Advances and Perspectives on Stratigraphic Trap Exploration-Making the Subtle Trap Obvious*

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Abstract

Stratigraphic trap exploration principles have been established for nearly 80 years since first being classified by A. I. Levorsen in 1936, and the fundamental principles of entrapment are well understood. Advances in understanding of the wide variety of traps accelerated in the 1950's and 70's, including hydrodynamic and pore-throat capillary traps. In 1977, a step change occurred when Exxon geoscientists released their classic papers on seismic stratigraphy in AAPG and SEPM publications. There remains, however, the fundamental need to integrate the revised correlations with seismic, wells, cores, logs, and petrophysics to recognize the seal geometries, understand the oil and gas shows, and find the traps.

Historical success rates at finding large stratigraphic, combination and hydrodynamically trapped fields, particularly giants, has remained low for decades, primarily due to a lack of stacked pays and an inability to sufficiently image the reservoirs and seals with seismic. As a result, stratigraphic/combination giant fields (> 500 MMBO) comprised only 10-15% of the volume despite the absolutely overwhelming numbers of many stratigraphic traps over structural traps in many basins. Many older exploration efforts were 'model driven', primarily with well logs and hand-contoured maps, and success rate remained low.

Since 2000, however, creaming curve data show a step change in volumes of oil and gas found in giant stratigraphic and combination traps, rising to nearly 50% in the last 17 years. This is due to the impact of 3D seismic reservoir and seal imaging, along with better tools to model hydrocarbon systems and migration.

The biggest growth in resources have been in 1) passive margin turbidite fan and channels, 2) carbonate reefs, and 3) tight gas (China Ordos Basin). Future success rates and volumes will continue to rise, with more advances in imaging and a better understanding of migration and charge. Unconventional reserve growth has been substantial and blurs the line between stratigraphic and source-rock related plays. The objective today is not to look for subtle traps, but to make the subtle traps obvious. For those that learn to do that, the future is bright.

An updated database originally published by Horn (2011), provides the basis for the maps and conclusions presented in this paper.

Introduction

Stratigraphic trap principles were perhaps first articulated 81 years ago (Levorsen, 1936). M.K. Hubbert, in a classic paper, clearly outlined the principles of understanding hydrodynamic trapping 64 years ago (Hubbert, 1953). It has been an additional 36 years since Michel Halbouty's classic paper on subtle traps appeared in the AAPG Bulletin (Halbouty, 1981, 1982).

Halbouty argued that big stratigraphic (subtle) traps would be a future huge resource largely because they were not being systematically explored for. Ironically, the three largest hydrocarbon accumulations in North America at that time were stratigraphic traps, particularly East Texas Field (unconformity trap), Hugoton (hydrodynamic/pore throat), and Prudhoe Bay (unconformity) (Sorenson, 2003, 2005; Specht et al., 1987; Wescott and Hood, 1994). Thousands of smaller pools were more common. Giant fields were overwhelmingly in large 4- way closures and fault traps.

The reason was fairly simple, and not just related to the effort to find these traps. Structural traps commonly have multiple stacked pay zones and hence more volume per area. Four-way closures, more importantly, require only an effective top seal, whereas stratigraphic traps require top, lateral, and bottom seals. While the same multiple seal systems are required for fault traps, there are more opportunities to seal across faults than are found in one or two targeted reservoir levels in a potential stratigraphic trap. As trap size is controlled by the weakest seal, it only takes one poor seal to reduce a promising large accumulation to a small pool. Additionally, turning a relatively thin single zone stratigraphic trap into a giant field requires a huge aerial extent.

Seismic data quality, early in the hunt for stratigraphic (subtle) traps, was too low a resolution to make traps obvious. An example is from East Texas Field (Figure 1). Bill Galloway, CEO of Amoco Production Co. in the 1970's kept this seismic line framed on his bathroom wall to remind himself what giant fields could look like in subtle traps. There is little point, however, in today's environment, to pursuing traps with this kind of limited resolution. The task is to use other tools to make the subtle trap obvious.

The central problem with many stratigraphic and combination traps remains the number of seals and pay zones (Figure 2). The thinner the pay zones, the harder it is to image the trap. Couple that with multiple seals required to create the trap and the non-structural/fault traps become increasingly difficult to find. Thinner pays with big reserves require larger aerial extent to the fields and that is limited by column height capacity vs. structural dip. Simply stated, the lower the dip rate, the larger a stratigraphic trap with a poor seal might be.

During the late 1970's and 1980's, emphasis turned to principles of seismic stratigraphy first elucidated by Vail et al. (1977) and followed a number of key papers (Haq et al., 1988; Hardenbol et al., 1998; Mitchum et al., 1993; Wagoner et al., 1988). Much of the potential impact of these papers was lost in debates or nomenclature, techniques, eustatic seal level changes. What was still needed was much better seismic visualization of the reservoirs and seals themselves.

In the end, it comes down to seal geometry, and the principles are well understood (Figure 3).

The fundamentals have not changed. No amount of haggling over sequence stratigraphic terms, methods, or ways to correlate fundamentally changes the challenge of using all the data possible to quantify and explain seal geometry. Once the seal geometry is mapped properly, and all the associated test, shows, and pressure data support the geometry, the trap becomes obvious. Speeding that process up, however, can take a step-change with good 3D seismic.

By the mid 1990's, more and more companies were switching from 2D to 3D seismic and showing remarkable changes in finding rates. One quantitative example is given by Dolson et al., 1997. Seismic imaging of reservoirs was becoming increasingly important and steadily replacing hand-drawn maps of facies belts. A key paper (Marfurt et al., 1998), showing semblance-based coherency in 3D imaging, help launch another decade of higher resolution reservoir imaging. An excellent summary of many of these advances is in Posamentier (2006a, b).

Techniques such as wavelet facies analysis, semblance, inversion volumes, AVO, and other techniques now clearly reveal depositional trends for the interpreter who can zero in on fine detail on the seismic. Maps of 'amplitude blobs' are no longer acceptable to reduce risks.

Seismic images need to show geological features clearly. If they do not, then trap, reservoir, and seal risk will remain high.

Historical Giant Field Exploration-Measuring the Impact of 3D

What has the impact been? One way to measure that is to study finding rates and volumes in giant fields. We study giant fields because they collectively hold about 40% of the world's reserves. AAPG has provided summaries for decades, the most recent of which is summaries by Horn (2005) and Merrill and Sternbach (2017a,b,c). M.K. Horn (Horn, 2011), provided AAPG with a comprehensive summary of published giant field data in GIS and Excel format. For this paper, we have updated that database from the original 996 fields to over 1142 fields, as well as location corrections and adjusted reserve volumes on over 360 fields. Included in this new analysis are 78 fields of significant size, that could become giants or are part of a cluster of large fields that collectively yield giant status (Figure 4).

The largest concentration of giants occurs in the Middle East, North America, and Russia, but nearly every working petroleum basin has the potential for giant fields.

The creaming curve (Figure 5) shows historical finding rates for giant fields since the late 1800's. Aside from earlier steep jumps caused by opening of big North American, Russian, and Middle Eastern Fields, a noticeable shift in 2000 occurred. This shift was first noted by Halbouty (2003), where he showed an increase in stratigraphic trap volumes in the 1990's to 15% of the giant fields, up from an historical value of 10%. He attributed this, correctly, to 3D seismic imaging.

A number of giant stratigraphic provinces exist in the world, summarized in Figure 6.

Most of these basins are characterized by having relatively simple and low-relief structural dip, where modest seals can result in aerially extensive traps. The steeper the structural dip, the more limited the trap size unless outstanding seals are involved. There is a noticeable lack of giant stratigraphic and combination traps in the Middle East, a point for later discussion. Giant stratigraphic traps are not limited by age

(Figure 7). Some of the largest gas fields in the world, in fact, occur in East Siberia in Neoproterozoic and Infracambrian stratigraphic traps (Clarke, 1985; Dyman et al., 2001; Nakashima, 2004; Ulmishek, 2001a, b). In the Middle East, Khazzan Field, a giant tight gas accumulation (Millson et al., 2008) produces an Infracambrian or Neoproterozoic source system, so the lack of additional giant stratigraphic and combination traps cannot be explained on age of source rocks.

The location of the combination/stratigraphic traps found since 2000 is shown on Figure 8. The big plays have been in a variety of traps, but turbidite plays and reefal buildups have dominated the volumes. Many of these trends are documented in Merrill and Sternbach (2017a, c) and Stark and Smith (2017).

By far the largest accumulations have been in clastic turbidite plays, large carbonate reefs, and in tight gas, notably the Ordos Basin in China. This is shown more clearly by breaking out the stratigraphic/combination traps found since 2000 by lithology (Figure 9).

Carbonate trends tended to have more oil than gas and the clastic plays are dominated by significant gas pays, particularly in the deep water turbidites. Huge reserve growth in the Ordos Basin in China is due to tight gas discoveries sourced by mature coaly source rocks (Dai, 2016).

Growth of Unconventional Plays

An argument can be made that 'unconventional traps' are actually another variation on stratigraphic traps (He, 2017). In his paper He covers the basics of how to model migration, entrapment, and phase with petroleum systems software in unconventional shale gas and oil plays.

Regardless of how they are classified, the numbers shown on Figure 10 show huge reserve growth globally, dominantly in North America shale plays, where over 1000 TCF of reserves have now been found. Additional information on resource potential is most recently summarized in EIA (2011, 2017).

These source rock plays, both oil and gas, will only grow bigger with time. Current growth is confined to mature provinces with good infrastructure, rapidly developing technology, huge demand centers nearby, and relatively shallow depths. Emerging plays like the Vaca Muerta in South America and Bazhenov in Russia, (EIA, 2015a, b) have substantial growth potential. In this figure, numbers shown for the Vaca Muerta and Bazhenov plays represent an arbitrary 20% of the 'technically recoverable' hydrocarbons cited in the EIA reports referenced.

Tight gas traps can blur the line between unconventional and conventional discoveries. Figure 10 shows some updated information presented in Stark and Smith (2017). For instance, Stark and Smith (2017) classify Khazzan and Sulige Fields as unconventional traps, but both of these traps may be conventional accumulations.
Figure 11 shows the Khazzan (after Millson et al., 2008) and Sulige accumulations (Dai, 2016).

The reserve growth in the Sulige Field area, as shown, has been phenomenal, with up to 145 TCF now attributed to this field, when prior resources 8 years earlier gave the entire basin only 18 TCF reserves. The trap is still not clear.

Stratigraphic Trap Principles

Stratigraphic traps occur in a wide variety of depositional systems and many fundamental components are covered in Dolson et al., (1999) and Dolson et al., (1994 a,b).

Figure 12 illustrates just some of the common depositional settings. The single most important element in stratigraphic traps exploration is recognition of seals. Migration routes and reservoir quality are also very important, but most stratigraphic traps fail by leaky seals. Low structural dip helps, as large traps with limited seal capacity can be developed over broad areas. Reservoir quality and diagenetic over-prints or hydrodynamic modifications are also important (Figure 13). These kinds of traps, particularly in mature source kitchens, blur the line between stratigraphic unconventional traps (Figure 13, bottom, after Sonnenberg and Meckel, 2017).

Sealing mechanisms as reservoirs transition downdip to tighter lithologies into many thermally mature source rock intervals becomes problematic to explain. The transitions can be readily mapped, however, generally by noting decreasing water recoveries on wells up dip and more gas with no water or only minor amounts within the mature source rock kitchens. On Figure 13 (bottom), the irregular dashed black line above the tight oil and gas level schematically represents the kinds of transitional seals that occur in these settings. Common to these ‘basin centered’ or ‘thermal traps’, are some intervals that are much more prolific than others. These ‘sweet spots’ can have significantly better production from horizontal wells and are typically subtle stratigraphic traps within the thermally mature shales. A good example is provided by Skinner et al. (2015) in the Bakken Formation of the Williston Basin.

Techniques for screening unconventional plays are beyond the scope of this paper, but involve a fundamental understanding of the maturity, thickness and quality of the source rocks as well as stratigraphic facies changes and lithologies within the source rocks themselves that might be targets for horizontal drilling.

Hunting for NULFS (Nasty, Ugly, Little, Facts)

Particularly in mature basins, finding pore-throat and diagenetic traps require looking at anomalous data. The senior author calls this ‘Hunting for NULFS’ (Dolson, 2017). The term comes from a quote by Thomas Huxley over a century ago: “the great tragedy of science is the slaying of a beautiful hypothesis by an ugly fact”. It might be as simple as a zone on a 4-way structural closure that has oil below structural spill point in one reservoir, indicating that the reservoir is not within the structural trap. Or it may be a well with by-passed pay that has been written off as ‘dry’. Our first job is to explain the obvious. The second job is to note the exception and then focus on it and try to understand it. That may be the clue to the next great discovery.

Many big stratigraphic traps, and certainly new play concepts, come from noticing the anomaly that doesn’t fit the existing ideas of an accumulation. This requires a sound understanding of rock petrophysics, pressure analysis, and careful examination of hydrocarbon shows. Shows in tight rock, particularly moveable oil, can indicate a column is present. The fundamentals of shows analysis and recognition of waste zones and techniques for estimating column height in a trap is covered in depth Dolson (2016b) and in classic papers (Schowalter, 1979; Schowalter and Hess, 1982). Understanding how to visualize an under-developed or by-passed trap where only a better reservoir facies is needed is a key to finding these types of traps.

good example is the case history of the 2001 discovery of the 1.4 BBOIP Buzzard Field in the North Sea (Carstens, 2005; Dolson, 2016b, 2017; Ray et al., 2010; Robbins and Dore, 2005). This field was found on acreage dropped by BP that was presumed too far from mature source rock to have a working petroleum system. Fortunately for the companies that drilled the discovery, there was a 'dry hole' downdip on a very small structural closure that had 3.5 meters of Jurassic oil pay on the logs, but was untested. The well de-risked reservoir, seal, and charge. 3D seismic found the up-dip turbidite fan pinch-out and lateral fault seal which formed the giant trap.

Hydrodynamic Traps

Hydrodynamic principles have long been understood and some of the most easily understood publications include those of (Dahlberg, 1982, 1995; England et al., 1987) and the topic is dealt with in detail in Dolson (2016b) with examples of how to model such traps with simple gridding algorithms available in many software packages.

Hydrodynamic traps are often overlooked, however, particularly in deep, over-pressured basins (Dennis et al., 2005; Ferrero et al., 2012; Muggeridge and Mahmode, 2012; O'Connor and Swarbrick, 2008; Riley, 2009; Robertson et al., 2013). An example in Egypt (Figure 14) illustrates how long it can take to recognize some of these tilted columns.

The 4.3 TCF Temsah Field was discovered in 1977, but it took 25 years to recognize the full field size and the tilted nature of the gas/water contact. For over 20 years, this accumulation was considered small and marginally economic, despite being a huge structural closure. This giant structure was an exploration disappointment with the Temsah-1 discovery well, which tested a thin gas/condensate column over a thick, over-pressured water leg. Interpreters viewed the lack of a full column as an under-filled trap. It took 5 years to drill another well, targeting an up-dip location that might test a gas cap with no water leg. Temsah-2, however, found gas at the same structural level, but no water. Faults were then invoked to explain the difference. What was missed was a look at the pressure data, which showed that the Temsah-2 and 1 wells had a common gas column. Had the structure been filled to spill, it would have had a column in excess of 500 meters and resembled Figure 14A, Figure 14C and Figure 14E.

The acreage was dropped in the mid 1980's as gas rights had not been awarded and the structure look under-filled. In the mid 1990's Amoco and IEOC assumed operatorship and began drilling development wells. Surprisingly, there was water at the base of many of the wells, but the contact kept getting deeper to the northeast. The explanation was then revised to 'complex stratigraphy, compartmentalization, perching and faulting'. This explanation was not born out by pressure data, however, as the gas gradients showed continuity between all the wells in the gas leg. This is a classic sign of either perching or hydrodynamic tilt (Cade et al., 1999; Dennis et al., 2005; Dolson, 2016b; Ferrero et al., 2012; Muggeridge and Mahmode, 2012). In 2007, a BP geologist proposed a hydrodynamic tilt. By now, many other fields in the Nile Delta were known to have gas deeper to the northward towards the deep water. It was difficult to explain all of these cases as caused by perched water alone.

To test this concept, the senior author converted a mud-weight map of the Miocene reservoirs (Heppard et al., 2000) to a potentiometric map (Figure 14B). Combining this map with the structure map and using Trinity software (www.zetware.com) yielded a tilted contact that almost precisely matched the gas accumulations in the field, particularly the Temsah-1 well (Figure 14D and Figure 14E).

The hydrodynamic flow is set up by increased excess pressure to the SW of the field by shale decompaction underneath the Nile Delta. To the northeast, the overburden is less, the water depth dramatically deeper and the resultant water flow is from SW to NE towards less excess pressure or hydraulic head.

This phenomenon must be common to all over-pressured settings and is almost certainly over-looked. I am certain many wells have been abandoned with gas or oil over water on what looked like failed traps. How many more big accumulations are out there waiting a downdip well with hydrocarbon shows over water to test for a tilted contact? It is unfortunately common to find companies that do not use potentiometric maps in migration analysis but should do so routinely where over-pressure is noted. A good Middle East example of tilted contacts caused by water flow from the highly over-pressured South Caspian Basin is provided by Riley (2009).

Recent Case Histories: Big Discoveries Since 2000 in Frontier Exploration

Frontier and mature basin exploration requires different skills and tools. Petroleum systems analysis, depth to oil and gas windows, pressures and basin evolution, including paleogeographic reconstructions, are essential in Frontier areas. Mature basins have abundant test data, hydrocarbon shows, pressures, logs, and other information which must be culled through and analyzed to find anomalous oil shows, compartmentalized reservoirs or by-passed pay. The work is data and time intensive but can yield substantial new reserves when coupled with new 3D seismic data, a re-look at cores and better integration.

Examples of both types of plays follow.

Carbonate Reefs

Kashagan-Aktote-Kairan-Tengiz Fields, Caspian Basin

Some of the largest traps found since 2000 have been in giant carbonate reef accumulations. Figure 15 illustrates classic examples from the North Caspian Basin.

The exploration potential of this area has been well understood since the discovery of the giant Tengiz Field in 1980. These fields have high H_2S values and are over-pressured with massive columns sealed by salt and evaporites. They are well described, particularly at Tengiz Field by (Collins et al., 2006; Kenter et al., 2006). The giant Kashagan Field waited environmental assurances in shallow water before finally being tested in 2000. 2D seismic was sufficient to delineate and drill these prospects. The combination of thick, permeable reservoirs surrounded by and overlying mature source rocks and sealed by evaporites makes for a near perfect petroleum system.

It is interesting to note that an analog to these traps existed and was recognized in Egypt (Dolson, 2000; Dolson et al., 2001; Dolson et al., 2000) and is shown on Figure 16, where it remained untested until drilled by ENI in 2015 as the Zohr Field.

Shell had acquired a very large deep-water block (Shorouk) in the late 1990's. As shown on Figure 16C, industry efforts were focused on Pliocene DHI clastics and deeper Miocene and Oligocene deep-water channels and fans. On the play diagram, large carbonate buildups speculated at the Cretaceous level and proven at the Eratosthenes sea mount were clear potential targets but received low interest. The Miocene reef target, in particular, was encased in salt, a potential outstanding seal.

The reefal play was overlooked by Shell, who drilled 9 dry or commercially unsuccessful wells on the block, and also the industry, which remained focused on the deep clastic play. ENI, however, recognized huge biogenic gas potential (ENI, 2015a, b) and tested the well in 2015. It remains the largest gas discovery in Egypt's history and broke the creaming curve (Dolson, 2016a, c) completely, opening up a huge new exploration frontier, including offshore Cyprus (Nikolaou, 2016). The prospect was a clear analog to the Tengiz Field and was so obvious it was discovered on 2D seismic. Multiple companies turned down opportunities to participate in the discovery well, citing a number of technical concerns which proved unfounded. The Zohr discovery is a classic case of 'out of the box thinking'. Creaming curves don't get broken by chasing the same old plays over and over again until they are exhausted.

Libra and Tupi/Lulu Fields, Brazil

New seismic imaging below salt has proven to be the key in unlocking one of the largest new oil and gas provinces in the world—the sub-salt carbonate play of the Santos Basin, offshore deep water, Brazil. This play is summarized in Figure 17 with data from the Libra Field. The morphology, although of a different kind of carbonate, is surprising similar to that of the Kashagan Field trap. The carbonate buildups are sealed by salt and are developed over high rift blocks best seen of Figure 18. The Libra discovery is well documented (Rassenfoss, 2017; Carlotto et al., 2017).

The senior author first looked at this area in 2002-2003 when a new round of long-offset 2D seismic became available. At the time, the area was considered gas prone and there was virtually no good sub-salt imaging of the Lower Cretaceous rift systems. The long-offset data, however, revealed the deeper rifts. Petroleum systems modeling suggested the deep water would be oil mature, not gas mature. Unfortunately, BP was unsuccessful in attempts to convince management to enter this area, despite numerous attempts by later workers. As they say, the "rest is history" and huge interest in participating only occurred after the discovery of the giant Tupi/Lulu Field (Figure 17), in 2007 (Estrella, 2012; Feijo, 2013; Mann and Rigg, 2012).

As the structural and stratigraphic evolution of the Atlantic margins is symmetrical between parts of South America and Africa, it is only a matter of time before many significant additional carbonate sub-salt plays are made in Africa (Mello et al., 2011; Mello et al., 1991). This has already started with the 2012 discovery of the giant Cameia Field sub-salt carbonates (2.8 TCF, 290 MMBO condensate) in Angola (Cazier et al., 2014).

The importance of having high quality seismic imaging cannot be over-emphasized. This play was not possible without advances in acquisition and imaging. It remains one of the most prospective trends in the world today. Additional deep rift prospects in other facies and plays will emerge as data quality improves.

Some additional carbonate examples are those of the Perla Field (Benkovics and Asensio, 2015; Pomar et al., 2015) and the Puguang deep gas field in China, with reservoir facies controlled by a narrow band of oolitic shoals (Ma et al., 2007).

Clastics: Deep Water Fans and Channels-DHI Driven

Perhaps the most active stratigraphic/combination trap play being made globally today is in deep-water turbidite channel and fan systems. These plays have thick, readily imageable facies and many companies are targeting these traps in mature source rock kitchens, primarily in Lower, Mid, and Upper Cretaceous source rocks surrounding the Atlantic margins of both South America and Africa. The play concepts and examples cited are shown on Figure 19.

Companies such as Tullow, Kosmos, Cove Energy, ENI and Anadarko have been at the forefront of this type of exploration. One of the real play openers was the discovery of the Jubilee Field (Dailly et al., 2017; Jewell, 2011) in offshore Ghana, West Africa. This was followed later by the Liza discovery in a similar play offshore Guyana, South America (Spectrum, 2016). Extensions of these plays have been made for years in the Campos Basin, Angola, and Kwanza basins. In the latter basins, salt was a significant component of trapping.

The Liza, Jubilee and other fields featured in this paper do not involve salt. They are combination or pure stratigraphic traps delineated by good 3D seismic and sound geological concepts. Increasingly, the targets are in progressively deeper water and in more distal facies (see Figure 19C).

