Understanding the Role of the First Carrier Bed: Simple Rules of Thumb and Best Practice That Can Help Reduce Dry Hole Rate*

Zhiyong He[1]

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[1]ZetaWare, Inc., Sugar Land, TX, United States (zhe@zetaware.com)

Abstract

The first carrier bed is defined as the migration carrier adjacent to the source rock. It has the most significant control on lateral migration of petroleum and of charge access to all traps above it. Observation of oil and gas fields and dry holes and building migration models to account for them allow some simple rules of thumb, or models, to be devised and used for charge risking. Globally, we find that success rates for wells targeting reservoirs within or adjacent to the first carrier bed/system are often above 80%. Examples include the Jurassic reservoirs of the North Sea, Arab formation in the Middle east, Silurian reservoirs of North Africa, the Paleogene of the deep Gulf of Mexico, the Norphlet play on and offshore GoM and many of the unconventional or hybrid petroleum systems. In fact, a significant fraction of world petroleum reserves is found in the first carrier bed. Success rates drop exponentially with increasing distance above the first carrier because lateral migration creates "shadows" for targets above the first carrier. Charging of younger reservoirs is only possible where the relief of the first carrier allows migrating petroleum to form a column tall enough to exceed the capillary resistance to migrate vertically. This typically happens where the first carrier forms a three or four-way closure or a stratigraphic trap. Probability of charge for traps located directly above such features are significantly higher than average. Larger drainage areas allow the gathering of large volumes which mitigates the risk of the deeper section consuming all available volume (especially in basins with a lower quality or low maturity source). Large discoveries in the Tertiary/Cretaceous reservoirs of the North Sea, Miocene reservoirs of the deep water GoM and the most recent discoveries such as Zama and Liza prove this principle. A useful rule of thumb is that charge access risk for shallow prospects is significantly reduced if the closure of the structure in the first carrier is > 500m in deep water marine systems or >150m in non-marine/deltaic systems. In most cases, we do not know a priori the capillary properties of the seal and there are significant uncertainties in extent and continuity of the first carrier and available expelled volumes. Hence, best practice is to assign a relative charge access risk based on the relief and drainage area of the first carrier. We will demonstrate the successful application of this approach.

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Understanding the Role of the First Carrier Bed: Simple Rules of Thumb and Best Practice That Can Help Reduce Dry Hole Rate

Zhiyong He, ZetaWare, Inc.

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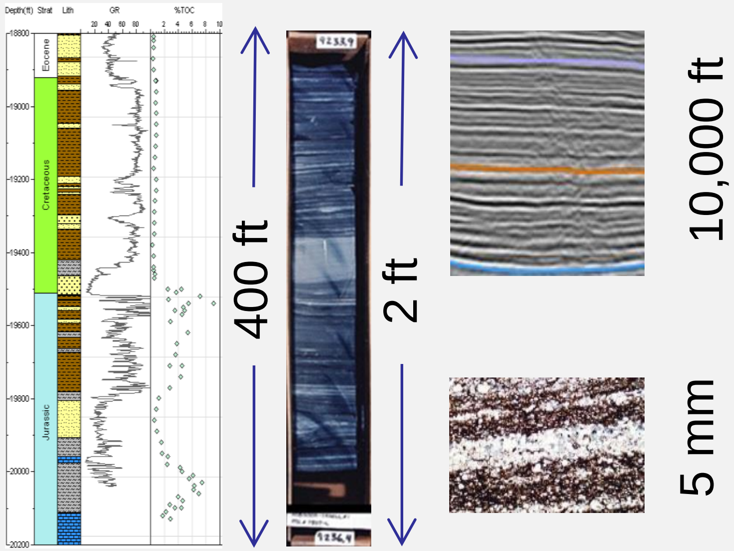
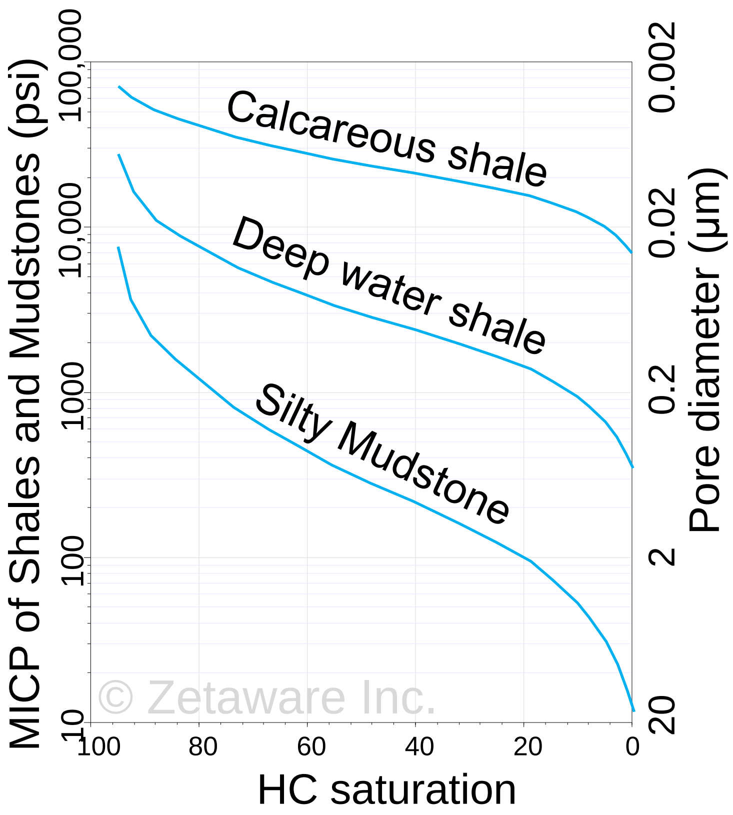
Introduction:

- Todays basin models are too complex and make way too many assumptions. Following William of Occam, we propose the simplest model that predicts migration and charge.
- The first carrier bed is defined as the migration carrier adjacent the source rock. Big data show it has the most significant control on migration of petroleum and charge access to all traps above the source rock.
- Observations from large field and fluid databases in geo-spatial context and the modeling to account for the patterns led to important conclusions that can be used for migration and charge predictions.
- First carrier beds themselves are most prolific reservoirs in the world and have high chance of success rate often 80-90% due to high probability of charge (low migration risk).
- Success rates decrease exponentially with increasing distance above the first carrier because lateral migration creates large “shadows” for targets above the first carrier. Traps above such potential vertical migration “chimneys” have greater probability of receiving charge.

