Capillary Seals and Petroleum Migration
Observations, Modeling and Risking

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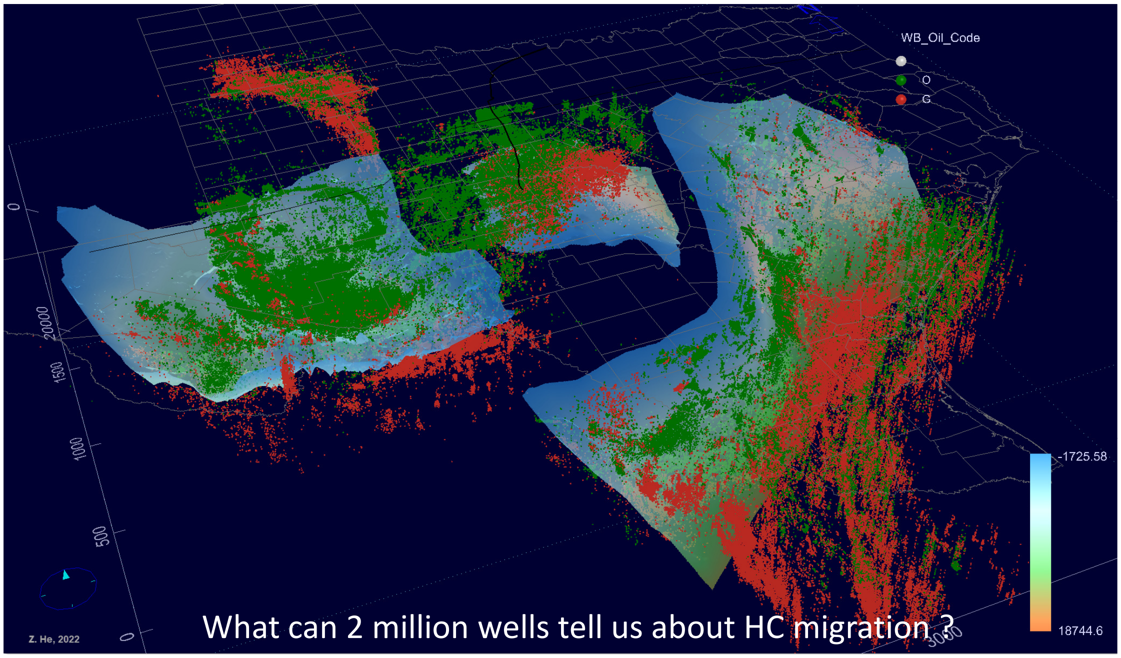
Observation of petroleum fluid accumulation patterns globally in stratigraphic and structural context show that migration patterns are strongly controlled by capillary heterogeneity of sedimentary systems and structural & stratigraphic elements. This provides a very useful general guidance to evaluation the main charge risk due to migration in petroleum system evaluations.

Migration FAQ

- ❑ How far can petroleum migrate?
  - Laterally 700 km, example Athabasca
  - Vertically > 10 km, example Gulf of Mexico
- ❑ What mainly controls the distance?
  - Available volume, and the complexity of carrier system.
- ❑ What is the fastest migration rate?
  - Primary migration: 0.0005 cm/year.
  - Secondary migration: 8 cm/year
- ❑ Does gas migrate faster than oil?
  - No. both are controlled by supply rate.
  - Gas is found near the kitchen and oil is found further out.

The observations are based on various public and private databases of oil and gas fields, production data, and fluid databases. Such data are visualized along with geological models (structure, stratigraphy and petroleum system elements, source rock type, maturity etc.) of the basins. Analysis of the relationship helped understand the geological control of the fluid distribution and properties. HotSpot^{tm} is a geospatial data analytics tool developed by ZetaWare for this purpose.



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Large production datasets are now available for us to study migration patterns. This slide shows perforation data of nearly 2 million wells in Texas. The patterns show many aspects of petroleum system behavior, including migration. These geologically controlled petroleum system patterns will be discussed on slide 14 after we explain some basic theory of capillary pressure. The colors on this slide are gas (>100,000 scf/bbl defined by the TRRC) vs oil. The deeper red colors in the Permian basin and Fort Worth basin are maturity related – such as the Barnett shale, while the red colors along the coast are due to the gas prone facies of the deltaic source rock type, of Cretaceous and Tertiary.

Outline:

- Physical principles of capillary properties
  - and the spatial variation in Sedimentary basins
- Observations – Big data in GeoSpatial context (HotSpot tool)
  - Millions of wells/production data from horizontal wells
  - 10s of thousands of conventional fields
  - Analog oil and gas field data bases
  - Fluid data bases (oil/gas geochemistry and PVT databases)
- Modeling migration for petroleum system evaluation
  - Scenarios and migration/chrage risking
  - Fluid phase and property risking

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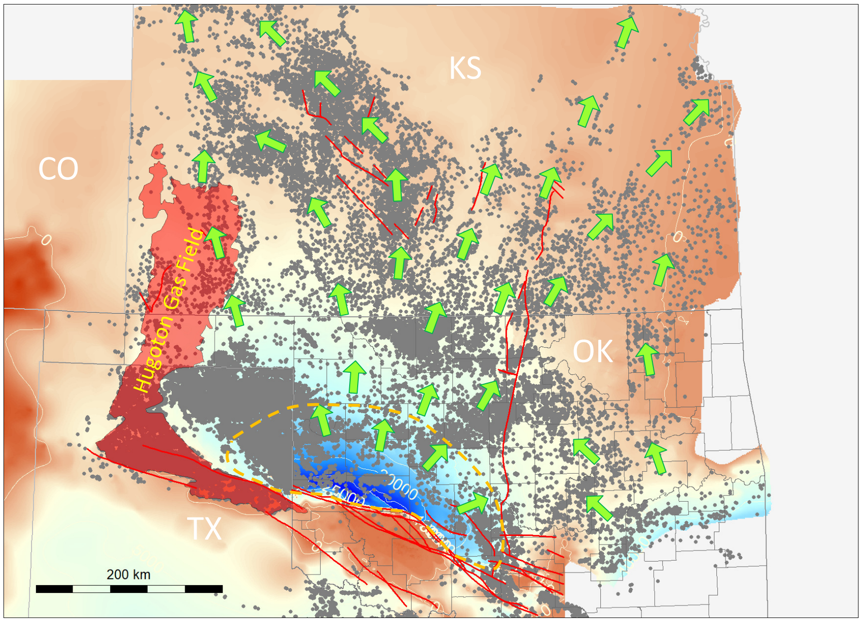
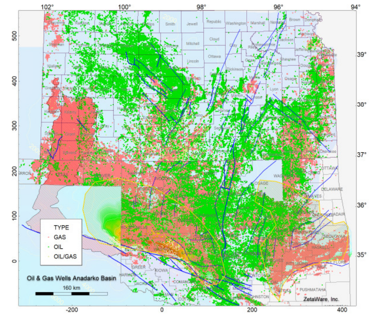




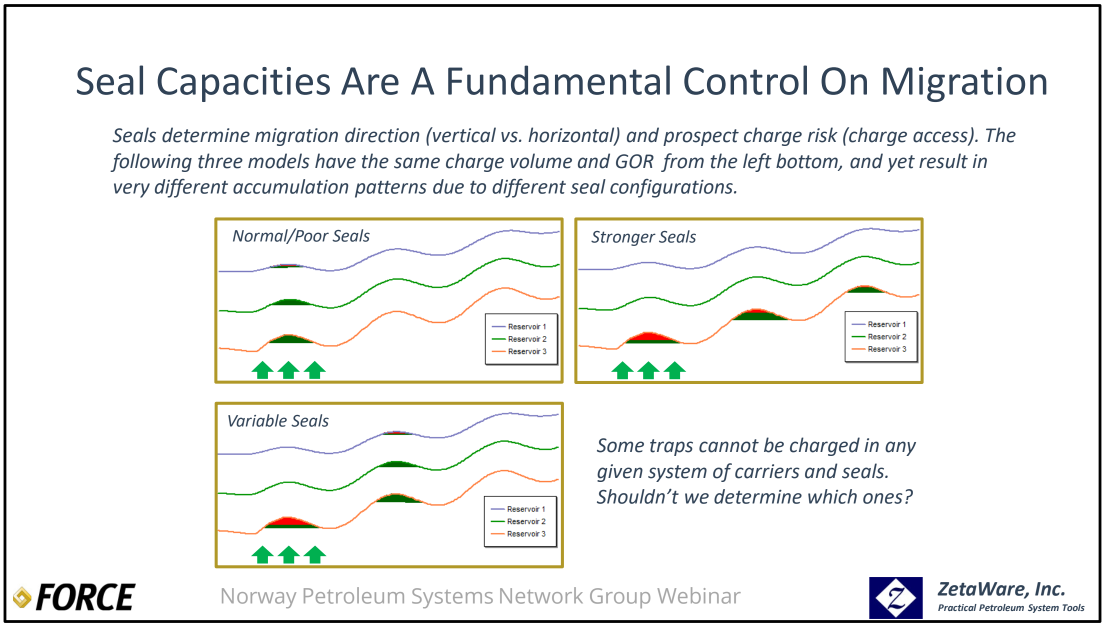
> 500 km Lateral Migration

Capillary Seals, Petroleum Migration and Charge Risk

Key Points:

- Capillary seals is the dominant factor in petroleum migration and entrapment, therefore determining charge risk
  Vast majority of basins we explore today have a working petroleum system. So much of the source rock, maturation focused modeling does not add to risk reduction.
- Capillary anisotropy of sedimentary rocks means petroleum much prefers horizontal migration. Vertical migration is only possible when horizontal migration is not possible, and where a HC column can be formed to allow buoyancy to exceed the vertical capillary pressure contrast.
- Petroleum accumulations occur most frequently along stratigraphy adjacent to the source rocks (>80% of the worlds HC accumulations).
- Traps further up in stratigraphy above the source requires focusing element and closure needed to allow vertical migration to receive charge, therefore higher risk.
- Theory and examples

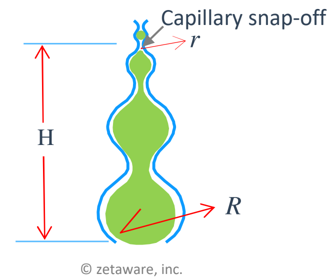
Capillary pressure is the most essential element in trapping hydrocarbons. All traps, structure or stratigraphic, are capillary. It also controls the direction of migration, and where accumulations occur. Unconventional plays are no exception. A tight rock, whether source rock or not, can become a reservoir if it is sandwiched in between even tighter (higher sealing capillary pressure) than itself, a tight siltstone between two shales (the middle Bakken), or a marl reservoir between two limestones (the Eagle Ford), etc. HC is able to build saturation in low porosity rocks because of the tighter rocks around it (He and Xia 2017, AAPG: http://shorturl.at/cnFU7). There is a general misconception that migration and trapping is controlled by permeability, but it is actually capillary pressure. Permeability is not zero in any direction, so it cannot trap anything. But HC cannot move through a seal unless it exceeds the entry pressure of the seal, although the seal has finite permeability. HCs cannot migrate in any direction without exceeding the capillary resistance in that direction – even if it is permeable. Although permeability and capillary pressure are often correlated, they control different aspects of migration.



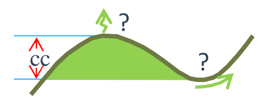
This is a simple demonstration of how capillary seals control migration pattern. There are 9 “traps” in this picture, and depending on seal capacities at each horizon, some traps are charged, and some are not. For us to know which ones receive charge and which ones don’t, we must know seal capacities. Since there is not a way to measure seal capacities from seismic, we can only define ranges based on depositional environments, and run probabilistic migration models. With a geometry like the above, we can determine that one of the traps are charged in more scenarios, and several are rarely charged, when random assumptions of seal properties are assumed. That is our recommended approach to migration modeling. Deterministic models are not helpful.

Seal Capacity and Column Height

Column Capacity $$H = \frac{2\gamma\cos(\theta)\left[\frac{1}{r} - \frac{1}{R}\right]}{g(\rho_w - \rho_o)}$$



- γ interfacial tension (N/m)
- r radius of pore throat in seal
- R radius of pore in reservoir
- g acceleration of gravity
- ρ_w water density
- ρ_o oil density
- θ contact angle (wettability)



Buoyancy of the column in equilibrium with capillary pressure with seal at geological charge rates.
Thickness is not one of the parameters, nor is pressure
Question: Can we measure any of these parameters from seismic?