Rovuma Basin, Mozambique

Mozambique has emerged as a giant gas province thanks to 3D seismic and exploration for a variety of traps types in the deep water offshore Tertiary and Cretaceous trends (Faid and Carvalho, 2013). The importance of seismic imaging on developing these plays is shown on Figure 20. The East Africa Rovuma Basin is a still emerging world-class hub of huge gas resources in deep water. Cove Energy turned a 1.35 MM$ start-up company into a 1.62 BB$ buyout between 2009 and 2012, initiating acreage purchase in the undrilled Rovuma Basin, offshore Mozambique and then drawing in partners to help fund an exploration campaign (Sharma, 2014).

Anyone working on turbidite trends has long ago ceased to be ‘model driven’. 3D seismic is essential to de-risk the traps, reservoirs and facies. DHI support is also a common theme in these plays and was a big part of the success in the Rovuma Basin play. The hydrocarbons are largely thermogenic, but the exact source is unknown and may be mixed layer deltaic source rocks disseminated throughout the system. The images in Figure 20 show geometries not readily predicted from any prior geological model alone (Fonnesu, 2013; Palermo et al., 2014).

Offshore Senegal

On the west coast of Africa, offshore Senegal has become a major new gas and oil hub, led by Kosmos and Cairn Energy (UK). These plays are targeting the deeper source systems and while not necessarily always finding the phase predicted, have done well with big traps (Figure 21).

(Reynolds, 2016) discusses some of the exploration history of the Cairn efforts which are further detailed in (Cairn_Energy, 2017). Perhaps even more significantly, the paleo-topographic SNE-1 trap shown may become a giant trend and has analog features all around many continental margins. It is charged from deeper, migrated oil, making the screening of these plays a bit more problematic. Outboard of the Cairn discoveries are large accumulations in the Yakaar-1, Teranga and Tortue Fields which are testing more distal facies. Another excellent example is detailed for the Janz-Io Gas Field, NW Shelf of Australia (Jenkins et al., 2017).

There is currently intense industry interest in the ultra-deep, distal fan fairways, where large, purely stratigraphic giants may still exist, much of that spurred by success in the ultra-deep offshore Senegal.

Sea Lion, Falklands

Lastly, the Sea Lion discovery in the Falklands Basin (MacAulay, 2015), illustrates a common reason to test flank structural traps: syn-depositional around older structures (Figure 22). A thorough analysis of this important play-opener is covered in the Petroleum Geoscience thematic set of which MacAulay's paper is 1 of 9 other papers dealing with this basin and play.

The key lesson here is one of creativity in an area written off by others. As in the case of the Zohr-1 reef discovery in Egypt, Shell and 3 other companies had drilled key wills on large inversion structures that had failed, but with the Shell 14/10-1 well actually recovering some oil near TD. Many of the other wells failed for lack of reservoir. Rockhopper Oil made a play looking for down-flank stratigraphic fan pinch-outs shown in Figure 22, that would be potentially in a migration path from the deeper proven source rock and recovered oil. Seismic 3D delineated the fan and the test was successful.

The pattern of playing downdip from dry structural highs is an old tactic, applied here in a remote basin where someone else spent the money to prove there was a working petroleum system. Another good recent example is in offshore Myanmar with the discovery of the Shwe Field (Yi and Lee, 2015).

A Note on DHI Exploration

Where possible, AVO analysis enabling direction hydrocarbon indicators (DHI) is essential in de-risking traps pre-drill (Figure 23). But the analysis should include good imaging of the reservoirs themselves and perhaps most importantly, a conformance of the possible DHI amplitudes to structure, supporting a trap. Residual gas can also create positive DHI signatures and will always remain a risk. Amplitudes that give an AVO response but don't have a trap geometry (amplitudes in space) remain high risk targets.

Mature Basin Plays

Mature Basin exploration requires digging hard into a lot of data. Dry-hole post appraisal is critical. There is also no substitute for good, new 3D seismic and going back and looking at core data or samples carefully. Figure 24 summarizes the challenge.

In the Figure 24 example, up-dip facies from a large carbonate stratigraphic trap consisting of irregular boundaries between macro-porous grainstones, meso-porous limestone, silty, micro-porous siliciclastic, and regional evaporite seals makes the trap identification difficult to the untrained eye. If you drill well 4 or 3 first, you are likely to abandon the play. If you are clever, however, finding a trace of oil in very tight rock (well 3) would suggest a substantial column at that location. The question becomes where to drill next. Your boss will probably tell you to "drill up-dip" -- everyone knows you go up-dip of a show. Your intuition and knowledge of the area, however, tells you to look for some better facies within that trap. Hence you argue for well number 2. After considerable haggling, you drill downdip, against the better judgement of your supervisor and find some oil with water. You supervisor tells you to abandon the project, there is nothing there. Again, your knowledge of capillarity, relative permeability and pressures with shows tells you from RFT data that you are indeed in the same oil column. Newly acquired 3D seismic shows you a grainstone shoal facies just downdip of well 2. You recommend going downdip again, to get irreducible water saturation.

Your boss thinks you are insane, and vows to drink all the oil in that downdip location. Your geophysicist likes the location, because that seismic looks so good--"what an awesome image", he tells you. You drill downdip, get a 10,000 BOPD well, irreducible water saturations and can finally sleep after days of sweating out the result. Your team has a big discovery party and your boss gets a big promotion for having allowed you to take such a huge risk on the company's behalf. You get an 'atta boy' pat on the back and enough bonus to take the wife to dinner.

If this sounds like fiction, it is not. Many astute explorers do this innately. A good documentation from a personal example is in Dolson et al., (1998). The principles are laid out clearly (Schowalter, 1979; Schowalter and Hess, 1982). Pseudo-capillary pressure plots (Hawkins et al., 1993) and others derived from porosity/permeability relationships estimating pore throat radius (Pittman, 1992) and detailed in Dolson (2016) can help determine the position of an oil recovery or show in a trap quantitatively. That information can help immensely in determining where to drill in a trap delineated only by tight oil shows in waste zones.

Mature Basin Case Histories: West Siberian Basin

Three examples from Russia's West Siberian Basin provide good examples. The basin is the largest contiguous basin in the world and one of the most prolific with source rocks spanning Neoproterozoic through Cretaceous age. The dominant source rock, however, is the prolific and rich Upper Jurassic Bazhenov Shale (circled at location 3 in Figure 25).

The Jurassic system is largely confined to broad paleo-valley networks overlying heavily eroded surfaces of Paleozoic clastics and intrusive granites and metamorphics. As shown chronostratigraphically (locations 1, 2) these broad valleys were buried by mid to later Jurassic time when the Bazhenov seaway covered the entire basin. Progradational Lower Cretaceous (Neocomian) clastic wedges prograded from both east and west into the Bazhenov seaway, setting up deltaic and turbidite 'clinoform' plays. With additional source rocks in the Lower Jurassic and Triassic, and a regional Aptian shale transgression sealing the 'clinoform' package, a near perfect charge and migration setting exists for any trap geometry.

The basin is perhaps a ‘type section’ for prolific stratigraphic traps, and has reserves in excess of 450 BBOE, with 28 BBOE in the Jurassic system (Figure 26). Seven of the world’s largest gas fields occur in the basin, all of which are in excess of 100 TCF in size (Igoshkin et al., 2008). More importantly, structural dip rates, as well as structural closures, have gentle dips, typically 5-10 meters per kilometer, allowing even modest seal capacity to develop stratigraphic traps of large aerial extent.

Uvat-Ust-Teguss and Tyamskaya Fields

The Uvat-Ust-Teguss-Tyamskaya study area is in the extreme southern portion of the basin as shown on Figure 26. Jurassic paleo-topography exerts a strong control on depositional facies, with a network of basal paleo-valleys extending over 2000 kilometers from north to south (Figure 26A).

These fields are located on the flanks of large paleo-structural arches formed in the late Triassic. These arches have been prominent topographic highs during multiple periods of Jurassic and Cretaceous transgressions and burial, showing up as yellow and orange colors on both the structural (Figure 26B) and isopach maps (Figure 26D). As a result, there are hundreds of meters of onlapping reservoir, seal and source rock geometries around the flanks. These geometries form stratigraphic traps with over 724 MMBO and 5.8 TCF of gas, covering a 3000 km^2 area in the Urna complex alone.

2D seismic delineated the overall structural shape and general nature of the onlap, but not the facies. Isopach maps from Bazhenov to Basement (“A” horizon locally) revealed a strong pattern of dendritic shapes assumed to be fluvial systems surrounding the high. The sub-regional pattern of the basal erosional valleys is shown in Figure 26D. Stacked sandstones on logs, interbedded with some thin coals led to an interpretation of the reservoirs as discontinuous channel sandstones.

The fluvial model was further supported not just by overall isopachs of dendritic or trellis patterns, but by time slices from 3D seismic (Figure 27).

Onlap traps are common globally, often as shoreline sandstones. This field offers a detailed look at one of the variances of an onlap trap. The fluvial model, with inferences of highly discontinuous reservoirs and compartmentalization, fell apart as abundant core data became available (Dolson et al., 2014). The cores showed marine, estuarine, tidal flat, tidal channel, and shoreface sandstones. Just as importantly, numerous paleo-sols, missing facies and a number of correlable *Glossifungites* ichnofacies showed that the drowning and onlap was episodic, punctuated by periods of lowstand and exposure.

Thin coals once used to support a coastal plain model turned out to be algal-rich estuarine coals and source rocks and the reservoirs and seals were nested in multiple incised valley fills as estuaries, tidal channels, tidal flats, and central basin muds. The uppermost levels were fully marine coarse-grained shoreface sandstones, reworked and re-deposited in sheet-like geometries. The high compartmentalization speculated from geological fluvial models disappeared and production later proved high connectivity between wells.

Re-correlation of the sequences (Figure 28) showed the most prolific horizon ("J2") was actually a sheet-like geometry of reworked shoreface and sandstones formed during marine ravinement during transgression.

The dendritic patterns of estuarine valley networks are clear on the 'J2' seismic image in Figure 28, as is the arcuate shoreline trend on the 3D. These results led to a dramatic increase in the recoverable reserves. Just as significantly, in a stratal slice just below the 'J2', the seismic shows a completely different pattern for the "J3". This level is dominated by tidal flats (generally poor reservoirs) and a narrow and isolated bay-head delta (good reservoir). At each level, the facies on seismic are different. The 3D seismic high-resolution facies analysis was critical to predict reservoir and seal extents and compartmentalization. This field is still one of the most productive fields currently owned by Rosneft (who bought TNK-BP in 2013).

The Tyamskaya Field area is located NW of the Uvat paleo-high and down depositional dip. The oil and gas shows could not be easily explained, since later 3D seismic showed that only one well (202) was actually drilled on a valid structural closure (Figure 29).

Well log cross-sections using traditional 'layer cake' fluvial models (Figure 30) could not easily explain the oil shows or variances in reservoir quality.

1. As data from a 500 + km^2 3D seismic program became available, a new look at the core and log data revealed a more complicated story similar to what was being uncovered in the Uvat area up-dip (Figure 31). Pressure data in well 270 to the south, indicated a possible free water level consistent with shows in the other wells with oil. Below this level, the reservoirs were wet and tested water. Just as importantly, well 314 drilled through tight tidal flat facies (not fluvial coastal plain) and tested oil in micro-porous facies. This well was a classic 'waste zone'. Capillary pressure data and SW in the well indicated a column height of at least 80-100 meters below the cored interval.

Seismically, a large incised valley deposit filled with tidal channels and containing a well-developed, but only lightly tested bay-head delta was delineated by the 3D data. The channel/delta image shown in Figure 29 was developed from an inversion volume modeling porosity and using seismic wavelet facies analysis. The results were surprising, but consistent with observations in the core. The main fairway was not tested thoroughly and well 314 was drilled within a micro-porous seal.

As at Uvat, multiple incision surfaces were found in the cored intervals and the facies once again proved to be estuarine and marine, with multiple sequences present. Correlations of the well section, using seismic, cores, and logs, resulted in a different pattern (Figure 31). A reservoir picture became clear with Winland plots of porosity vs. permeability with calculated pore throat aperture lines overlain (Dolson, 2016b; Pittman, 1992; Winland, 1972, 1976). Data falling below .5 mu R_{35} aperture are micro-porous and act as seals. These were consistently in tidal flat facies. Values between .5 and 2 mu are meso-porous, behaving as transition zones in an accumulation and above 2 mu are macro-porous, high quality reservoirs. Tidal channels and bayhead deltas were consistently macro-porous. The high flow rates in well 202 were due to high quality bayhead delta reservoirs located 150 meters above free water, where water saturations were low. Poorer performing wells downdip in macro-porous strata were simply very low on the trap, with low buoyancy pressure. Well 314 only flowed because it was high in the trap, with enough buoyancy pressure to reach 30-50% Sw in tight rock (Figure 32).

Despite shooting a huge 3D survey, the total trap turned out to be larger than the survey shot. Figure 33 shows the maximum possible extent of the trap. While parts of this trap remain speculative, the nature of the stratigraphic seals is clear. Tidal flat facies commonly rim the sides of the valley sequences and are waste zones and seals, despite being silty and fine-grained sandstones. Visualizing porosity and permeability in terms of pore throat size is a better way of predicting seals vs. reservoirs. Height above free water calculations can be used with capillary pressure data, or, lacking that, with pseudo-capillary pressure curves (Dolson, 2016) to estimate position of an oil or gas show in a trap of unknown size.

This is a huge potential trap and many analogs of this trap type occur in Jurassic and other strata elsewhere in the West Siberian Basin.

The learnings from these efforts should be applied globally. Be data driven, not 'concept' driven. Strive to squeeze as much stratigraphic imaging as you can from the seismic. 3D is essential to do this, but it is up to the interpreter to use the right software, right level of detail, and appropriate tools to achieve the right results.

Priobskoye Field Analog

Lastly, Priobskoye Field in West Siberia provides another important stratigraphic trap analog (Dolson et al., 2014; Hafizov et al., 2014). The field is located northwest of the Tyamskaya area (Figure 34). It was discovered accidentally in 1980 and is a pure stratigraphic giant trap. A subtle arch exists near the field, but plays no role in the trapping geometry, which is controlled by numerous deltaic pinch-outs (Neocomian topsets) and basinal turbidite fans (Achimov facies).

Traps are set up by multiple ravinement surfaces developed during transgressions of lowstand deltaic topsets as well as pure stratigraphic traps in the 'Achimov' turbidites (Figure 34E). Figure 35 summarizes a seismic view of just one of these clinoform packages. Traditional 'layer cake' correlations, done without seismic, cross the seismic facies and do not explain the accumulations. The term 'Achimov' is applied to any facies developed at the toe of a clinoform and 'Neocomian' to any facies in the topsets below Aptian flooding shales. Multiple seals exist, despite the lithostratigraphic nature of the nomenclature.

Additional detail (Hafizov et al., 2014) includes images and core facies analysis from other parts of the field. The shelf to slope transition is clear seismically, as well as the fine-grained slope fan facies. There are few to no shelf canyon incisions and even the top-set deltaics are fine-grained. In this part of the field, the best facies are usually meso-porous, with some isolated macro-porous zones related to meso-fauna trace fossils creating 'cryptic cross-bedding'. These kinds of stratigraphic traps are common across West Siberia and well understood by most explorers.

North Slope Analog: Mature Basin Fans and Deltaics

Since 2015, a huge new stratigraphic province has been opened up in the mature North Slope passive margin of Alaska. Long considered drilled up after the 1969 discovery of Prudhoe Bay and decades of exploration focused on the deep Triassic Shublik source rocks (Figure 36), innovative explorers recognized pay behind pipe and stratigraphic potential in the overlying Nanashuk Formation, largely considered by many as 'overburden'. As in the Priobskoye Field analog, basal turbidites are termed 'Torok' Formation, despite the obvious diachroneity in the correlations.

Interestingly, Caelus Energy was formed by ex-Kosmos staff members who had experience developing the turbidite plays in West African mature source rock kitchens. They simply took their model to the North Slope and drilled a 700 km^2 + turbidite fan trap at Smith Bay (CaelusEnergyAlaska, 2017).

The Willow and Pika/Horseshoe fields keyed off pay behind pipe in a 2002 well plugged by Conoco-Phillips without testing. 3D seismic illuminated the topset traps. The plays are still being made (AlaskaDeptNatResources, 2017a, b).

These discoveries have completely 'broken' the yet-to-find estimates by the USGS over several decades for this area. The play is a 'mirror image' of the West Siberian Neocomian plays. Sometimes, new ideas simply take some lateral thinking and paying attention to oil shows pays off.

Some Final Thoughts, Other Tools and Middle East Implications

Carbonate margins have the similar progradation geometries as those found in deltas (Figure 37). The figures (modified from Handford, 2007), illustrate the differences between lithostratigraphic vs. chronostratigraphic correlations in the Jurassic Smackover Formation of the Gulf Coast.

The sequence shown in Figure 37B show obvious room for additional trapping in multiple facies, none of which are apparent in the lithostratigraphic correlation (Figure 37A). In the Middle East, much of the production is carbonate related. It would seem impossible not to have additional stratigraphic traps in the carbonate facies by utilizing the principles outlined in this paper.

One interesting regional observation is that the slope carbonate turbidites and breccias, productive in many basins, and particularly well illustrated in the giant Poza Rica Field of Mexico (Janson et al., 2011) have not been discovered in giant field volumes since 2000. Many of these carbonate breccia trends are targets of both unconventional and conventional drilling and represent down-slope trends (Janson et al., 2007; Playton and Kerans, 2002). Are similar plays present in the Middle East?

Many additional tools are available beyond those illustrated in this paper (Figure 38).

Figure 38A shows an automated technique used at ION Geophysical (through contractors) to take seismic data and convolve a Wheeler Diagram (Wheeler, 1958, 1964) of time equivalent strata. This kind of tool is an excellent initial screening method to identify large scale sequence stratigraphic packages.

Figure 38B shows a 'quick look' depth seismic section modeled for migration using Trinity software (also illustrated in He, 2017). The technique is simple and fast to run, simply by converting various amplitudes to relative arbitrary seal capacity in meters of column height and then using the map as a seal map and running it against a project set up with regional ramp structural dip. This technique is simply a good way to look at potential migration pathways in a frontier or lightly drilled basin. Obviously, building a robust model, even on a 2D depth section, that honors quantitative seismic velocity data, is enormously time consuming and not necessarily practical given time and effort required if screening plays or basin. This simple technique is fast and generates ideas, so it is worth trying and then 'ground truthing' with other well or seeps data at the sea floor.

Migration modeling is still in its infancy, when it comes to building full volumes of quantitative seals and reservoirs in a seismic and well constrained 3D volume. But even simple models shown in examples Figure 38B and Figure 38D are good ways to visualize risk and generate ideas. Many of the pitfalls and techniques are covered in Dolson, 2016 (chapter 9).

Regardless of which petroleum systems modeling software is used, it is essential to take a stab at modeling migration with facies and fault seals. The more quantitative your model is with both seismic inversion volumes, facies visualization, and calibration to cores, fault throws, and other seals, the more predictive the models become. But calibration to known oil and gas shows, accumulations and dry holes is the only way to verify these models (Figure 38D). A good example of calibration of residual and continuous phase shows to migration history is from the Barmer Basin of India (Naidu et al., in press).

In addition, one of the best tools for visualizing migration pathways and seals is fluid inclusions stratigraphy (Dolson, 2016b; Hall, 2008), and shown on Figure 38C. The technique is relatively inexpensive and fast, involving mass crushing of cuttings and analysis of over 20 different hydrocarbon species, as well as intensity of the inclusions. Fluid density (API gravity), water salinities, geothermometry, temperature of emplacement of the inclusion, and a host of other data can be generated quickly from bulk cuttings. There is no limit to age of the cuttings and this is a cost-effective way to garner new information on old dry holes. By-passed pay, proximity to pay, and migration pathways (when coupled with other wells with similar analysis) become more readily apparent.

Another technique frequently used to refine correlations in difficult environments is chemostratigraphy (Ramkumar, 2015). This technique can help define subtle stratigraphic pinch outs where traditional lithostratigraphic correlations may not. Undoubtedly, new tools will continue to evolve in the future.

The Middle East Dilemma

A fundamental problem remains in the Middle East (Figure 39). The Middle East is the world's largest and most prolific hydrocarbon province. Working petroleum systems exist from Neoproterozoic through Tertiary strata (Figure 39A). Even cursory seismic images (Figure 39B), show periods of syntectonic growth and deposition.

Hydrodynamic traps are known in Qatar (He and Berkman, 1999), and over-pressured basins exist where deep basin upward flow and tilting is documented as discussed earlier in the Caspian Basin (Riley, 2009). Abundant anhydrites and salts are interbedded with carbonate reservoirs that could set up large stratigraphic traps. Onlap wedges are clear on many seismic sections, with an example shown in Figure 39B.

A giant tight gas accumulation (Khazzan Field), as discussed, has been found in Oman only in the last decade. In structural provinces with steep dip, outstanding seals are required for big accumulations. Evaporites and salts provide some of those outstanding seals, particularly along carbonate shorelines. In addition, many areas in the Middle East have more moderate dip and the flank potential of many drilled structures offers potentially untapped prospects.

Conceptually, there is no reason why large stratigraphic traps shouldn't exist in the Middle East. Perhaps in this region, Michel Halbouty was right 37 years ago, arguing that these kinds of traps simply have been not been systematically explored for.

Summary

The last 17 years have seen a truly global step-change in finding rates for giant and significant combination, hydrodynamic and stratigraphic traps. Future success will come from the increasing ability to image progressively thinner reservoir levels with 3D seismic, and with new methods of extracting more seismic information. Success will also come from better integration of petroleum maturation, migration, and entrapment. The line between classic stratigraphic traps and unconventional traps will continue to blur, especially as it relates to locating 'sweet spots' within shale or tight gas plays.

When 3D seismic images yield images that no longer are simply 'amplitudes in space', but geomorphological features readily understood by geologists, then the road to de-risking prospects has begun. Integration of migration modeling with facies and fault seals, calibrated to oil and gas shows, provides another missing step in exploration, and is essential in mature basins.

In the last 17 years there have been many 'winners' and a number of losers. Many of the innovations have come from smaller, more 'nimble' companies with experienced staff willing to 'think out of the box'. Many large companies have missed out on the new discoveries. Cultures of conformity, fear of failure, over-reliance on a couple of play types, and playing the same old plays over and over with ever diminishing results leads to failure.

The future belongs to those companies that have challenged and will continue to challenge conventional wisdom, guide decision making with solid risk analysis and utilize as much data as possible to define the trap.

When that is done, the subtle trap becomes obvious.