HC Migration Is Dominantly Controlled by Capillary Forces

Various scales of capillary bedding





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

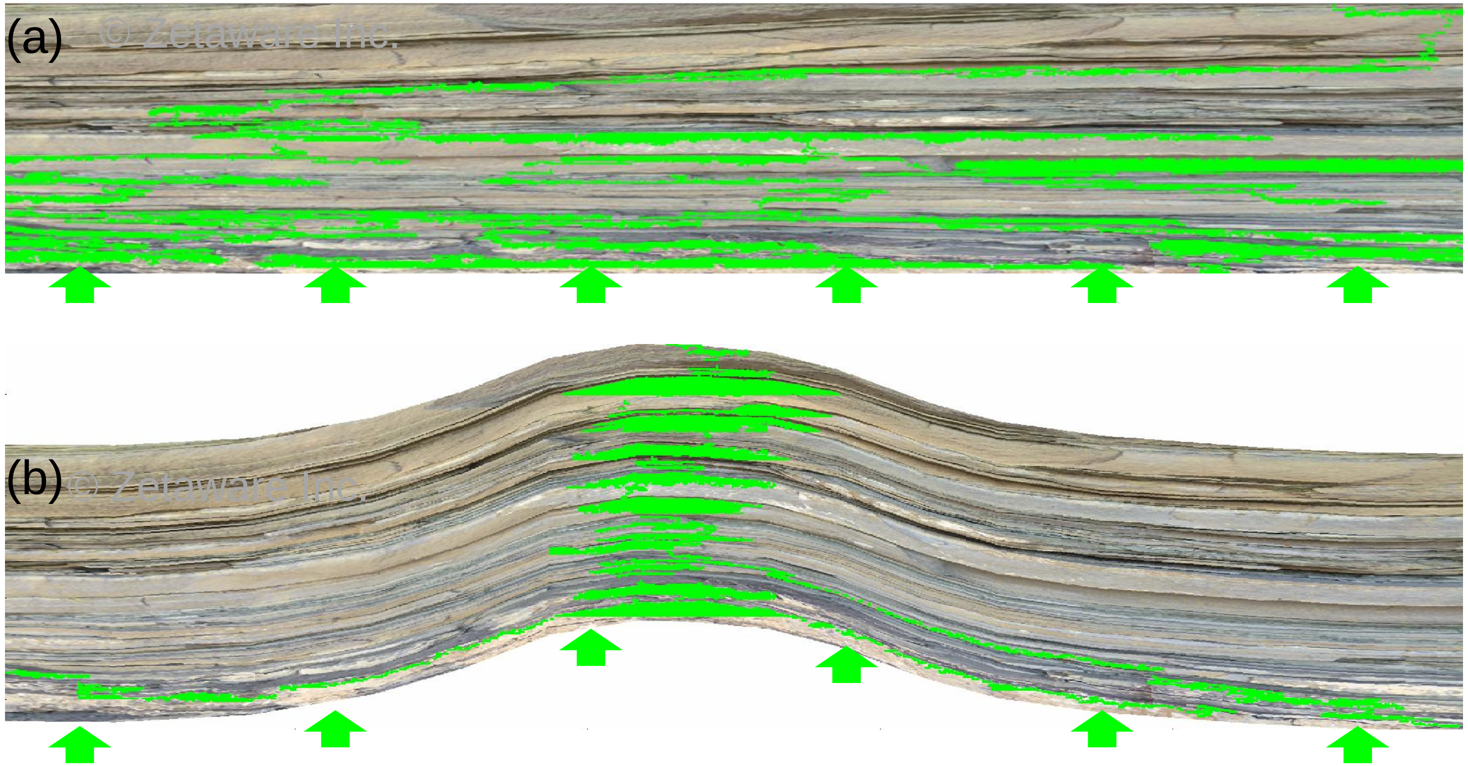
$$H = \frac{2\gamma\cos(\theta)\left[\frac{1}{r} - \frac{1}{R}\right]}{g(\rho_w - \rho_o)}$$

Typically up to hundreds of meters of HC column

- Sedimentary rocks are much more laterally continuous. Vertical capillary contrast is much stronger than buoyancy 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.
- Relief/Column height required vertically migration through interbedded shale and more porous rocks is typically 100s of meters in marine systems, 10s to 100s of meters in deltaic systems.

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)

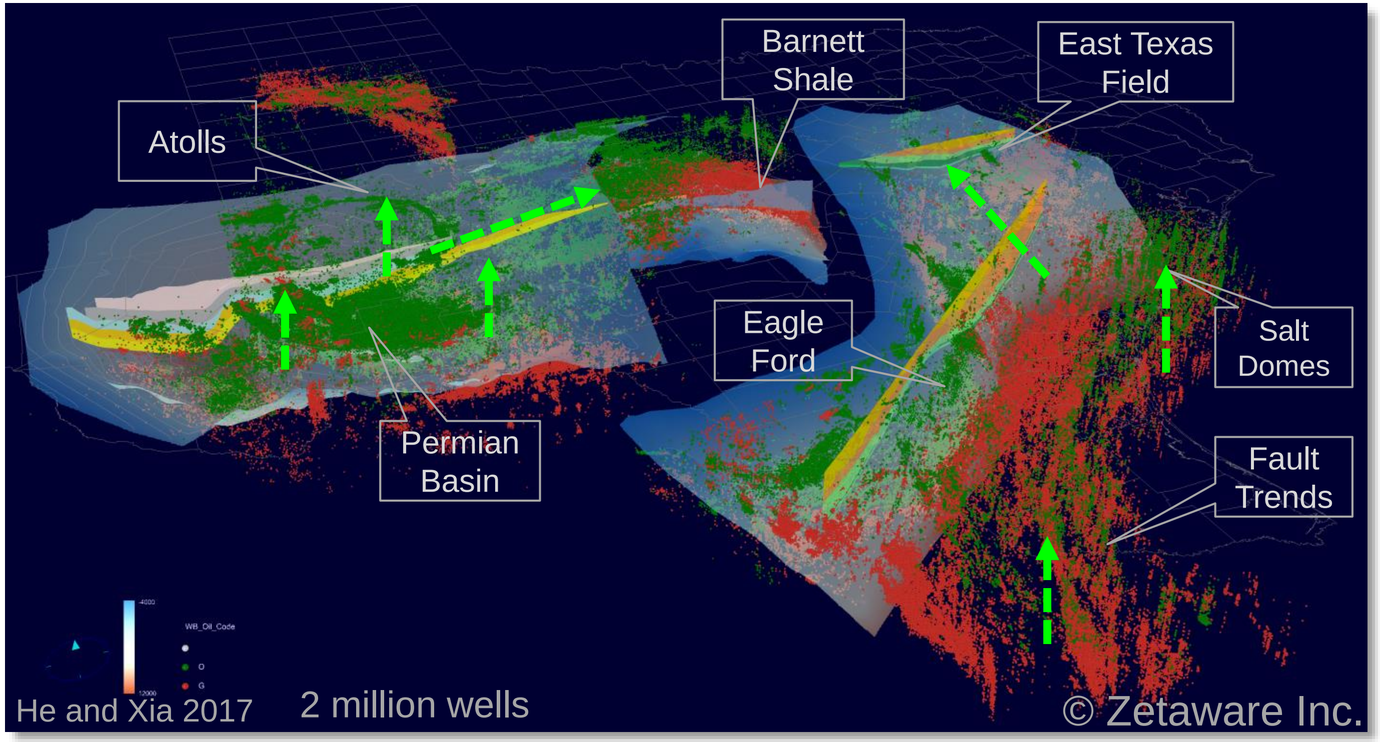


(a) This "flat" model requires 10 x the volume to reach top due to formation of low column/saturation pools. Entire volume generated by a typical source rock may be "spent" in just 100 to 500 meters (incurring significant migration loss)

(b) This model is far more efficient for vertical migration, allowing columns to exceed capillary resistance and concentration of volumes for further migration

Another important implication is that HC generated before structure formation, may not migrate very far, and may re-migrate during structure formation.

