

Formation Ductility and its Critical Role in Buoyant Fluid (CO₂ and Hydrocarbon) Entrapment

Adapted from a Presentation Given to the Midland Texas Chapter of the Society of Independent Society of Professional Earth Scientists

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This subject of ductile geological formations has long been on my mind. Many specialized treatments of ductility in geologic formations and metals are addressed in the literature but rarely treated in a more general way. I am attempting to do this with this discussion/presentation. We will be covering 1) the related 'plasticity' definitions and begin to use the more definitive visco-plastic term for it, 2) why visco-plastic formations (VPFs) are important considerations, and 3) how they explain some behavior and features in oil and gas and, more generally, in the earth that might be unanticipated to some in the audience. Much of what I am presenting will be familiar to most of you but maybe not in a complete sense or with the case histories I use to demonstrate the commercial importance ductile behavior. Much of this comes from a presentation I recently gave for a group of professional earth scientists in Midland Texas.

Abstract

The roles that plastic, i.e., non-brittle, formations are actively playing in the subsurface is beginning to get greater attention today. The conversations generally involve either drilling difficulties or their influence on hydraulic fracturing geometries. In those two arenas it is the so-called clay-rich shale zones that prompts the interest. It stems from the oil and gas industry's worries about avoiding drilling failures and in modeling visco-plastic formation roles in forecasting hydraulic fracture geometries.

But this plasticity, alias visco-plasticity (*vp*), has two other important roles it plays; 1) in hydrocarbon maturation, migration, and accumulation and 2) where reservoir fluids find containment during the process. The latter role has a more current and analogous issue related to over-pressuring and over-loading formations during large volume water disposal and CO₂ sequestration projects. *VP* formations (*VPFs*) are critically important considerations in all the aforementioned processes.

The enhanced pore pressure lessons the petroleum industry are learning can also be witnessed elsewhere. Those enhanced pore pressures have found pathways to propagate downward into critically stressed crustal faults and Induced (aka 'triggered') seismic events. Here again, the presence of plastic formations play a critical pressure insulating role.

We review here the origins of typical *VPFs* via reconstructing the geologic history of a basin while coupling industry's newfound horizontal well field insights to long-observed entrapments. Fluid sealing properties are reviewed in multiple perspectives including tectonic stress space and fault/fracture sealing.

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Formation Ductility and its Critical Role in Buoyant Fluid Entrapment

Outline of Talk

- I. What is Elasticity; What is Ductility (i.e., Viscoplasticity {VP}), Creep?
- II. Why the Special Worry With VP Formations (VPFs)?
- III. Geologic Basins are Not Static (Permian Basin Stress History Example)
- IV. What Lithologies can be VPFs? aka “the creepers”
- V. VPFs as Seals
 - A. For Pressure & Fluid Confinement
 1. As Frac Barriers
 2. During Migration of Buoyant Fluids
 3. For Isolation from Surface and Crustal Basement
 - B. For Re-sealing Post Fracturing (Man’s and Nature’s Fracs)
- VI. In-Situ Stress Frameworks and the Role of Geologic History in forming Regional Folds and Natural Faults
- VII. Degree of VP and How Best to Measure
- VIII. Summary

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We will start this by reviewing some related definitions and some of the standard laboratory-oriented characterizations of ductile behavior. We will settle on the use of our preferred term of visco-plasticity. Then we introduce the many roles that inelastic formations play in our subsurface world. That often requires an understanding of the dynamic histories of a geological Basin of interest. We will use the Permian and Gulf Coastal Basins as two very different examples. The observers will not be surprised that many formations fall into the category of expected visco-plastic lithologies at high stress levels while others can take on VP behavior characteristics at only a few tens to hundreds of pounds per square inch.

Perhaps one of the most important roles of VP formations is in the role of acting as seals to transmitting fluids. The ability to block fluid passage can be related to either rock strength or formation plasticity. In the wildly expanding world of hydraulic fracturing treatments in the oil and gas industry, VP formations can play a key role in induced fracture geometries. It almost goes without saying that high strength and low permeability formations can act as fracture barriers but thick VP formations also can inhibit and redirect fracture propagation. My favorite analog there is that these concepts can be extended to the natural process of in-situ refining of organic material to natural gas or oil. As a Basin gets buried deeper and pressures and temperatures increase, the organics can be refined into oil and gas and begin the overpressuring of

pores with tendencies to seek pressure relief. These generated fluid pressures can encounter barriers to flow just as the hydraulic fracturing stimulations do. Since the naturally generated oil and gas is buoyant, migration can advance to lower pressure formations until it reaches a seal or relief to the atmosphere. Some Basins are effectively barren of mobile oil and gas due to the lack of an effective vertical seal.

In the process of reconstructing a Basin's geologic history, some knowledge of plate tectonics will be required. This field has become more widely known and appreciated over the last several decades. Those plate movements can be inferred to have created a stress history for the Basin's formations and those stresses likely played key roles in formation and fluid property changes over geological time with structural contortions in many cases as well. Those contortions most often create faults and fractures that further complicate fluid movement.

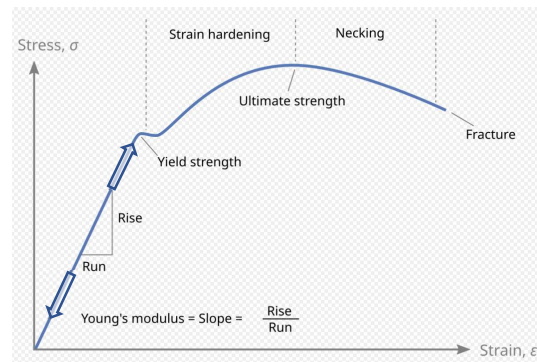
Finally, we discuss the common tools to identify and assess the presence and degree of VP behavior.

The Basics (Section I)

Definitions: Elasticity & Beyond

Elasticity is the ability of a material to return to its original shape and size after a distorting force is removed

Brittle and Ductile Materials



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Most geologic materials initially (at least at low stress levels) observe some degree of elastic behavior. Eventually though, a threshold value of stress will challenge the material's ability to return to its original shape. That transition level may result in a classic failure as in brittle materials or it may transition to behavior often defined as ductility. What is important to understand is that in many lithologies ductility can occur at very low stress levels. Take the case of clay-rich shales or salt where the elastic region can be as low as a few psi. That means that there are materials at depth (i.e., under lithostatic stressed conditions) that are able to flow when the stress conditions change. We'll dive deeper into actual stress space representation and conditions later.

What is Ductility (i.e., Viscoplasticity)

- Ductility in engineering is the physical property of a material, particularly metals, to plastically deform (stretch, bend, or draw into thin wire) under tensile stress without fracturing
- Geology: In earth science, it refers to rock deformation under high pressure and temperature without breaking.
- Viscoplasticity is a theory in continuum mechanics that describes the rate-dependent, irreversible (inelastic) behavior of solid materials. It applies to materials that undergo permanent deformation when a specific yield stress is exceeded, with the deformation rate depending on how fast the load is applied

definition of ductility in science
 definition of ductility in engineering
 definition of ductility and malleability
 definition of ductility in chemistry
 definition of ductility in materials
 definition of ductility in physics

Let's think about the subsurface where the formations are confined. Ductile materials will deform inelastically under additional stress **without** fracturing.

DUCTILE FORMATIONS AT DEPTH

- 1) Some Clay-rich Basin Deposits
- 2) Salt beds
- 3) Anhydrite
- 4) Others

Some materials are ductile at any Incremental Stress

Here is another Term of Value: What is Creep?

Creep is a failure mode in which a material deforms or thins over time when subjected to a continued stress (load) Let's look a bit harder at that term

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Here is another view of the definitions. Engineers commonly use the term for building materials and often in a tensile state of stress. Geologic references bias toward contrasting of rupturing/breaking (brittle behavior) vs. ductile (deformation) behavior. Often, no consideration is given to the stress levels at which the plastic deformation can occur. Now we can look more specifically at VP materials where the plasticity has a rate dependency of the response to applied stress. Most materials take time to strain thus exhibiting a rate sensitivity in the deformation response.

Since time to strain is a real response to stress, creep is a useful term for us to keep in mind moving forward

Creep Defined (from several sources)

- A time-dependent, permanent deformation of shale 'rock' or most evaporitic rocks under constant stress, often triggered by drilling-induced stress changes, such as reduced mud weight. In some shales it is driven by high clay/organic content and can cause borehole closure, casing damage, and decreased fracture conductivity.
- The process involves viscoelastic and viscoplastic (*vp*) deformation, often accelerated by high differences in stress states, temperature, and moisture.
- Drilling Impacts: Salt beds and creeping shale often have in situ stresses near their shear capacity*. Drilling activities (e.g., removing rock) can cause the salt or shale to move or "creep" into the wellbore, creating hole stability issues.
- Creep is not uniform, with studies showing highest deformation when any bedding planes are at a steep angle to the stress (think drilling curves)

* We will come back to this reference to **effective** natural sealing rocks

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Creep has a special meaning in the drilling world. Drilling of the borehole creates a changed stress condition in the penetrated formation. If one is drilling into a soft shale or salt bed, those changed stress conditions and are occurring above their very low stress (shear) capacity, they will exhibit time dependent flow. Highly weighted mud columns are often used to minimize the changed stress conditions thus limiting the creep as the hole advances.

Section II

Why Concern Yourself with Ductile Formations (VPFs)?

APPLICATION

- Drilling
- Well Stimulations
- Hydrocarbon Entrapment (or Lack Thereof)
- Produced Water (or CO₂) Disposal
- Diapirs

EXAMPLE; CASE HISTORY

- Lost (Collapsed) Wellbores
- Clay-rich Basin Sediments
- Vertical (& Horizontal) Seals
- Basement (Crustal) Stress Communication
- Salt and Shale Structures

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By this point you have likely seen some of the applications and issues of VP behavior in the subsurface. Instable or lost wellbores are clearly important. Another has to do with ability hydraulic fracturing a formation. Permeable and brittle rocks are ideal while dense and ductile rocks non-ideal. The oil and gas industry has learned that hydraulic fracturing models should consider both. My common analog I like to refer to has in conducting a mind experiment in hydraulic fracturing a salt body. How successful will be a stimulation in a pure salt layer? Without any porosity, an application of even an intense load on the sale will not fracture it. And this is due to its plastic behavior. Given enough time, the zone may squeeze but not break. The same is true for a soft, clay-rich shale.