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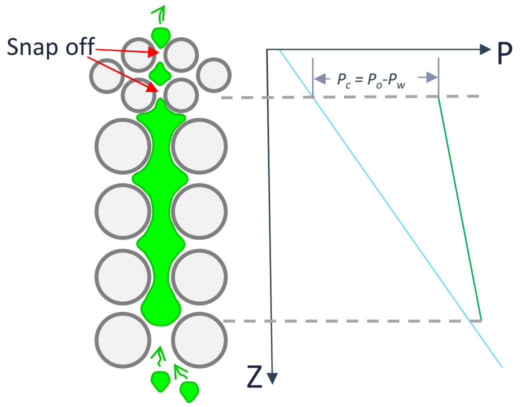
Physics of capillary seal is expressed as a balance of buoyancy force due to differences in density and the capillary force due to the interfacial tension between the non-wetting HC phase and the wetting water phase and the pore throat diameter. The column supported by a capillary seal is expressed in this equation. Among the variables the most important one, which varies the most (several orders of magnitude among different lithologies), is the radius of the pore throat in the seal. Other variables, including densities, interfacial tension, vary only up to a factor of 2. The uncertainty in seal capacity prediction comes mainly from the pore throat size in the shale.

A common misconception may be that a thicker seal is better, but note the equation does not include a thickness parameter. In various databases that contain seal thickness and column heights, there are no correlation between the two. It is our experience that deep water condensed (thin) marine shales are the best seals among clastic rocks, which promotes lateral migration along carrier beds, and deltaic mud stones are much weaker which promotes multiple reservoir stacked pay systems.

One misconception is that shales are “impermeable” which is not true. ALL shales are permeable and would allow migration through it once the capillary displacement pressure is exceeded. At geological times, even very tight shales can easily accommodate the rate of migration necessary to explain the field observations of how far the accumulations are from the source.

How A Capillary Seal Works



Balance of buoyancy and capillary pressure of a reservoir (large grains and pores) and a seal (small grains and pores) pair.

- When at seal capacity, if an extra oil of drop is added at the bottom, buoyancy increases and overcomes capillary pressure of the pore throat at the top seal. The top of the column is pushed into the smaller pore, temporarily connects the bubbles in the seal, and pushes a bubble out from the top. Pressure is now reduced, and the connected stringer snaps off and becomes disconnected again due to capillary pressure. The same column is retained. This is analogues to a dam on the river that spills off any additional water added from up stream.
- Near the top of the reservoir, buoyancy pushes non-wetting phase to invade into smaller pore spaces, and therefore oil saturation is higher. Near the bottom of the column, buoyancy/capillary pressure is low and oil is only in the large pores, and saturation is lower.
- Buoyancy force is transformed into capillary pressure ($P_c = P_o - P_w$), which is what pushes the oil into smaller pores. It is a form of potential energy.

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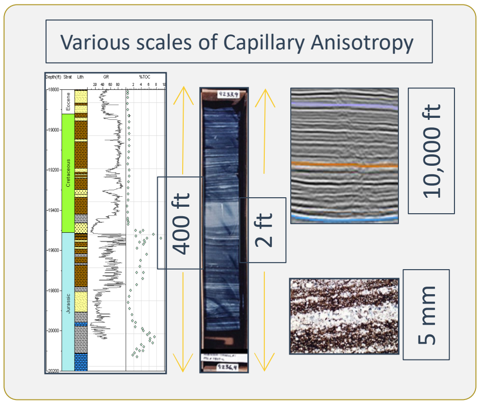
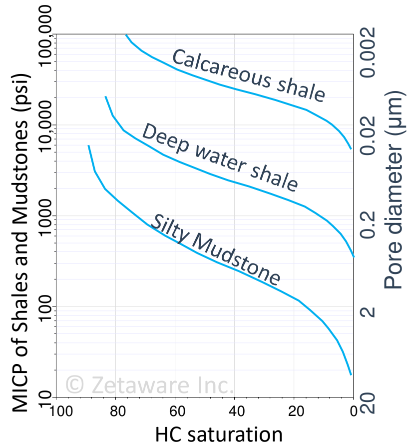
Another misconception may be that if a seal is leaking, it may not retain hydrocarbons in the trap. The physics is that if a seal capacity is exceeded by buoyancy, it is actually trapping the maximum column it can hold. It is just it can trap no more than that capacity. This happens for a good marine shale at about 200-400 meter of oil column, and for a poor deltaic mudstone, it is much more likely to be less than 100 meters. A leaking seal is required to create (and promote the formation of) stacked pay accumulations, such as those typically found in large numbers of stacked reservoirs along listric faults in a deltaic basin (South Texas, Niger delta), or up and down the flanks of salt diapirs (East Texas coast – see image of Texas on slide 3, Angola), and many South East Asia basins.

Petroleum Migration Is Dominantly Controlled by Capillary Forces





HC Column Needed for vertical migration a function of capillary contrast:

$$H = \frac{2\gamma\cos(\theta)\boxed{\frac{1}{r}-\frac{1}{R}}}{g(\rho_w - \rho_o)}$$

Up to hundreds of meters of HC column for marine systems

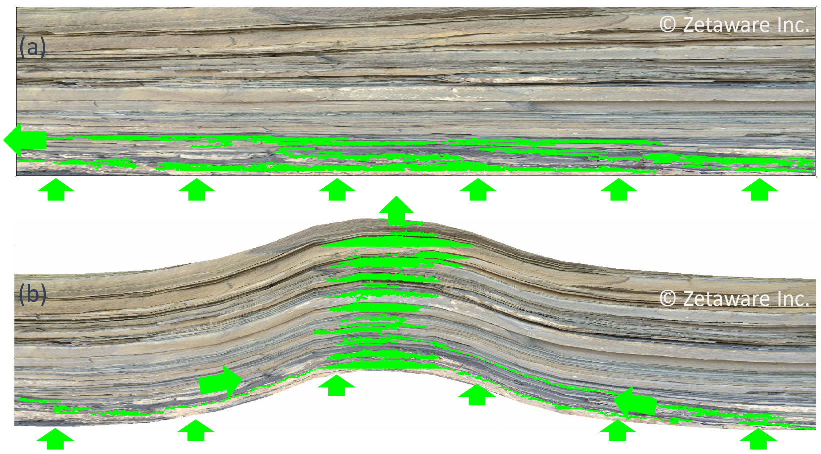
- ❑ Sedimentary rocks are much more laterally continuous. Vertical capillary contrast is much stronger than the buoyancy forces of small columns therefore usually forces lateral migration along bedding. Vertical migration is only possible where capillary pressure can be built up by a tall enough HC column, or high enough saturation in discontinuous beds.
- ❑ Relief/Column height required for vertical migration through interbedded shale and more porous rocks is typically 100s of meters in marine systems, 10s to 100s of meters in deltaic systems.

Because sedimentary basins are vertically stacked layers of sedimentary rocks of different grain sizes, from fine clays, to coarse sands, the pore throat sizes vary by several orders of magnitudes. As capillary entry/displacement pressure is mainly a function of pore throat sizes (slide 7), this becomes the most important physical parameter that control migration and accumulation.

Given the difference in of capillary entry pressures between the typical sand and shale, vertical migration is difficult as it requires certain column of hydrocarbons to be able to overcome capillary entry pressure at each shale/sand interface. To form this column, there needs to be a mechanism that blocks lateral migration. It may be a four way closure, a three-way closure (against a fault or salt barrier), or a pinch out closure. Without these, hydrocarbons tend to migrate long distances along the first (bottom most) carrier it sees. The numerous examples in this presentation will demonstrate this clearly.

Structure Focusing Effects on Migration

These two models are based on same outcrop stratigraphy. One is deformed to form an anticline. Capillary contrast used are of typical marine sedimentary sequence (ΔMICP ~1000 psi). Source rock is assumed immediately below section.



(a) Lateral migration (to the left) dominates because there is no room to build columns to overcome the strong vertical capillary contrast. Accumulations/Migration occur near the source rock.

(b) A structure closure allows columns to exceed capillary resistance and concentration of volumes for further migration. Lateral migration in areas without structure.

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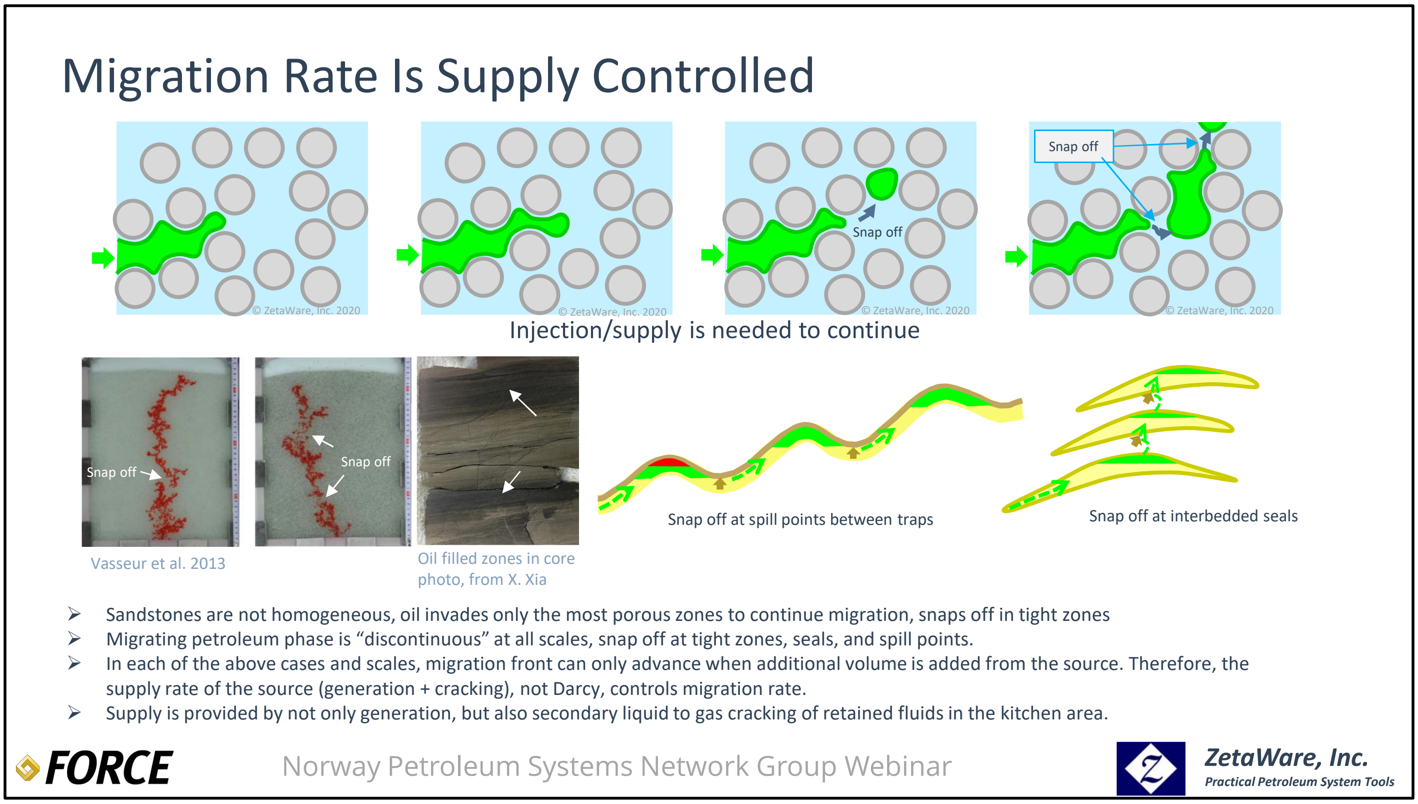
First let’s look at a numerical model. We take an identical set of sand layers interbedded with some fine grained silt and shales and map them to two different geometries, one a simply incline, and another a simple anticline. We inject the same amount of oil from the base of this layer and model migration only based on capillary displacement pressure. It clearly shows that the incline without closure promotes lateral migration along the base of the layer, and the structure works to focus migration and allow columns to build up to allow vertical migration.