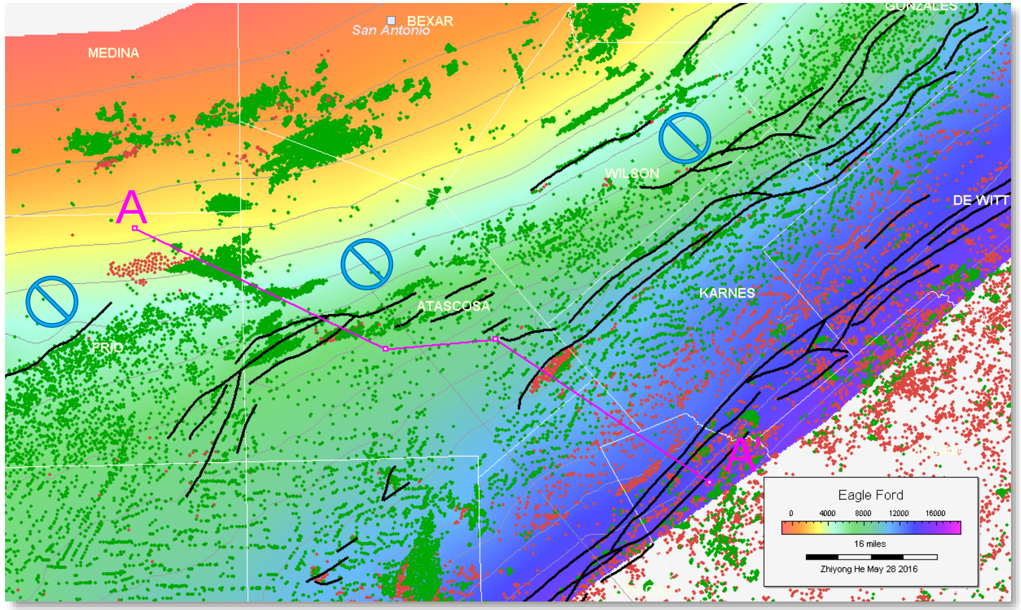
Petroleum System Behavior from Production Data



Production data from the Texas Rail Road Commission. This image composed of ~ 2 million wells. Red color represent gas wells with <10 barrels/mmscf.

Observations from large field and production data set show migration patterns. The vertical arrows are locations vertical migration (stacked reservoirs) are observed. They are associated with high relief features such as large fault closures in SW Texas, salt diapirs in SE Texas, Central platform and shelf edges of the Permian basin where deep water turbidite siltstones pinch out. Long distance (100s of km) migration is evidence in areas with little vertical relief. The East Texas Field is far from the nearest mature source rock.

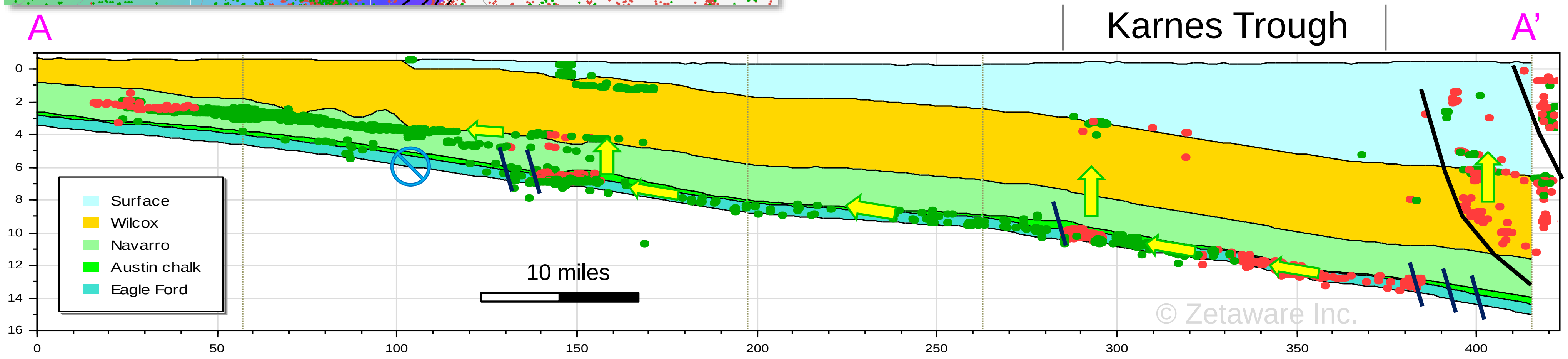
Lateral vs Vertical Migration Tendencies



- ❑ Evidence for lateral migration with the Eagle Ford and migration shadows up dip from faults
- ❑ Faults seem to restrict lateral migration and cause vertical migration downdip from the faults to charge shallow reservoirs.
- ❑ Observation is generally true in many shale and conventional plays , see next few slides.