Now let's transition from oil and gas production to Mother Nature and the application of excess pressure when she (slowly) refines organics into oil and gas and creates the excess (enhanced) pressures. Those excess pore pressures will seek relief by migrating into lower pressure pore space. Hard dense and unfractured rock will contain those pressures as will bedded salt and anhydrite acting as a VP seal. Those excess pressures may not just move upward to the lower pressured rocks but may move laterally or downward as the pressures increase until they find a lateral or bottom seal. Without a bottom seal, the pressures may find the faulted crustal rocks where the enhanced pore pressures can cause the faults to slip. The slip causes relative motion of the sides of

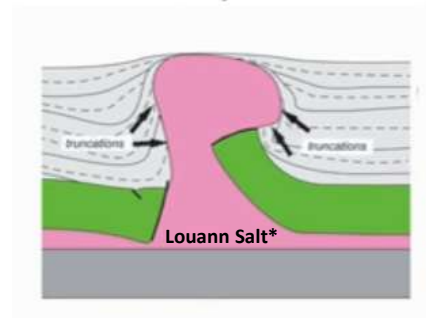
the fault and an induced seismic event. We'll address that with a produced water disposal case history later.

Last on our list of ductile rock applications here is the observation that these VP materials can actually flow to find a weak spot in the earth (e.g., fault) and form a structural body like a piercement dome or even flow to the surface as in a salt or shale diapir. Although interesting, we won't spend much more time that showing the following case history in the Gulf Coast.

Real World VPF Examples (1)

- Salt Domes in the Gulf Coast?
- How about that Problematic Clay Rich Zone in the Permian Basin Barnett Shale?
- And How about Zones Resistant to Frac'ing?

Submarine salt mobility with sedimentation



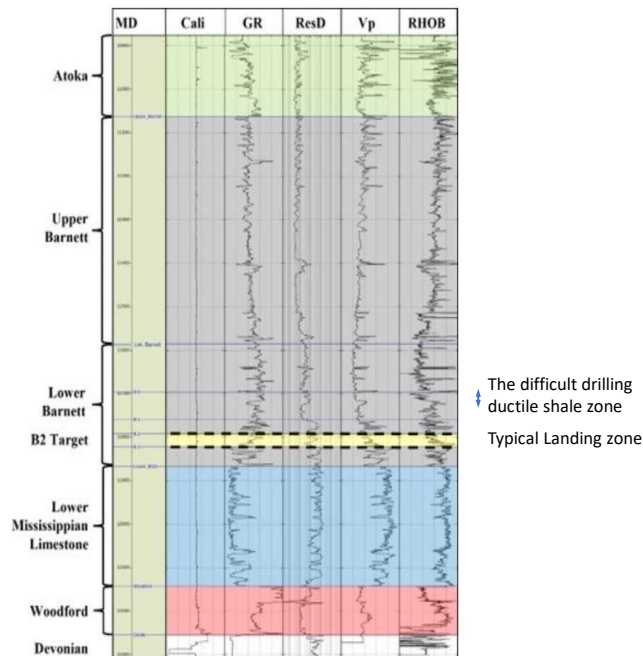
* Up to as much as 4000' thick in the diverging No. & So. American Plates in the Jurassic

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For now, let's just remind the audience that salt domes and salt pillars have been an important strategic target for oil exploration. The U.S. Gulf Coastal area was the first in a long line of key oil/gas provinces exhibiting numerous traps for oil and gas. The increasing burial of the thick Jurassic salt bed (Louann Salt) exerting excess hydrostatic pressures on the VP salt finally was relieved when faults were found to create shear stresses and begin the flow into the plains of weakness.

Real World VPF Examples (2)

- Salt Domes in the Gulf Coast?
- A Problematic Clay Rich Zone in the Permian Basin Barnett Shale?
- And How about Zones Resistant to Frac'ing?



• Adapted from Andrew Lewis et al, URTEC Paper DOI 10.15530/2024-4055274

Figure 2. Formation expressions on wireline logs from a vertical well within the study area.*

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Here is a very modern example of a VP clay-rich shale formation creating challenges. This is an example from the Barnett formation horizontal well oil/gas play in West Texas. A thin clay-rich zone in the Lower Barnett was encountered when drilling a vertical to horizontal “curve” to land in a oil/gas rich target several tens of feet below. The lessons learned as several drill holes were lost was that a heavy mud column was required to maintain integrity of the hole in the curve section and intersected at a shallow angle. Such a zone came as a surprise as something like it was not seen in the horizontal wells and curves drilled in the overlying Spraberry and Wolfcamp plays.

Real World Examples 3a: Re: Zoback and Singh

Their Research and Paper are Directed to Allow a Better Understanding of hydraulic fracturing Shale Sequences with Effects of Interbedded "Clay-rich" Shales with ViscoPlastic Behavior

Zoback, M.D. and Singh, A. (2026), "Development of Continuous Estimates of the Least Principal Stress with Depth for Application to Multi-stage Hydraulic Fracturing, Geomechanics and Geophysics for Geo-Energy and Geo-Resources, Special Issue: Optimizing Production and Recovery from Naturally and Hydraulically Fractured Formations, 25 Feb 2026; <https://link.springer.com/article/10.1007/s40948-026-01119-5>

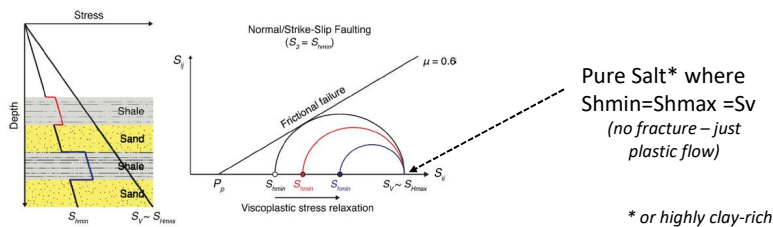


Fig. 8 Schematic diagram illustrating how viscoelastic stress relaxation results in decreasing stress anisotropy due to increasing the magnitude of the least principal stress (after Zoback and Kohli 2019) representative of a strike-slip/normal stress state as illustrated in Fig. 5b ($S_v \approx S_{Hmax} \geq S_{min}$). The simplified cross-section on the left shows the least principal stress in the sands being consistent with friction equilibrium

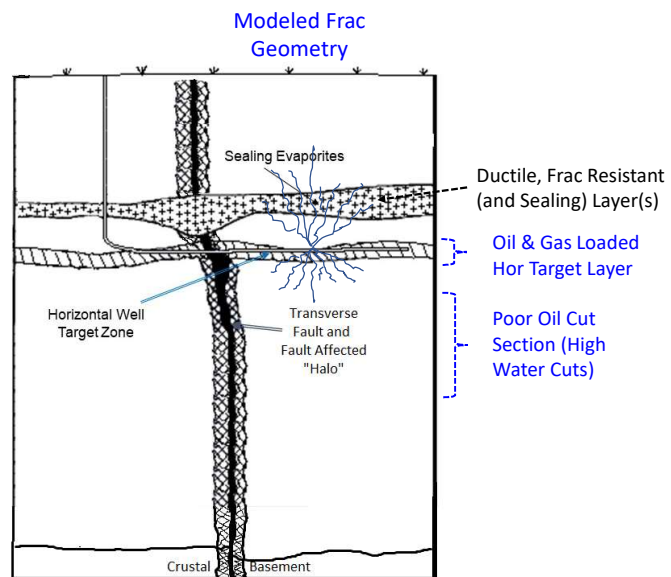
(as illustrated by the Mohr circle shown with a black line). A moderate increase in the magnitude of the least principal stress above the upper sand results from a minor amount of viscoplastic stress relaxation whereas a greater amount of stress relaxation in the shale below the sand creates a larger stress difference and thus a more effective barrier to vertical fracture growth

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This chart uses the classic Mohr Circle display to illustrate approaching failure when the shear stresses (aka deviatoric or differential) stresses are sufficient to reach the failure limit of a material. At depth in the earth, a salt or highly clay rich zone will be in an isostatic condition where the principal stresses are all equal. The paper emphasizes the nature of a VP zone at depth cannot fail since the material behaves as a fluid with principal stresses stay equal even when subjected to intense hydraulic fracturing pressures. This is unlike the common situation where more brittle behaving rocks (say the common basin shales or sands) fail with increasing, hydraulically imposed differential stresses.

Real World Examples (3b)

- Salt Domes in the Gulf Coast?
- That Problematic Zone Permian Basin Barnett Shale?
- And How about Zones Resistant to Frac'ing?

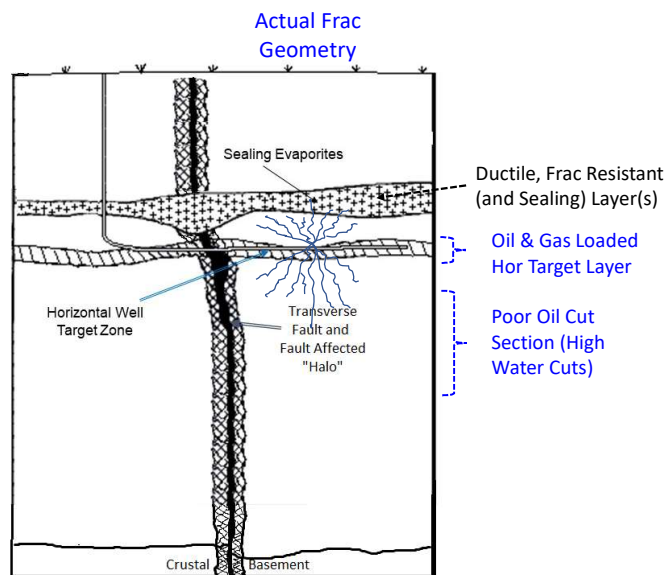


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This graphic is an example of a horizontally drilled oil-bearing interval capped by a section of salt and anhydrite beds. Early hydraulic fracturing models were ineffective at forecasting the geometries of the frac treatments. This is an idealized representation of several horizontal well case histories in the thick San Andres formation residual oil zone (ROZ) play in central Yoakum County and Gaines County. When the early hydraulic fracturing models were run (one cluster shown), the fracture geometries forecasted the patterns to look very typical to the shale frac geometries in that the **frac height was approximately twice the frac depth below the well lateral**. In actuality, the frac models did not take in to account the impenetrable VP nature of the salt and anhydrite cap. The actual geometry was more like 1/3 up (to the cap) and 2/3 down. As a result, the energy and effect of the hydraulic fracturing treatment was directed below into the high-water cut producing zones below the target. This naturally resulted in lower oil cuts and many uneconomic wells.

Real World Examples (3c)

- Salt Domes in the Gulf Coast?
- That Problematic Zone Permian Basin Barnett Shale?
- And How about Zones Resistant to Frac'ing?