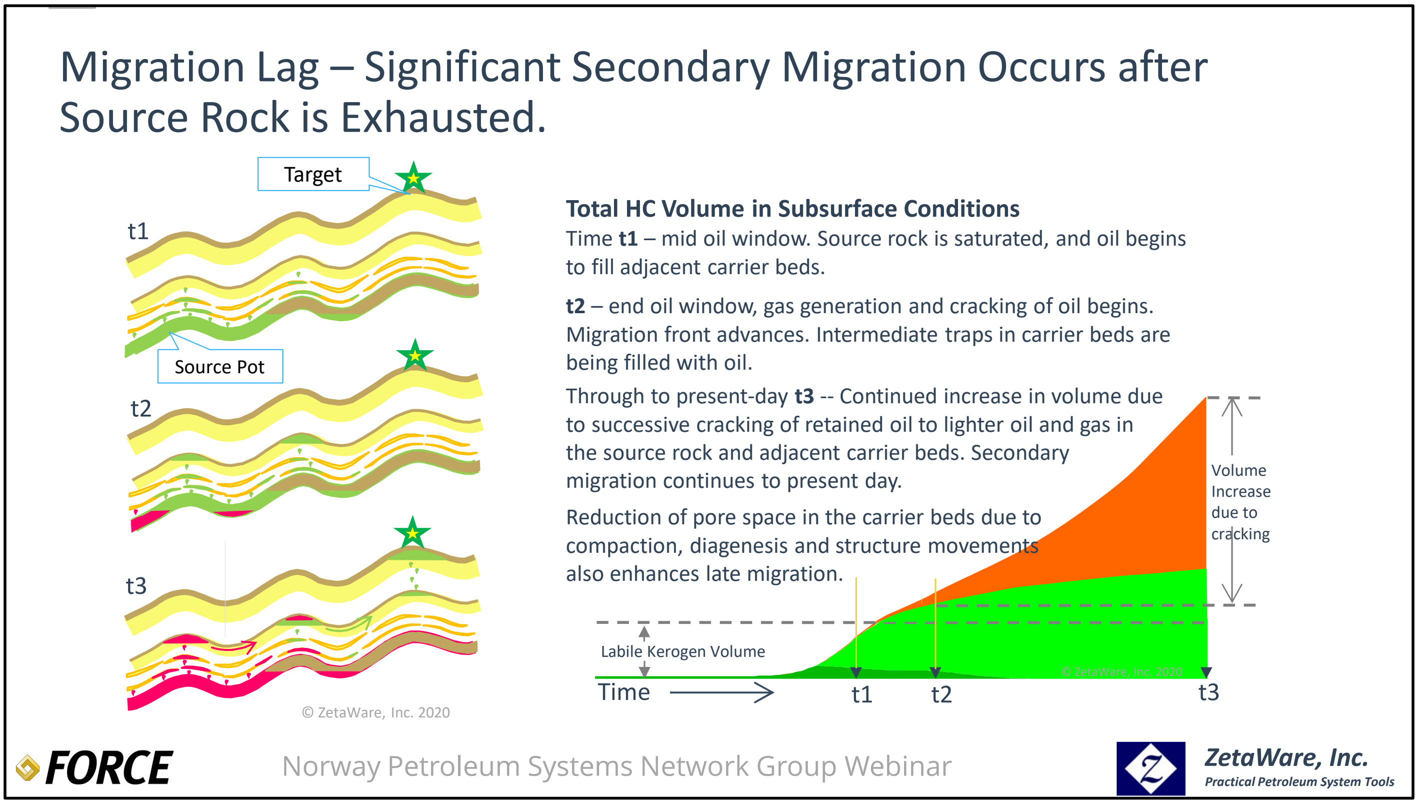
This contrast is clearly observable in nearly all basins we have looked at with enough data, including the image from Texas on slide 3, the Anadarko basin, the Alberta basin, Llanos basin, North Slope of Alaska, Bohai, the Gulf of Mexico, The North Sea, Bohai Bay basin, Cooper basin in Australia … the middle East, West Africa, North Africa … and the list goes on. We will present some of these examples in this presentation.



From physical principles, a hydrocarbon trap can be defined as a collection of connected pores enclosed by smaller pore throats with high capillary entry pressures, at least in 3 directions because buoyancy can help only from the bottom. If we don’t impose a size limitation, this will include a single pore, or a cluster of few pores, small structure, and all the way to giant structure and stratigraphic closures. A sedimentary basin contains endless number of such traps with all sizes of fractal distribution, and the migration process is simply filling them one at a time along the paths of least resistance.

The upper row of images show a migration “front” attempting to invade the pore system along the path of largest pore throats. Once it pushes through the next smallest pore throat, it will start growing into the next pore. As it grows, the ganglion will break at the pore throat due to capillary snap off (Carruthers 2003). This is not only observed in various lab experiments of migration such as Vasseur et al, 2013 (photos, lower left), but also describes fill-spill, or fill leak migration chains at large scales (lower right).

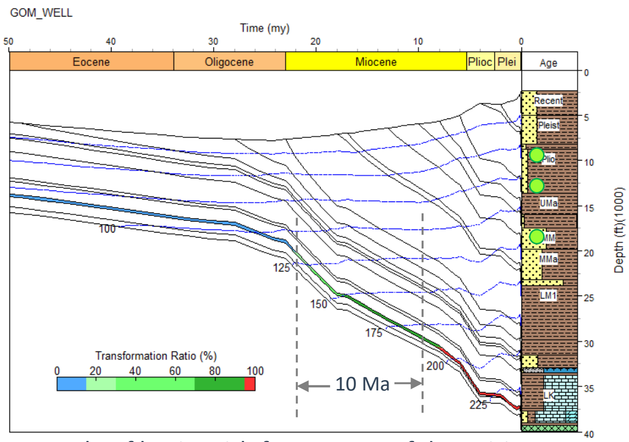
The conclusion is that from microscopic scales to large geological scales migration (rate and distance) is controlled by supply, as when supply stops or runs out, migration front will also stop. The snap off of a HC stringer at the smallest pore throat, and at break at the spill point of a large structure, or the break at a top seal, work the same way to prevent further migration when supply stops. Here is an analogy to think about. You take a bottle of water and empty it on the street in front of your house, it will flow down the slope, but will stop after filling some small puddles but not run all the way down the street. If you add another bottle, it will go a bit further, and will stop again. The rate of advance and how far it will reach is simply a function of the number of bottles you pour and how rough the street surface is. In between the puddles, the water becomes disconnected when supply is stopped.



When we realize that petroleum migration is supply drive and volume limited, it may be attempting to think that migration stops when source rock is exhausted. On the contrary, if we also consider that volume of petroleum continue to increase after the main generation window due to continued cracking (increasing GOR and therefore volume) of remaining fluids in the source rock and in the carrier beds as long as overburden and burial continue to increase. Additional volume of supply is provided by loss of porosity in the deeper traps due to diagenesis and compaction.

In this slide we explain why there is more secondary migration after peak oil generation window, which explains what we observe in various basins, that charging of reservoirs seem to be millions of years after generation (GoM deep water as show on slide 12, West of Shetland basin, Bohai bay, for examples) – migration continues as long as deposition continues.

Estimating Migration Rates



Example of basin with fastest rate of deposition
Deep water Gulf of Mexico

- GoM Tithonian Source Rock
  - Excellent Source Rock (100m, 5%TOC, 600mg/g) UEP = ~50 MMBOE/km2
  - Very short generation time ~ 10 my
  - Primary migration rate = 0.00001 m/year.
  - Note that is 1 million times faster than the typical glacier!
- **Highest rate of primary migration takes one year to move rom one clay sized pore to the next**! At the trap, filling rate ~300 bbl/year, due to focused flow from a large area.
- Darcy does not apply at these rates (see next slide). Petroleum migration is driven by the generation and volume expansion with increasing maturity.

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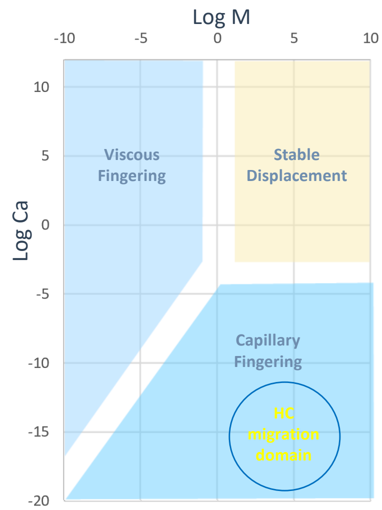
This examples is from the deep water of Gulf of Mexico, one of the basins the HC generation rate is the fastest. The excellent Tithonian source rock is about 100 meter thick and has a generation potential of about 60 barrels (~10 cubic meters) of oil equivalent. The burial history shows about 10 km of sediments deposited in the last 20 million years. The model shows that the source rock went through the oil generation window in only about 10 million years. Assuming all 10 cubic meters of hydrocarbons generated over that 10 million years migrates vertically out from the top of the source rock, the vertical flux per square meter is only 0.00001 meter per year!!! And that means it takes several years, to traverse a single pore. At that rate, viscosity has no effect compared to capillary forces, and the rate limiting factor is the rate of generation.

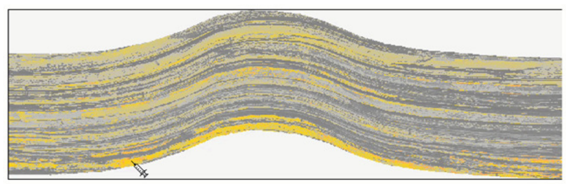
If a large structure that drains 100 square kilometers (typical of this area), and captures 50% of the generated volumes, which would be about 3 billion barrels in 10 million years (300 barrels/year or ~50 m^3 /year). Even assuming all of that oil enters the trap migrating through an only 1 km wide, 1 m thick cross section with 10% porosity, it would be just 0.5 meter per year – that is much slower than a typical glacier. As mentioned, this is probably one of the fastest cases. Most basins and most cases are much, much slower than that.

Migration Rate & Modeling



M – viscosity ratio (μ_{hc} / μ_w)
Ca – Capillary number = (vμ)/σ

- Migration rates are limited by rate of supply (generation), with capillary number (Ca) around 10^{-15}.
- At these conditions, viscous forces are negligible compared to capillary forces and the appropriate migration model is capillary invasion percolation (IP).
- The non-wetting HC phase simply invades the next pore throat that has the lowest capillary & buoyancy potential (path of the least capillary resistance).
- **Migration rate, distance and number/volume of traps filled, are all controlled by volume available and the capillary space.**



Additional animations here:
http://zetaware.com/products/trinity/seismic_2d_migration_movie.html

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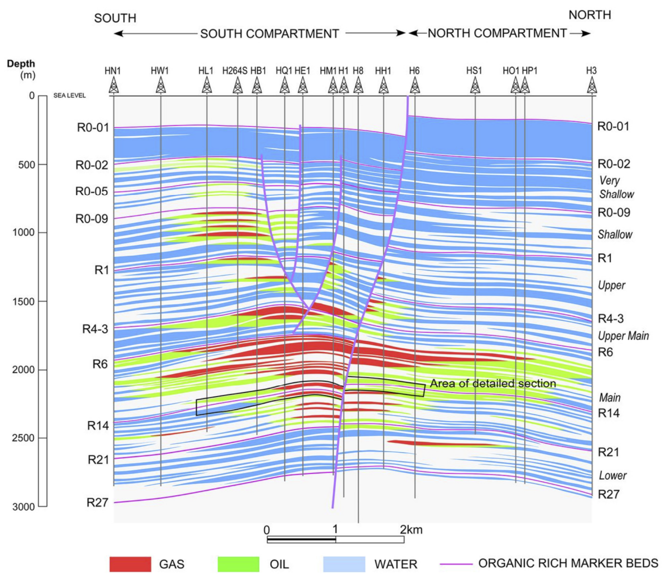
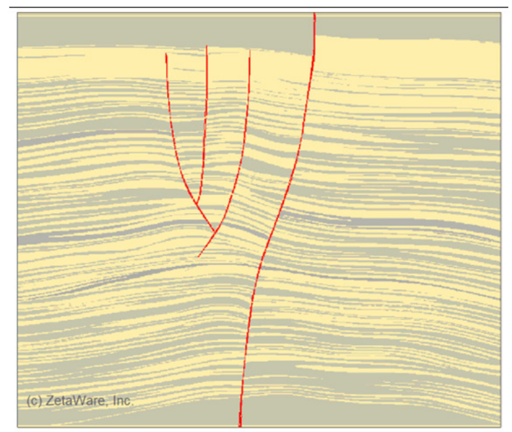
This left figure shows where typical migration rates would fall on the capillary number (the ratio of viscous forces over capillary forces) scale. Darcy flow is appropriate when capillary number, Ca, is above 10^{-5}. Migration rate is 10 orders of magnitude below that. The effect of viscosity is negligible compared to capillary forces.