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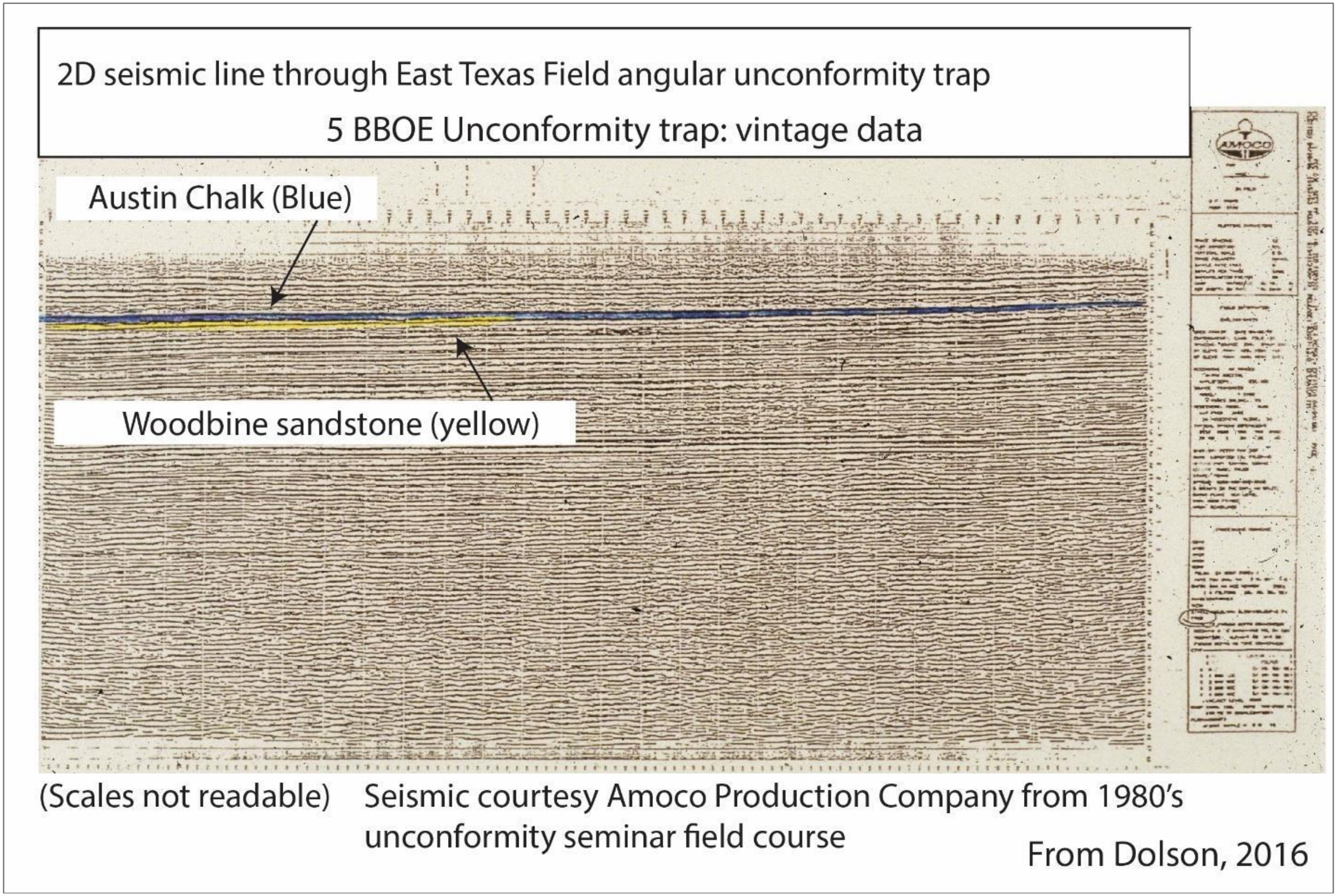


Figure 1. Historical 1950-1970's seismic version of a subtle trap. Image modified from Dolson (2016).

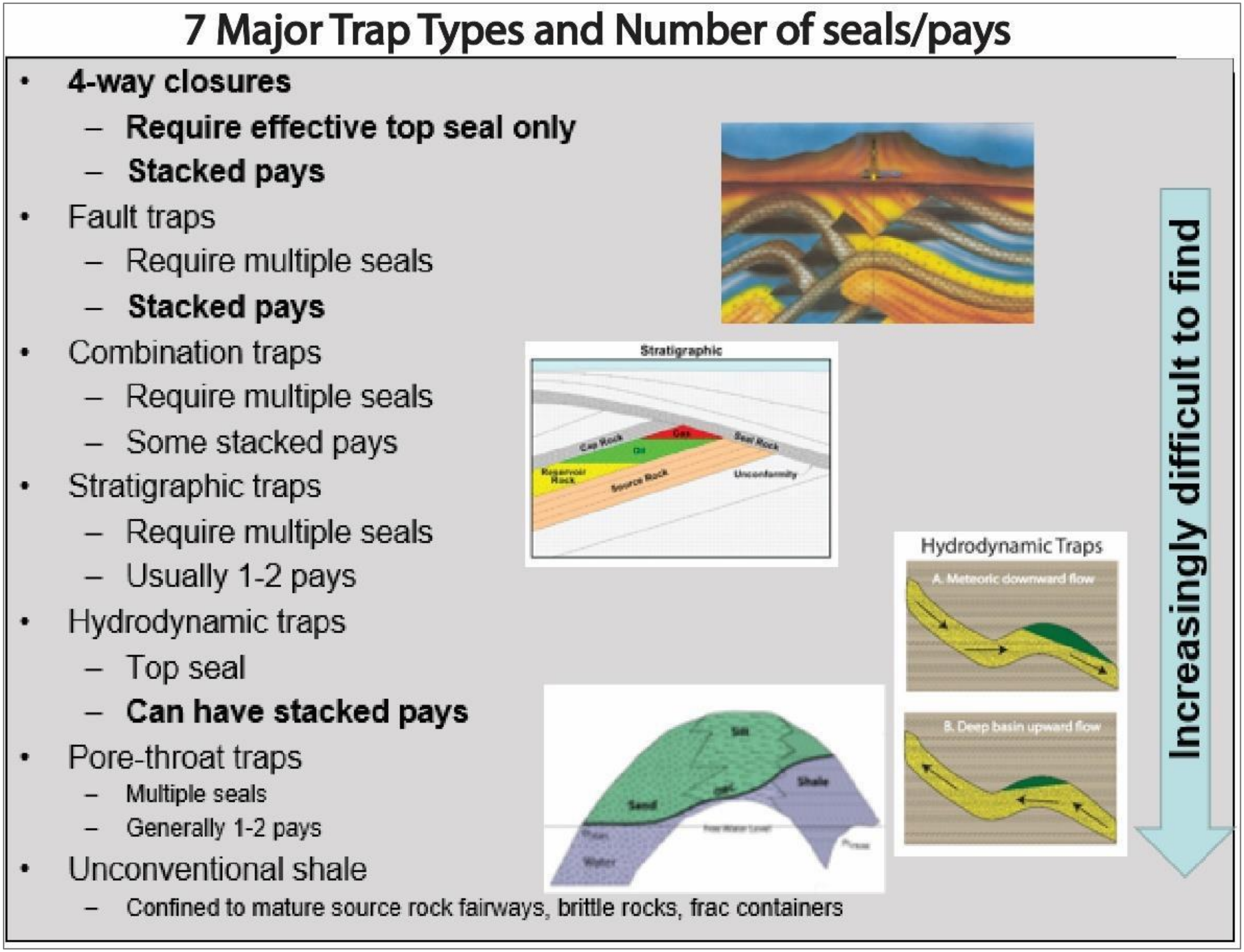


Figure 2. Traps and seals/pay zone pairs. Unconventional traps are surpassing conventional traps in volume, but cover vast areas requiring tens of thousands of wells to develop. A good giant strat trap in a reasonably sized area is still a good financial bargain.

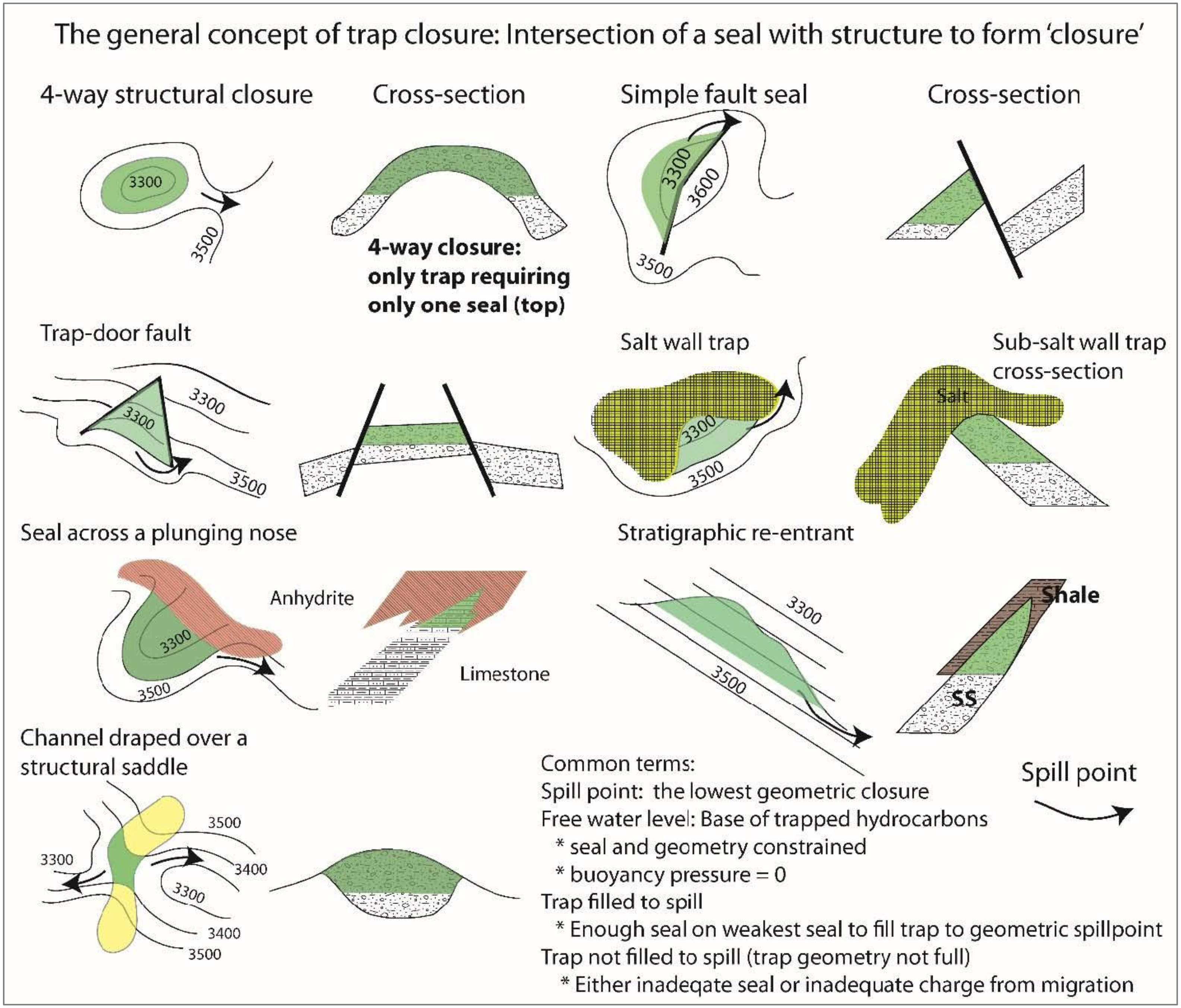


Figure 3. Closure as a concept of seal geometry. From Dolson, 2016.

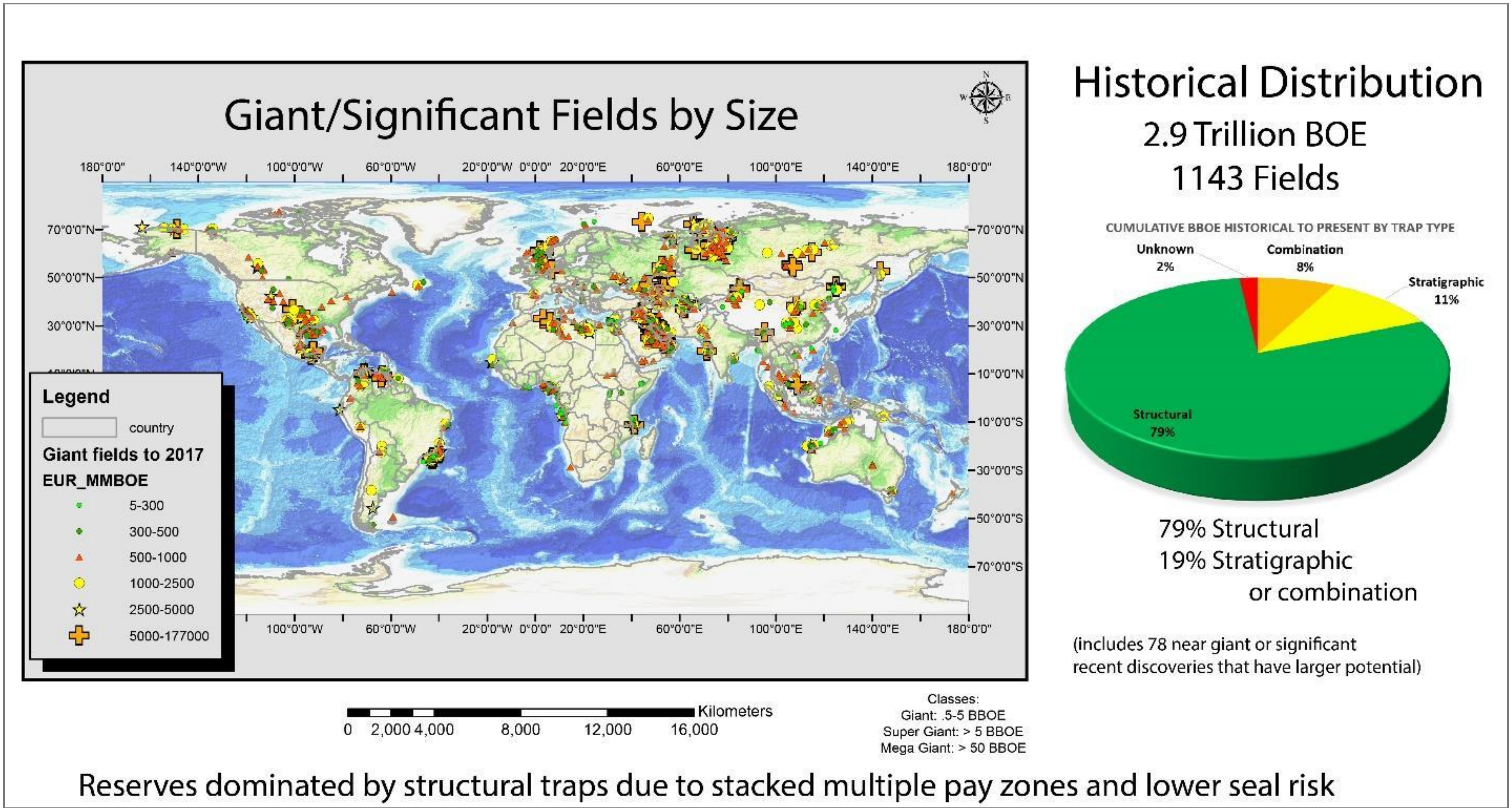


Figure 4. Distribution of giant fields to year 2017. Stratigraphic and combination traps historically comprise 19% by volume, but those numbers have changed in the last 17 years.

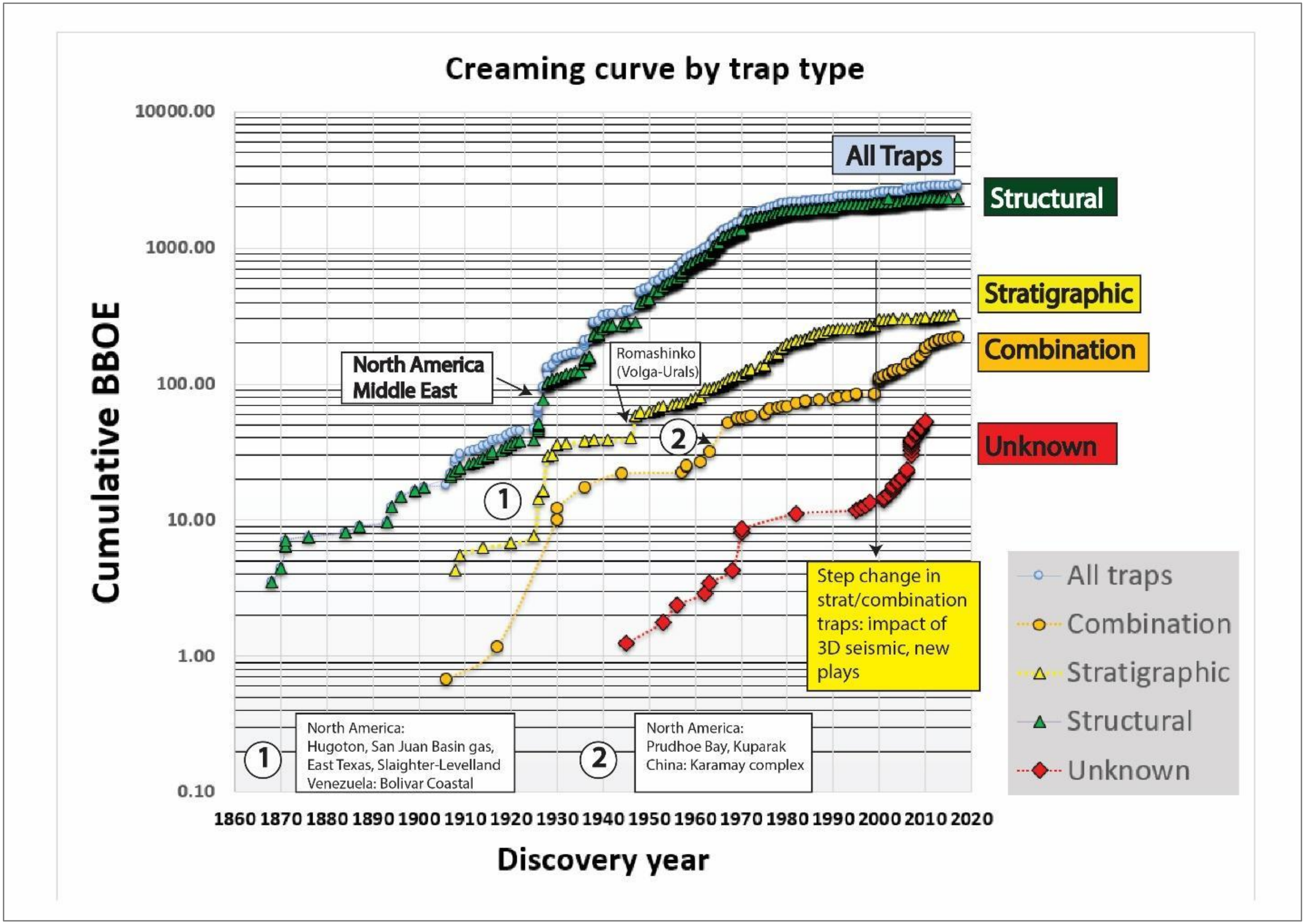


Figure 5. Creaming curve of giant/significant traps with time.

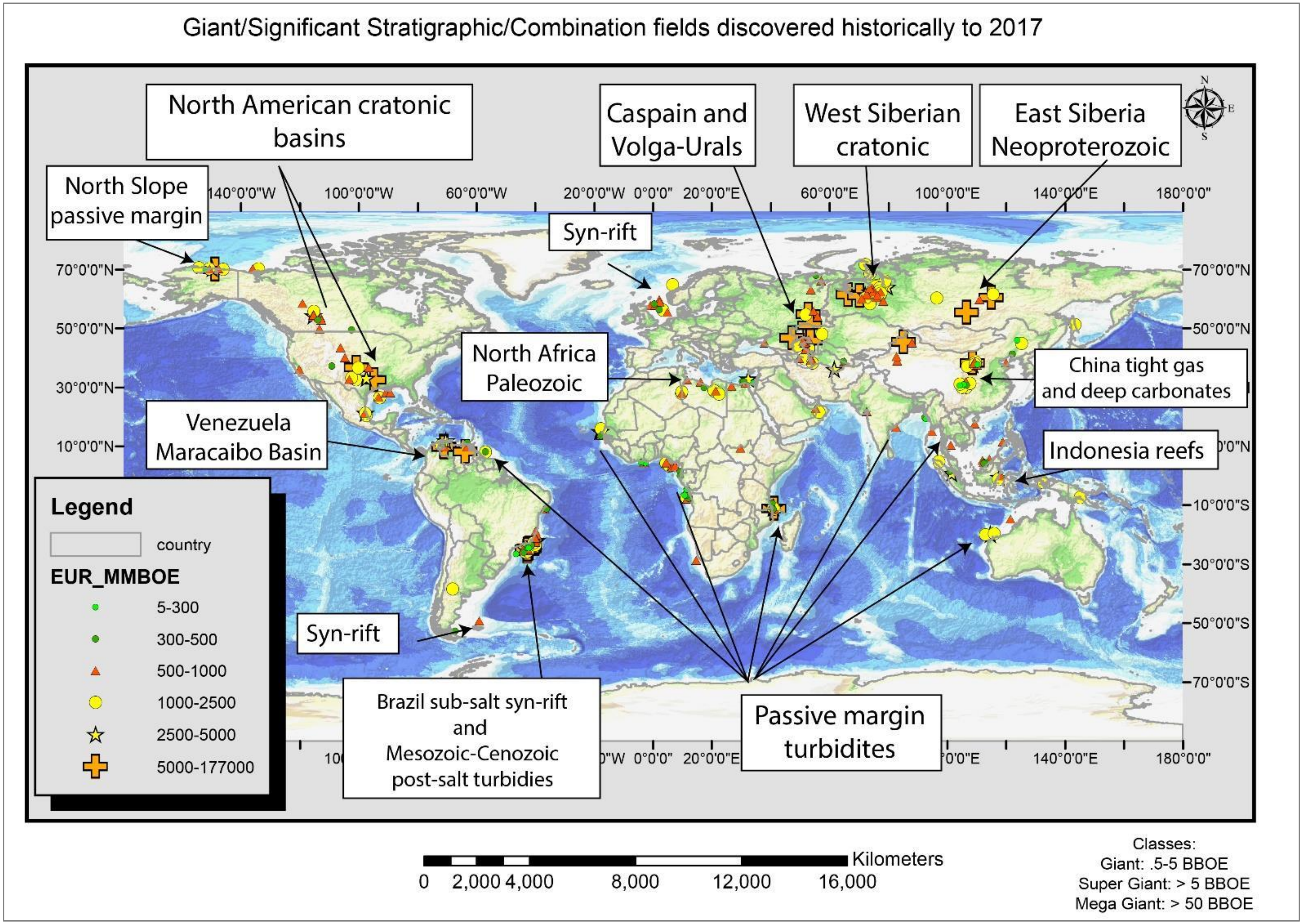


Figure 6. Major basins with giant stratigraphic and combination traps.