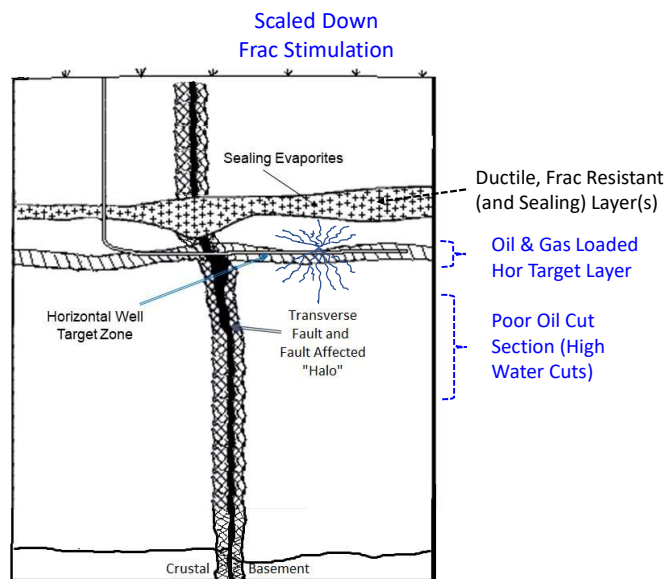


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The actual geometry was more like 1/3 up (to the cap) and 2/3 down. As a result, the energy and effect of the hydraulic fracturing treatment was directed below into the high-water cut producing zones below the target. This resulted in lower oil cuts and many uneconomic wells.

Real World Examples (3d)

- Salt Domes in the Gulf Coast?
- That Problematic Zone Permian Basin Barnett Shale?
- And How about Zones Resistant to Frac'ing?



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The actual geometry was more like 1/3 up (to the cap) and 2/3 down. As a result, the energy and effect of the hydraulic fracturing treatment was directed below into the high-water cut producing zones below the target. This resulted in lower oil cuts and many uneconomic wells. **Once the problem was identified and the early versions of fracture models ignored, stimulations were more volume limited to avoid fracs propagating too deep.**

Section III- Geologic Basins are Dynamic

A Permian Basin Stress Reconstruction History
of the Major Tectonic Stages of the Permian Basin

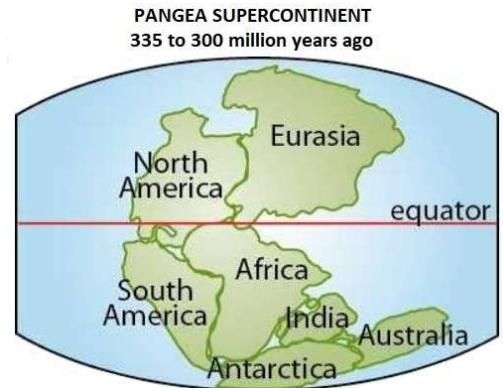
With a Quick Look at the Gulf Coastal Basin Area

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Attempting to reconstruct the geologic history of a Basin is easier now than ever before. We will do a reconstruction of the Permian Basin as an example here then look at a contrasting type of Basin (Gulf Coast) next.

Formation of the Supercontinent Pangea then the Breakup and Gulf Coast Basin Formation

Pangea formed approximately 300 to 335 million years ago during the late Paleozoic era, as plate tectonics forced earlier landmasses—the So American /African Plate (Gondwana) and No. American/Asian Plate (Laurasia)—to collide and unite. The forming supercontinent (Pangea) was assembled via continental drift resulting in massive compressive and shear forces before breaking apart roughly 200 million years ago. Rifting and stress relief followed (Late Triassic - Early Jurassic, ~200 Ma) as Pangea separated, leading to crustal thinning and the creation of the Gulf Coast Rift Basin. Its origin is dated to approximately 200 million years ago (Early Jurassic) as North America separated from South America and Africa. The massive Luann evaporitic salt formation (middle Jurassic ~170 million yrs) is the "mother salt," whose ductile properties formed over 500 salt domes and other tectonic features in the Gulf Coastal region.



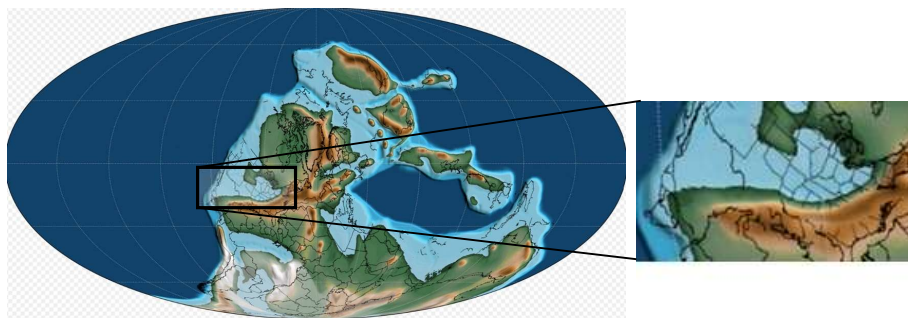
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We'll start with the late Paleozoic era about 300-335 million years ago when the South American plate was approaching the North American plate. The graphic shown here was the idealized combination commonly referred to as the Pangea SuperContinent.

The Imminent Continent Collision Early Ouachita Tectonics in the Permian Basin

The Huge Foreland Carboniferous Basin Prior to the Collision

The Carboniferous Period
330 million years ago



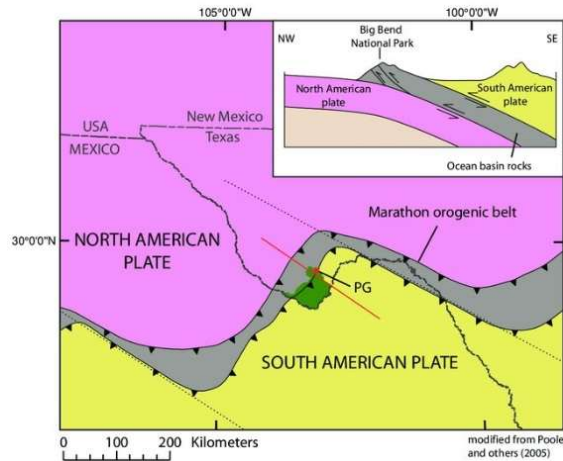
A mollweide map of Earth 330 million years ago, overlaid by a black outline of present-day countries in their respective locations.

Scotese, Christopher R.; Venzel, Christian; Bargar, Landon; Eiling, Renee P.; Kocsis, Adam T. "Phanerozoic supercontinent supplementary material to "The Cretaceous World: Plate Tectonics, Paleogeography, and Paleoclimate (doi:10.1146/annu.2024.28)" from the PALEOMAP project". doi:10.5281/zenodo.10659112

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Before the SuperContinent was forming about 300-350 million years there was a huge foreland shallow land mass that collected highly organic material, now we recognize as the organic shales so common and widespread in the mid-continent (e.g., Barnett, Woodford, New Albany, Chattanooga formations) collectively. Much of the Permian and Ft. Worth Basins were classic examples.

SW Texas Ouachita Related (Collision of No. & So. American Plates) and Left Lateral Fault Development



Map showing the Marathon orogenic belt and subduction zone formed from the collision of the plates. The black lines are the traces of the left-lateral transform fault to be discussed later. The inset figure cross section line is shown in red. PG is short for Persimmon Gap located just north of Big Bend National Park.

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Once the collision was occurring in Texas, generally referred to as the Ouachita Orogen, the NW – SE collision forces were in full force in Central Texas. As one moves to the west, the northwesterly directed compression shifted to create strong NNW to ESE shear conditions and left lateral (LL) transverse faulting. More detail is coming on the major LL transverse crustal faults as one moves north into the southern Permian Basin

Step 1. Reconstructing the PB Tectonic Stages

Major Tectonic Stages of the Permian Basin

- Stage 1. **Tabosa Basin** – Early Paleozoic through Middle Mississippian when the Carboniferous Foreland Basin forms and the Coming Ouachita Plate Collision* is first evident.
- Stage 2. **Ouachita** starts in the late Miss. Major movement thru the lower Permian [Wolfcamp]. The critical NNE-ESE Left-lateral faults either start here or possibly even earlier. Central Basin Platform uplift begins developing
- Stage 3. **Development of the Delaware and Midland Basins.** Maximum subsidence of the Delaware Sub-Basin begins mid-Wolfcampian, post-dating the development of the Central Basin Platform **initial** Uplift. The thick sediment accumulations in the Delaware followed the initial Ouachita collision that formed the CBP.
- Stage 4. **Laramide:** Entire Permian Basin get buried deeply with Cretaceous subsidence then, beginning in early Tertiary with uplift in the western PB, with anywhere from 1000' to 5000'. This stage also creates the Permian age formation outcrops and source of lateral Residual Oil Zone (ROZ) sweep in the what were the huge Paleo oil Entrapments in the San Andres, Yeso etc.
- Stage 5. The Coming Partial Compressive Stress Relief in the **Basin and Range and New Mexico Rio Grande Rift.** Early rise of the Rio Grande Uplift in Lower Oligocene – Early Miocene [40 ma – 25 ma] then Relief and development of the Trans-Pecos Magmatic Province [Texas & New Mexico 26 – 38 ma]. This Rapid Extension and associated Basin and Range development is lower to Middle Miocene [25 – 15 ma]. Followed by Slow extension during Pliocene to Recent [15 ma -present]. Shift of western maximum stress from E-NE to W-NW extension during 15 – 2 Ma, resulting in NE trending graben-boundary faults in the Delaware Basin. Some faulting continuing in the Salt Flat Graben and Apache, Guadalupe, and Glass Mountains.

* The U.S. East Coast is affected earlier and called the Allegheny Collision there

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We start here with the Tabosa Basin, one of the foreland basins prior to the So & No American plate collision. Once the Ouachita orogeny and plate collision was in full force, the intense compression and shear stresses were working together to create the upward fold forming the Central Basin Platform (CBP) and the downwarping of the Midland and Delaware Basins. The thick basin sediments of the Wolfcamp and Spraberry formations provided the fill sediments of the two Basins.

Things were not yet complete as the Farallon Oceanic Plate collision with the No American plate out west formed more intense compression we call the Laramide orogen. The Rockies is often thought to be first but it is actually the Pacific Coastal Ranges. Nonetheless, the collision caused subsidence forming the Cretaceous inland to the east. This downwarping created the thick Cretaceous shale formation and helped to bury the Permian rocks further. This progressing collision was responsible for the uplift of the Colorado Plateau extending into New Mexico and the western side of the Permian Basin. The uplift was so impressive that it exposed the formerly buried Permian rocks in central New Mexico.

As with many plate collisions, the converging energy played out and the compression was partially relieved so that normal faulting occurred and formed what we call the Basin and Range province.