As shown on the lower right figure (animation), a migration model (using Trinity software) can take advantage of this concept that it is supply driven and volume limited. The algorithm can be very efficient and fast even with high resolution facies distribution.

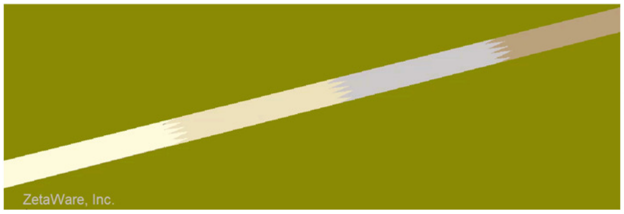
As a side note, because migration rate out of a source rock is on the order of 0.00001 m/year, and viscosity/permeability does not play a role, there is also no need for the commonly believed micro-fracturing to assist in primary migration. The literature on primary migration/expulsion is littered with statements that HC generation may cause microfractures due to extremely low permeability. Examination of widely published core and SEM photos of the Eagle Ford for example, in most cases do not show any microfractures. When fractures do exist, they do not show a scale and distribution pattern that would be consistent with HC generation. Often fractures in most cores are parallel to bedding and simply related to breakup during coring.   Some published attempts using pyrolysis to study HC induced fracturing seem to neglect the high possibility that fractures are caused by differential thermal expansion, whether the samples are source rock or not.



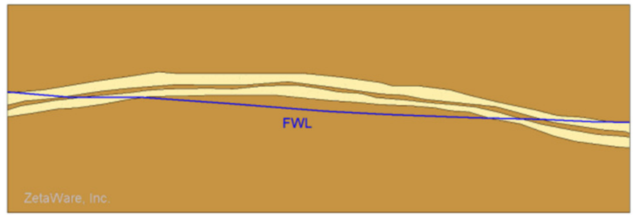


Handil Field, Mahakam delta, Indonesia, Antony Reynolds, 2016

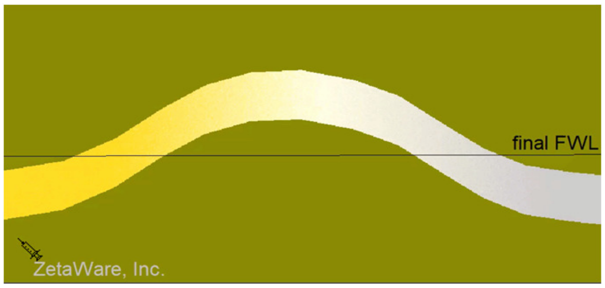
Facies Change & Hydrodynamics, etc.



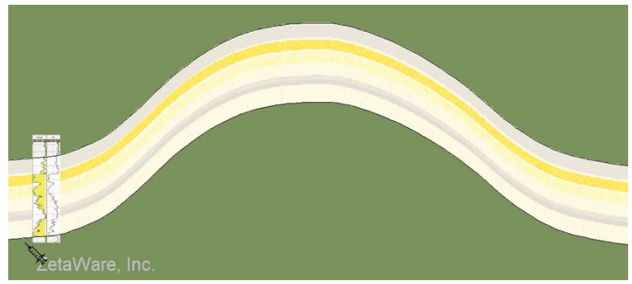
One man's reservoir is another's seal



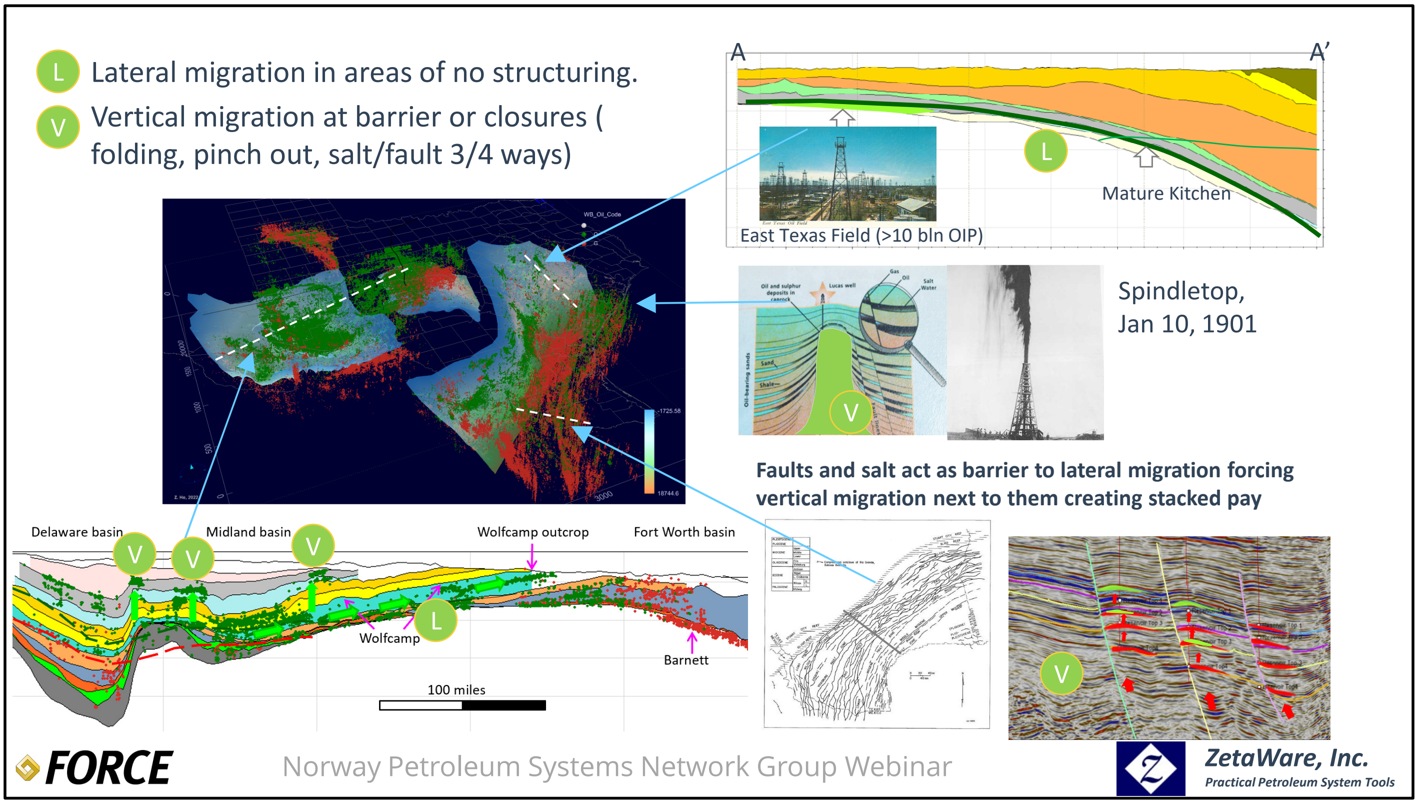
Hydrodynamic



Rocks control OWC & Sw



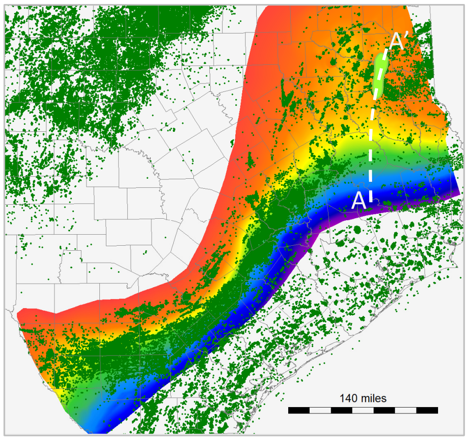
More Rocks control OWC and Sw



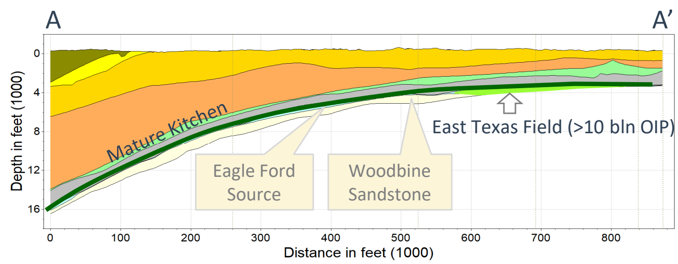
Now let's look at some more detailed examples where we observe migration patterns. The green circles with the letter V are areas of vertically stacked oil and gas reservoirs, and vertical migration is necessary to explain them. These mostly occur where there are significant structures, and closures aided by either salt or fault as the barrier to lateral migration. Without these geological features, migration is dominantly lateral and can be long distance, show as areas with the letter L (for lateral). This is a result of the orders of magnitude difference among the different stacked lithologies in any sedimentary basin, explained earlier on slide 9.

The fact that we can observe this among all the basins we have enough data to see the patterns makes it clear that this is the dominant control on migration. Vertical migration requires a structure relief in the carrier bed significant enough to allow buoyancy to overcome the vertical change in capillary displacement pressure. Such relief can be formed with 4 way or 3 way (with faults, or salt), or be a up dip pinch-out of the carrier bed. Without such relief, HC migration will be primarily lateral along stratigraphy.

East Texas Field, Largest Stratigraphic Trap in the US



- Largest Stratigraphic oil field in US
- 7 billion barrels has been produced
- Reservoir directly below source
- Long distance(>100 km) migration



https://en.wikipedia.org/wiki/East_Texas_Oil_Field

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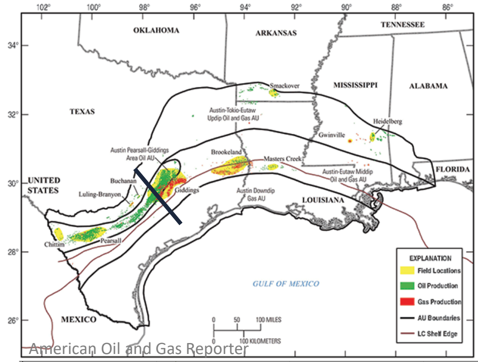
The East Texas Field discovered in 1930 is the largest conventional oil field in the lower 48 of United States. It is a stratigraphic trap in the Woodbine sandstone below (and charged by) the now famous Eagle Ford formation, an excellent source rock, but 100 kilometers up dip from the mature kitchen. The oil expelled downwards into the Woodbine sand and migrated up north for 100 kilometers until the reservoir pinches out against the Sabine uplift in East Texas.

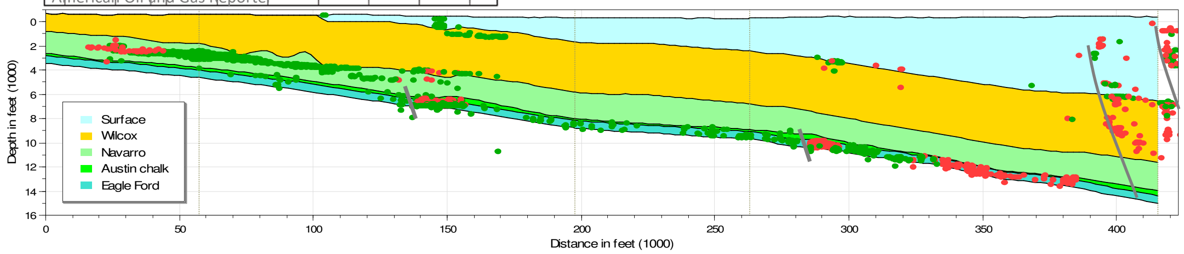
The simple syncline geometry of the carrier bed and lack of structure closures to allow buoyancy forces to exceed the sealing capacity of the Eagle Ford itself cause migration to be simply along the Woodbine for such a long distance. The field itself has many other interesting aspects that is part of the history of our industry (https://en.wikipedia.org/wiki/East_Texas_Oil_Field).