Lateral migration shadows

Inferred migration direction



He and Xia 2017, Faults from Hammes et al. 2016

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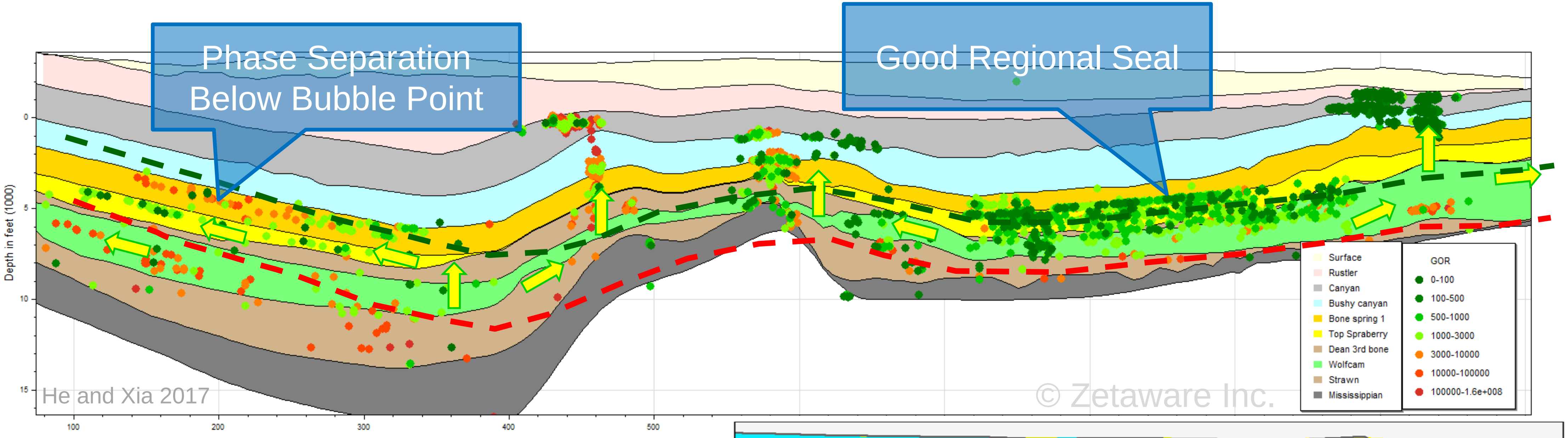
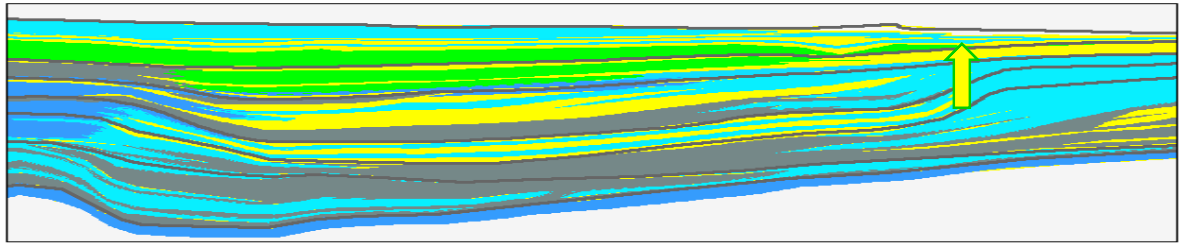
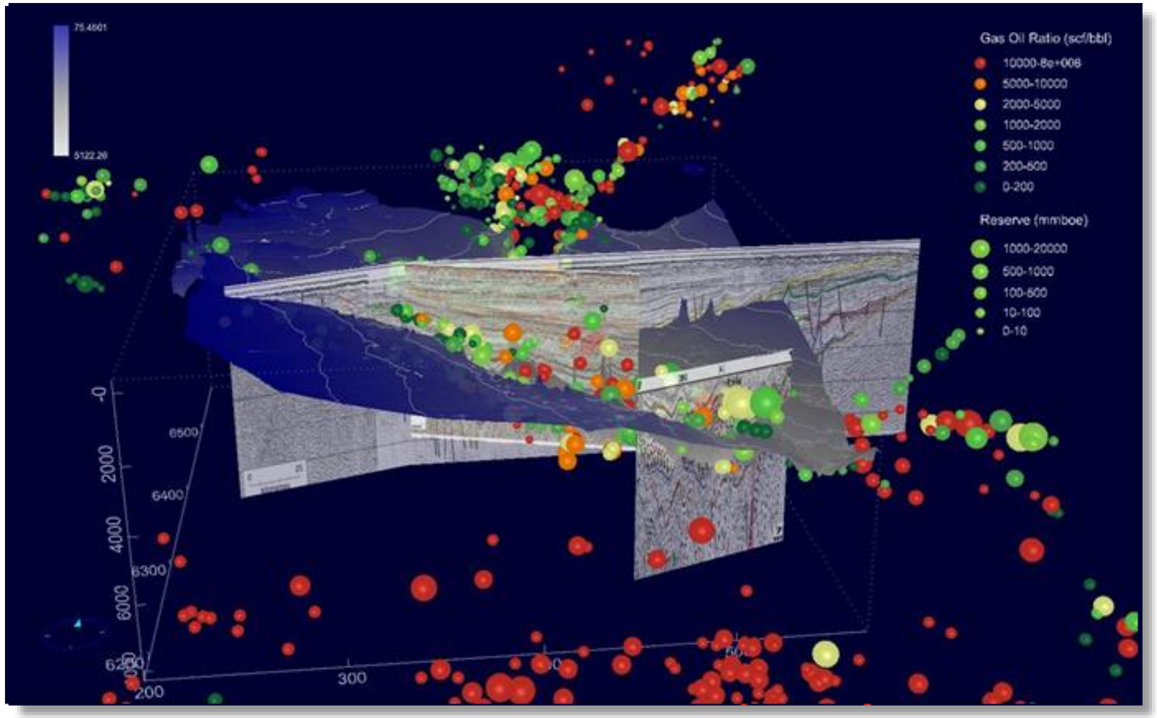
Lateral vs Vertical Migration Tendencies

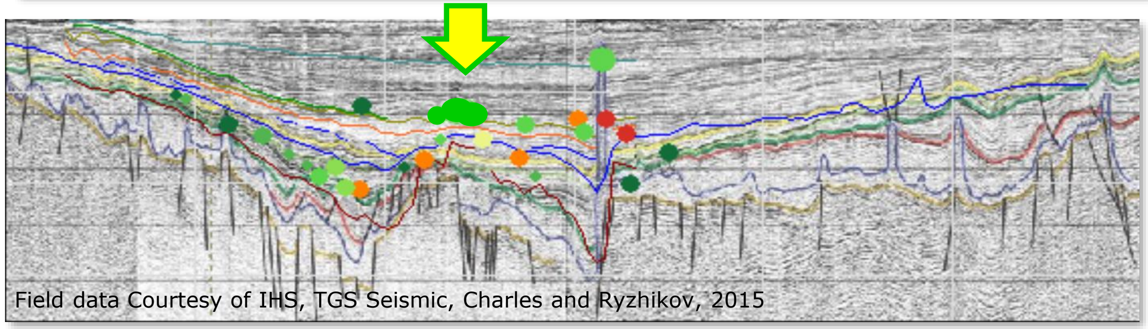




Vertical migration only occur at facies boundaries along shelf edge (pinch outs) and near central platform (high relief and/or fault barriers). He and Xia, 2017

Petroleum System Behavior from Big Data





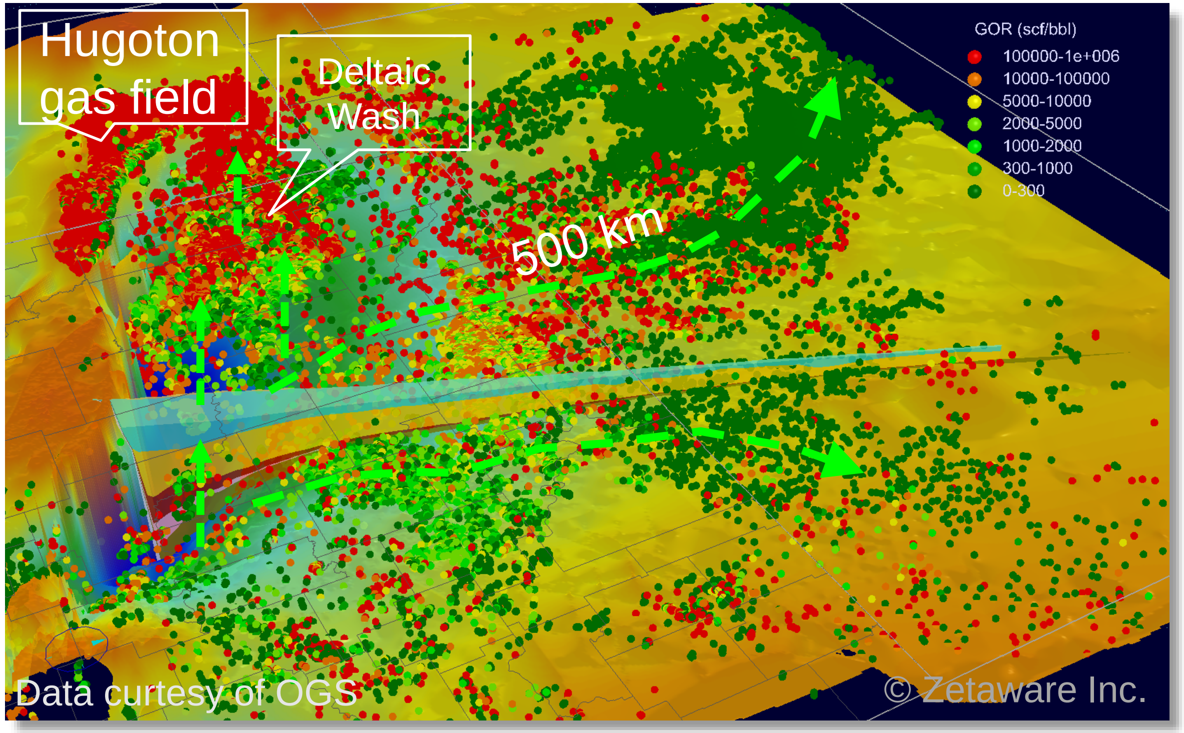
Field data Courtesy of IHS, TGS Seismic, Charles and Ryzhikov, 2015