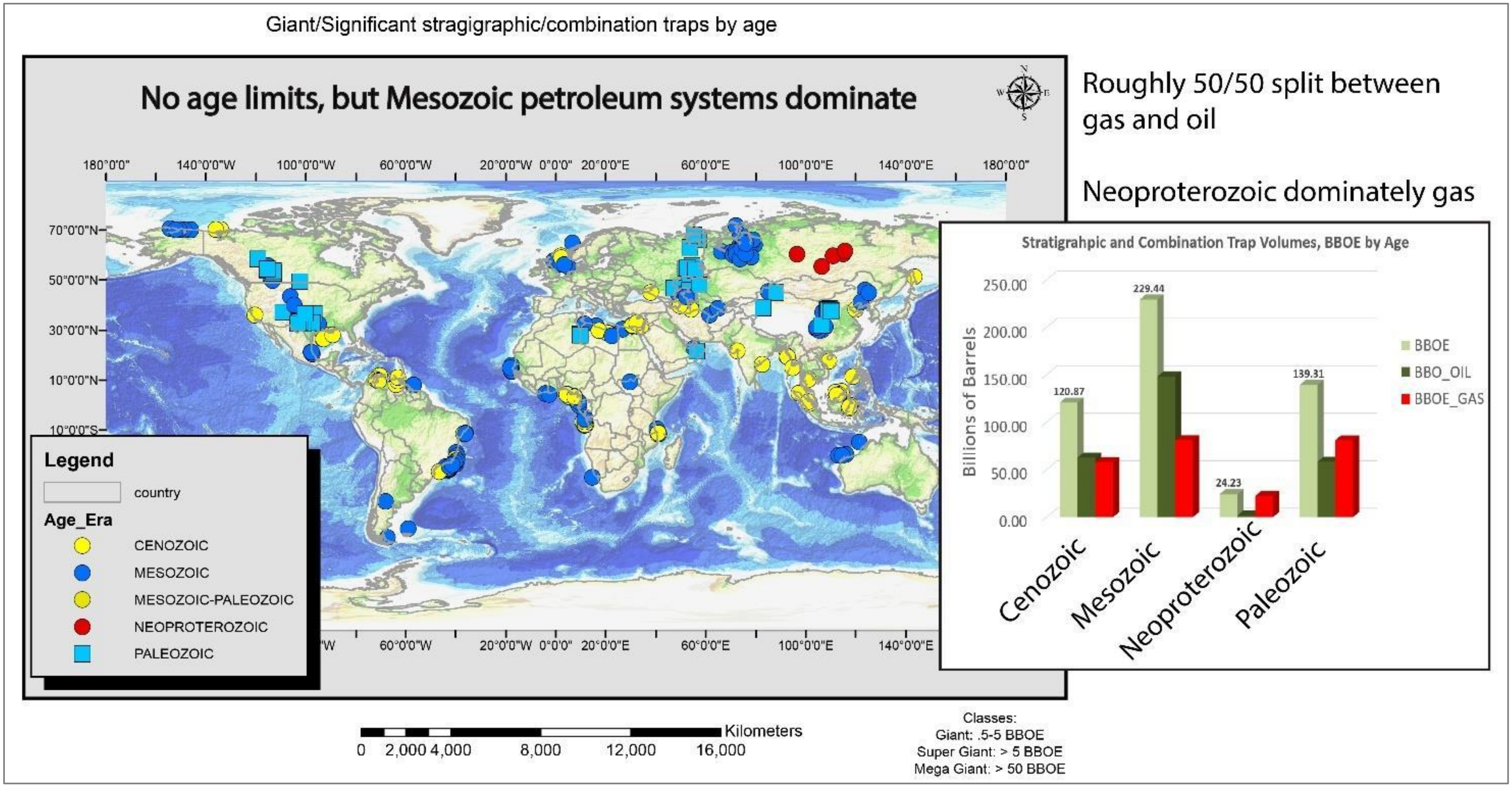


Figure 7. Giant stratigraphic traps by age.

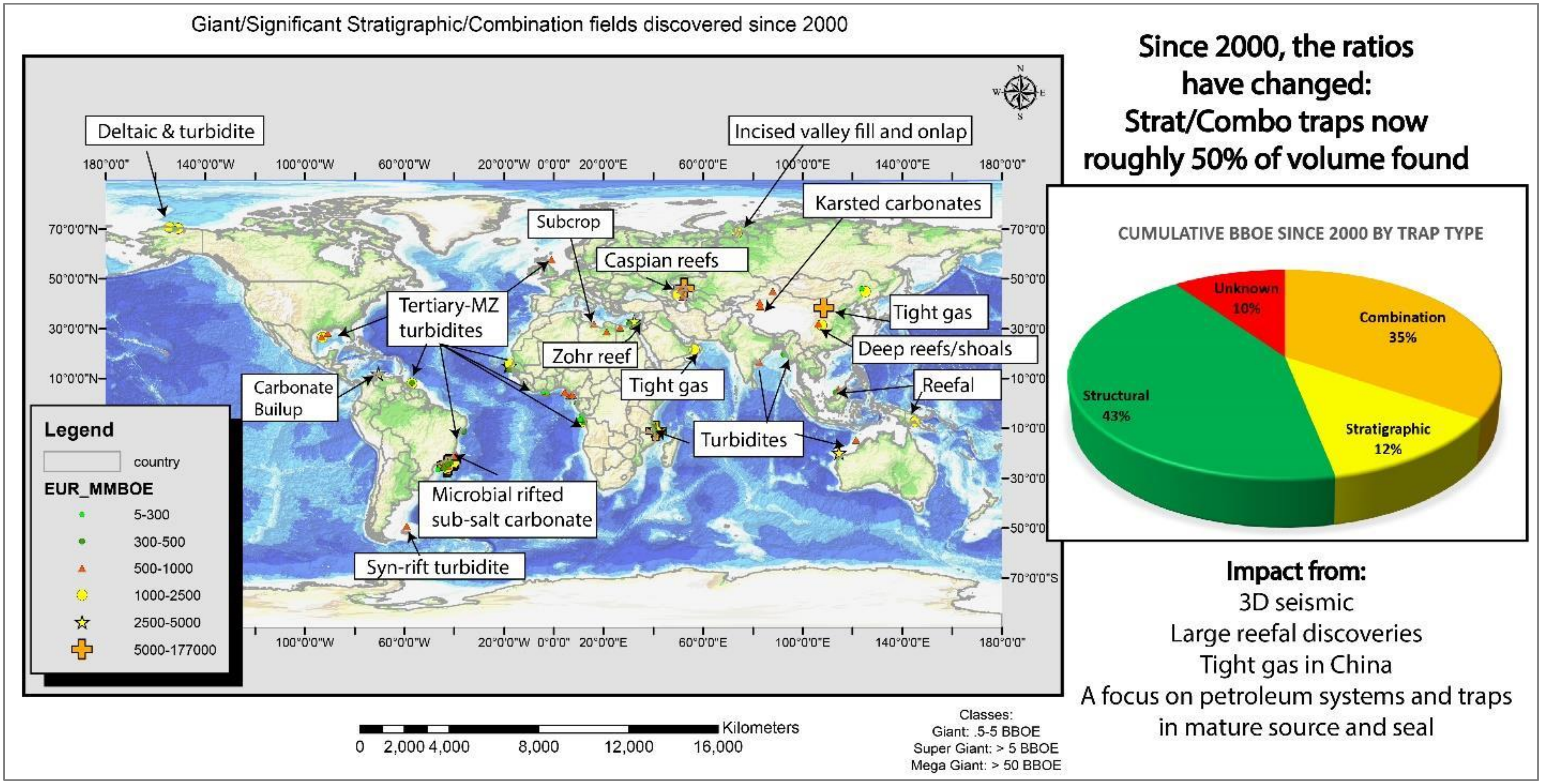


Figure 8. Giant/Significant strat/combo traps made 2000.

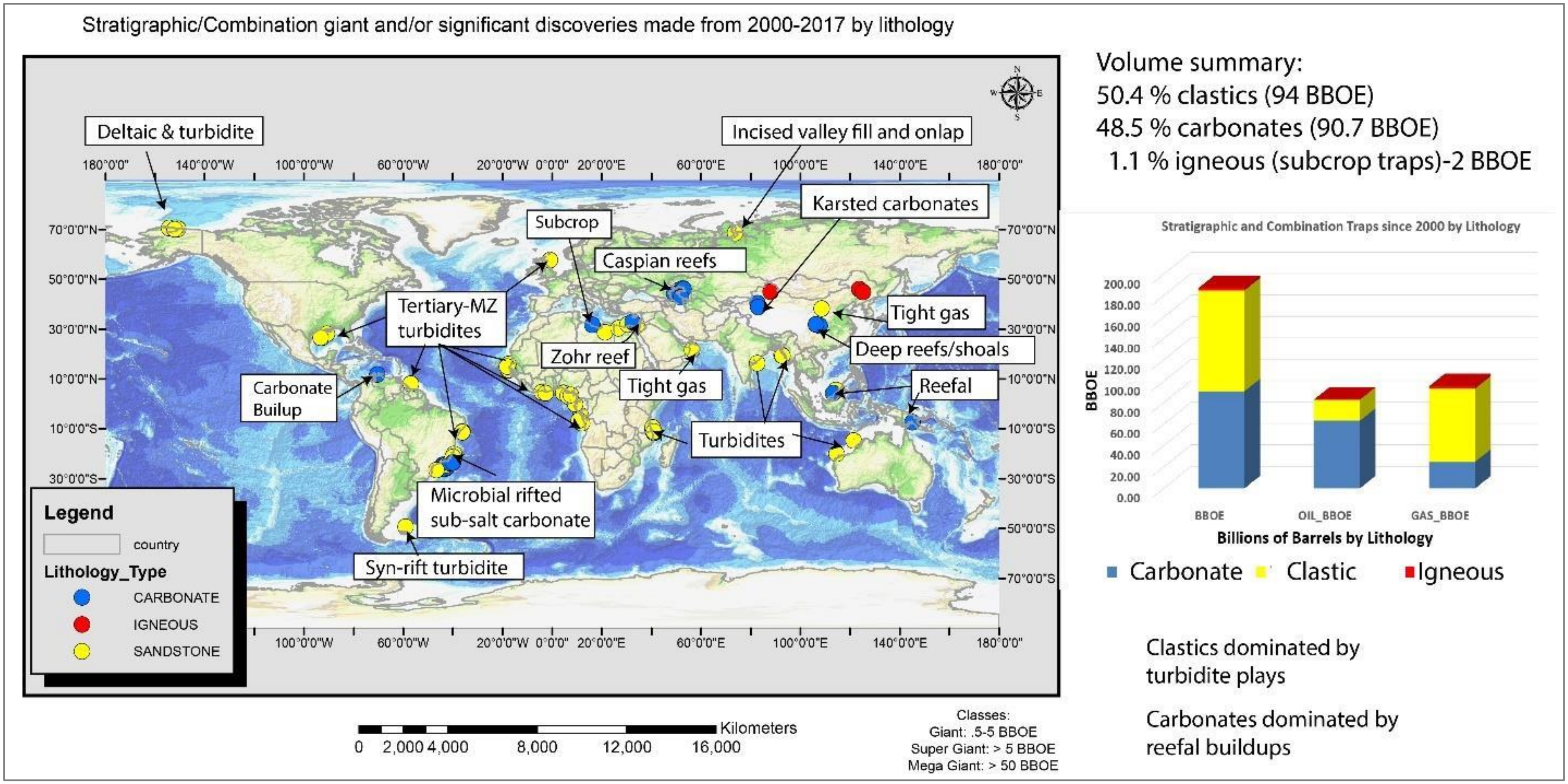


Figure 9. Giant Stratigraphic/Combination traps by lithology and fluid type.

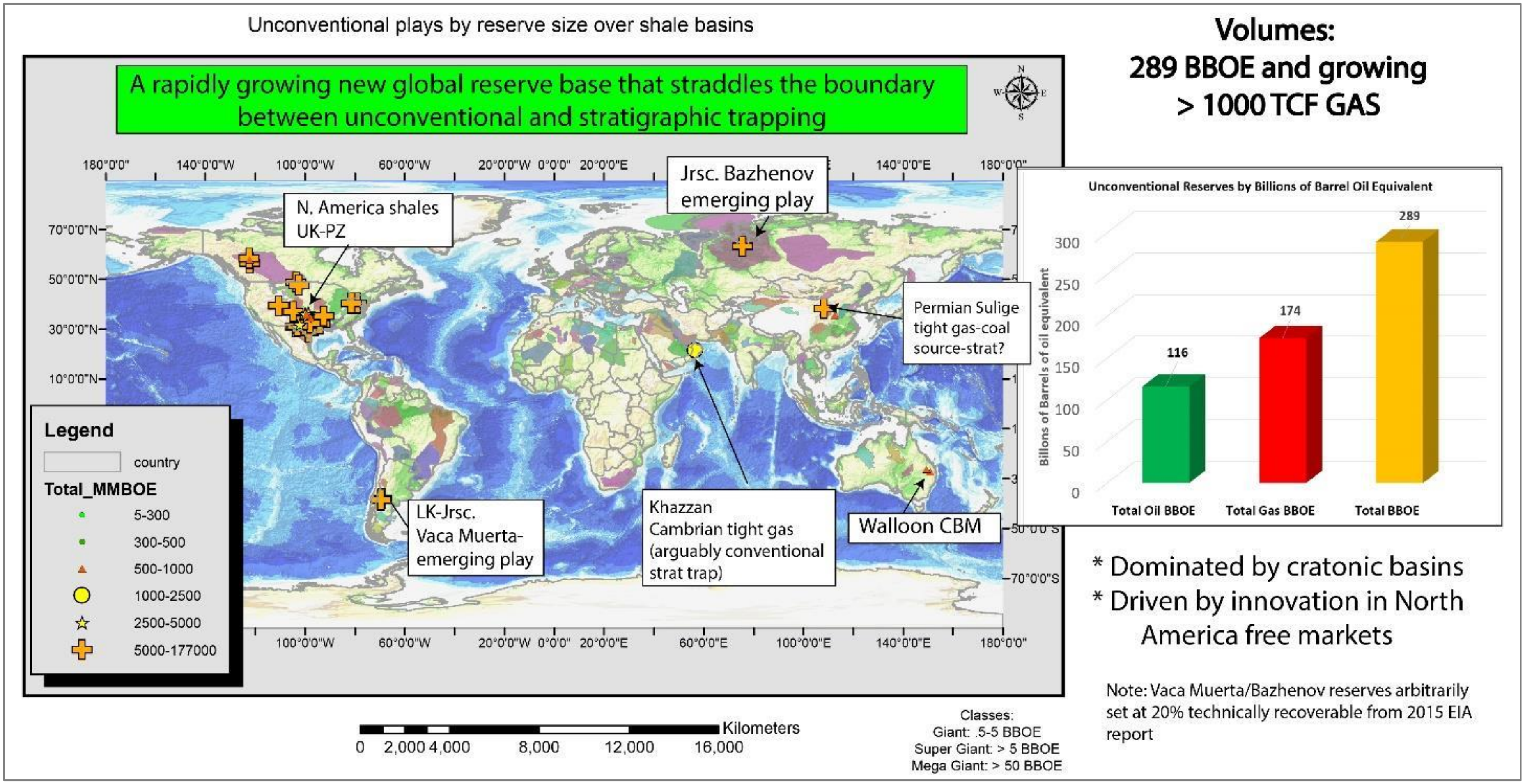


Figure 10. Unconventional reserve growth. Various shale basins are shown in lightly colored polygons (WRI, 2013).

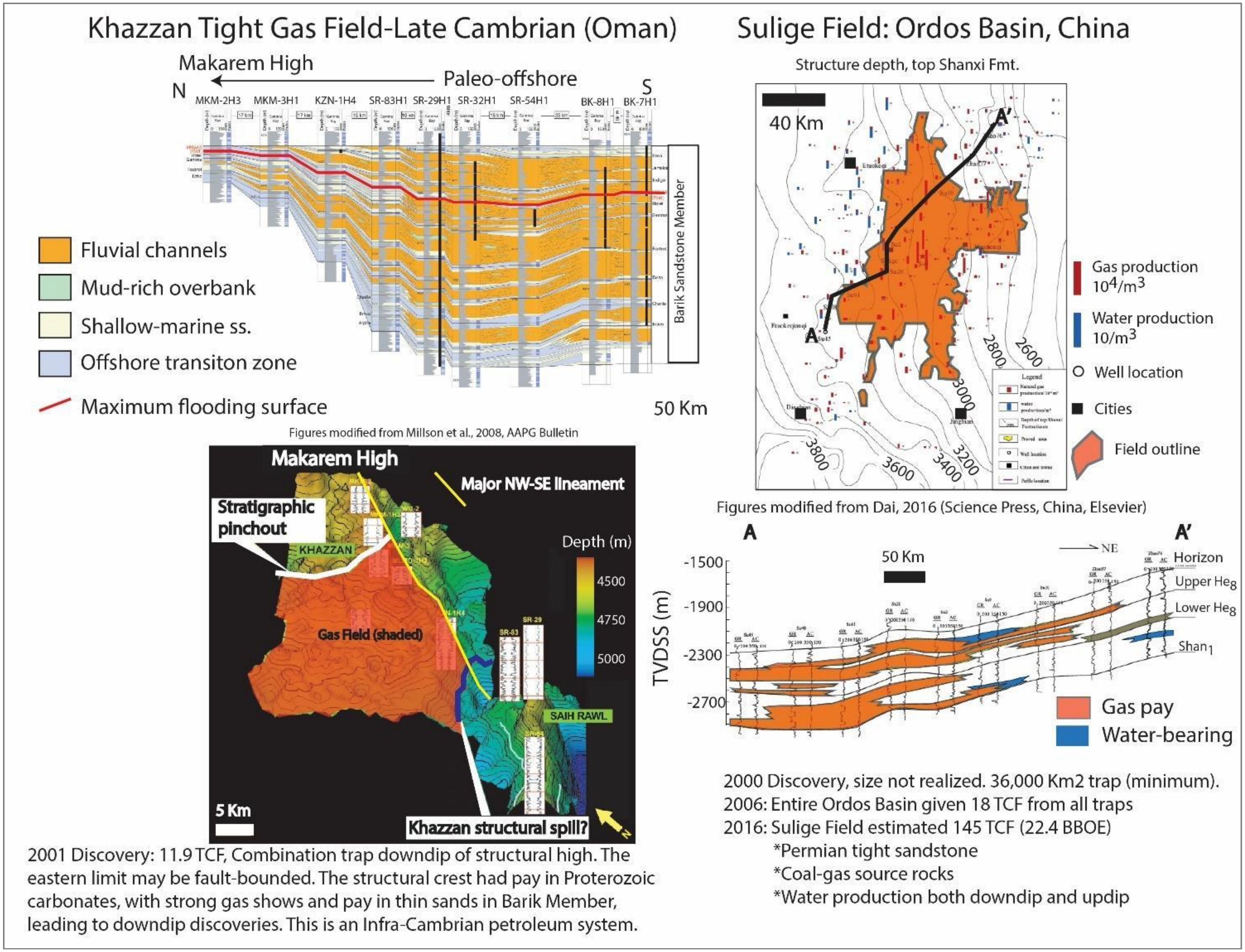


Figure 11. Khazzan and Sulige tight gas discoveries. Khazzan is interpreted as a conventional trap, but the full limits appear to be unknown. Sulige Field contains many discontinuous continental and fluvial reservoirs encased in mature coaly source rocks. The trap is not well understood.

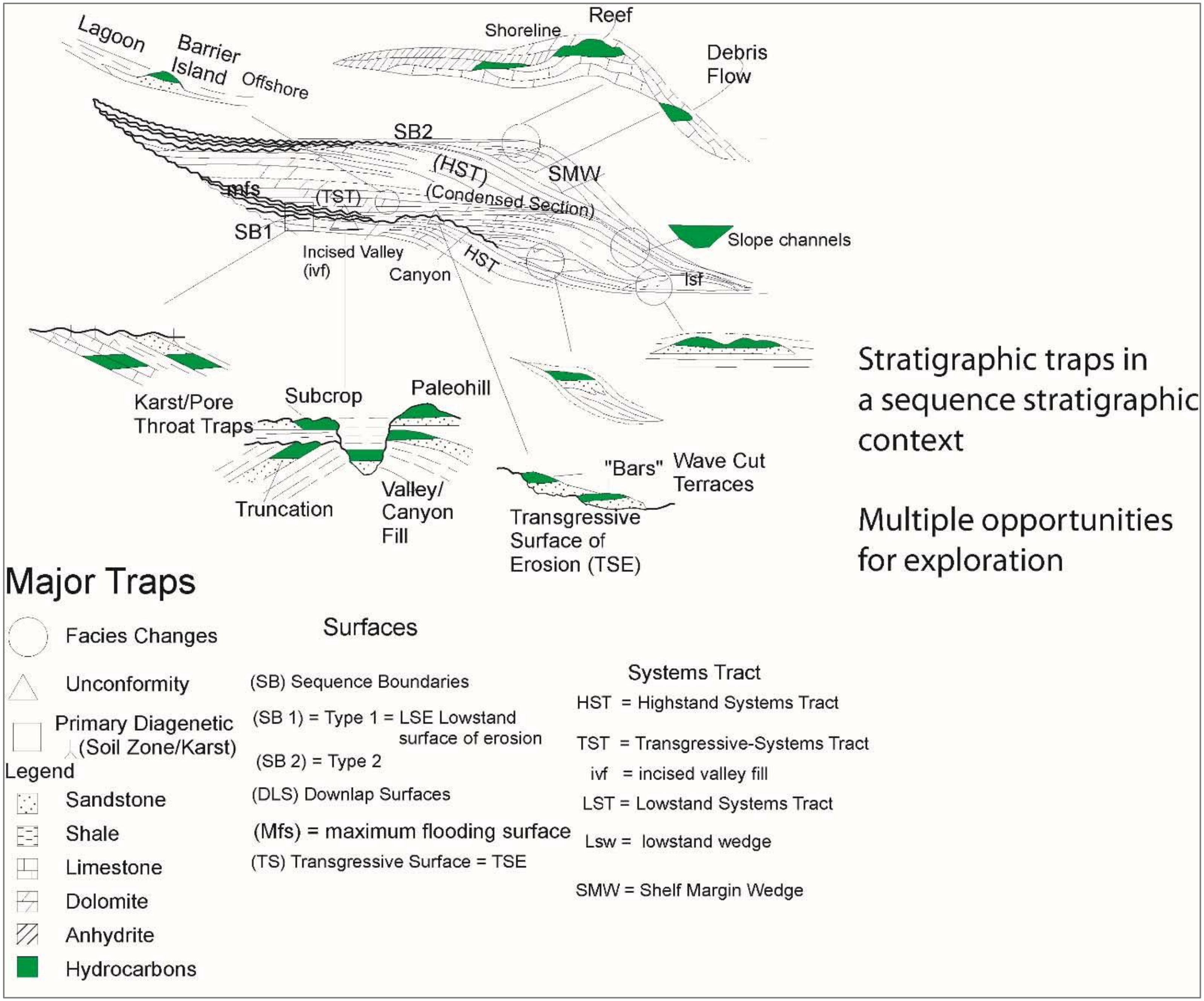


Figure 12. Traps in a sequence context. Modified from Dolson et al., 1999.