Giddings Field (Austin Chalk/Navarro), Texas



American Oil and Gas Reporter

- Multiple reservoirs produce above the Eagle Ford.
- Reservoir directly above source



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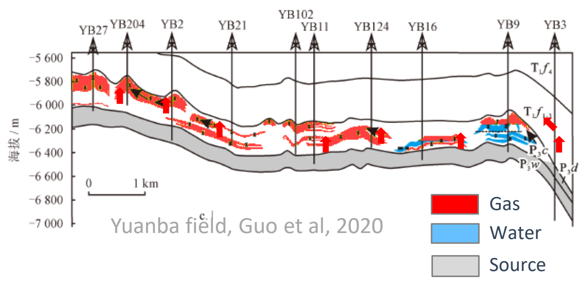
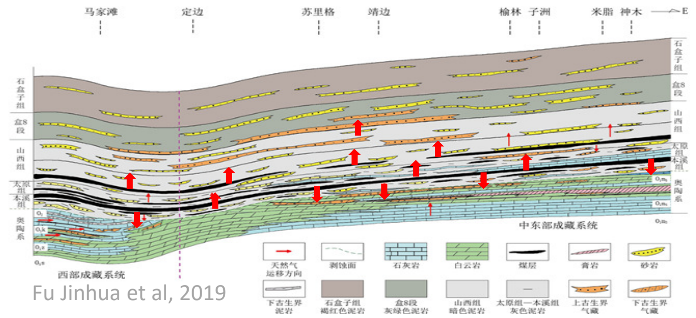
NW-SE cross section through the Eagle Ford play showing dominant lateral migration and accumulations in the Pearsall and Giddings fields in the Austin chalk formation directly above the source rock. Tertiary production, which require vertical migration, is typically related to faults that interrupt lateral migration. Sealing faults helps build columns required for buoyancy to exceed vertical capillary seal. Vertical migration at right end of the line is the heavily faulted deltaic SW Texas, where stacked pay in roll-over structures occur next to large listric faults.

The 3 Largest Gas Fields in China (Puguang/Yuanba/Suheli)



Yuanba field, Guo et al, 2020

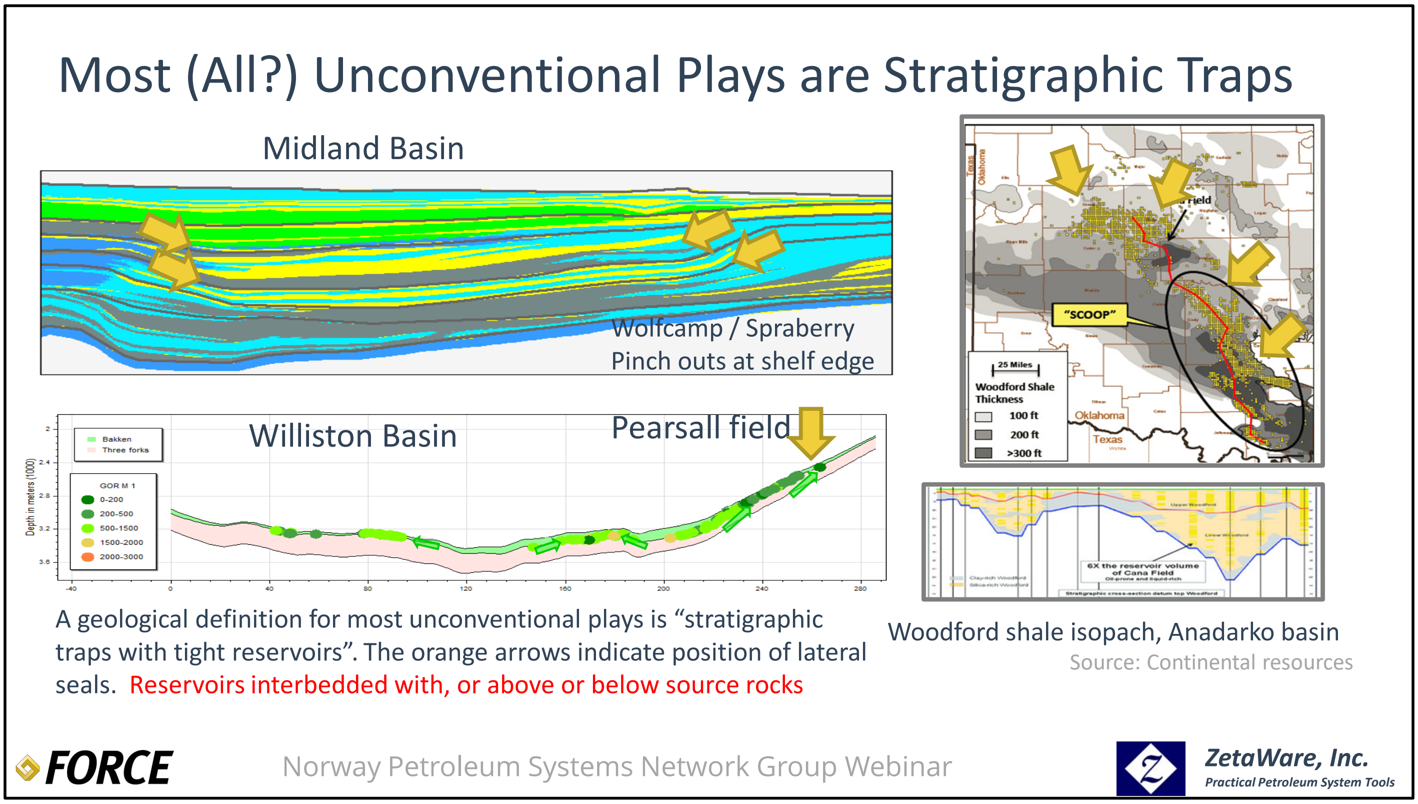
- > 25 TCF sour gas
- Reservoir directly above source
- Early charge as oil (Triassic), Cracked to gas with burial and TSR (Jurassic)



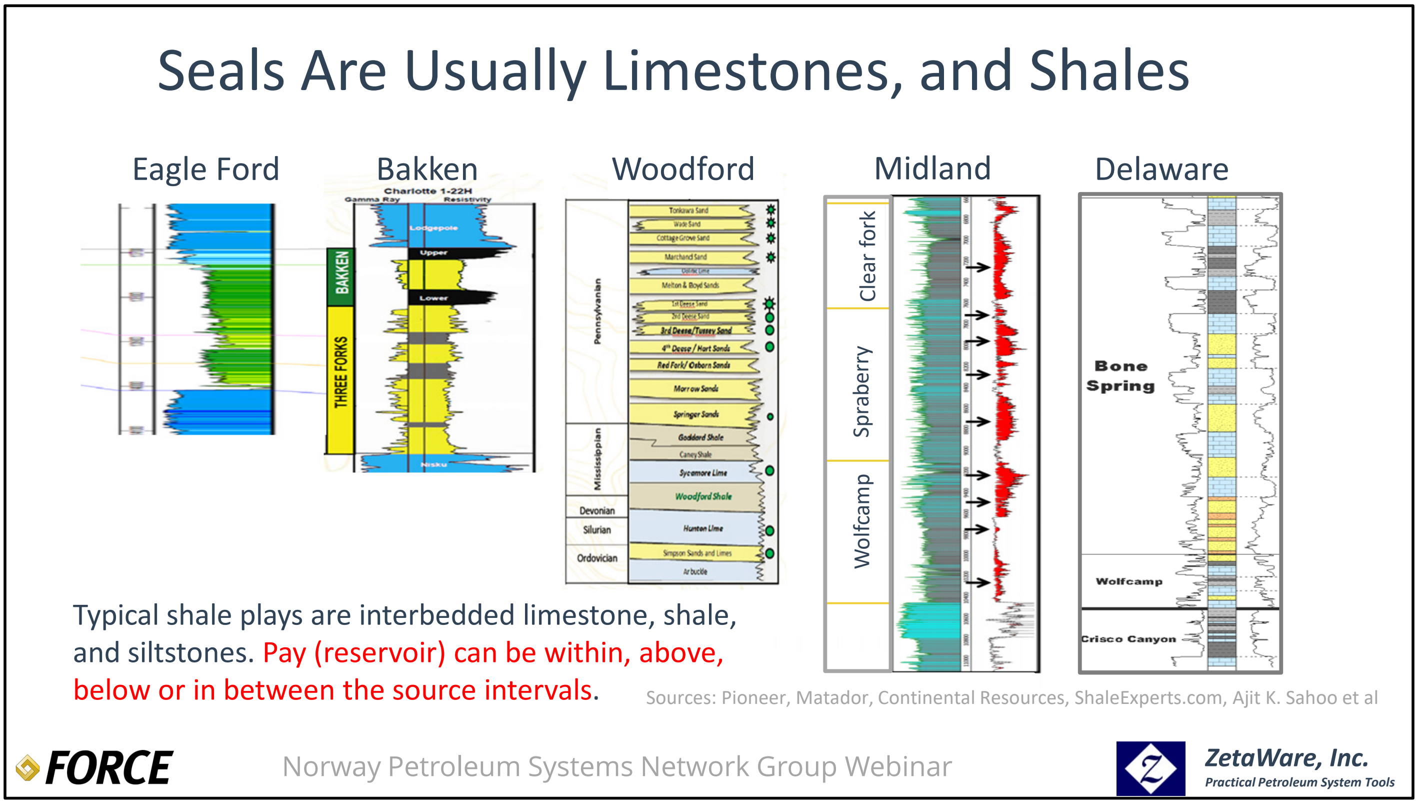
Fu Jinhua et al, 2019

- Sugeli tight gas (18 TCF), Ordos basin
- Reservoir directly below/above source (coals)
- No pay in shallower reservoirs

The three largest gas accumulations in China are all stratigraphic traps that form immediately above the source rock. Further vertical migration is difficult as there are no structure relief for buoyancy to exceed capillary resistance. Note the wet sands further up stratigraphy on the figure to the right.



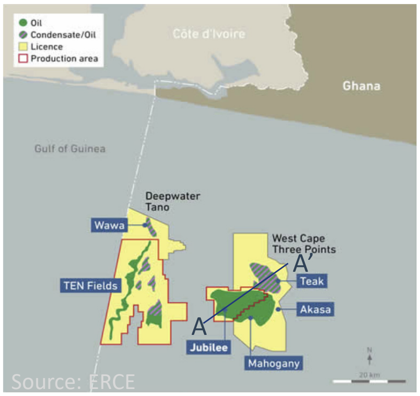
Here are a few examples from the "unconventional" plays in the United States. The typical unconventional play is a stratigraphic trap, or series of stratigraphic traps directly above, below or inter-bedded with the source rocks. The side seals are generally pinch outs, facies changes and sometimes faults. There are often a amalgamated systems of smaller scaler stratigraphic traps due to depositional sequences within the larger scale reservoir.

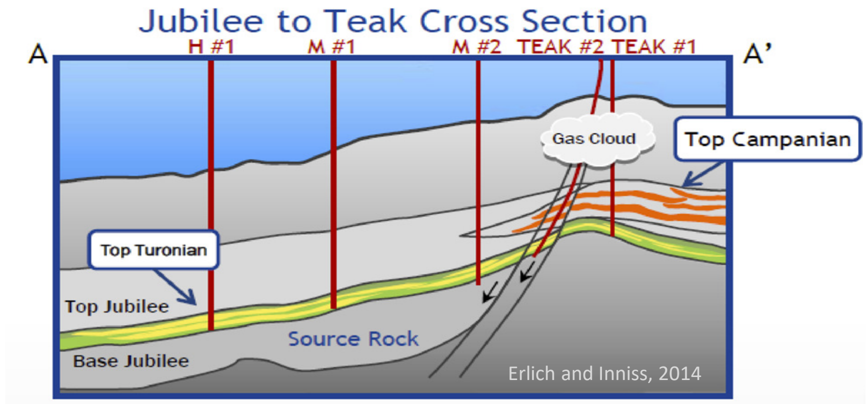


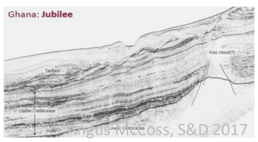
Details of stratigraphic relationship between the source rocks and the reservoirs in typical unconventional plays in the US. The reservoirs are usually siltstones, or marks, and the seals are usually limestones (He and Xia, 2017), and occasionally shales. The source rock can be either the reservoir (Eagle Ford) or the seal (Bakken), but not both. The capillary pressure (difference in pressure between the wetting and non-wetting phase) increases with saturation of the non-wetting phase, so if a seal has a higher capillary entry pressure, it will result in a higher saturation when the trap is "full", whether the petroleum is generated within the reservoir (Eagle Ford, Wolfcamp, Woodford), or migrated into it (Bakken, Bone Springs, Meramec etc.), or often both.