Step 2. Reconstructing the PB Stress Histories

Ouachita starts the *intense compression and lateral shear stresses* first seen in the Carboniferous foreland basin development then seen in the PB in the late Miss. Major movement thru the lower Permian [Wolfcamp]. The critical NNE-ESE left-lateral transverse faults either start here or possibly even earlier. CBP uplift begins developing

Development of the Delaware and Midland Basins. *Continued compression and subsidence* of the Delaware and Midland sub-basins begin mid-Wolfcampian, post-dating the development of the Central Basin Platform's **initial** Uplift. The thick sediment accumulations in the Delaware and the thinner Midland Basin fills followed the initial collision that formed the CBP.

Laramide: *Continued compressive forces* as entire Basin get buried deeply with Cretaceous subsidence then, beginning in *early Tertiary with uplift in the western PB* – anywhere from 1000' to 5000'. This stage created the 'oven refining' of the organics and uplifted the west side Permian to outcrops and source of lateral ROZ sweep in the San Andres, Yeso etc.

Basin and Range and New Mexico Rio Grande Rift are overlapping events creating *relief of some of the lateral compressive stresses* especially in the western half of the PB. Early rise of the Rio Grande Uplift in Lower Oligocene – Early Miocene [40 ma – 25 ma] and associated with the development of the Trans-Pecos Magmatic Province [Texas & New Mexico 26 – 38 ma]]. This created rapid extension and associated Basin and Range development is lower to Middle Miocene [~25 – 15 ma]. *More lateral stress relief and slow extension* during the Pliocene to Recent [15 ma -present]. Shift of western maximum stress from E-NE to W-NW extension during 15 – 2 Ma, resulting in NE trending graben-boundary faults in the Delaware Basin. Some faulting continuing in the Salt Flat Graben, Apache Mountains, Guadalupes, and Glass Mountains.

Compressive and Shear Stresses

Partial Compressive Stress Release

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The various tectonic stages provides a look at what stress changes the rocks were undergoing. As mentioned, the maximum horizontal compressive Ouachita forces were directed NW-SE with the relatively minor principle horizontal stress in the NE-SW orientation. This resulted in the significant folding creating the CBP, Delaware and Midland Basins. Ultimately, NNW-ESE transverse faulting terminated a lot of the crustal folding tendencies.

But the intense horizontal compressive forces were not over – especially in the west. The Laramide redirected the maximum horizontal stress from NW-SE to NE-SW and the shallow nature of the Farallon plate collision provided the uplifting forces seen in the Colorado Plateau and down in to central NM. As mentioned, the compressive forces were more intense in the northern Delaware Basin than across the border into Texas and the Midland Basin but still were manifested in a basin forming warp leading to the Cretaceous inland sea

A very important stress relieving plate divergence occurred next that formed the Basin and Range Province grabens and forming tensile stresses in vertical fractures seen in the basin sediments today. Controversies are occurring even today about the frequencies and nature of the stress relief in the vertical fractures and their role in the permeability and early production results of the horizontal Wolfcamp and Spraberry laterals.

Section IV

20

Now Back to the Subject of Ductile Formations and their Significance VPs as Seals

And the Classically Understood Ductile Lithologies

1. Evaporites (Salt beds, Anhydrites)
2. Clay-rich Shales

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By now the non-geologists are pretty bored so let's return to the classic VP formations and their importance in both hydraulic fracturing potential and production

VPFs Threshold Pressures to Flow

- Salt

The threshold pressure on bedded salt to flow—often referred to in geomechanics as the creep threshold stress or yield threshold—typically requires a differential stress of 150 to 1500 psi. Below this critical threshold, salt behaves elastically. When this pressure gradient is exceeded, the rock exhibits ductile, time-dependent creep.

- Shales

- Clay Bed physical flow (Failure/Landslides). The minimum pressure or shear stress required to make the clay bed itself flow (as a submarine landslide, debris flow, or fluid mud), depends on its Yield Stress.
 - Yield Stress: Yield stress is the minimum shear pressure required to break the structural network of the clay and cause it to act like a fluid rather than a solid. It usually ranges from roughly 50 Pa (7 psi) in weak-gel states to thousands of Pa (>>150 psi) for relatively stiff, compacted clays.
 - Water Content: The yield stress drops precipitously as water content increases. If the bed's bulk density is less than 1.2 g/cc (heavily saturated with water), it is essentially fluid mud and will flow continuously under very low pressures.
 - Permeability of the Clay: If the clay somehow retains its moisture (without consolidating to a stiff shale), the clay retains its ability to flow. Example of this are shale diapirs and the Problematic Clay-rich Shales at Depth.

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Factoids on Possible Clay-Rich Shales

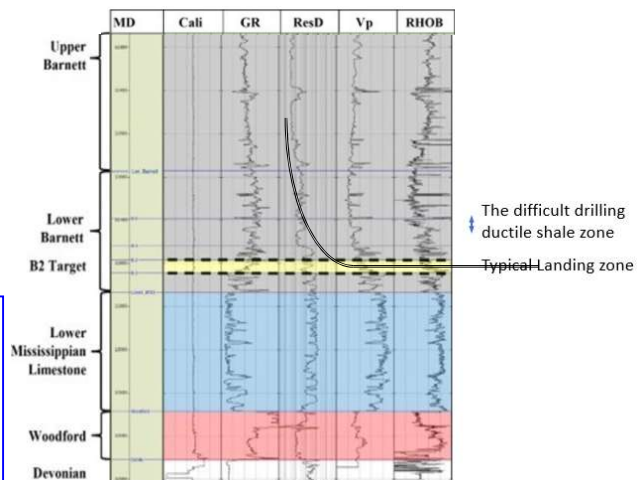
- Swelling clay minerals (expansive clays) are 2:1 layer-silicates that expand in volume by adsorbing water between their structural layers. The most common and highly expansive mineral in this group is montmorillonite (a type of smectite).
- Smectite Group (Montmorillonite/Bentonite): These are the most expansive minerals known. The internal crystal surface area is incredibly large, allowing massive amounts of water to be drawn in electrochemically.
- The primary geological source of swelling clays (smectites like montmorillonite) is the chemical alteration of volcanic ash deposited in marine or alkaline environments. Over millions of years, these deposits transform into clay-rich sedimentary rocks and highly expansive soils.
- In shale diapirs (also known as mobile shales or mud diapirs), the mobile core is dominantly composed of highly hydrated, undercompacted, and overpressured smectite group clays, alongside intermediate mixed-layer illite-smectite (I/S) minerals.
 - For a shale body to become ductile and rise buoyantly through overlying strata, it must maintain a low shear strength and high pore-fluid volume. The specific clay mineralogy dictates this behavior.

[Let's Return to the Real-world Examples](#)

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Drilling the Barnett “Curve”

- Encounters the Ductile Clay-rich VP Lower Barnett Shale in the ‘Curve’ Before Landing the Well Lateral Sections Below
 - Good Designs Keep Curve Angle in VPF Less than 45 degrees
 - Requires Heavy Mud Columns and Oil Base Muds
 - Several Examples where Zone Caused Loss of Hole
- Although Not a Thick Zone, it can Act as Stimulation Ceiling and Offer Isolation from Overlying Fluids
 - Barnett Oil/Gas Generation - Trapped Below the VP Ductile Zone thus Offering Production with Low Water Cuts and High GORs



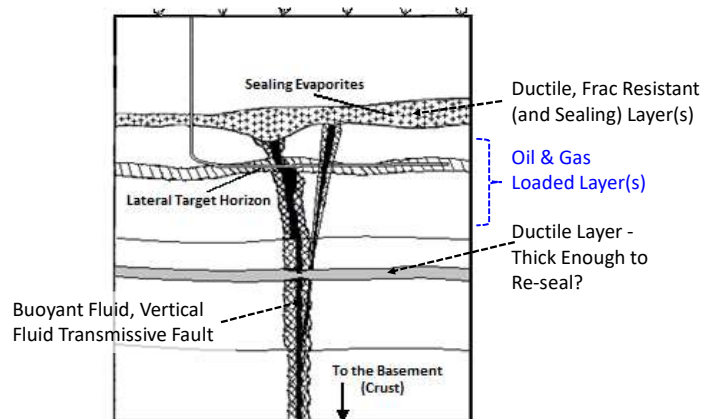
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You'll remember this chart but now shown with the typical drilling “curve” section through that problematic clay-rich shale zone and early lessons learned about hole loss. Today, the drilling folks mud up with oil based mud (swelling clays?) and to manage the “creepy” VPFs.

But here is another aspect and believed positive aspect of the VPF. The B2 target zone has proven to be a very low water-cut zone. My theory is that the VPF, although a drilling nuisance, is a classic isolation zone for containing fluids from above (more on this aspect on the next slide). The dense and low permeability Devonian Limestone further isolates the producing interval from water bearing porous siliceous Devonian carbonates below the Woodford interval.

Hydraulic Fracturing Basin Sediments For Zonal Isolation from Above (and Below as from Crustal Rocks)

1. Thick VPFs Act as Frac Barriers
 - A. For Mother Nature's Hydrocarbon Generation and Migration
 - B. For Man's Hydraulic Fracturing Treatments
2. As in PB Barnett Example, VPFs will Contain Fluids from Escape
3. Even in Vertically Faulted Basins, thick VPs Can Reseal Fluid Transmissive Fractures
4. As in Permian and Williston Basins, Thick Evaporite Caps Prevented Oil/Gas Vertical Escape
5. Carbonate Ramp Reservoirs as Many Examples of Lateral and Vertically Sealed Stratigraphic Traps



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You saw a version of this graphic earlier. But this chart has added a vertical, fluid transmission strike-slip fault with its origin in the crust. Of course, transmissive fault planes can prove very problematic for concentrating hydraulic fracturing energy and opening the “valve” to lower water bearing zones. The possible presence of clay-rich VPFs in the section below the horizontally targeted zone can seal off the formation fluids from moving vertically in the fracture.

In a horizontal core drilled in the Spraberry formation southeast of Midland in the 1990s proved the presence of open fractures as often as every 5 feet!! That made the research team wonder why one could drill deep into the Spraberry (say the Dean formation), and still find excellent oil cuts. It forced us to believe that the intermittent VPF clay-rich zones throughout the Spraberry section were capable of isolating oil/water contacts between them by shutting off the vertical transmission of formation fluids. This again illustrates that thick VPF shales can be your friend.

Let's Dive Deeper Into the Seismicity Issue

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What the industry can do with the high water-cut horizontal wells is the next challenge in the PB.

Excess pore pressures being created in large volume water disposal injection wells in combination with adding new wells with high water cuts are clearly a problem now in the PB – especially in the Delaware Basin. The 1st solution was to drill deep injection wells into the lower Paleozoic formations. Those deep formations looked very promising at first since they would take high volumes of water. The highly permeable, dense carbonate formations were brittle formations and possessed connections to transmissive fractures. Ultimately they were being overpressured but local disposal wells causing the overpressure to move down into the crustal fault. The Arbuckle Formation experience in Oklahoma had shown only a small increase in pore pressures transmitted into the faults and into the crust would cause the induced seismicity.

