretation: Secor (1965) believed these were natural hydraulic fractures.
Not every scientific paper is a smash hit!
Hydrodynamic Pressure

Toth, 1962

Oliver, 1986
Rule #1: Methane at pressure drives joints!

Lacazette & Engelder, 1992

Savalli & Engelder, 1992
Rule #2: Orientation of NHF controlled by superposition of gravity-related stress and tectonic stress yoked to pore pressure!
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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. Aydin¹, Terry Engelder*
- 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.
Chattanooga (Upper Devonian) black shale

Rome-Conasauga (Cambrian) shale

24 km of foreland slip

28 km of continuous rupture in the Chattanooga

6 km

Mitra, 1988, GSAB
Topography (DeCelles & Coogan, 2006)

Sea Level

Scale 1:1

3 km

10 km
extent to Silurian salt

extent of Ohio Shale
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)
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
Progressive mineral development on slip surfaces.

Pyrite and quartz entrained in fibers.

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

Calcite and chlorite entrained in a mirror surface.

A matrix breccia entrained in calcite fibers.
Distribution of ISS in four ABBSG cores
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.
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.

Wastewater
Leaky ponds
Contaminated wastewater from fracking is often stored in surface ponds, which can overflow or leak, polluting streams or groundwater.

Faulty wells
Wells are reinforced with steel casing and sealed with concrete. But poor cementing can leave gaps that allow methane or fracturing chemicals to contaminate drinking-water aquifers.

Fissures
Fracking fissures might connect to natural ones, allowing pollutants to migrate. Whether they’d climb thousands of feet to shallow aquifers isn’t clear.

Diagram not drawn to scale

National Geographic

Taughannock Falls State Park, Trumansburg, NY

GOOD GAS BAD GAS

Fracking for Methane 90
A Spirited Revival for Shannons 710
The Last World of Diggerland 122