It seems that many geologists have a hard time imagining migration of petroleum within, or through shales. Perhaps it is because we often use (incorrect) words like "impermeable" to describe a shale. The reality is that ALL shales ARE permeable. As discussed earlier, migration is limited by rate of supply (generation), which spans over 10s of millions of years and at rates so slow that viscosity (therefore permeability) is not even a factor (See slide 13).

Jubilee Field, Tano Basin



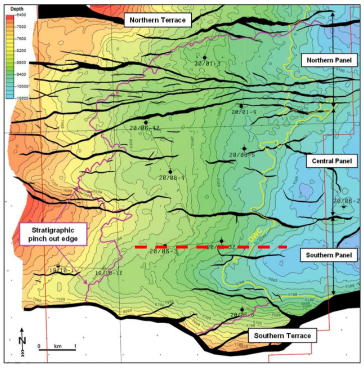




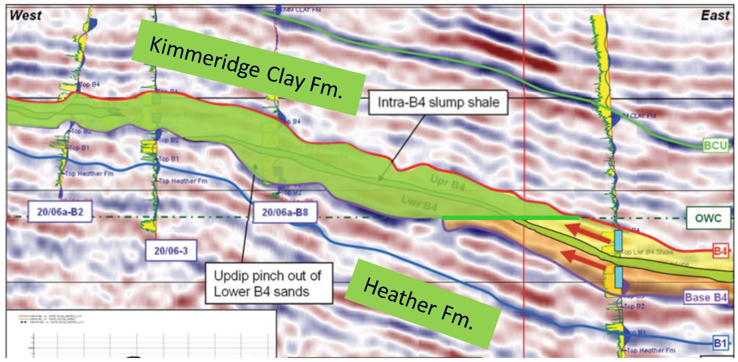
- Turonian reservoir
- Upper Albian source below, CT source downdip
- Reservoirs directly above source

One of the biggest stratigraphic type fields discovered in the last 20 years is the Jubilee field offshore Ghana in 2007. Again, the simple fact is that the reservoir is directly above the source rock. The Teak field up-dip involves more vertical migration but then the fault related structure makes that possible.

Buzzard Field, North Sea



F. M. Ray et al., 2018/ PESGB Blog

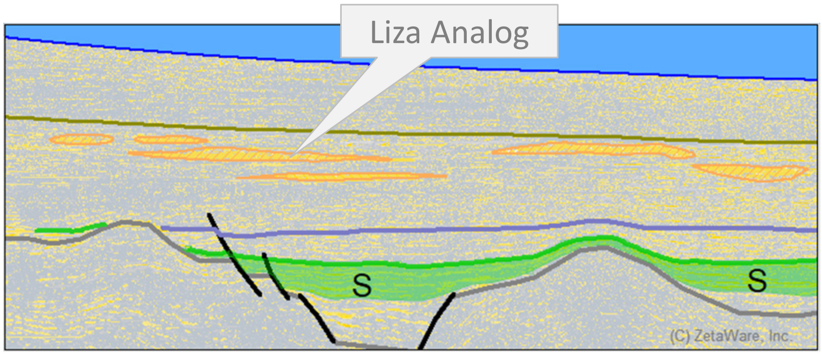


F. M. Ray et al., 2018/ PESGB Blog

- Largest stratigraphic field in North Sea (1.5 billion bbls)
- In between Kimmeridge Clay Fm and Heather Fm
- Reservoirs between two source rocks

The largest stratigraphic field in the North Sea is the Buzzard field discovered in 2001. The reservoir is sandwiched between the two well known source rocks, the Kimmeridge Clay Formation and the Heather.

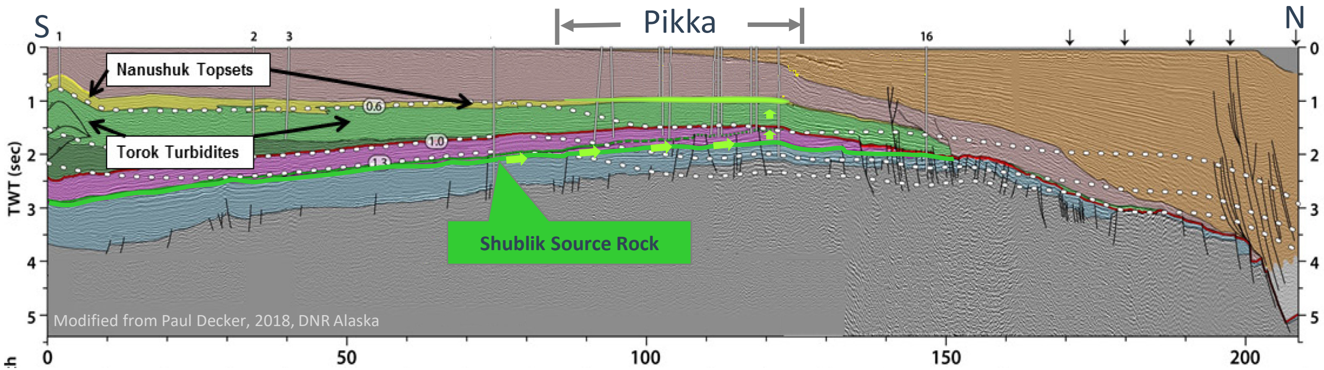
Stratigraphic Traps Need Focusing (Guyana/Suriname)

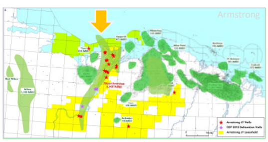


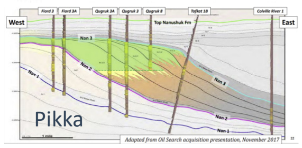
Migration model shows large relief structures at the source rock level help vertical migration and charging Liza reservoirs. Faults may help by disallowing lateral migration. Shallow traps without deep focus elements have higher migration risk.

All previous examples show that most stratigraphic traps occur directly in contact with the source rock. It is not common to find stratigraphic traps further up stratigraphy. A mechanism for vertical migration is necessary if shallower stratigraphic traps are to be charged. We provide a couple of examples here. The example is the Liza field, along with the main productive trend in the Guyana/Suriname basin. The vertical migration into the younger reservoirs is helped both by some of the structure features below at the source rock level and the seemingly abrupt discontinuation of reservoir facies up dip at the foot of the paleo-shelf to the south. These features help produce the buoyancy force necessary – by not allowing lateral migration. The above is a Trinity migration model demonstrating how these features help vertical migration and charge the accumulations in the area of Liza (apologies that the animation does not work in pdf format).

Stratigraphic Traps Need Focusing (Alaska)



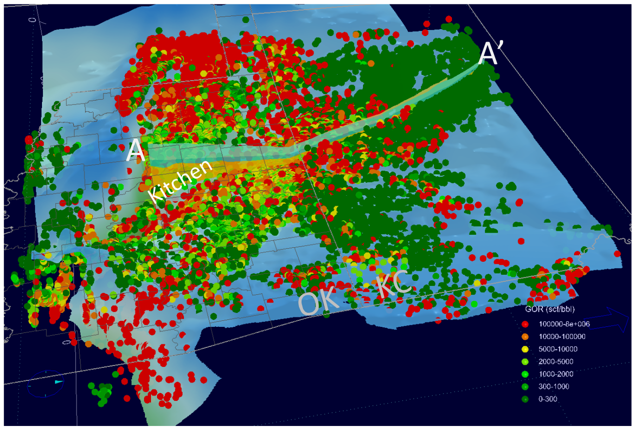




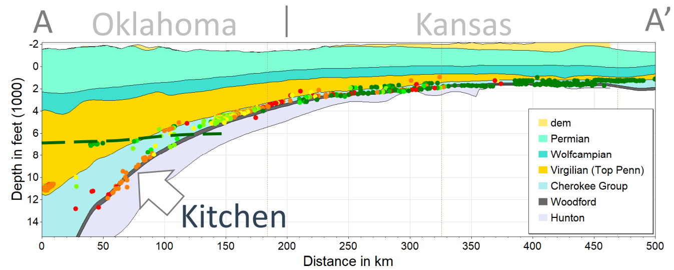
- Recent large discoveries, Pikka (3.9 billion barrels), Willow (1.3 bnbl), … in the Nanushuk top sets.
- Focusing at Shublik source rock level provided by regional high, along the giant Prudhoe, Kuparuk fields.
- West Sak above Kuparuk is analog for Pikka

The other such example is the Brookian discoveries in Alaska in recent years. The reservoirs are the Namushuk topsets of the deltaic progrades. The source rocks are further below. The migration model necessary to explain the charging of the shallow reservoirs is shown in this slide. The lateral migration (green arrows) occurs first at the source rock level (marine sequence with high vertical capillary contrasts) – toward the structure highs along the Barrel arch, where some giant structure fields were found in the past. In the locations of these fields, the structure highs provided the buoyancy needed to overcome the vertical capillary barriers to migrate up stratigraphy to the Nanushuk reservoirs. The key for targeting the Nanushuk play and risking migration and charge access should be looking for/mapping structure highs at the source rock levels.

Stratigraphic Traps Can be Far Away from Kitchen



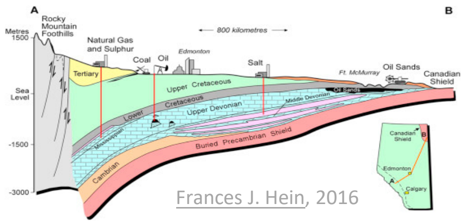
- Anadarko basin
- Long-distance migration: > 500 km
- Oil stays in Mississippian formation
- Directly above Woodford source rock

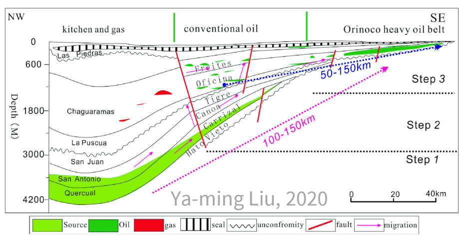


In foreland and continental basins, the lack of structure relief means the dominant migration will be lateral. If that is combined with a super rich source rock, migration distances can be very far, up to hundreds of kilometers. This and the following slides are some examples.

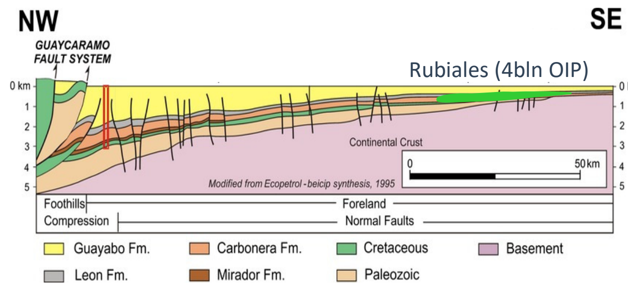
In the Anadarko basin (this slide), the kitchen is limited only to the depocenter in southern Oklahoma. Yet, hydrocarbons migrated along the Mississippian all the way across northern Oklahoma and Kansas, even to Nebraska, over 500 km away from the kitchen. Note the lack of production in the shallower formations. Vertical migration is limited to southern Oklahoma along the thrust front, where there are large faults and high relief structures.

Stratigraphic Traps & Long-Distance Migration





- Many are giant fields, two of the world's largest fields
- Long distance migration: Athabasca (800km, Orinoco 100 km, Llanos 100 km, Anadarko 500 km, …
- May not require a seal (self sealing)
- Typically, near fore bulge of Foreland basins.