Basement (Crustal) Stress Communication

ISSUE

- Oklahoma (Arbuckle Fm) and Ellenburger (PB) Injection Resulting in Induced Seismicity

PROBLEM

- Enhanced Pore Pressures in the Fractured Disposal Formation Communicating to Basement Rock Faults with No VP Seal Between

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The Permian Basin had the advantage of the lessons learned in the Oklahoma Arbuckle Formation (some call the analog to the Ellenburger Formation in the PB). The local pore pressures from multiple injectors with large volume water disposal finally built to a regional pore pressures that were sufficient to move downward into the crust. The 2011 5.7 magnitude quake near Prague, Ok forced the Oklahoma Corporate Commission to limit injection volumes and ultimately to force disposal operators to shut in wells near the larger magnitude seismic events.

The PB hasn't had not had a 5-magnitude event yet but several high 4s now populate several localities that have now been designated Seismic Response Areas. The TX Railroad Commission paid attention to the curtailment lessons learned from OK and implemented similar restrictions when those large seismic events occurred.

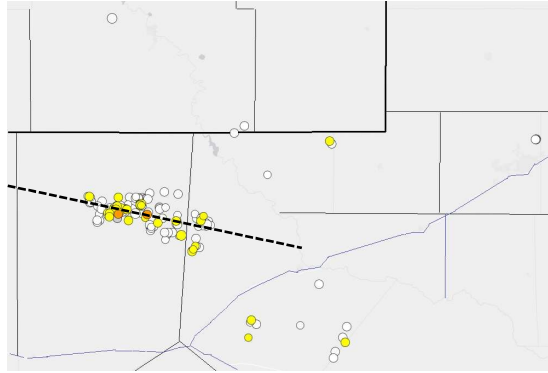
The water disposal industry was forced to abandon some deep disposal wells and limit others but they still had the large formation water volumes to handle. The reactions were to 1) attempt to further process and provide much of the water in the hydraulic fracturing of new wells and 2) going to disposal into shallower formations. The disposal volumes remain very large so that many areas in the Delaware Basin have now overpressured the shallow zones. The seismic problem and fault connections of the deep disposal zones has not gone away entirely and a second issues has developed. The shallow injection pressures have found their way to inadequately

plugged vertical legacy wells that have transmitted to pore pressures to shallower zones. An occasional pressure transmission to the surface has created yet another problem, i.e., so-called ‘zombie’ wells. Quite naturally, this has forced new regulatory actions to restrict shallow injection in several regions.

Once again, the continuing drilling and increasing volumes of produced water remains both a cost and disposal issue. Much work is underway to process much of the water for some surface use, heretofore disallowed. Until that is to change, the next solution is to build longer distance pipelines to inactive regions as far away as 100 miles. Some have termed this “kicking (rolling) the water barrels down the road.”

For Isolation from Crustal Rocks

- Overpressured Zones Can Transmit Pore Pressures Down and Reactivate Crustal Faults Causing Seismicity
- Deep, Thick VPs Can Insulate the Downward Pore Pressures and Avoid Seismicity from Overlying Injection Zones
- VPF Presence Can Provide Containment (Seal) Water (and CO₂) Disposal Zones



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So what is worse – deep or shallow injection? Let's quickly return to the seismicity issue. We mentioned the left lateral transverse crustal faults created in the Ouachita orogeny. There is evidence that many of these have periodically moved throughout geologic time – some even to the present time. That so-called fault recurrence effectively ensures that they communicate fluids vertically until a thick VPF can reseal the fault plane. But there are no deep VPFs below the injection zone of those early deep disposal wells.

This is a group of calculated epicenters of seismic events in the Delaware Basin. This graphic provides a snapshot in time of the calculated epicenters in the Delaware Basin that line up along one of my transverse crustal fault planes I mentioned earlier. Had those deep injection intervals had a good VPF below the perforations, either in the Anadarko Formation in OK or deep Paleozoic Formations in the PB, the seismicity might not have happened in spite of the huge volumes injected.

Section VI

In-Situ Stress Frameworks and the Role of Geologic History in forming Regional Folds and Natural Faults

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With the importance of geomechanics we have shown in the selected case histories, let's review the history of in-situ stresses in the PB again for a minute then reemphasize the compressional stress periods followed by the Basin and Range Period of stress relief

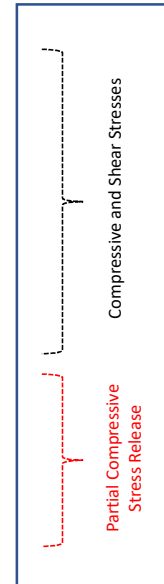
Step 2. Reconstructing the PB Stress Histories

Ouachita starts the *intense compression and lateral shear stresses* first seen in the Carboniferous foreland basin development then seen in the PB in the late Miss. Major movement thru the lower Permian [Wolfcamp]. The critical NNE-ESE left-lateral transverse faults either start here or possibly even earlier. CBP uplift begins developing

Development of the Delaware and Midland Basins. *Continued compression and subsidence* of the Delaware and Midland sub-basins begin mid-Wolfcampian, post-dating the development of the Central Basin Platform's **initial** Uplift. The thick sediment accumulations in the Delaware followed the initial collision that formed the CBP.

Laramide: *Continued compressive forces* as entire Basin get buried deeply with Cretaceous foreland subsidence then, beginning in *early Tertiary with uplift in the western PB* – anywhere from 1000' to 5000'. This stage created the 'oven refining' of the organics and uplifted the west side Permian to outcrops and source of lateral ROZ sweep in the San Andres, Yeso etc.

Basin and Range and New Mexico Rio Grande Rift are overlapping events creating *relief of some of the lateral compressive stresses* especially in the western half of the PB. Early rise of the Rio Grande Uplift in Lower Oligocene – Early Miocene [40 ma – 25 ma] and associated with the development of the Trans-Pecos Magmatic Province [Texas & New Mexico 26 – 38 ma]]. This created rapid extension and associated Basin and Range development is lower to Middle Miocene [~25 – 15 ma]. *More lateral stress relief and slow extension* during the Pliocene to Recent [15 ma -present]. Shift of western maximum stress from E-NE to W-NW extension during 15 – 2 Ma, resulting in NE trending graben-boundary faults in the Delaware Basin. Some faulting continuing in the Salt Flat Graben, Apache Mountains, Guadalupe, and Glass Mountains.



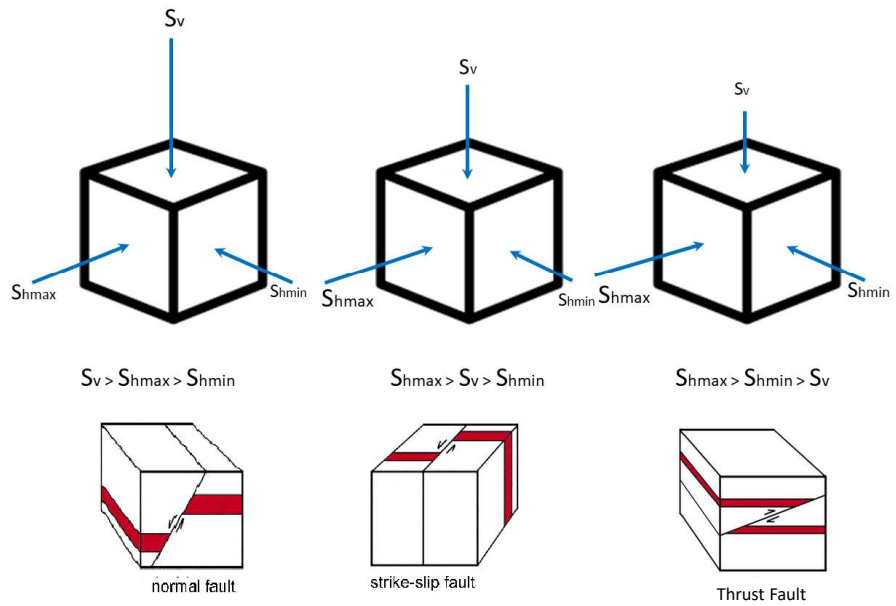
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Remembering those first three major orogenies, we can believe the PB formations were undergoing some intense compressional horizontal stresses as the Ouachita plate collision (with maximum principle stress directed roughly SE to NW. This phase of compression was followed by the Laramide orogen forces (~W to E).

The last stage (B&R) begins with the passive end and relaxation of the Farallon plate subduction out west) clearly relieved some of the stresses especially in the western regions of the PB. One can naturally wonder why all those vertical transverse and recurrent faults, now relieved of some of the lateral compressive stresses, didn't cause vertical loss of the generated hydrocarbons to the surface. Here again is a positive aspect to VPFs in the geologic section and especially the VPF Ochoan (late Permian) salts/anhydrites, that sealed off the faults and contained the deeper buoyant fluids from vertical escape. Let's look and idealize the stress states that the PB formation underwent.

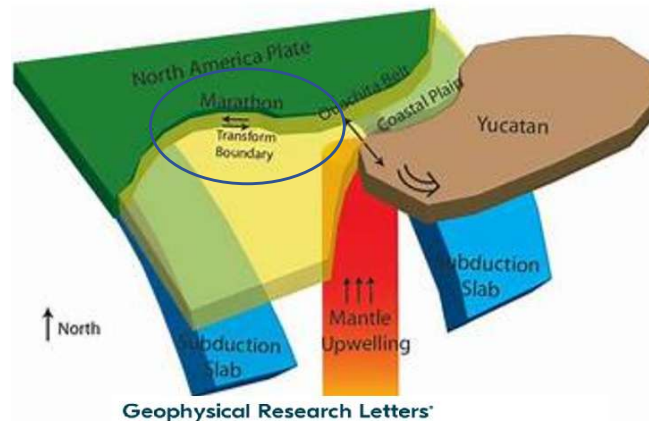
Principal Stress States and Fault Tendencies

Normal Faulting, Strike-Slip, and Thrust Faulting Stress States



This is work that I like to credit to Stanford's Mark Zoback and his students. Changes in the horizontal stresses, like what we have discussed in the Permian and Gulf Coast, help explain the types of faults created. Let's look first at the Ouachita orogeny.