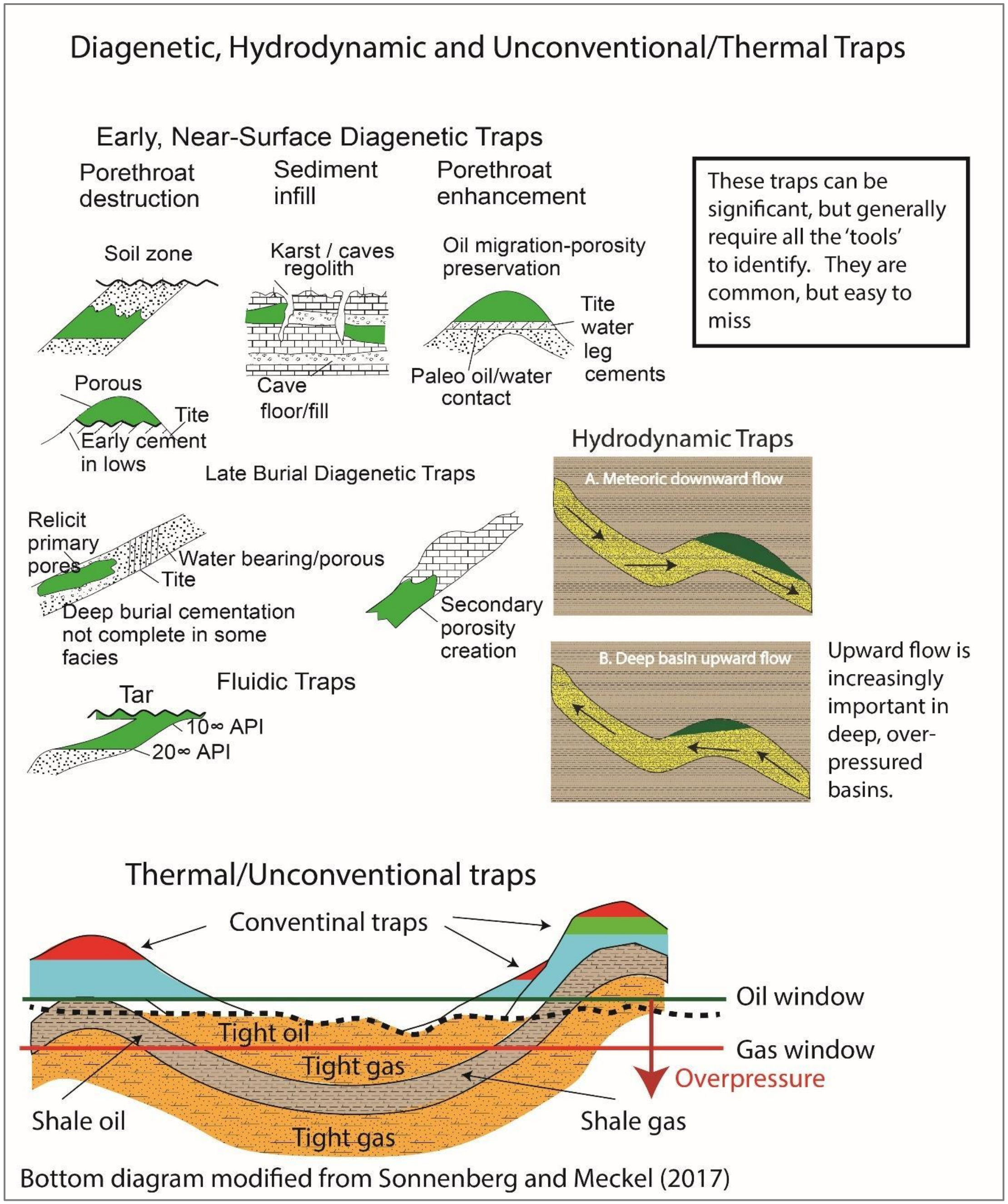


Figure 13. Diagenetic, hydrodynamic traps and unconventional traps. Modified from Dolson et al., 1999 and Sonnenberg and Meckel, 2017.

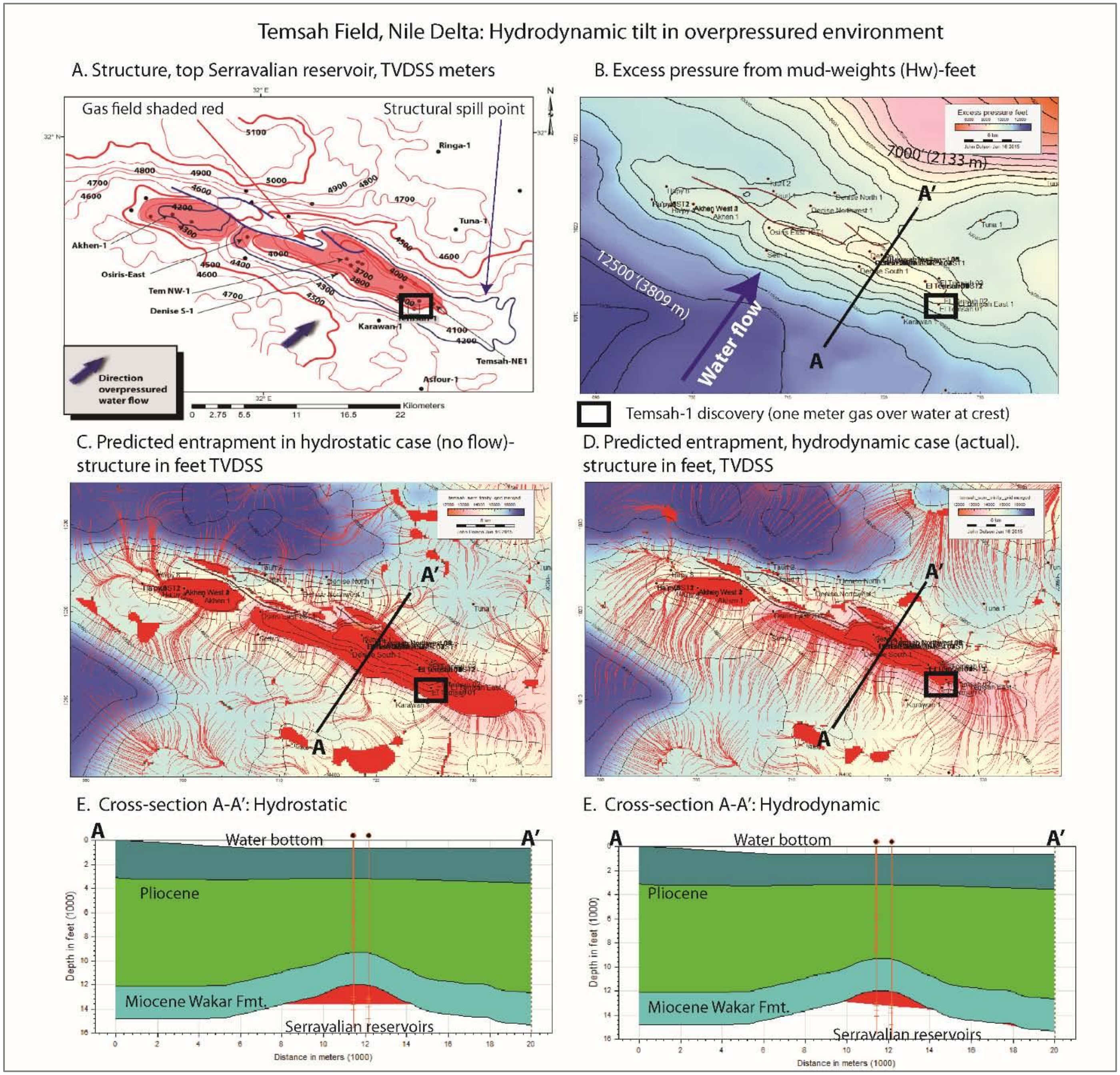


Figure 14. Temsah Field hydro-dynamically modified gas accumulation, Egypt (From Dolson, 2016).

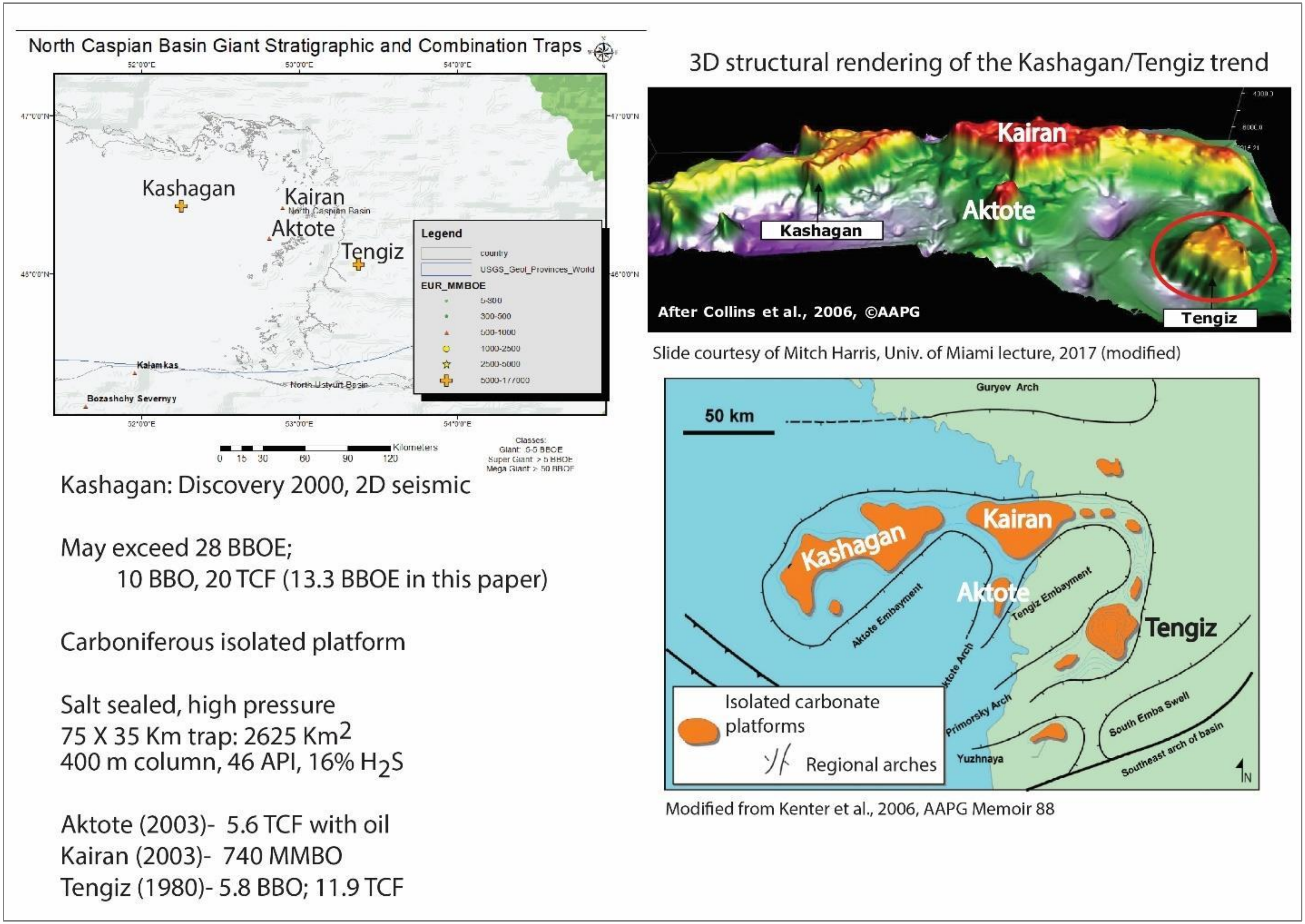


Figure 15. North Caspian Basin giant reef fields.

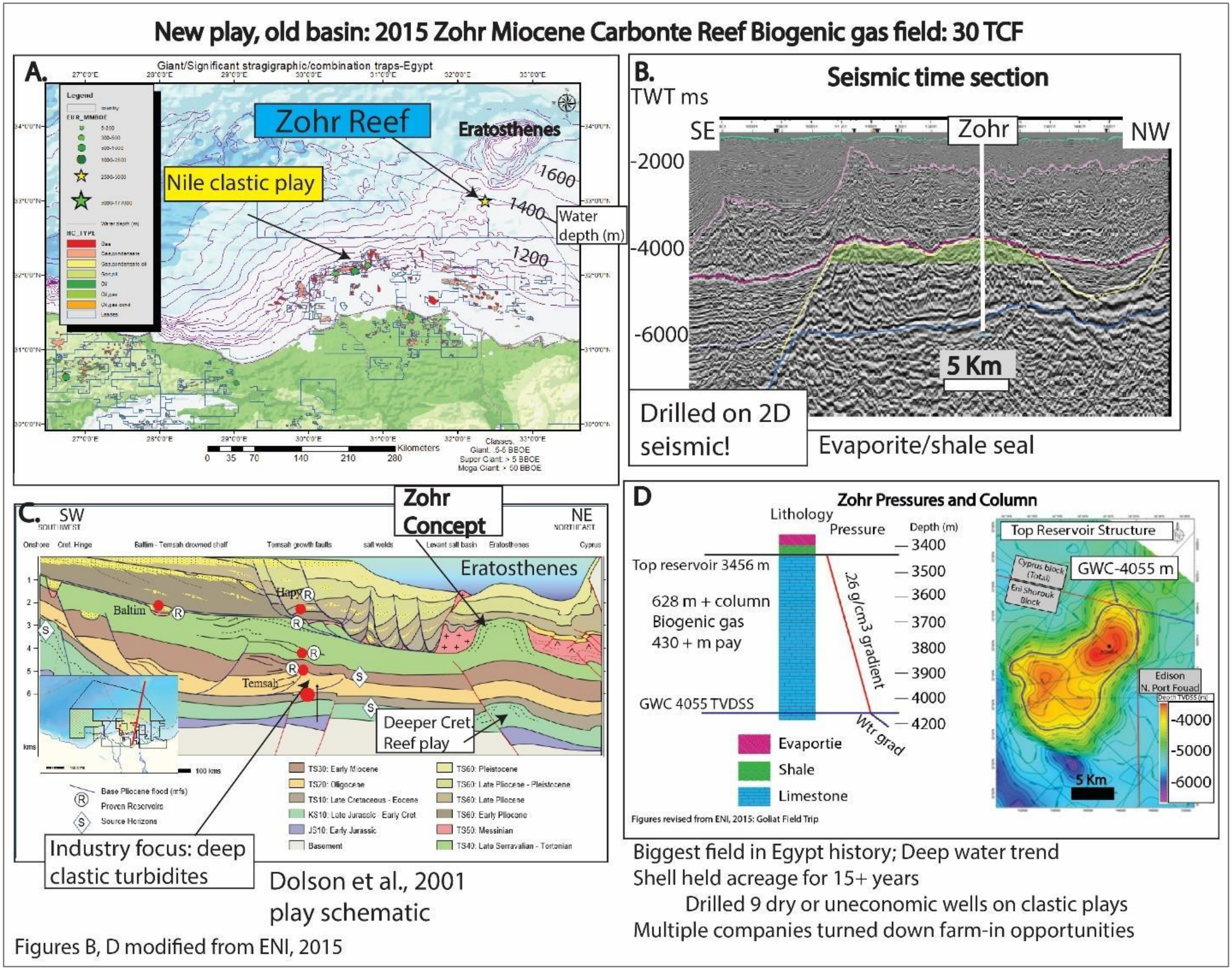


Figure 16. Discovery of the giant Zohr Miocene reef complex, offshore Egypt and Cypress.

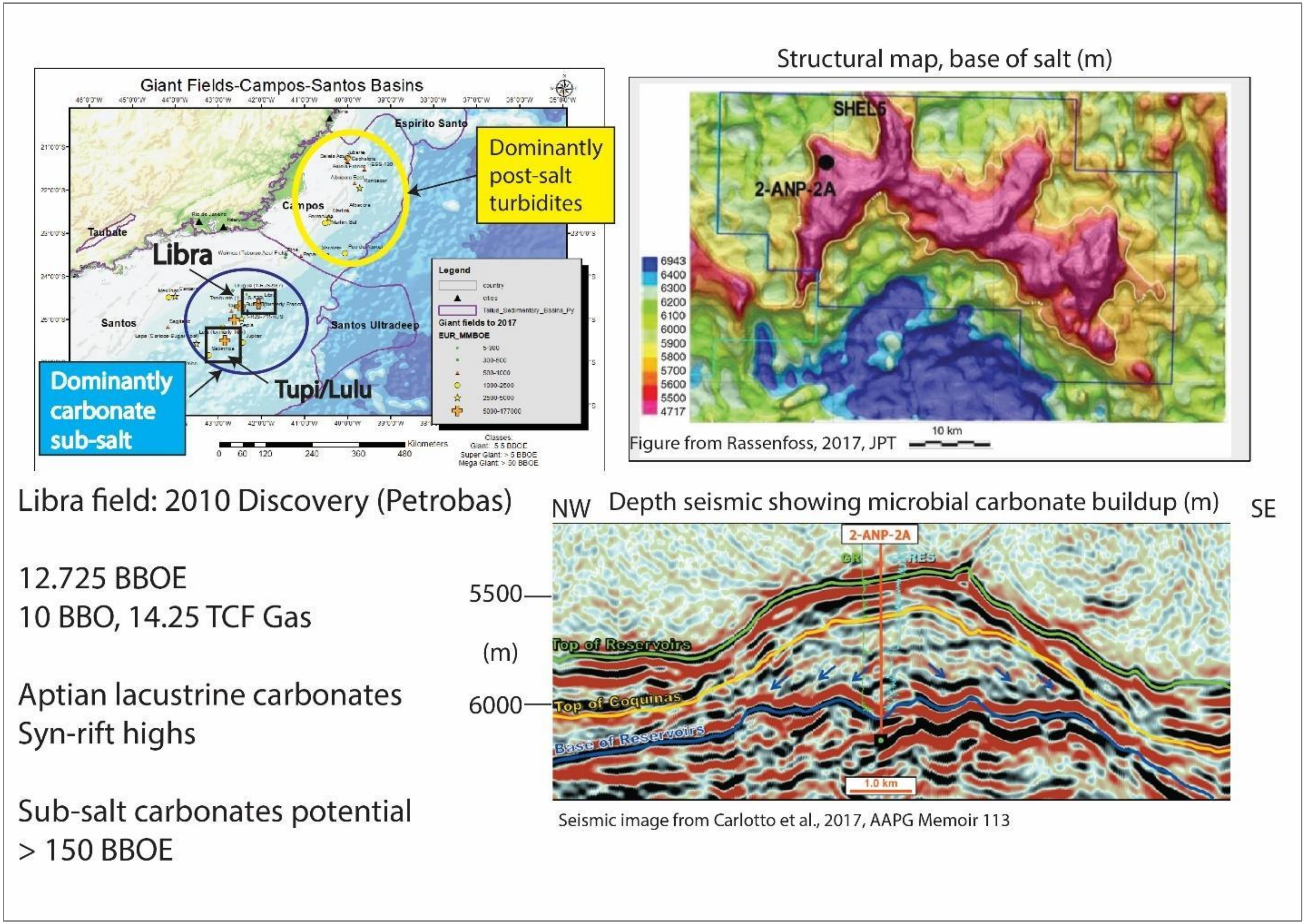


Figure 17. Libra Field carbonate build-up, Santos Basin.

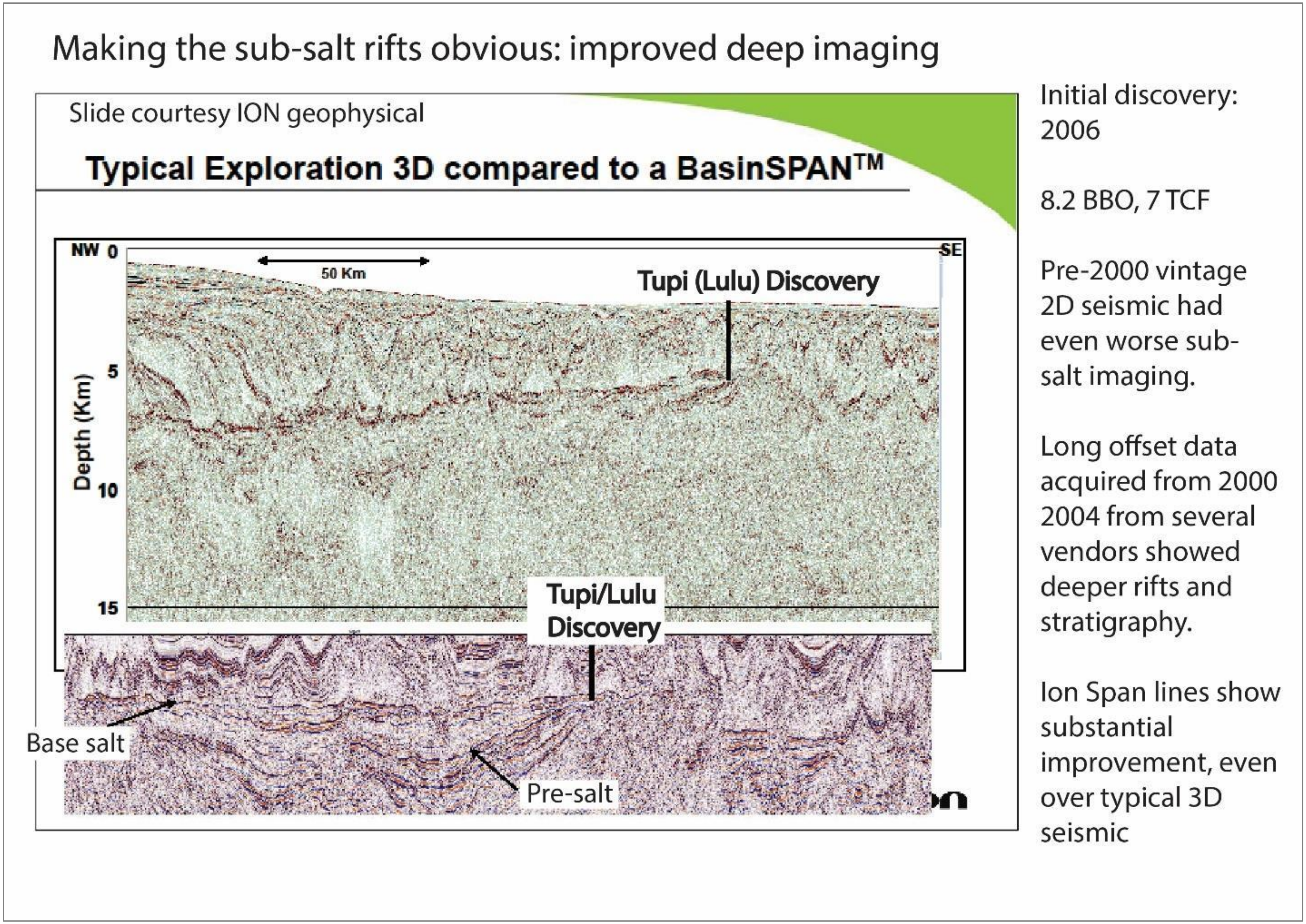


Figure 18. Advances in seismic image quality have allowed the prolific Santos Basin sub-salt play to work.