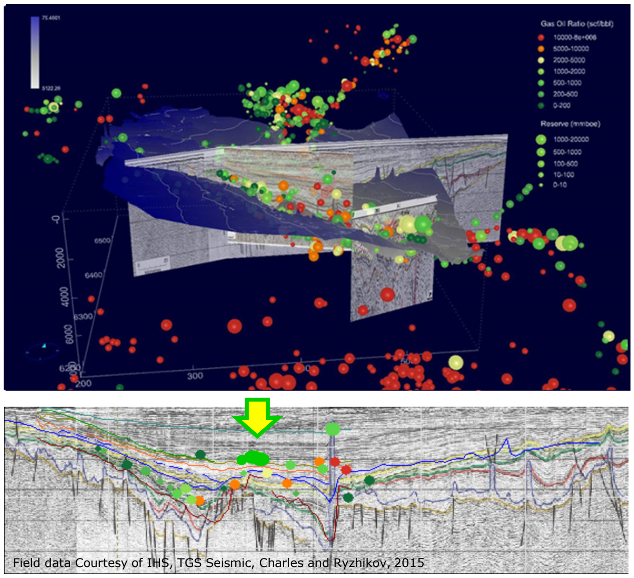


Similar patterns are found in other foreland basins. The largest oil deposit in the Alberta basin is 800 km away from the source kitchen. The Orinoco oil belt is also 100 km away from the kitchen. The largest oil field, Rubiales, in the Llanos basin, Colombia, is over 100 km away from the kitchen. Vertical migration and charging of younger reservoirs mostly occur along the thrust belt and foot hills where high relief structures and thrust faults prevent lateral migration, such as the Cusiana, Cupiagua fields in the Llanos basin.

Key Conclusions I

- Because vertical migration is difficult without structure closures, vast majority of stratigraphic accumulations are found adjacent to (above/below/between) source rocks. But for the same reason, they can be found long distance away from the kitchen, still adjacent to the source.
- If the target traps are higher up in the stratigraphy (> 500 meters above), we should look for focusing elements (3-way or 4-way closures) at source level, as shown in the Guyana and Alaska examples.
- Most unconventional plays are stratigraphic accumulations and fit the above discerption.
- Migration and charge risk high without these two conditions.

Petroleum System Behavior from Big Data (North Sea)



Visualization of large field/fluid databases along with seismic and structure geometry reveals important clue for HC migration.

Vertical migration into Tertiary reservoirs are mostly over basement, fault block high and salt diapirs. Surface shown is top Jurassic.

The largest fields in Cretaceous and Tertiary reservoirs are located above basement highs (yellow arrow). The high relief of these structures promote vertical migration, by gathering large volumes, and create buoyancy drive. These include the Montrose and Forties fields.

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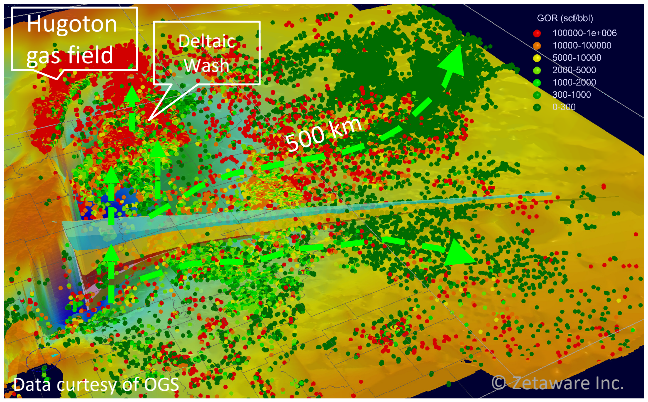
As explained earlier, vertical migration needs to overcome significant capillary barriers, and therefore require significant columns to provide the buoyancy. This is why most accumulations stratigraphically higher up than the source rock are associated with significant structuring, which include 3-4 way structures, structures associated with salt/shale diapirs or faults. Most significant vertical migration occurs over large basement highs which not only provide the structure high to create the buoyancy, but large drainage areas to provide the volumes. This is where most of the world's giant fields are found.

The Central Graben high in the North Sea example above, is such an example. Along the central high, are some of the largest fields in the North Sea, such as the Forties and Montrose fields.

Faults are required to form 3-way structures and often 4-way structures have faults at their crests, this creates the apparent association of vertical migration with faults. This association lead to wide believe that faults are necessary conduits for vertical migration. Faults are helping vertical migration by preventing lateral migration and creating 3 way structures who's relief is the reason for vertical migration. Significant stacked pay in 3way structures along large faults demonstrate that faults are mostly sealing (not leaking!). Almost every single oil and gas field in the North Sea is bound or intersected by faults, which would not be fields if the faults were leaking.

Migration Tendencies, Horizontal vs Vertical



Production cumulative GOR data with Woodford structure surface, Anadarko Basin, US

- ❑ Long distance migration along low relief marine, foreland strata
- ❑ Vertical migration in fan/deltaic systems where lateral continuity is poor, high relief "foothills" structure, and lateral fault barriers
- ❑ Oils migrate further out than gas.
- ❑ The above patterns are observed globally in many similar basins

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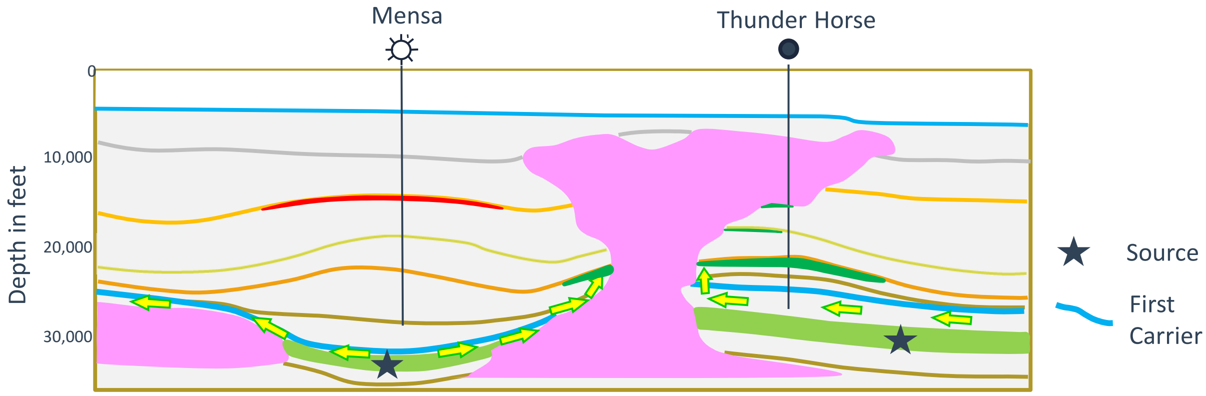
Similar to other foreland basins, accumulations in Anadarko basin form dominantly two major trends. One is the long distance migration along the Mississippian strata, mostly subtle structures and stratigraphic in nature. The second trend is along the thrust zone and mostly vertical migration into shallower reservoirs.

Classic Example of Deep Focusing in Deep Water GoM

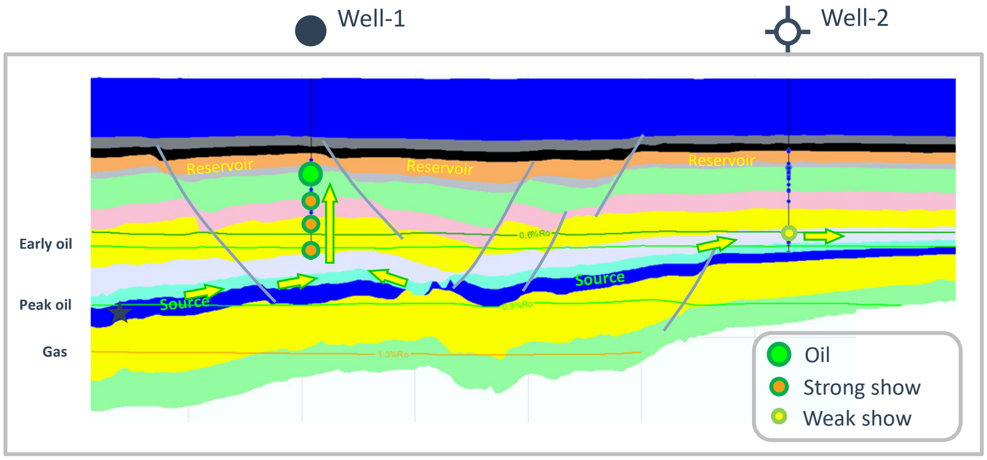


The four-way turtle structure at Mensa does not receive deep charge as the geometry at the first carrier (Cretaceous) is divergent and promotes lateral migration away from the structure. Biogenic gas is discovered in upper Miocene.

Thunder Horse structure around the salt has deep focusing at the first carrier level to promote migration and > 1bln bbls oil in place. Salt walls act to restrict lateral migration and force vertical migration

This example illustrates a typical migration risk scenario for Miocene targets in the deepwater Gulf of Mexico. Miocene structures that have a significant structure high below are lower risk than those that don't' have such a structure. Some companies have followed this concept to de-risk their prospects with great success. P.S. in the Mensa vs Thunder Horse case, there is also a possibility that the Tithonian source rock may not be present under the Mensa structure.

A Recent Example, On Shore Africa



Recent drilling on shore Africa, again proving the concept.
> 100 meter closure at deeper levels below the discovery and < 50 m closure below the dry hole

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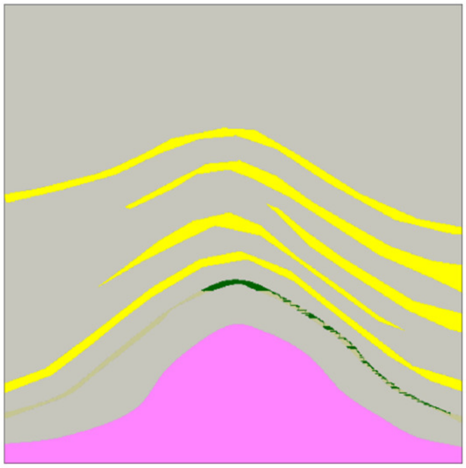
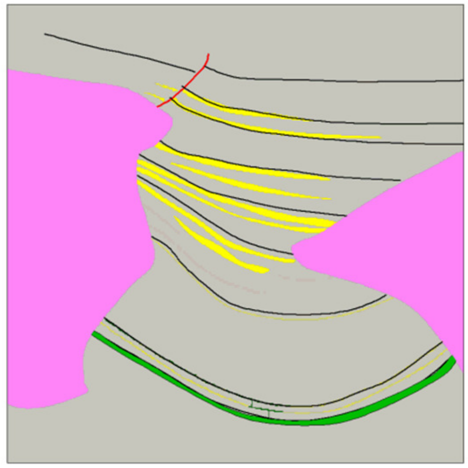
Another example that shows vertical migration in location of higher structure relief. Well 1 is a discovery and charged due to vertical migration allowed by the structure below. At the location of well-2, the carrier bed has no relief and therefore only lateral migration is possible, the reservoir is not charged, but the well encountered shows at the deeper carrier bed.

Vertical Migration in 4/3 Way structures

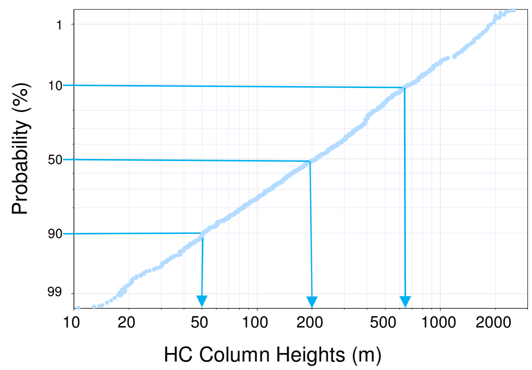


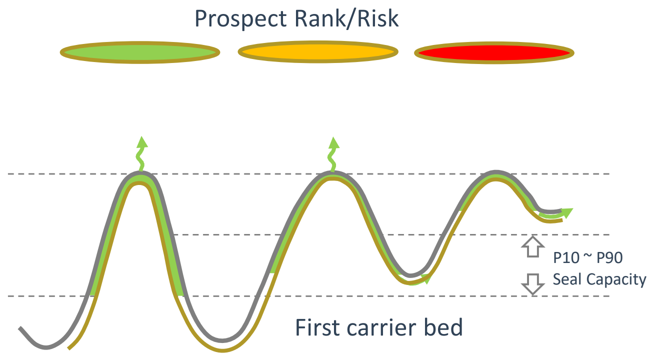


Mars field on the right in GoM. These have shown to be consistent with fluid property composition distribution within and across reservoirs – e.g. Milkov et all, on Horn Mountain Field

Probability of Seal/Leaking & Vertical Migration

Global HC Column/Seal Statistics (P50=200m)





Probability of seal capacity distribution based on analog statistics can be used to risk migration and charging of shallow prospects, combined with the structure relief map of the deeper carrier beds. And for a given structure closure, it provides a probability of leaking vs spilling.