Ouachita Tectonics in the South and Southwest Texas



Geophysical Research Letters

Research Letter | Free Access

Lithospheric velocity model of Texas and implications for the Ouachita orogeny and the opening of the Gulf of Mexico

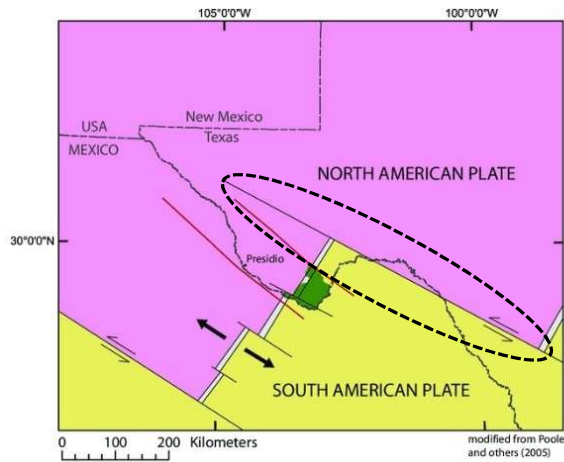
Yao-Yao | Ailing Li

First published: 16 November 2016 | <https://doi.org/10.1002/2016GL071167> | VIEW METRICS

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This cartoonist graphic attempts to define both the collision and then divergent phases of the South and North American Plates in the Region of modern South and Southwest Texas. Note the identification of the transverse boundary in the west

SW Texas Ouachita Related (Collision of No. & So. American Plates) and Left Lateral Fault Development



Index map showing transform faults and lineaments related to Proterozoic rifting along the southern edge of North America. Solid black lines are Neoproterozoic continental transform faults (Poole and others, 2005; Thomas, 1991); arrows show relative motion of continental plate offset; gray double-banded line is main rift zone between North and South American plates; solid red lines are Texas lineament (Albritton and Smith, 1957; Muehlberger, 1980); and dark green area is BBNP.

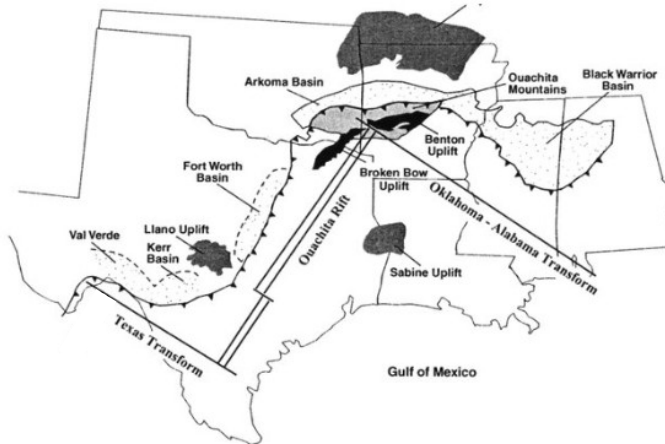
Melzer Consulting

This comes from another reference with a closer look at the Ouachita collision with its left-lateral transverse forces in the southern PB

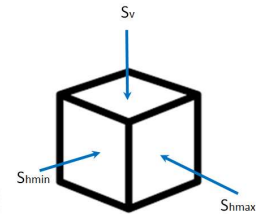
Ouachita Tectonics

Adapted from Figure 1 in
"Gravity constraints on
lithosphere flexure and t
structure of the late Pale
Ouachita orogen in Ark a
Ok, So. Central NA"

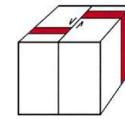
April 1998 *Tectonics* 17(2):187-202
DOI: 10.1029/97TC03786



Shear Conditions and Strike-Slip Faulting



$$Sh_{max} > S_v > Sh_{min}$$



strike-slip fault

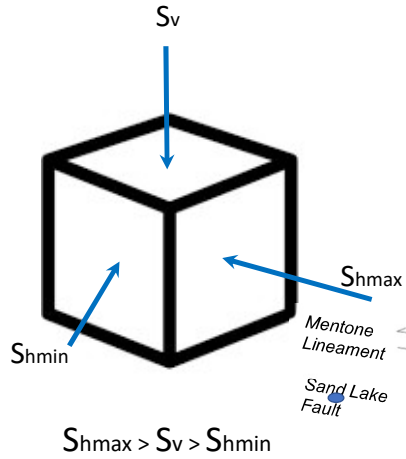
Intense lateral pressures in one direction
with high vertical confinement
create folded structures eventually rupturing
with transverse (strike-slip) faults

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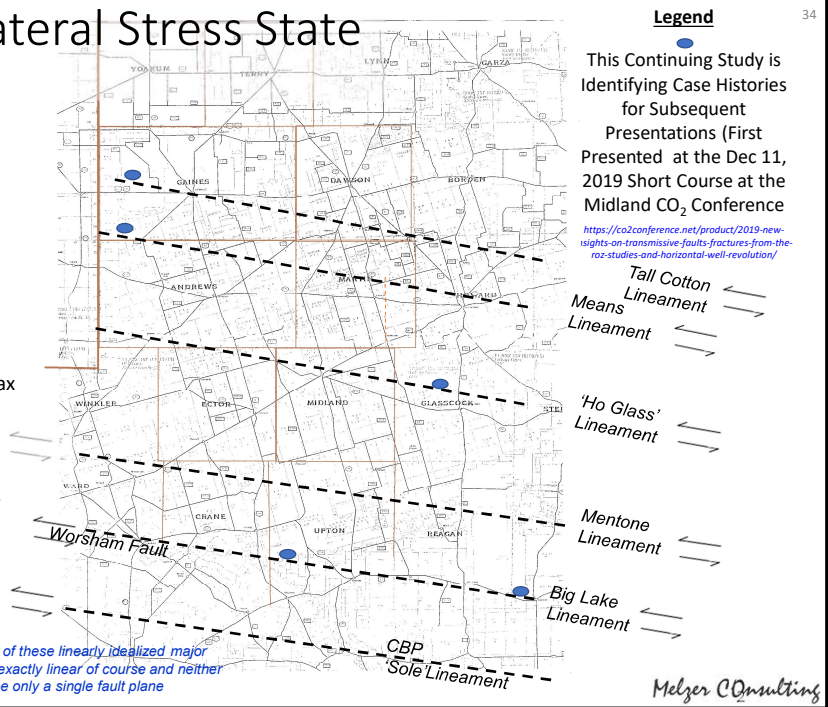
The South American plate collision with the North American plate greatly increased the horizontal stress from the SE to the NW. The orthogonal SW to NE horizontal stresses were the minor stress component (less than the vertical) leading to the predominant ~N-S fold tendency and ultimate failure state of strike-slip or transverse faulting. Those ~N-S epirogenic Central Basin Platform, Delaware Basin and Midland Basin folding ultimately gave way to the SSE-WNW transverse left-lateral vertical faults as shown in the stress blocks on the right.

PB Ouachita Left Lateral Stress State

~Roughly NNW-ESE

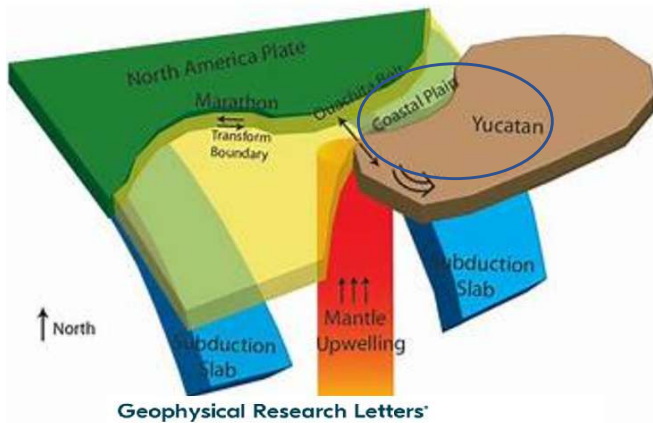


* Note that none of these linearly idealized major Crustal Faults are exactly linear of course and neither will they be only a single fault plane

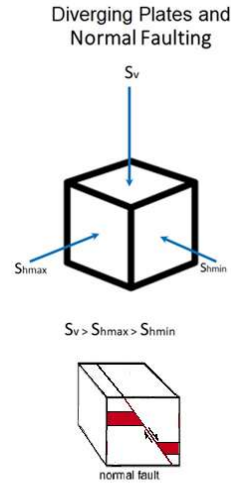


This is a second look at the stress field and a set of recognized major left-lateral strike slip faults through the Midland Basin, Central Basin Platform and into the Southern Delaware Basin. Some have been recognized and published and given local names but I've named other major faults and identified some case histories I've encountered in or very near the faults over the years

Post Ouachita Supercontinent Pangea Breakup: Horizontal Stress Relief with Spreading Plates in the Gulf Coast



Geophysical Research Letters
 Research Letter | Free Access
Lithospheric velocity model of Texas and implications for the Ouachita orogeny and the opening of the Gulf of Mexico
 Yuo-Yuo | Ailing Li
 First published: 16 November 2016 | <https://doi.org/10.1002/2016GL071167> | VIEW METRICS

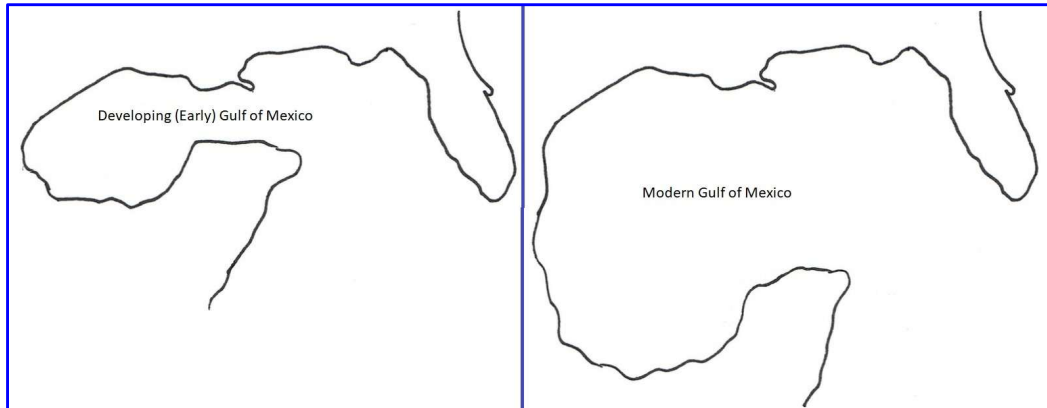


Diverging Plates and Normal Faulting
 $S_v > S_{hmax} > S_{hmin}$
 Spreading plates reduce lateral stresses as sediments fill the Gulf with increasing vertical stresses

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Let's look again at the cartoon shown earlier. This time let's focus on the post-collision (Triassic & Jurassic Period) spreading plates and the change in stress states. We see that the horizontal compressive stresses are relieved so that the maximum principle stress is vertical, The Gulf of Mexico is widening and beginning to fill with continental sediments. The widening is shown on the next slides