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.

Migration Tendencies, Horizontal vs Vertical

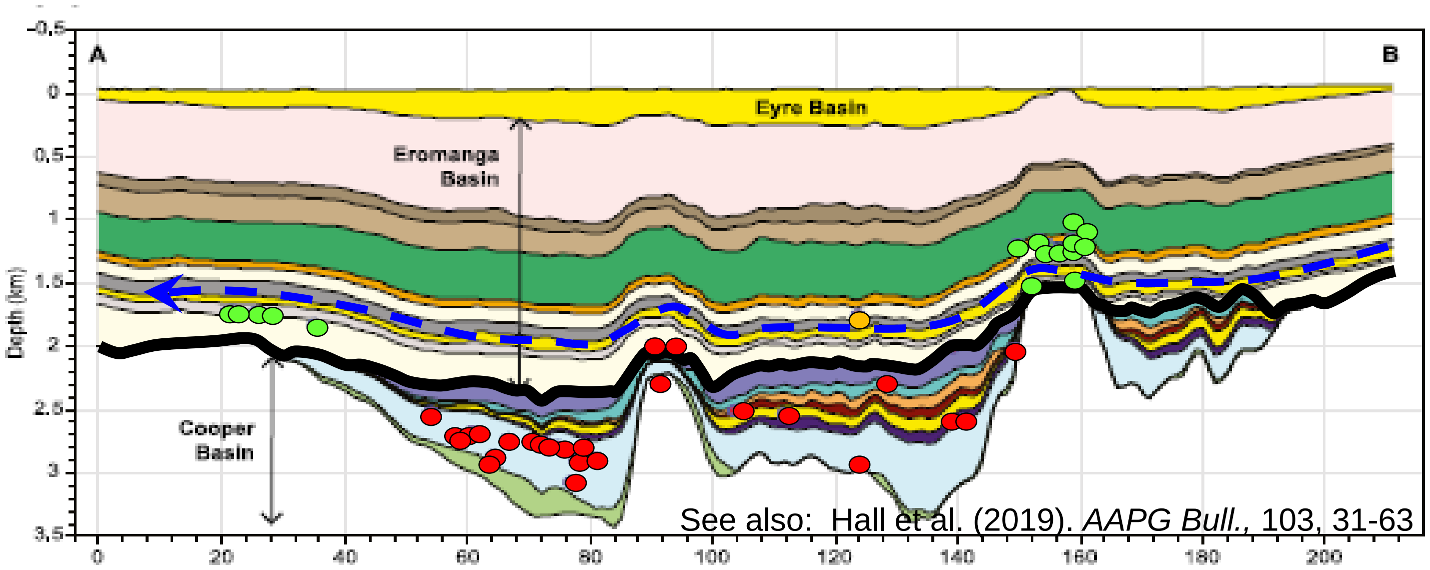


Production cumulative GOR data with Woodford structure surface, Anadarko Basin, US

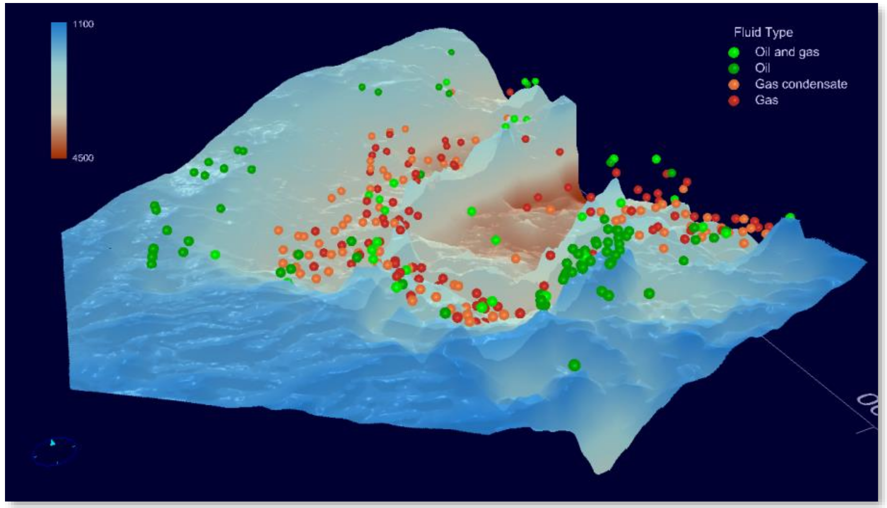
- ❑ Long distance migration along low relief marine, foreland strata
- ❑ Vertical migration in fan/deltaic systems where lateral continuity is poor, high relief "foothills" structure, and lateral fault barriers
- ❑ Oils migrate further out than gas.
- ❑ The above patterns are observed globally in many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