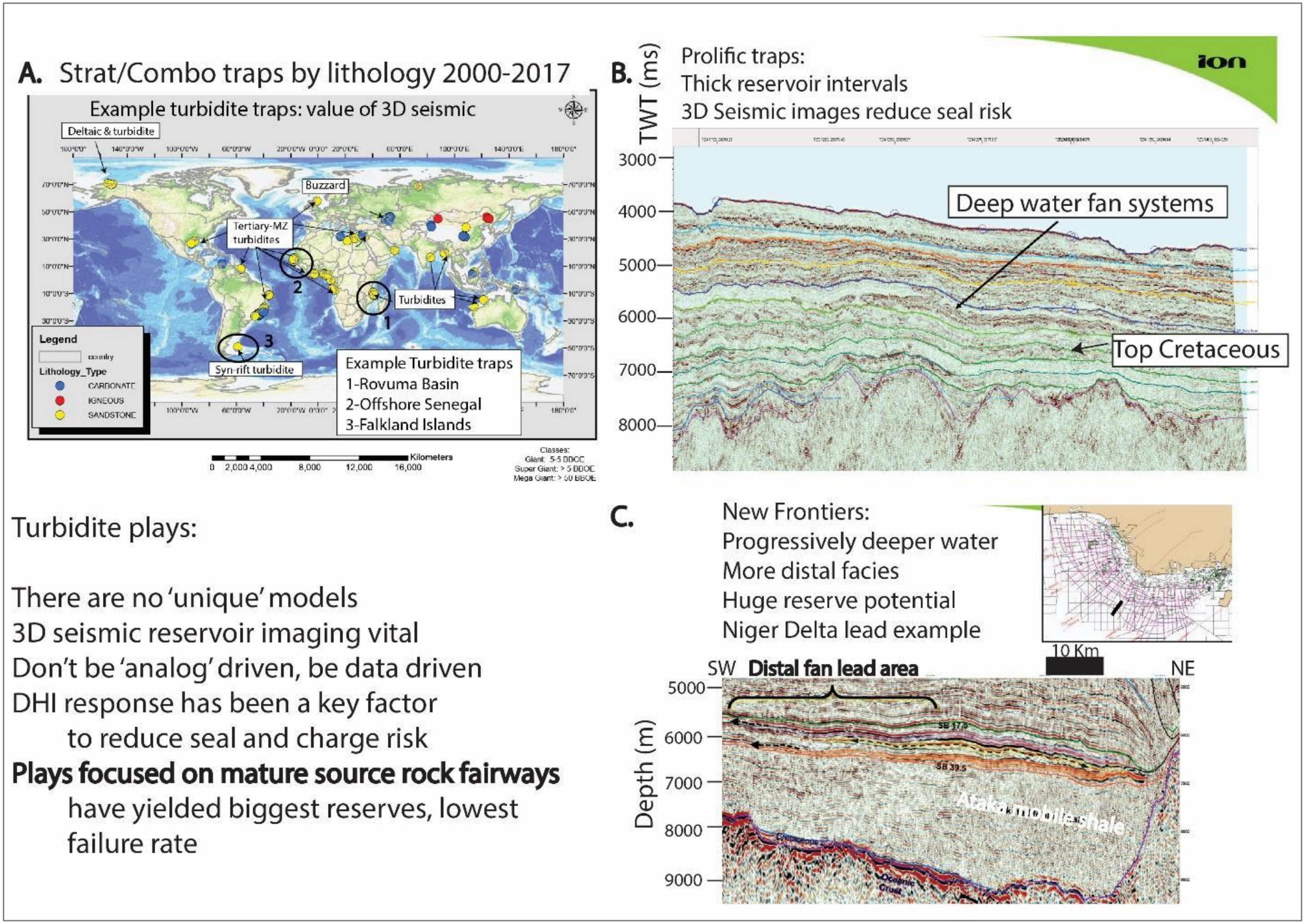


Figure 19. Deep water play fairways. Plays are being pushed seaward, sometimes beyond continental crust in ultra-deep water, in search of terminal turbidite fan facies in pure stratigraphic traps.

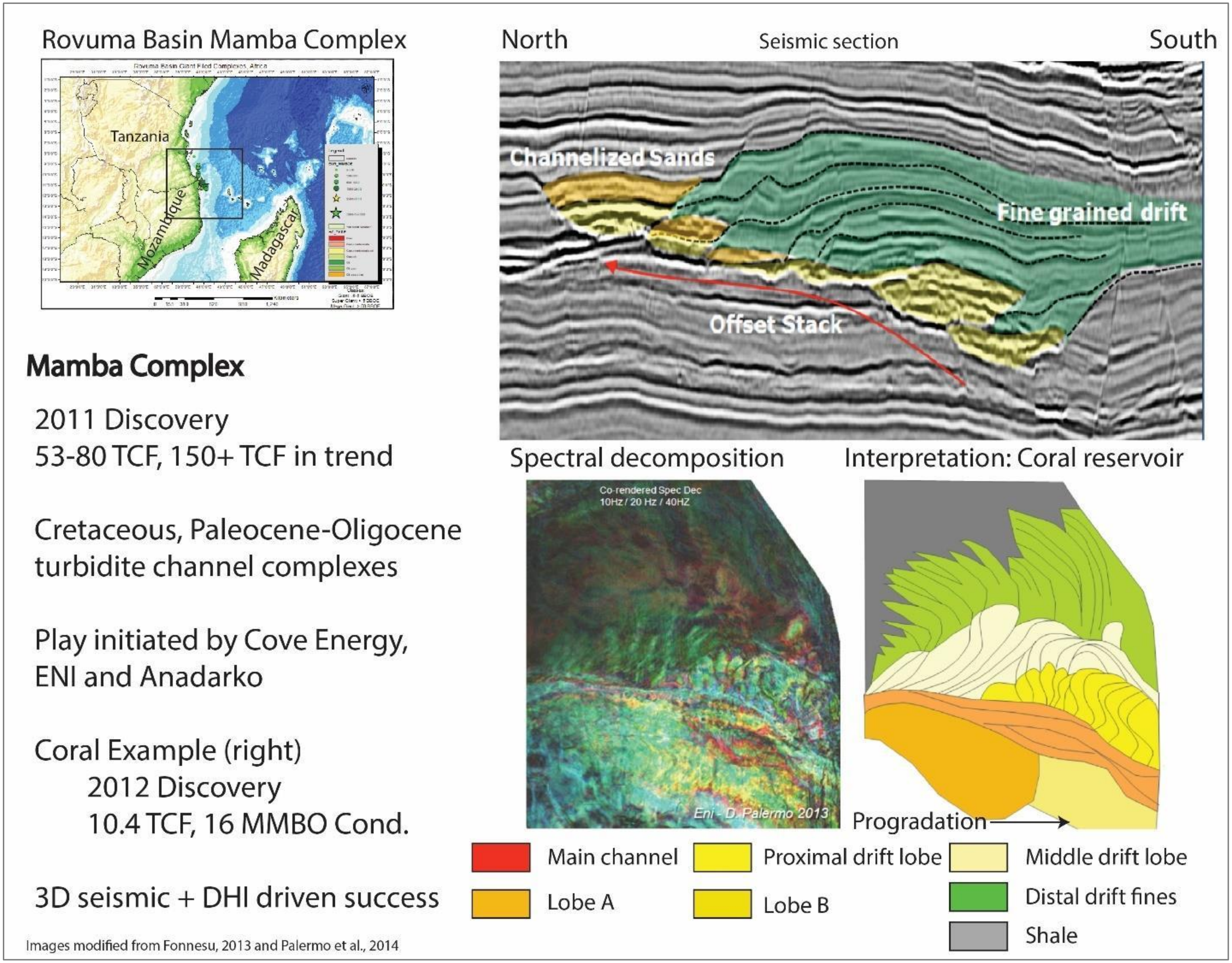


Figure 20. Rovuma Basin discovery, East Africa.

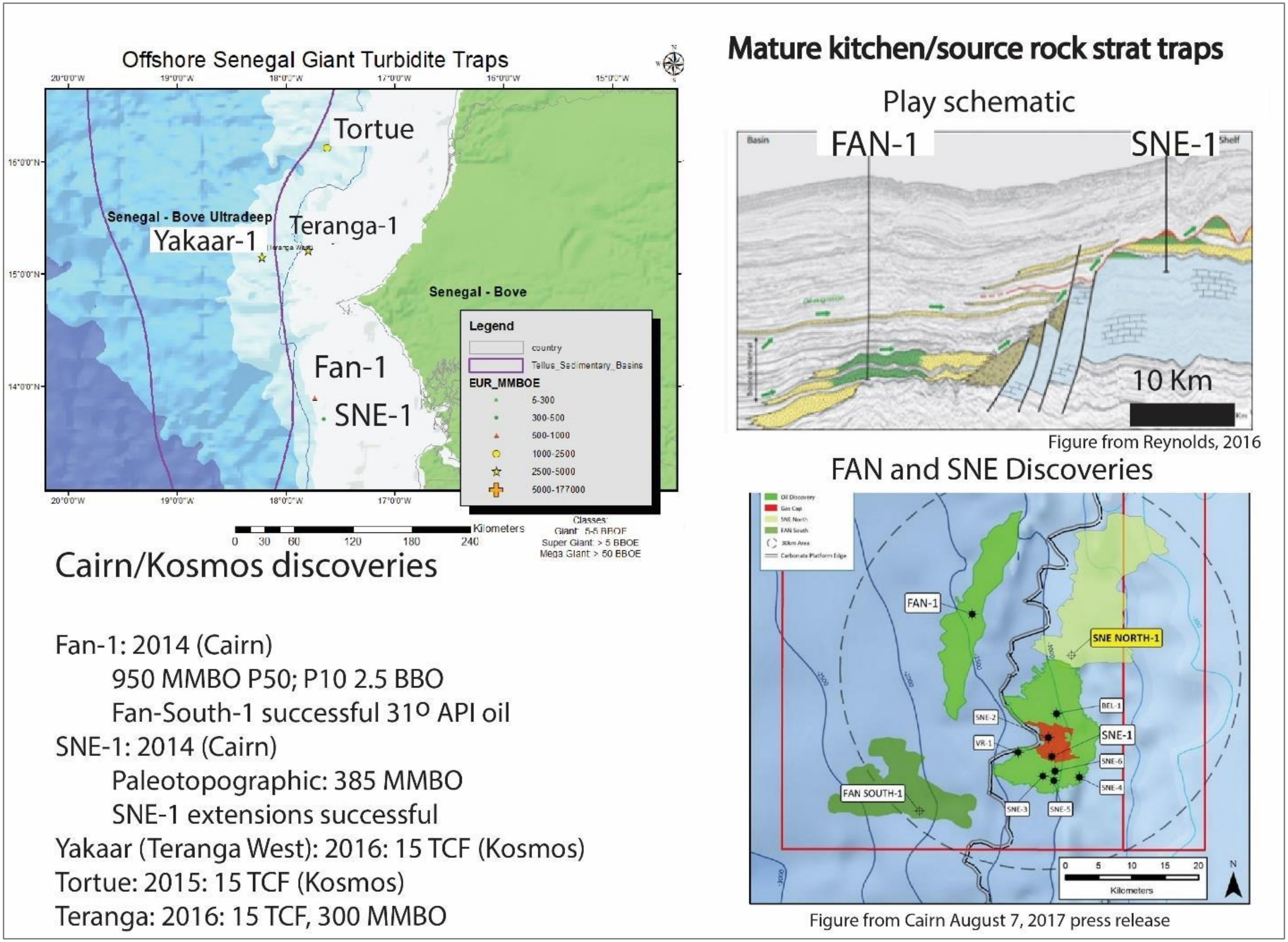


Figure 21. Cairn and Kosmos discoveries of fan, channel and other traps, offshore Senegal.

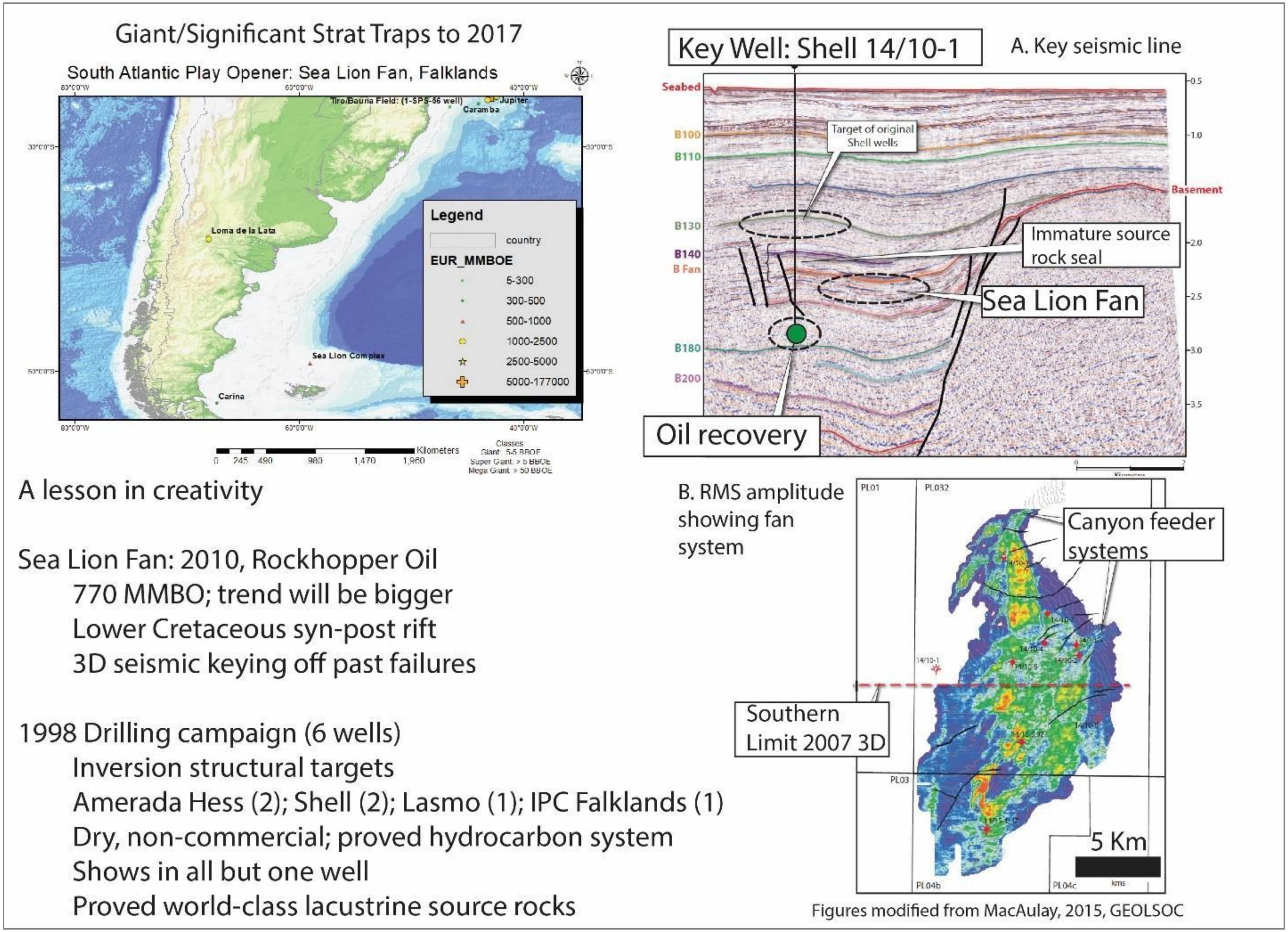


Figure 22. Sea Lion fan discovery, Falklands.

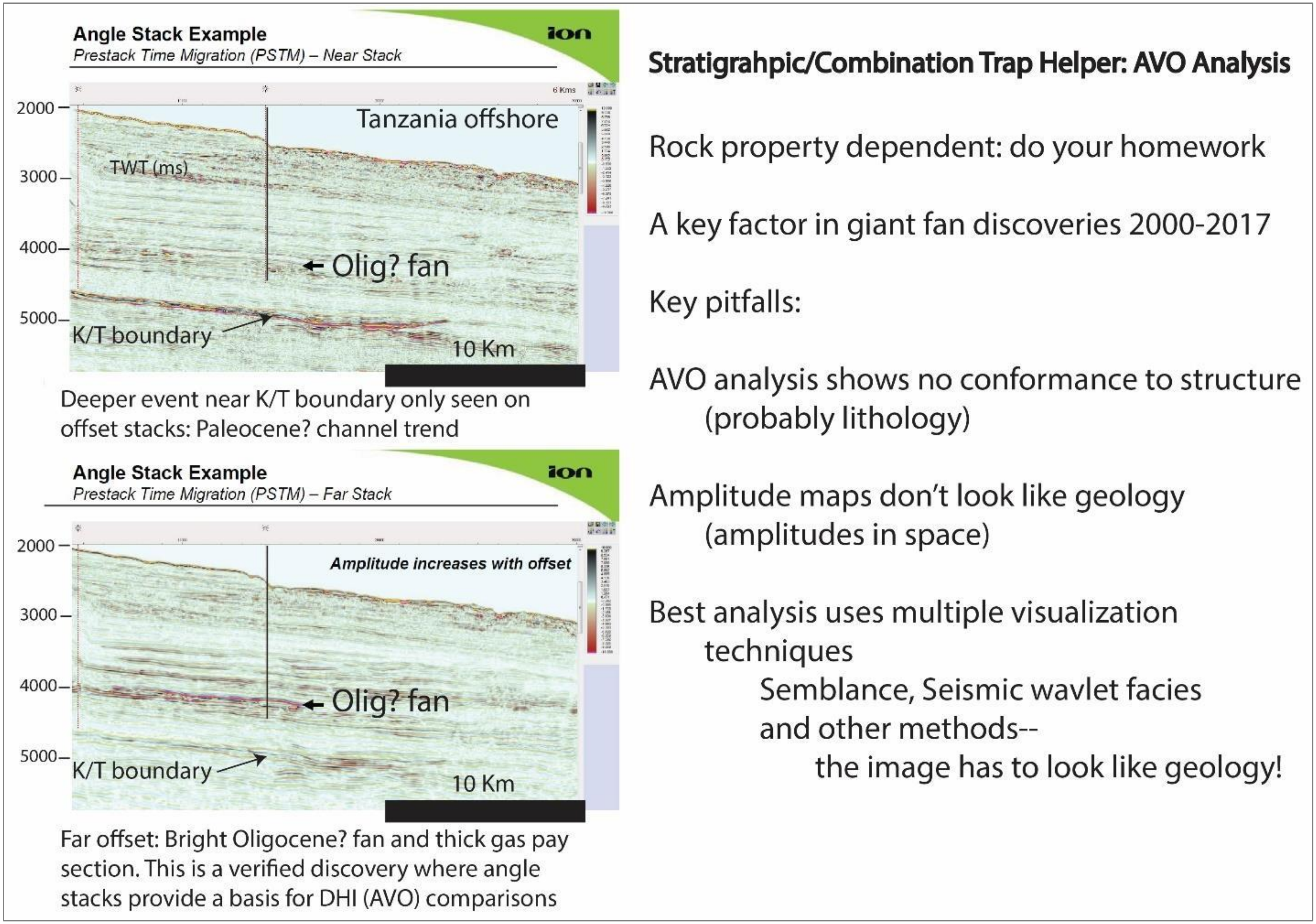


Figure 23. AVO analysis is not enough by itself to de-risk DHI-driven prospects.

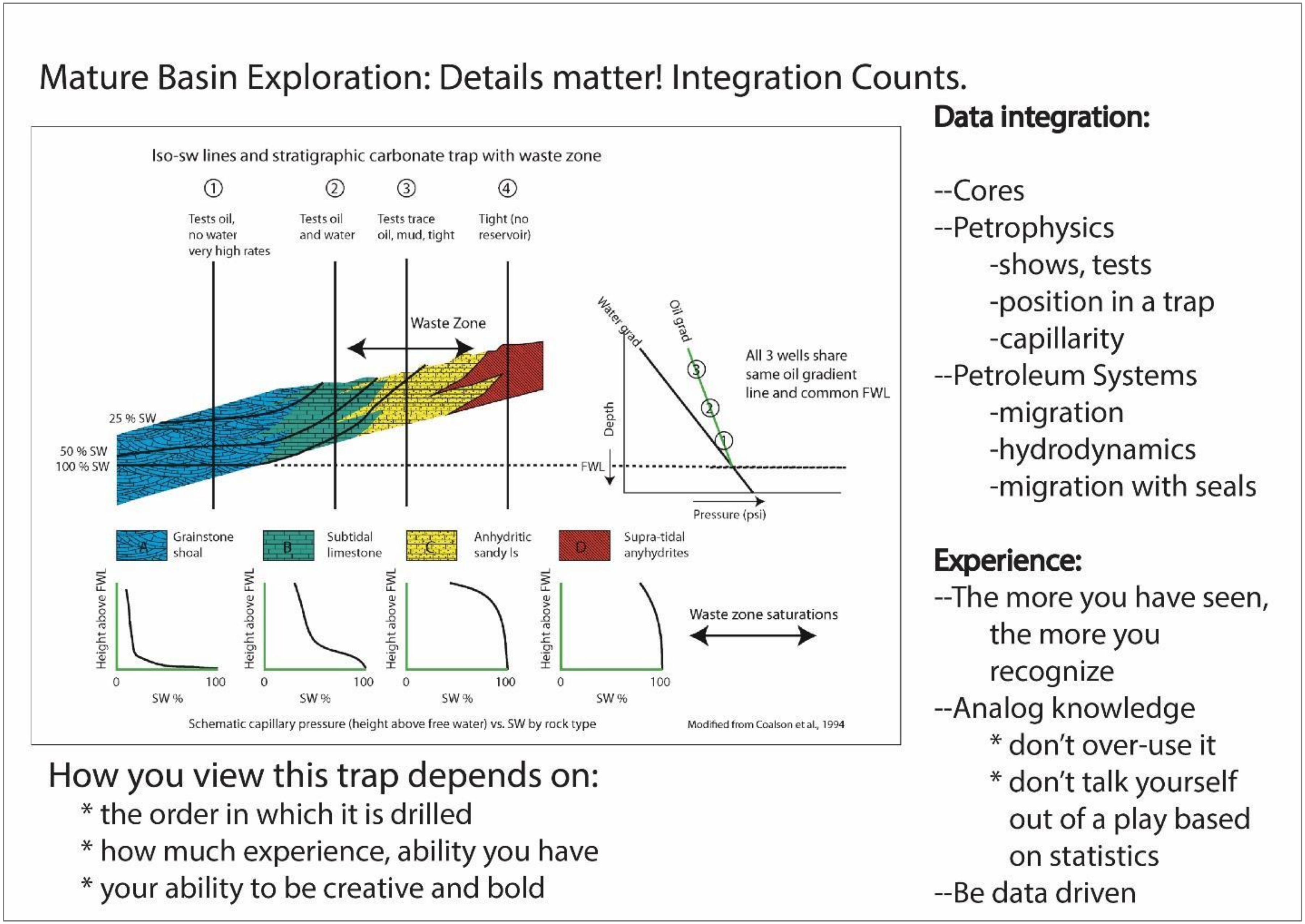
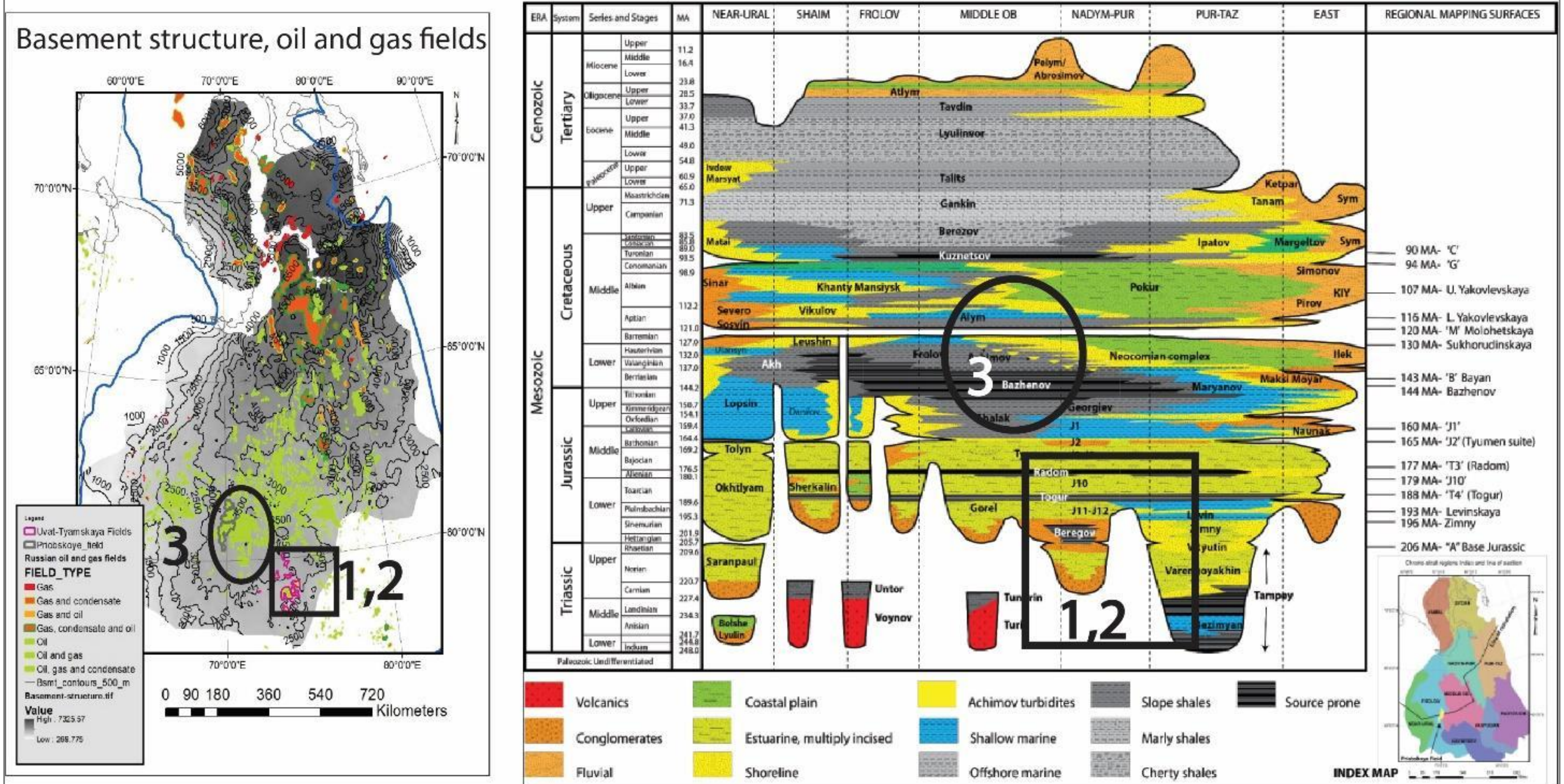


Figure 24. Waste zones, SW variations by rock type can mask a big stratigraphic trap. See text for discussion. The more you've seen, the more tools you have, the more you'll recognize potential. From Dolson (2016).