Intermittent Isolation (Restricted Marine) of the Gulf & Jurassic Age Deposition of the Louann Salt

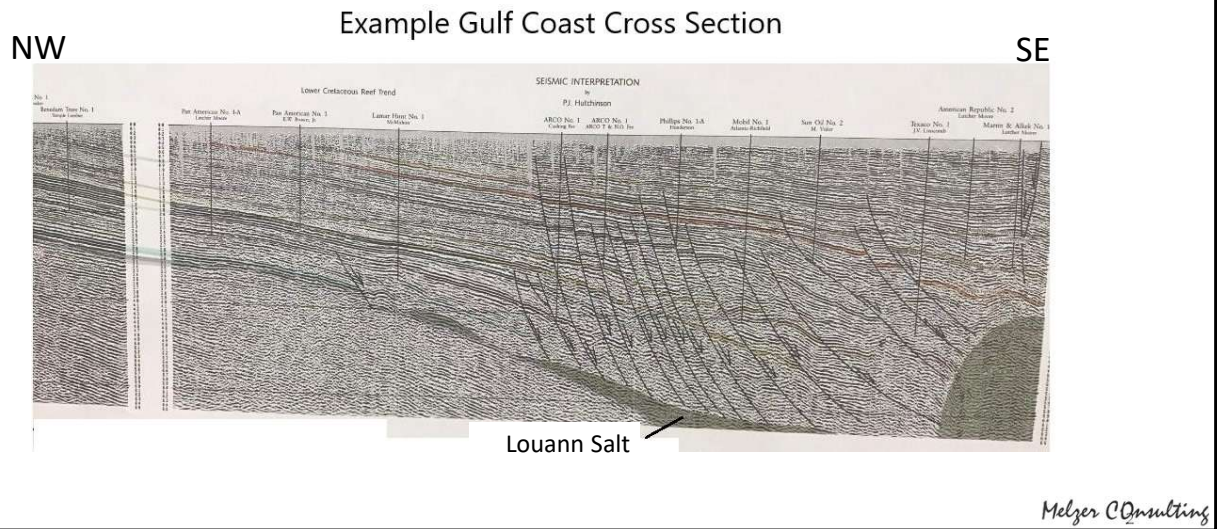


<https://en.wikipedia.org/wiki/File:GulfGif.gif#/media/File:GulfGif.gif>

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As can be the case for post collision, receding plates, they are often isolated (or occasionally isolated) from the open ocean and can concentrate salinity leading to the deposition of evaporites. The Gulf is noted as depositing up to 4000 feet of thick salt called the Jurassic Louann Salt. Salt is known worldwide as a valuable preservative but here we are emphasizing its property as a VPF and able to flow under load. The salt pillars and piercement domes shown earlier are classic structures created by salt flowing, finding a weak pathway, and moving upward.

“Down to the Coast” Faults as No. & So. American Plates Diverge and No American Sediments fill the Void



The increasing loads on the salt in the diverging plates created the thinning of the salt and giving way to a large number of down to the coast faults as shown in this seismically interpreted cross section.

Recap of the Two Contrasting Cases Permian Basin & Gulf Coast Faulting

- Permian Basin
 - Ouachita Orogeny (Collision of No & So American Plates)
 - Predominant Compressive Forces; Horizontal Anisotropic Stresses and Formation of Central Basin Platform and Delaware and Midland Sub-basins
 - Left Lateral Transverse (Vertical) Faulting
 - Evidence of Recurrent Movement Over Geologic Time
 - Ongoing Reactivation During Localized High Volume Formation Water Disposal
 - Late Stage and Open Ocean Isolated Basin with VPF Ochoan Salts/Anhydrite Cap Sealed Vertical Faults and Confined Deep Fluids 
- Gulf Coast
 - Post Ouachita Orogeny with Spreading of Plates, Horizontal Stress Relief
 - VPF Jurassic Aged Thick Salt Deposition
 - High Volume Sediment Filling of Gulf Basin Stimulating Plastic Flow of Instable Salt Basement, Salt Piercement and Pillar Features 

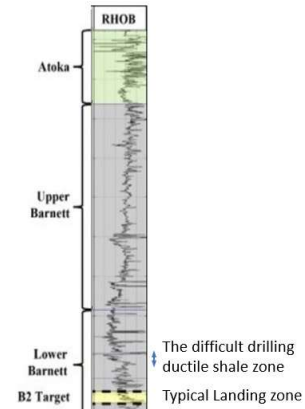
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This is a summary of two very different basins – the Permian and Gulf Coast Basins. First is the PB formed with plate converging compressive forces and capped with impermeable and thick evaporate VPFs and second is the Gulf Coast Basin formed from diverging crustal plates with its thick and important basal VPF.

Section VII

Now, How to Identify & Measure Degree of Plasticity?

- For Basinal Deposits
 1. Open Hole Caliper Logs
 2. Shaliness, Porosity, Sonic Crossplots
 3. Degree of Organic Maturity
 4. Differential Fracture Injection Tests (DFITs) aka Minifrac
- For Other Lithologies
 - Mineralogy Logs
 - Low Density with 'Normal' Sonic Velocities
 - Differential Fracture Injection Tests (DFITs) aka Minifrac



The Good News is that Reflection Seismic Surveys Will Generally See the Reflectors if they are thick enough (>20 feet)

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The science of basin history reconstruction and why VPFs are important gives way to identifying when, how and where can they be found. VPFs do have some common properties that can be used to identify them, how thick, and their laterally consistency. The degree of VP in shales is a subject of future study and documentation.

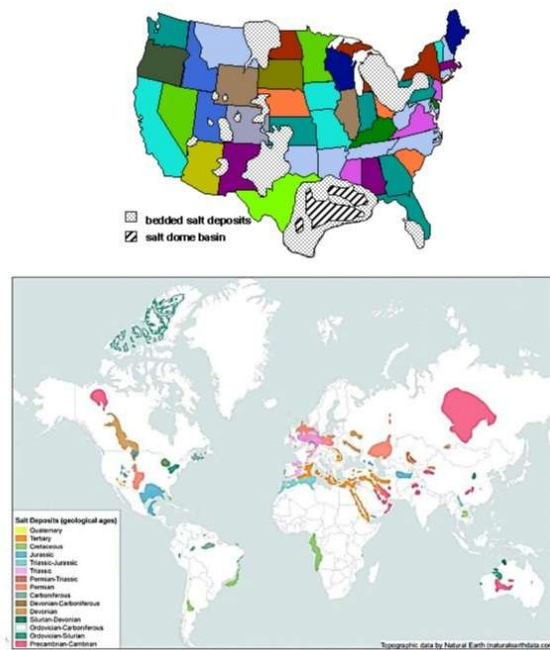
Section VIII Summary

- ViscoPlastic Formations Can Play a Number of Roles in Many Basins
 - Examples Include
 - Influence the Costs of Drilling,
 - Affect Hydraulic Fracturing Geometries
 - Whether a Set of Hydrocarbon Bearing Formations is Vertically Capped or Laterally Sealed thus Retaining Mobile Hydrocarbons,
 - Insulate Fault Conductivity for Buoyant Fluid Entrapment, and
 - Isolate Basement Faults from Overlying Excess Pore Pressures thus Causing Induced Seismicity
- Regional Basin Geologic History Reconstruction can Assist with Explaining Structural Features and Basin-wide Stress State History thus Leading to Identifying VPF Deposition and Assist with Prospect Development Strategies
- Help Explain Apparent Thickening and Thinning of Formations in Seismic Profiles for
 - 1) Identifying Low Risk Containment Intervals for either Water or CO₂ Disposal
 - 2) Possible Instable Footing with Increased Disposal Formation Loads

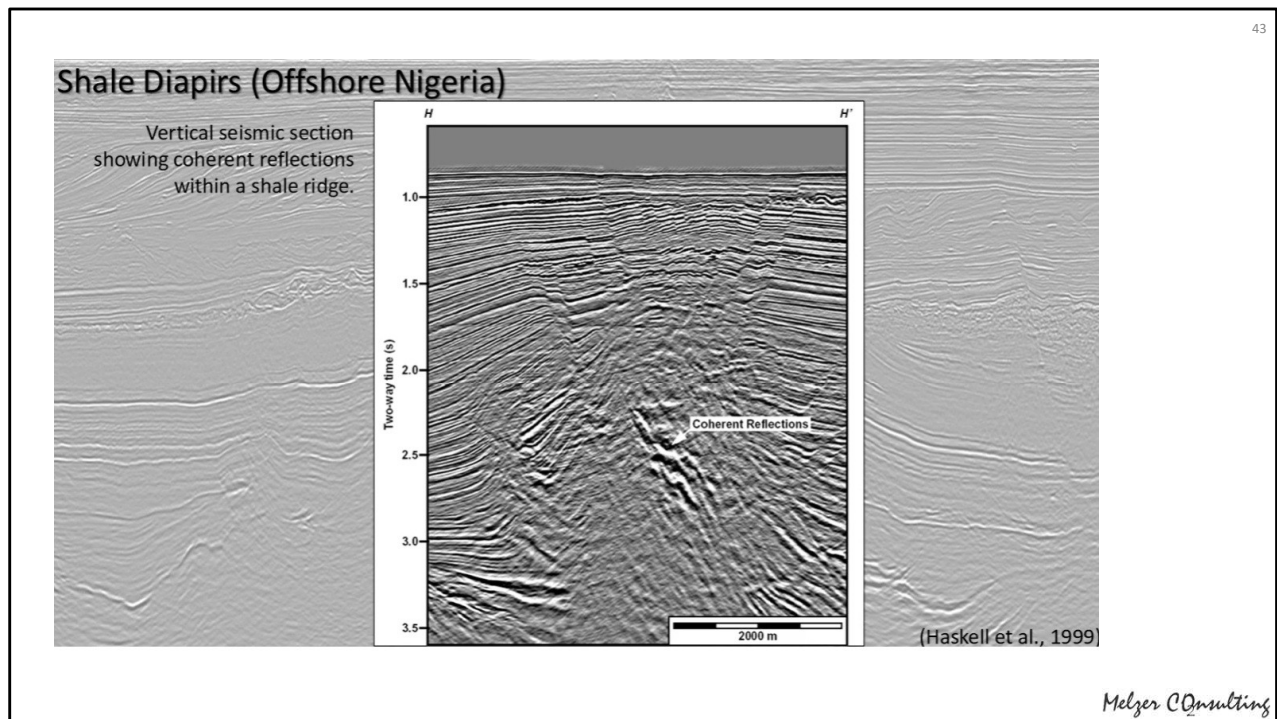
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Supplementary Slides

Salt Basins in the U.S. and Worldwide

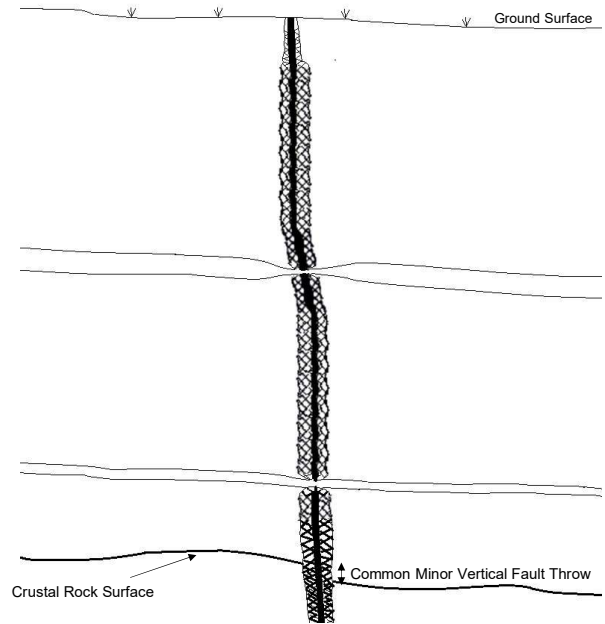


These two maps show the major occurrences of salt beds around the U.S. and world. We should point out too that relatively minor accumulations are not shown. One example are playa lakes which are local in nature and valuable to humans and animals for balancing nutritional needs or in preservation of foods.