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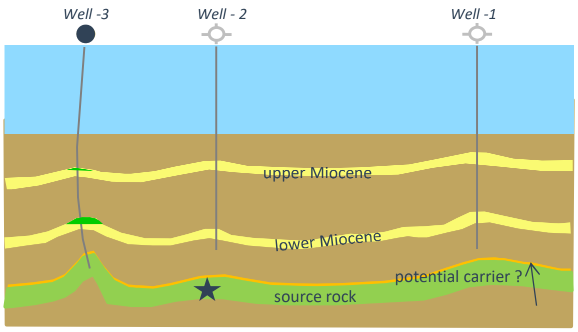
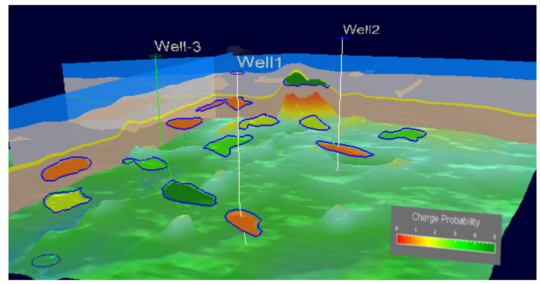
Vertical migration occurs when buoyancy exceeds the sealing capacity of the overlying formation. It is necessary to know not only the structure relief which typically can be measured/mapped, but the displacement pressure of the top seal for the given HC/water fluid pair. The latter is very variable and leads to large uncertainties even for a given lithology. Deterministic prediction of vertical migration is not likely very successful. The recommended approach is the probabilistic simulation that provides a probability of vertical migration at each location and the input parameters of the model should be determined from analog statistics. This will help evaluate and rank migration risk for prospects stratigraphically younger than the source rock with significant vertical distance between reservoir and source. Such models can be improved when local HC column statistics and capillary pressure data are available.

Best Practice: Prospect Charge Risking



Based on an offshore West Africa basin



Lower Miocene charge risk from seal and source scenarios. Red high risk, dark green low risk.

Wells 1 and 2 are dry holes and well 3 is a discovery – simply because the higher relief structure below well-3 allowed vertical migration.

Trinity 3D Migration Risking Lower Miocene prospects are ranked by testing scenarios of seal capacities at the first carrier level, so high structures are more likely to leak. Prospects are colored red for high risk and green for low risk. The second dark green polygon in the distance become the next discovery.

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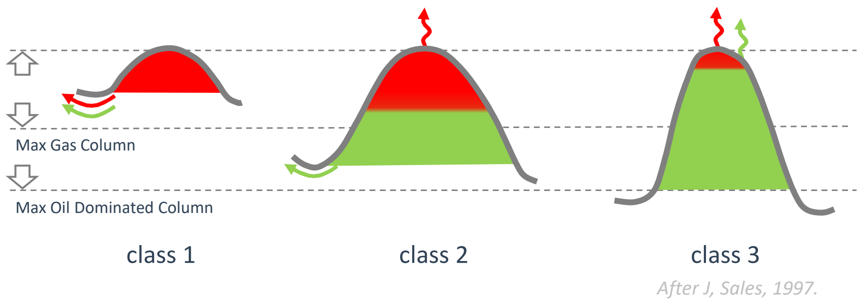
Example of the probabilistic model prediction. The colors represent low and high charge risk for the lower Miocene leads. This is done by running 3D migration scenarios by varying seal capacity at the first carrier (directly above the source rock). The prospects that receive charge in more scenarios is assigned a lower charge risk, and vice versa. Other petroleum system factors can be included in the risking as well, such as the source rock quality, maturity etc.

Seal Strength vs Closure

"A Fundamental Control on the Distribution of Oil and Gas"



In a dual HC phase system (pressure < Psat), a small relief trap is more likely to spill the oil phase and contain only gas (class 1). A tall enough trap will retain mostly an oil column, while a small gas cap may remain due to interfacial tension differences (class 3 – e.g. deep-water Sabah). If closure is greater than the maximum gas column but less than the maximum oil column, it will end up with both phases (class 2). After J, Sales, 1997.

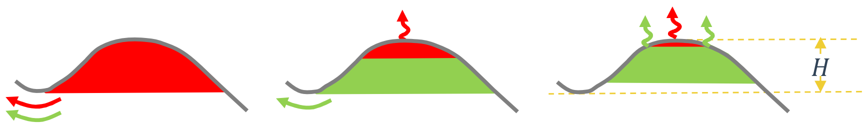
A prediction of likely phase in a trap can be made if seal strength can be estimated.

1) Incoming GOR is based on analog and should be a range, so there will be a probability of under saturated gas condensate when incoming CGR is less than 50 bbl/mmscf, and a small probability of undersaturated oil as well. The pie chart should have 30% chance for single phase gas
2) Perhaps the P vs Psat plot can be replaced with a Psat vs GOR graph (we need a name for that plot!!!) and the Tawhaki pressure & GOR range indicated on the graph.

Capillary Seal is also an Important Controls on HC Phase (Oil vs Gas)

For any given structure closure that is in the two-phase region (reservoir pressure below bubble or due point) of a petroleum system, the seal capacity dictates which phase ultimately remain in the trap, assuming charge volume is sufficient. This figure is a modification of Sales' (1997) trap classes.

If the capillary seal is greater than the buoyancy of a full gas column, the trap will end up containing gas only. If the seal capacity is less than the buoyancy of a full oil column, the trap will contain oil only. In all other conditions, the trap will contain both a gas cap and an oil leg.



$P_c > H \cdot (\rho_w - \rho_g)$

$H \cdot (\rho_w - \rho_g) > Pc$
$P_c > H \cdot (\rho_w - \rho_o)$

$P_c < H \cdot (\rho_w - \rho_o)$

Where, P_c is the capillary seal capacity of the shale, H is the closure (crest to spill point) of the trap, ρ_w, ρ_o, and ρ_g are the in-situ densities of the water, oil and gas columns, respectively.

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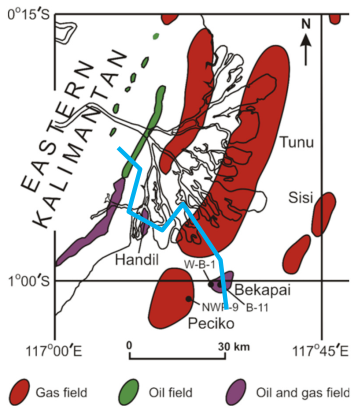
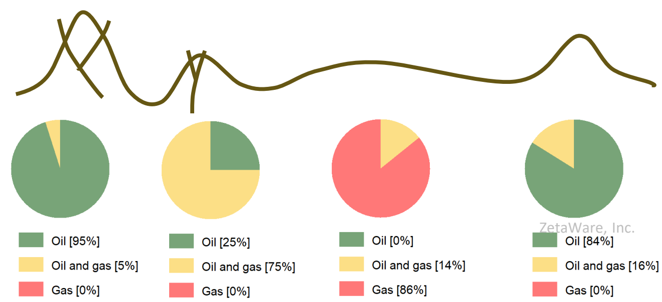
The previous slide shows how seals control migration and the distribution of hydrocarbons in a basin, that determines if a given trap can or cannot be charged. This slide is a modification of J. Sales 1997 trap classes that explains how seal capacity also controls the hydrocarbon phase (oil vs gas) of a fully charged trap. We believe that seals are THE most important factor to study in order to evaluate charge and phase risk, based on such considerations these two slides, and the observations we will present in the rest of the presentation.

It should be pointed out, that although seals obviously has the biggest influence on migration and charge risk. Yet in the last 30 years, the focus of so called "BPSM" (Basin Petroleum System Modeling) have been mostly elsewhere, such as heat flow, kinetics, debate about flow mechanisms, and the literature is scarce in how capillary properties are modeled or calibrated. In this presentation we show the two main approaches we use for evaluating charge risk.

Best Practice: Prospect Phase Risking

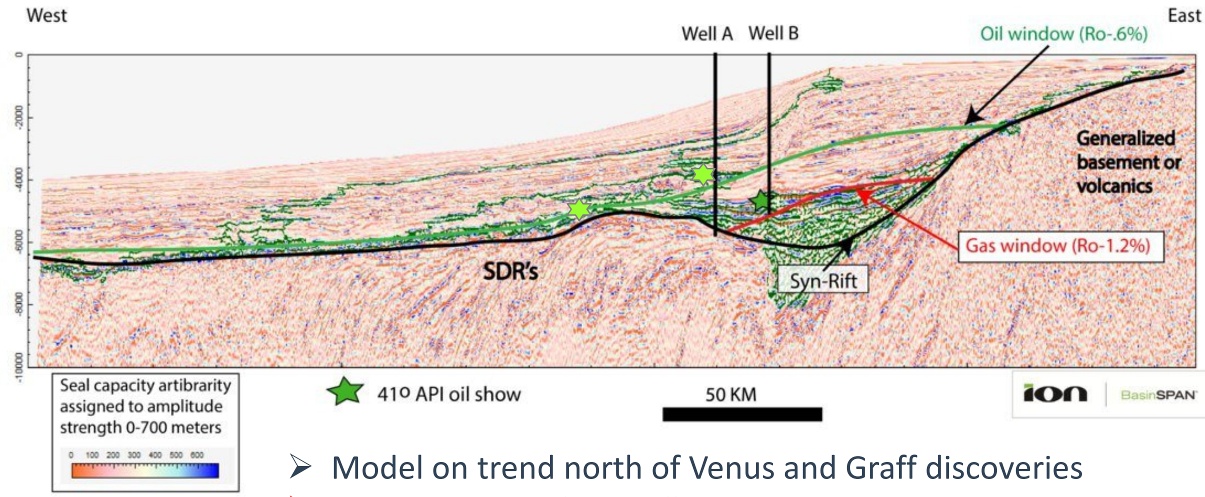


Sanga sanga >500 m | Handil 50-250m | Tunu 40m | Bekapai 400m



Trinity 3D phase risking results with same input parameters on charge (1000-10000 scf/bbl) and seal (25 to 120 psi seal Pc). Only variable is closure height among the traps. Map courtesy of Ramdhan and Goulty , 2018

Migration Model Orange Basin



- ➢ Model on trend north of Venus and Graff discoveries
- ➢ Understanding the capillary system & Top-down PSA

Hunting for NULFS, John Dolson 2017

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This cross-section based migration (courtesy of John Dolson) model demonstrates the charging scenario for the Venus and Graff discoveries (the two light green symbols). Outboard in deep water there is little structuring and migration tend to be mostly lateral. Fortunately, the Venus 1 reservoir sits directly on the source rock and therefore has very low risk receiving charge. The Graff however, is at a higher stratigraphic level, and may require a focusing element at the source rock level. This understanding can help evaluate migration risk for other similar prospects.

Key Observations

- Not only vast majority of stratigraphic accumulations are found adjacent to (above/below/between) source rocks. Structural traps are also much more likely charged when adjacent to the source.

- Observed vertical migration “chimneys” are associated with lateral barriers and structure closures.

- Globally, estimated >80% of the reserves are found adjacent to source, in “first carrier” beds – Canada/US/Venezuela/West Siberia/Middle East/North Africa

- And exploration success rate for traps adjacent to source are 2-3 times higher than further up stratigraphy in the same area.

Key Conclusions II

- The capillary system, is a very anisotropic (high Y/X ratio in capillary pressure), slow supply driven/limited process, and understanding the geological/geometry control on it is key to exploration success.
- Lateral migration is naturally the dominant direction.
- Vertical migration occurs where structure or stratigraphic elements create barrier to lateral migration. Such barriers need to be at least 3 way to create a column to allow buoyancy to exceed capillary pressure. Structure 4 way, or 3 way with faults or salt, pinch out.
- **To increase success rate, target first carrier beds adjacent to (above or below) source. For shallower prospects, require significant focusing & closure at the source rock level.** Or at least highly rank prospects that meet one of these two criteria.

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