Location of 3 analog giant stratigraphic traps in the West Siberian Basin, Russia



Cases 1 and 2: Uvat/Tyamskaya Fields:

Onlap, incised valleys, pore-throat

Case 3: Priobskoye Field

Deltaic and turidite traps ('clinoform play')

Figure 25. Location of analog field cases, mature basin exploration, Russia.

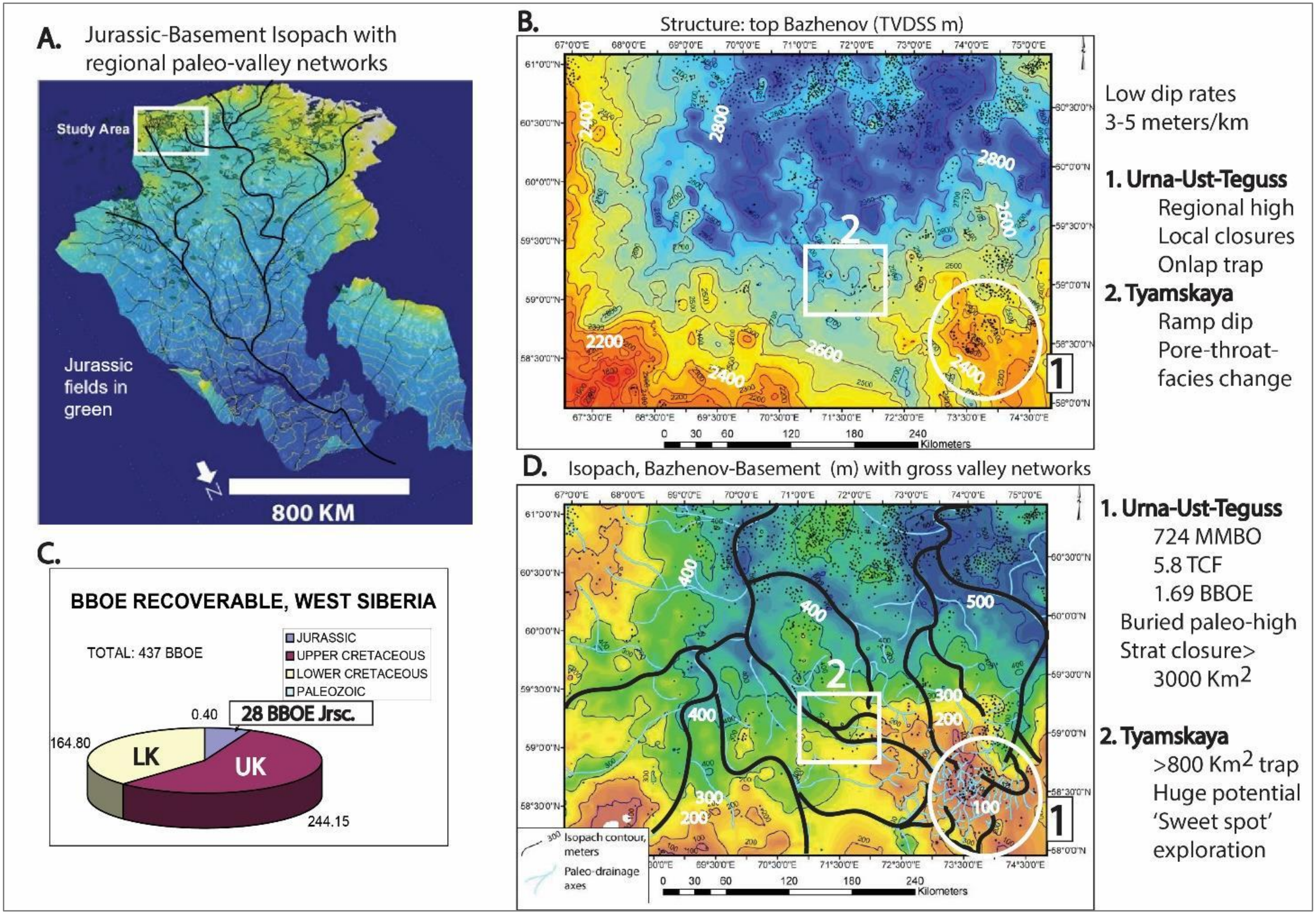


Figure 26. Overview of Jurassic paleo-valley networks and structural, stratigraphic setting of the Urna-Ust-Tegus and Tyamskaya Field areas.

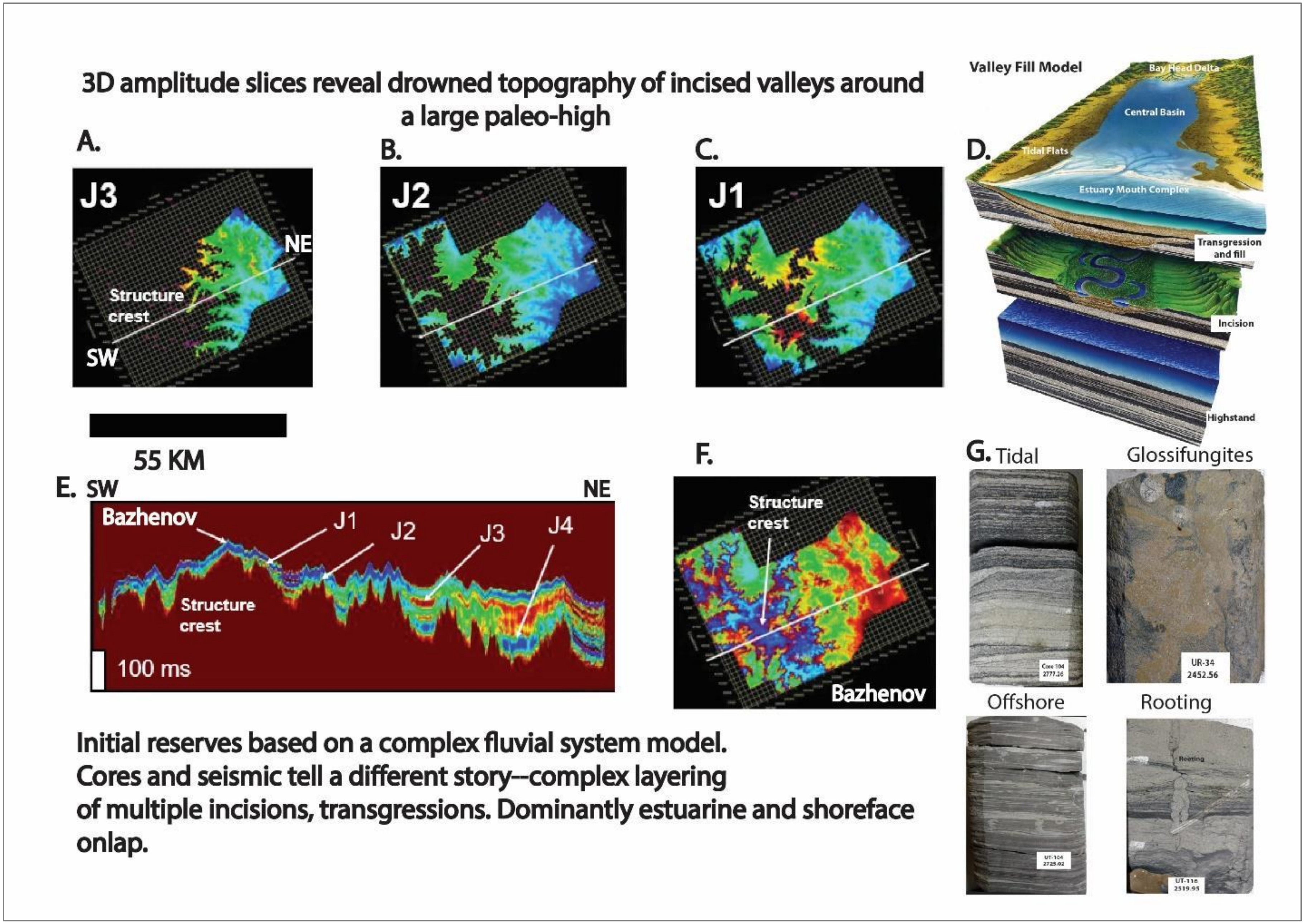


Figure 27. Time slices from 3D seismic showing the dendritic pattern of progressive drowning of the Uvat paleo-high, core data and an incised valley-fill model which eventually replaced fluvial systems models of deposition.

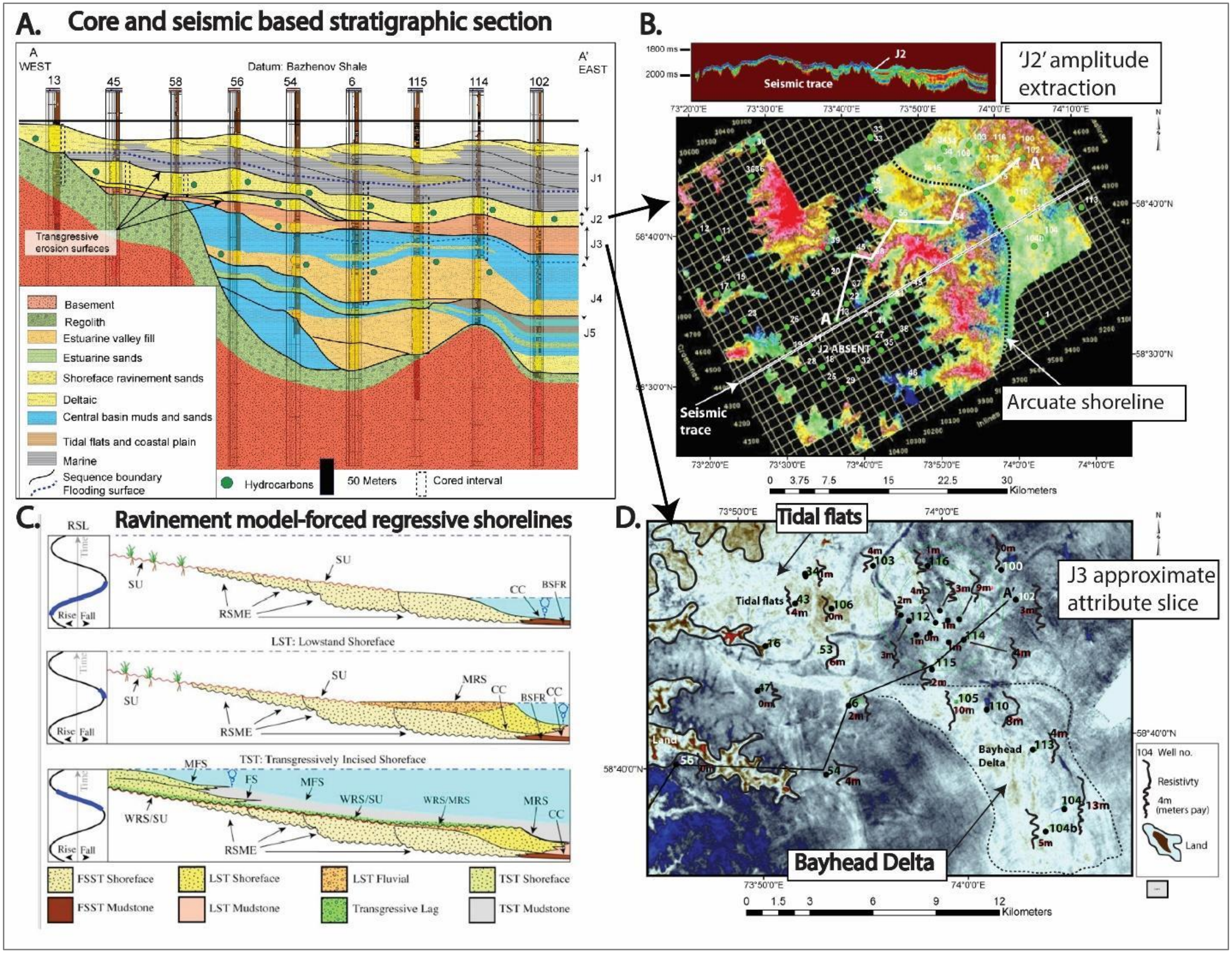


Figure 28. Seismic imaging and correlations from wells and core, giant Uvat-Ust-Teguss Field, Russia. See Figure 4 for location in the West Siberian Basin (incised valley fill and onlap example noted).

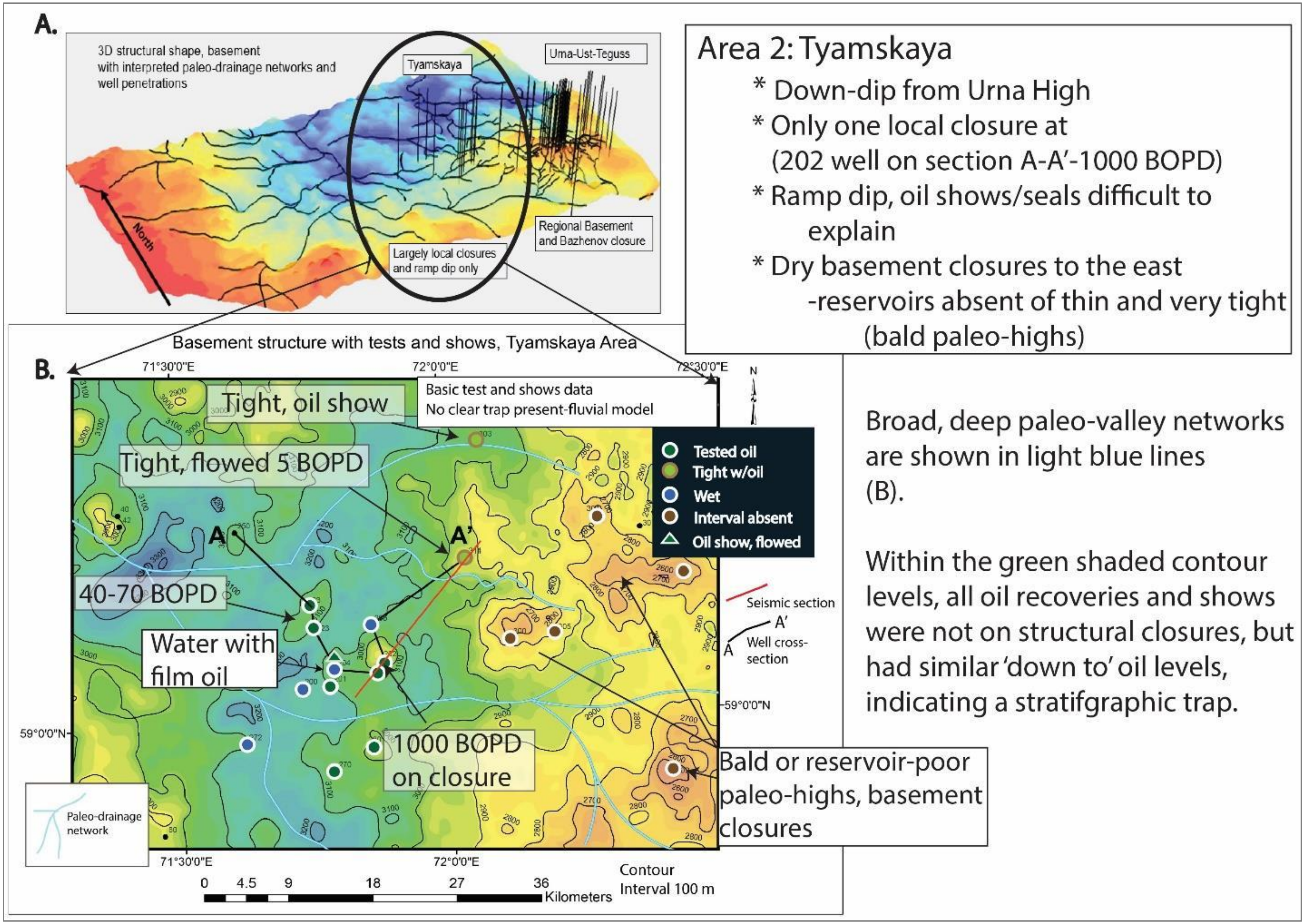


Figure 29. Overview of Tyamskaya area dhows and paleo-geography.

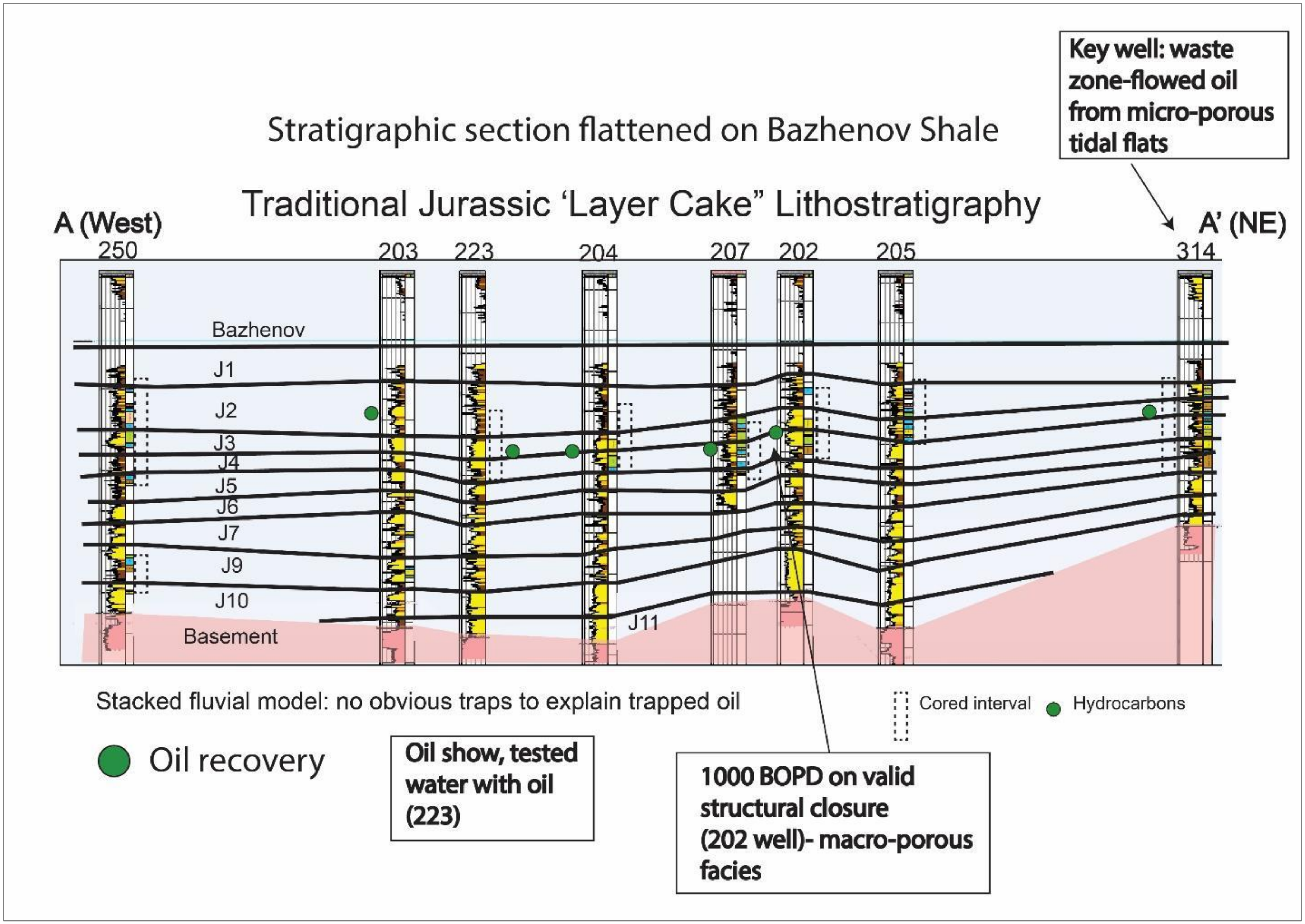


Figure 30. Lithostratigraphic correlations fail to reveal causes of reservoir differences or location of moveable oil. Key wells are noted.