This is included only to point out that the VP clay-rich shales in parts of the world are known to flow to form a diapir (as was shown in the salt dome earlier) when subjected to a differential stress like when encountering a fault.

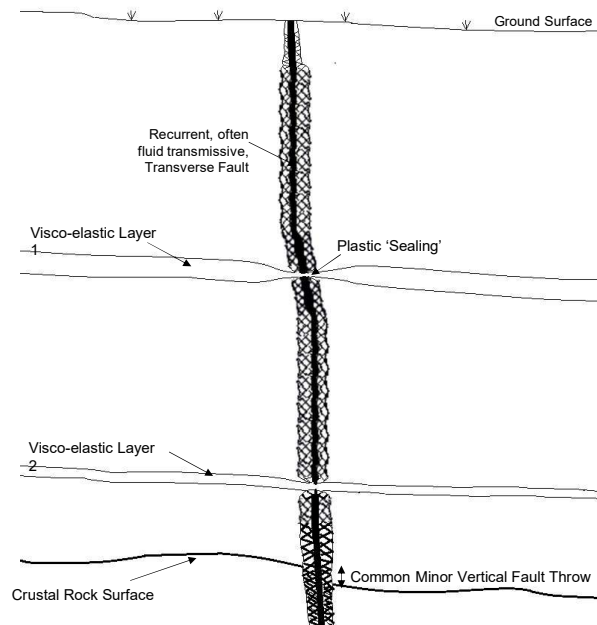
Conceptual View of Transverse Crustal Faults (aka Lineaments) in Many Basins around the World (1)



- Let's Point out:
- 1) Basement Fault with minor vertical offset
 - 2) Common that the Faults are Recurrent (Episodic Movement) over Geologic Time and, with recent reactivation, can transmit fluids to the surface

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Conceptual
View of
Transverse
Crustal Faults
(aka Lineaments)
in Many
Basins around
the World (2)

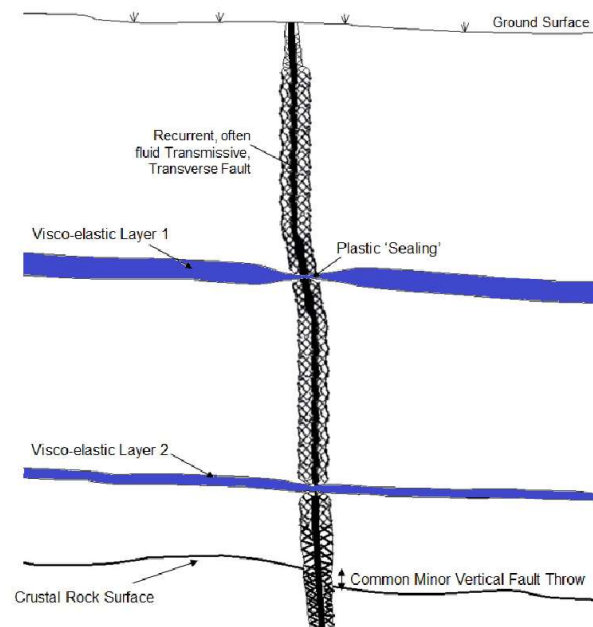


Let's Point out:

- 1) Basement Fault with minor vertical offset
- 2) Common that the Faults are Recurrent (Episodic Movement) over Geologic Time and, with recent reactivation, can transmit fluids to the surface
- 3) Common that they can Transmit deep fluids upwards to lower pressure zones

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Conceptual
View of
Transverse
Crustal Faults
(aka Lineaments)
in Many
Basins around
the World (3)

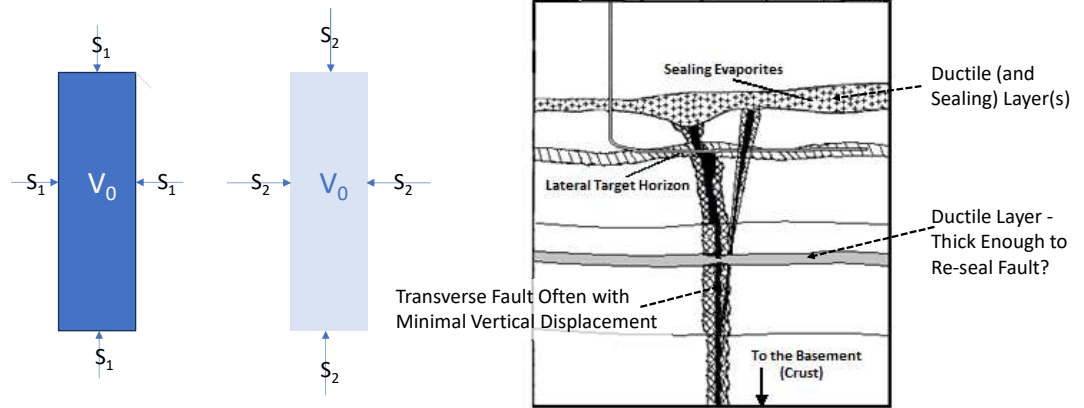


Let's Point out:

- 1) Basement Fault with minor vertical offset
- 2) Common that the Faults are Recurrent (Episodic Movement) over Geologic Time and, with recent reactivation, can transmit fluids to the surface
- 3) Common that they can Transmit deep fluids upwards to lower pressure zones
- 4) Visco-plastic Zones in the subsurface can seal the fluids off from continued flow

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Incremental Vertical Load & In-situ Confinement of Ductile Rocks (IsoStatic)



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Barnett Play Example

From "A Case Study on the Emergence of the Barnett Shale in the Midland Basin, Ector County, Tx"

URTEC paper 2024

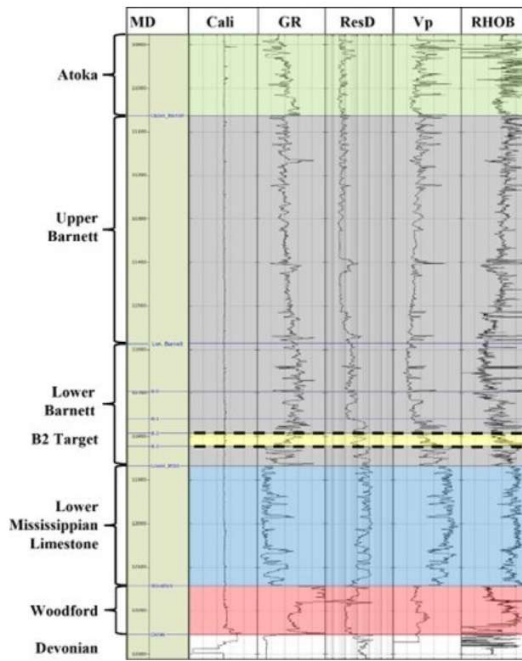


Figure 2. Formation expressions on wireline logs from a vertical well within the study area.

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History of the Gulf Coastal Geologic Environment

- The formation of the super continent Pangea, formation of Laurasian, combining of the North American and Eurasian Plates, then began to start breaking up after about 250 million years ultimately leading to plate rifting and the formation of a basin between the new plates. The ancestral Gulf basin water evaporation created super saturated salts which led to the deposition of the multi-thousand foot-thick Louann salt of Triassic period.
- The rifting continued during the Tertiary Period forming what would ultimately become part of the Atlantic Ocean. The deep Gulf accumulated huge thicknesses of sediments from the land masses of North America and Mexico. As the sediments accumulated during the continued rifting, the earlier deposited sediments were deepening, pressures increasing and the sediment columns on top of the salt were sufficient to cause the salts to become ductile. The pressures in the salt quite naturally sought relief resulting in places of upward flows to form salt pillars, piercement domes and continued flow and pressure relief. Where the salt beds were thinning, faults were necessary to fill the low regions thus displacing the overlying sediments. Figure 1 illustrates an example cross section from on-shore Texas to the waters of the Gulf. The observed major normal fault features there are often called down-to-the coast faults since the footwall fault displacements were to the deeper side and toward the deepening Gulf. As the Gulf continued to rift and deepen, the coastal edge would move outward creating more land mass while exposing older sediments at the surface.
- All of this crustal movement, sediment accumulation and shoreline changes occurred on millions of years. So what could accelerate the natural processes at work? Removal of subsurface fluids first comes to mind. The demands of fresh water have required on-shore aquifer pumping and results have been mixed. Both subsidence of land and salt water encroachment from downdip (more offshore or coastal positions) were recognized requiring more limited pumping.
- Adding fluids without removal of fluids (i.e., mass balancing) to existing reservoirs is what comes to mind next. What are the consequences of sediment or fluid loads added to reservoirs without removal of equal mass? Would a different form of surface subsidence come to play? With large volume injections, would shorelines tend to move landward due to increasing loads on the down-to-the-coast faults? One begins to ask who could model these injections and forecast when and where are the thresholds for concern?

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Additional Subjects for Future Research

- 1) The Growing Evidence of Major Transverse Faults in the PB
- 2) The Growing Pore Space Crisis and The Mineral Rights - Storage Rights Skirmish
- 3) New "Bolt on" Science to Finally Explain Mixed- and Oil-wet Reservoirs

Back to the Permian Basin

Selected (and Linearly Idealized*) Recurrent Basement Faults (aka Crustal Lineaments)

** None of these identified Crustal Faults are exactly linear of course and neither will they be only a single fault plane*