Gas in Basin Center and Oil on Highs & Basin Edges

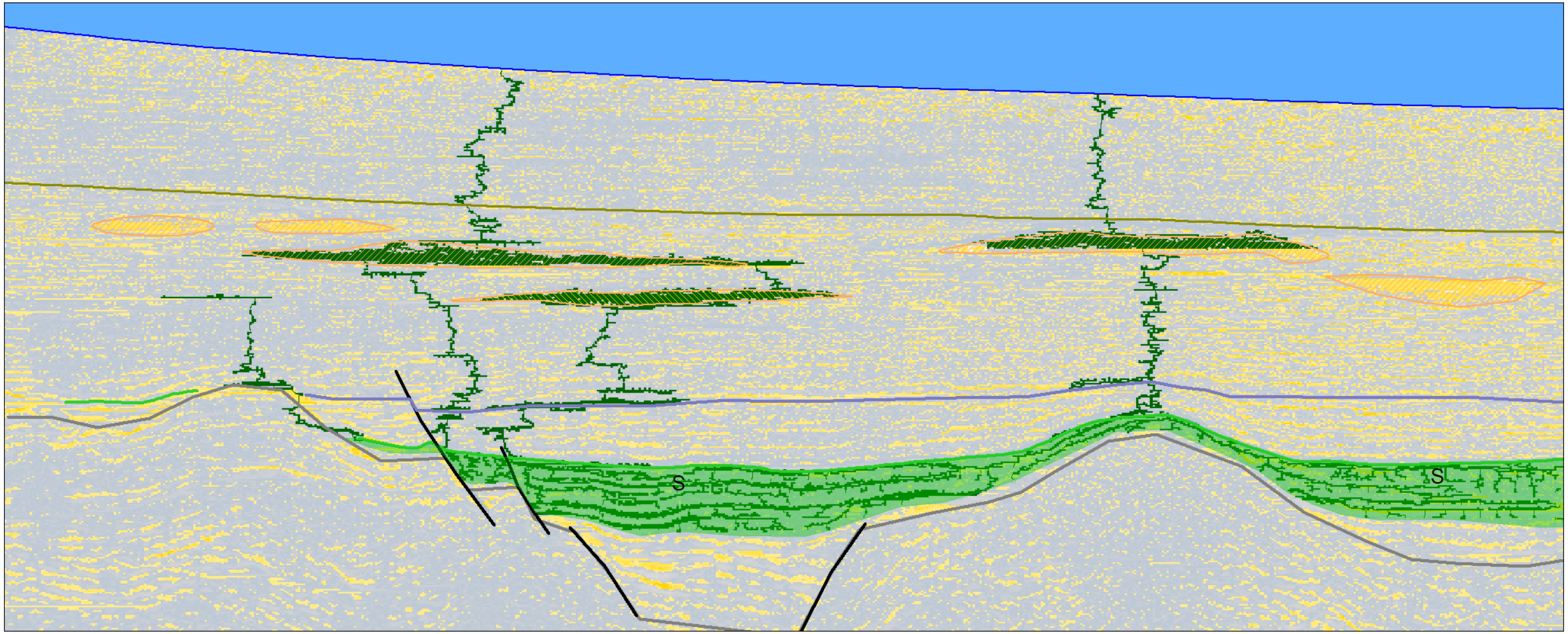
- Oils mainly found on the fringes and in the Eromanga reservoirs over basement highs, gas in the deeper centre and in the Cooper Basin reservoirs. Permian coals are the only significant source rock.
- Interpretation: Vertical migration over structure highs and lateral pinch outs.
- High API “oils” are actually condensates from gas after gas removed by meteoric water



See also: Hall et al. (2019). *AAPG Bull.*, 103, 31-63

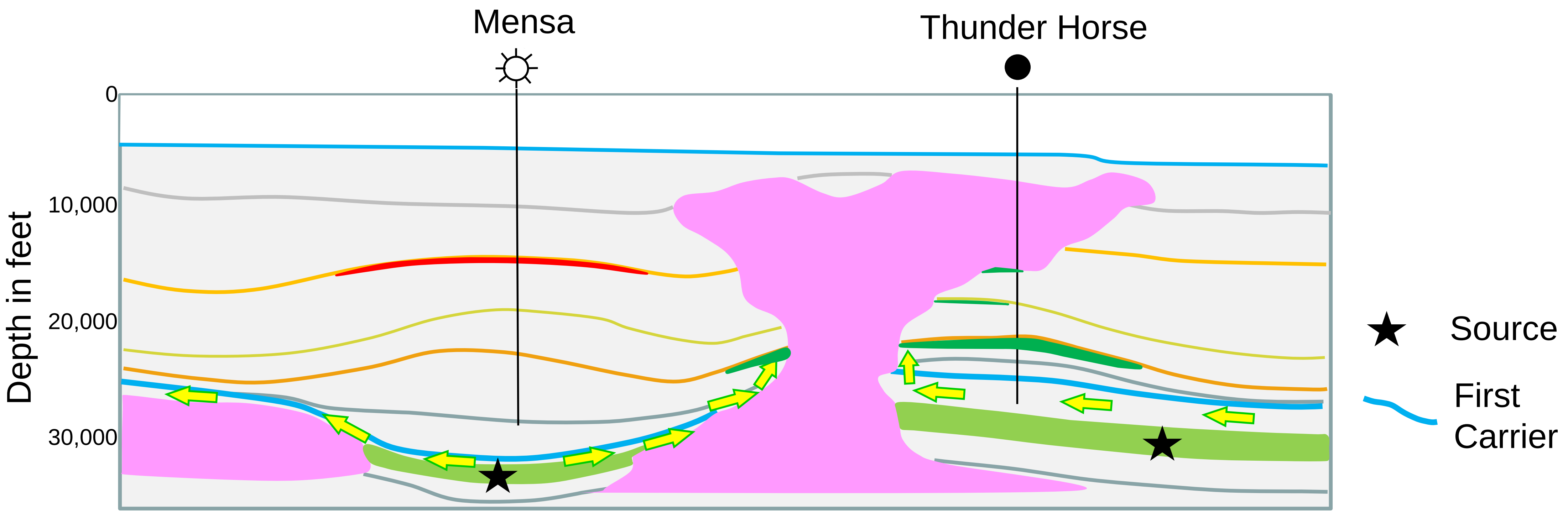


Stratigraphic Traps Especially Need Deep Focusing



Simple migration model shows large relief structures at the source rock level allow vertical migration and changing stratigraphic traps. Traps without deep focus elements have higher migration risk.

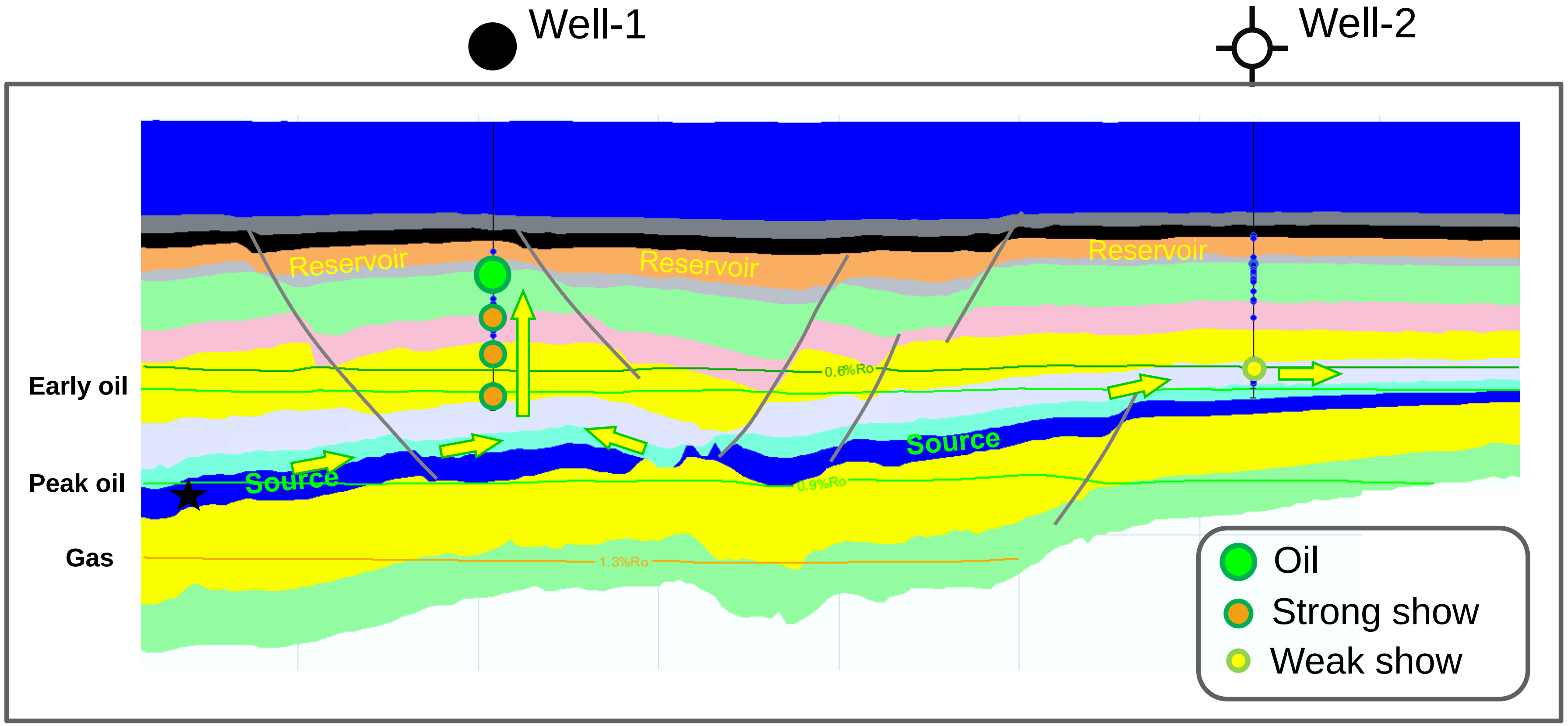
Classic Example of Deep Focusing in Deep Water GoM



Four way turtle structure at Mensa does not receive deep charge as the first carrier (Cretaceous) is a low, migration away from the kitchen below. 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

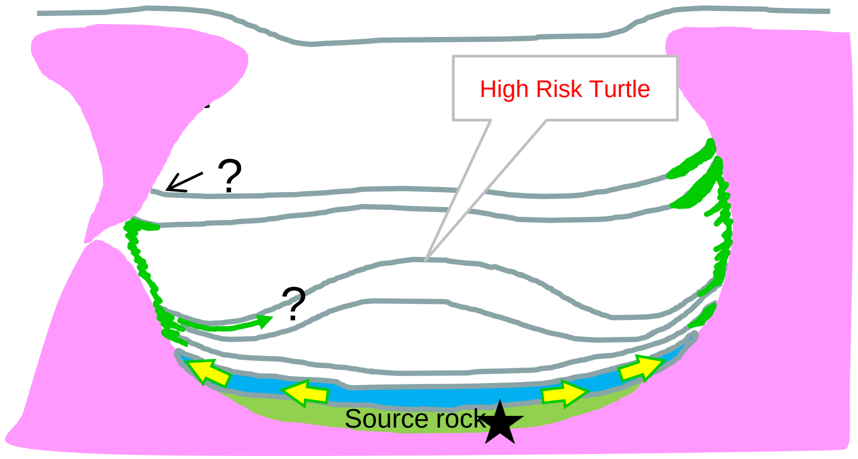
A Recent Example, On Shore Africa

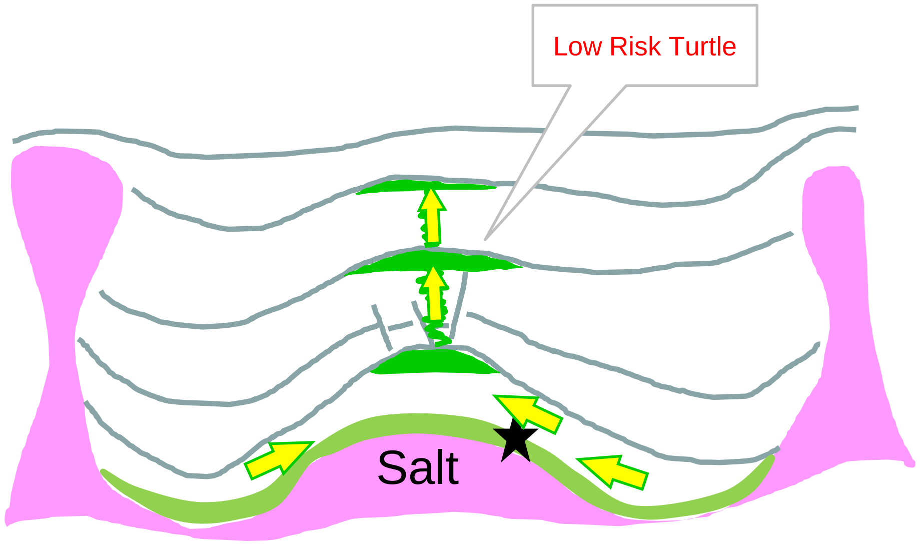


Recent drilling on shore Africa, again proving the concept.

> 100 meter closure at deeper levels below the discovery and < 50 m closure below the dry hole

Not All Turtles are Created Equal

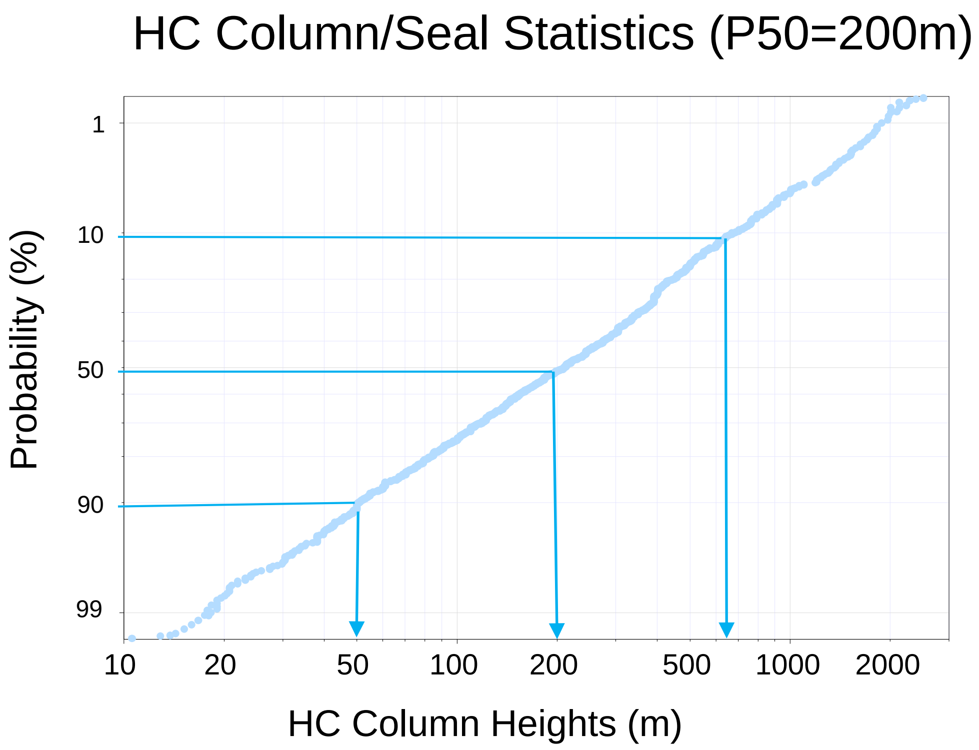


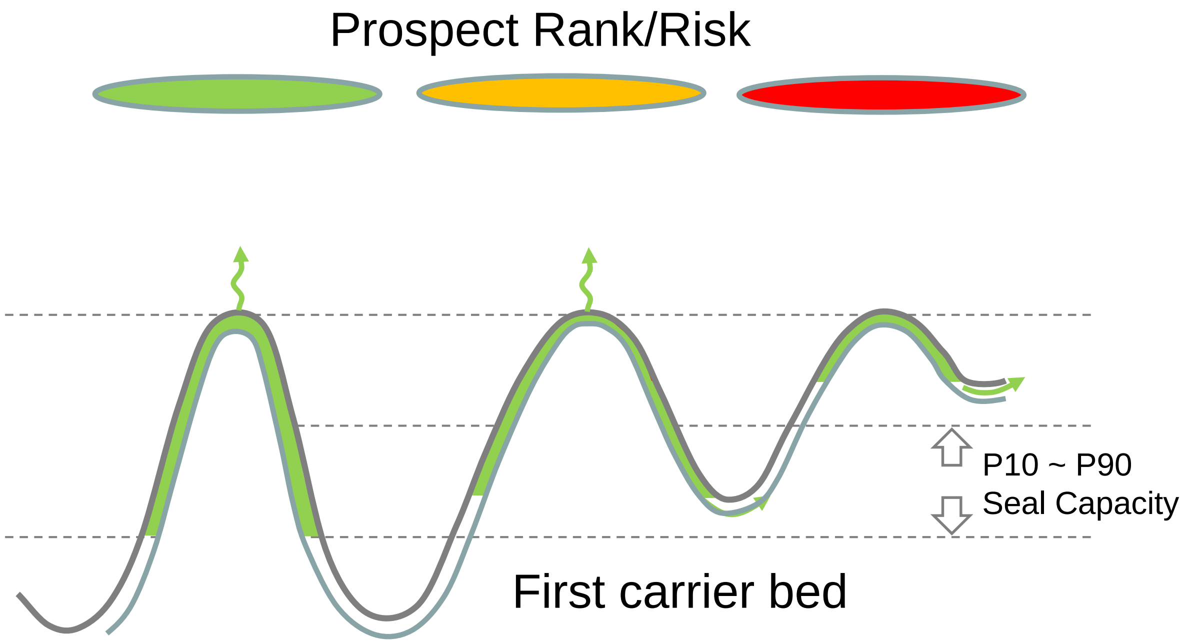


Turtle structures with a de-focused bottom is riskier than those with a salt pillow below

Some may still work as there may be a probability spilling from low relief three-way closures against salt

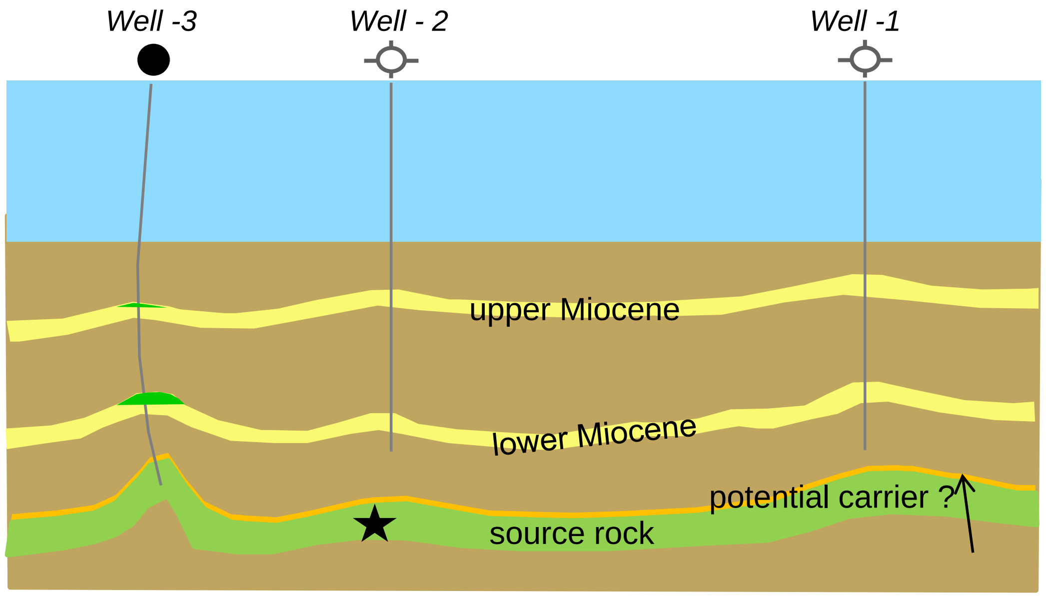
Probability of Seal/Leaking & Vertical Migration



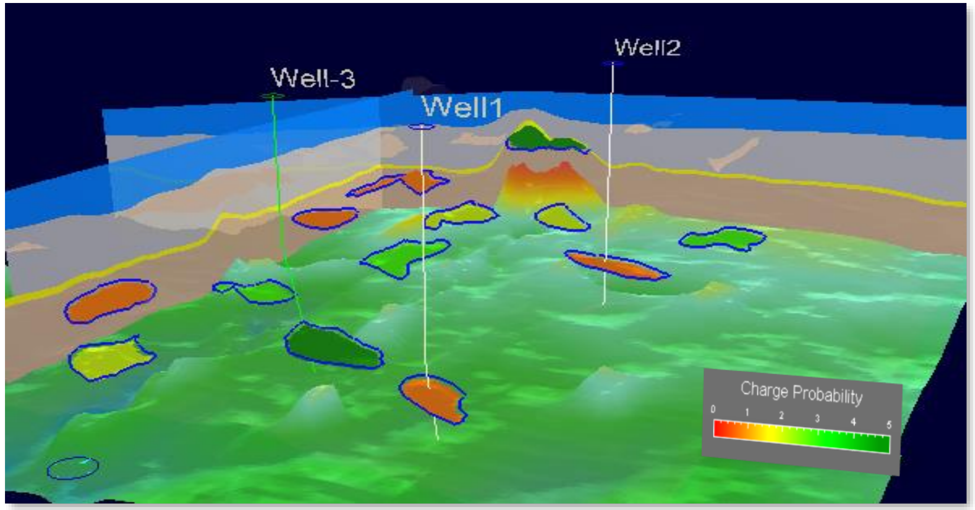


Probability of seal capacity distribution can be used to risk migration and charging of shallow prospects, combined with the structure relief map of the deeper carrier beds. And for a given structure closure, it provides a probability of leaking vs spilling.

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.

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.

Conclusions:

- Vertical migration requires structure relief high enough so buoyancy can overcome capillary resistance

- Larger drainage area at deeper carrier level help focus enough volume to migrate to younger reservoirs above

- Big data and Bayesian priors (analogs) show that this principle is widely observable

- Ranking prospects by migration and charge risk based on structure relief and drainage area at the source rock level should help reduce dry holes

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