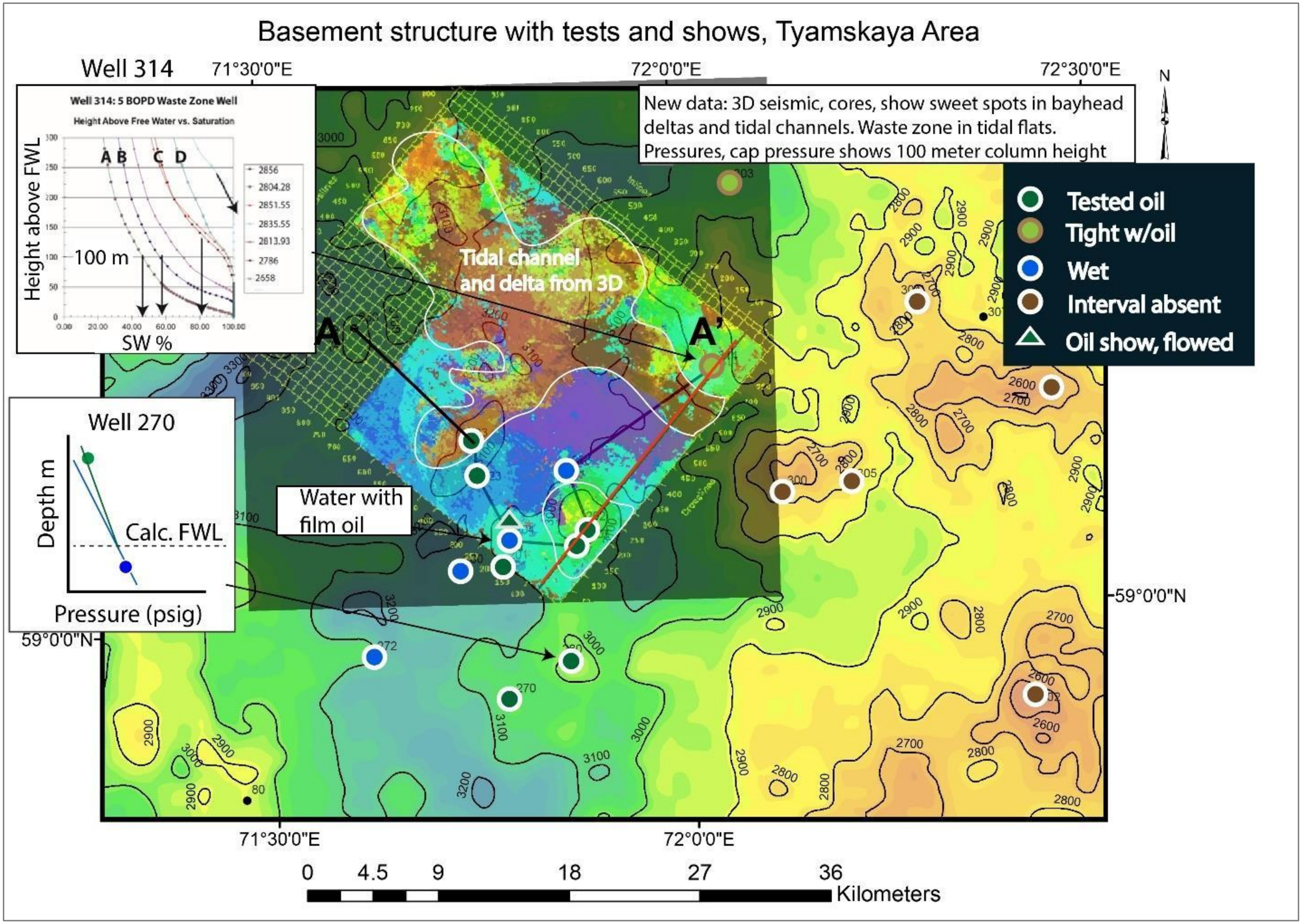


Figure 31. New seismic data enhanced learnings about column height and free water levels from pressure and SW/Height functions.

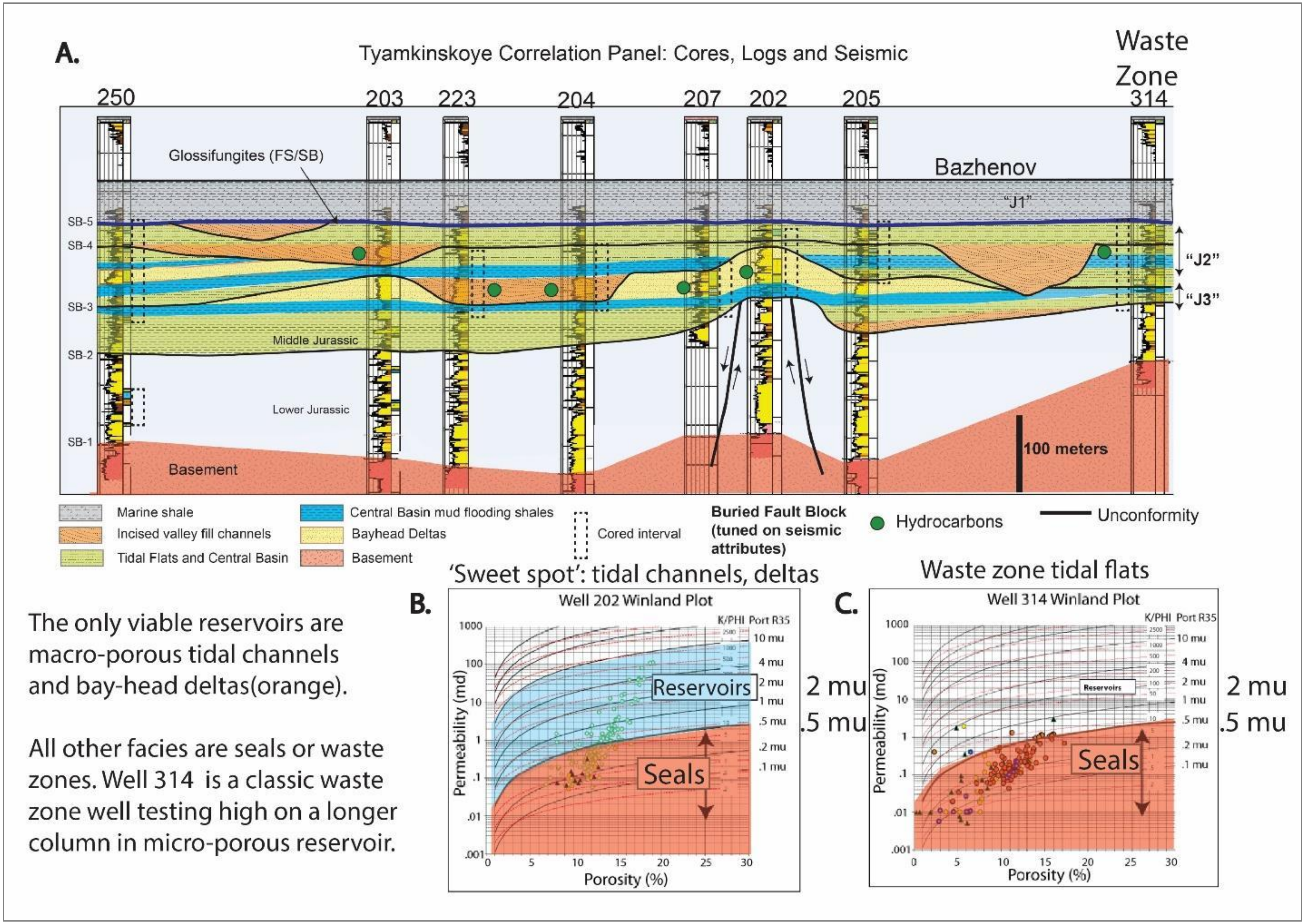


Figure 32. Final correlations and reservoir quality.

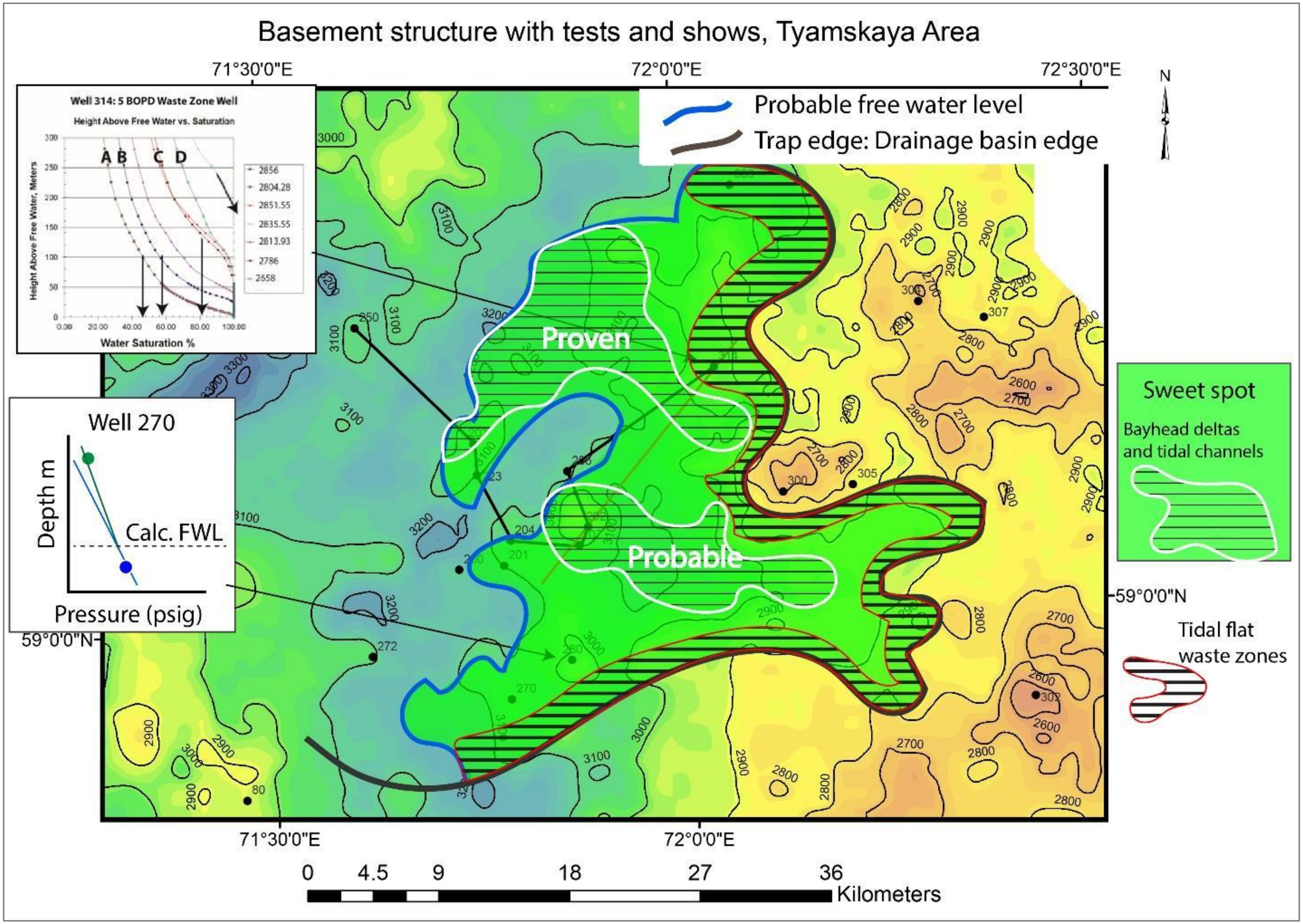


Figure 33. Final trap. Wells above the blue line tested oil, below it, water. Up dip seal facies are proven by dry paleo-structures. The southern seal is speculative, but required to explain the oil accumulations in the 270 and other southern wells.

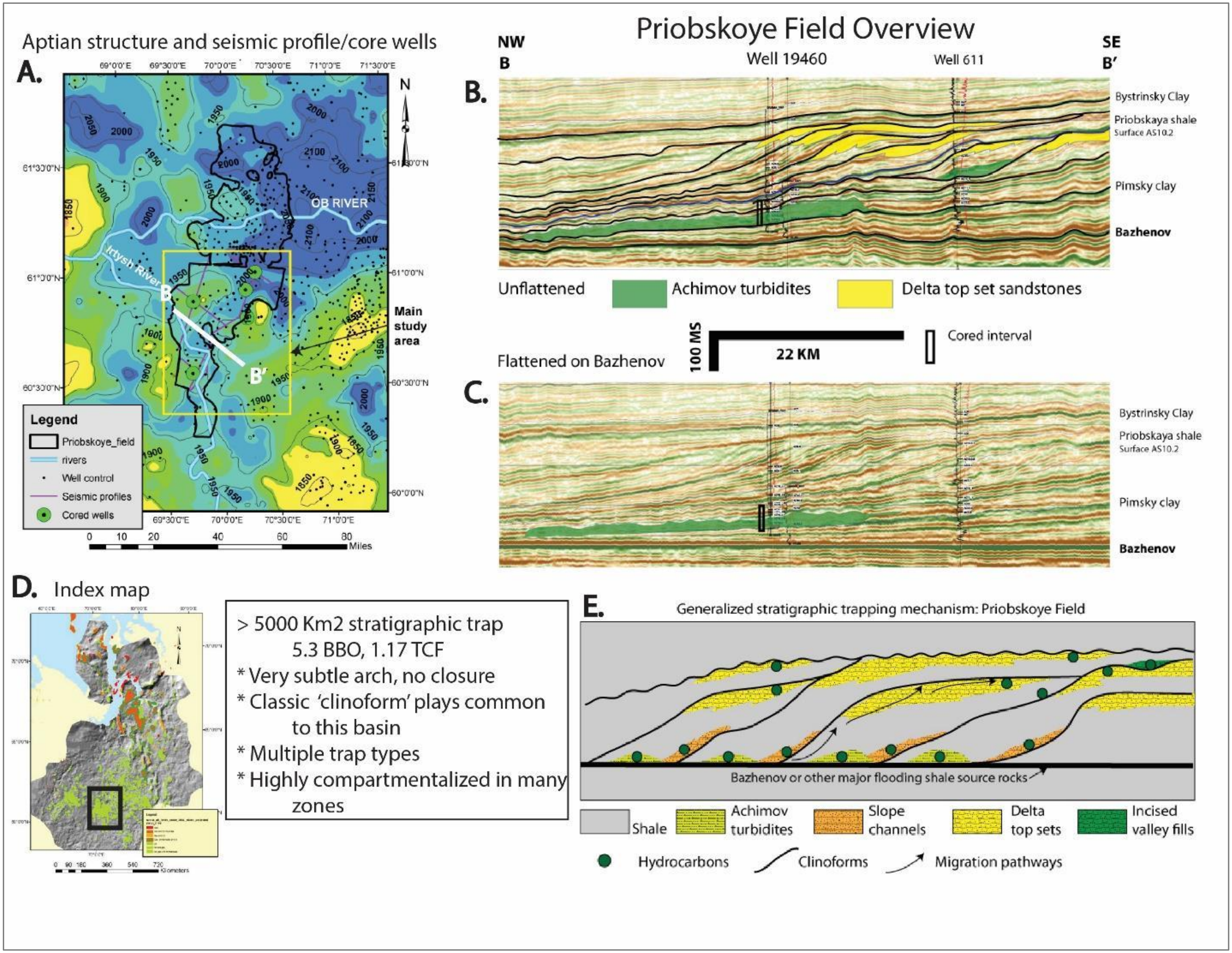


Figure 34. Priobskoye Field overview.

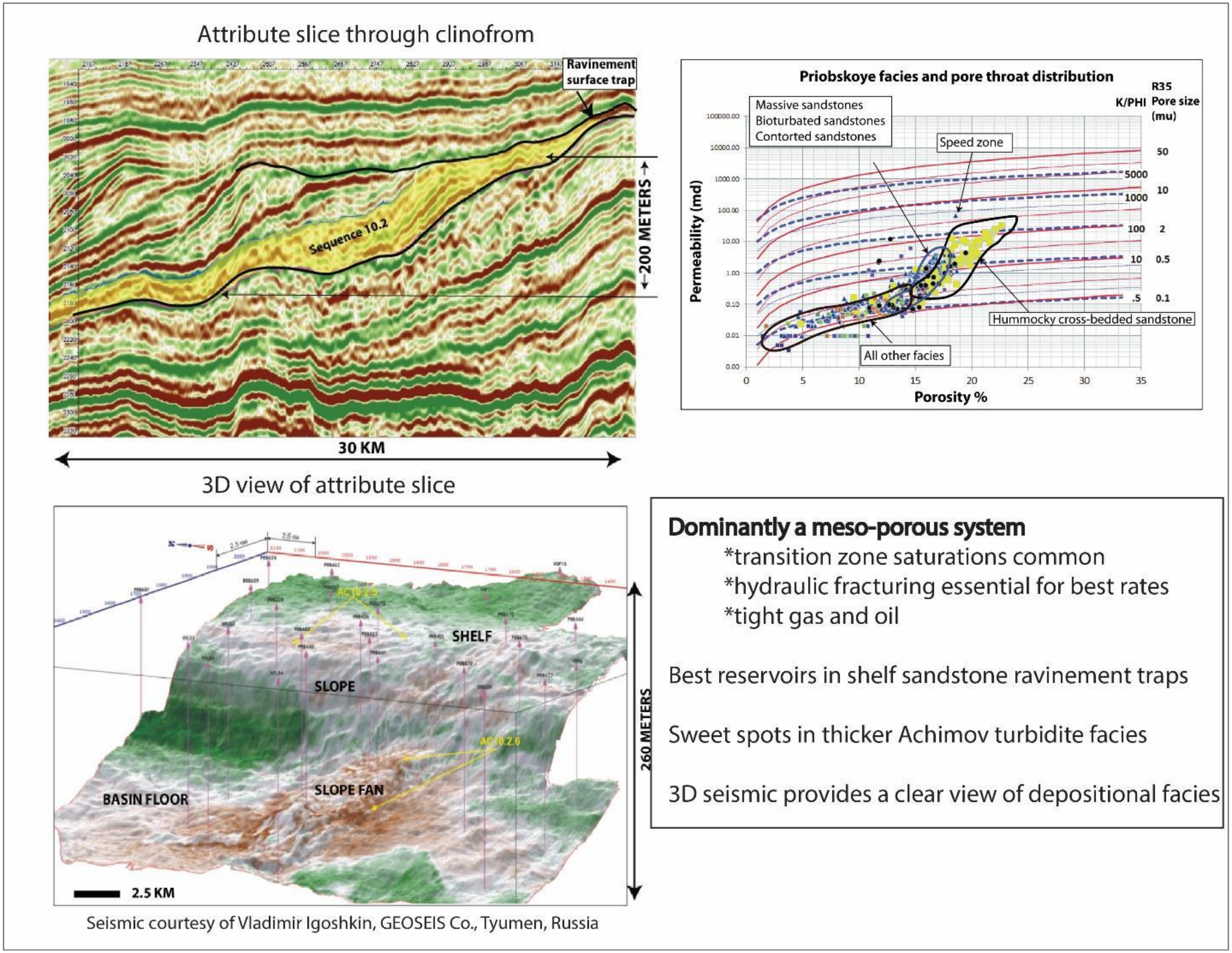


Figure 35. Seismic facies and reservoir properties of one of the clinoform traps at the Priobskoye Field.

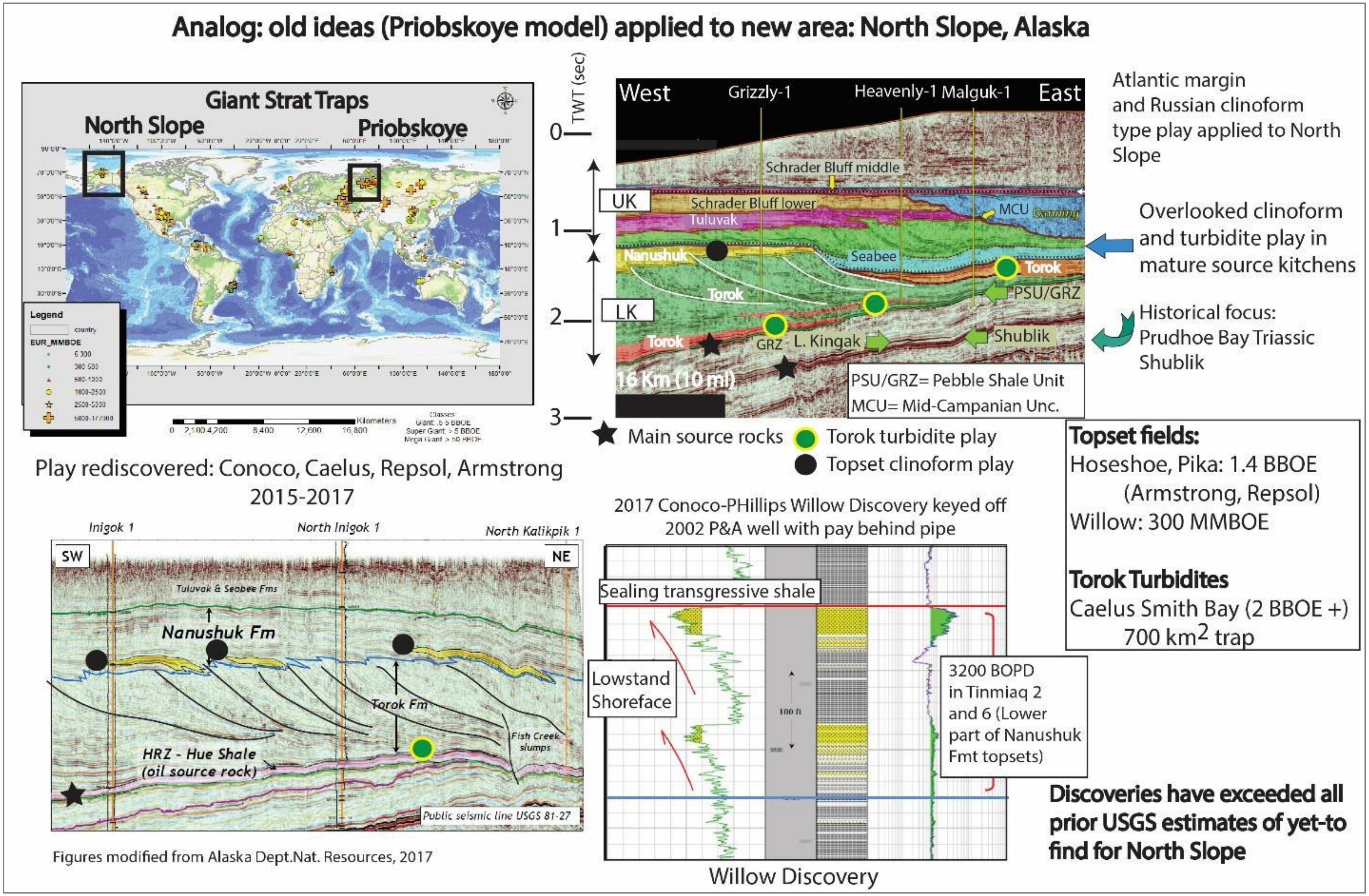


Figure 36. North slope deltaic and turbidite fan play--a Priobskoye look-a-like.

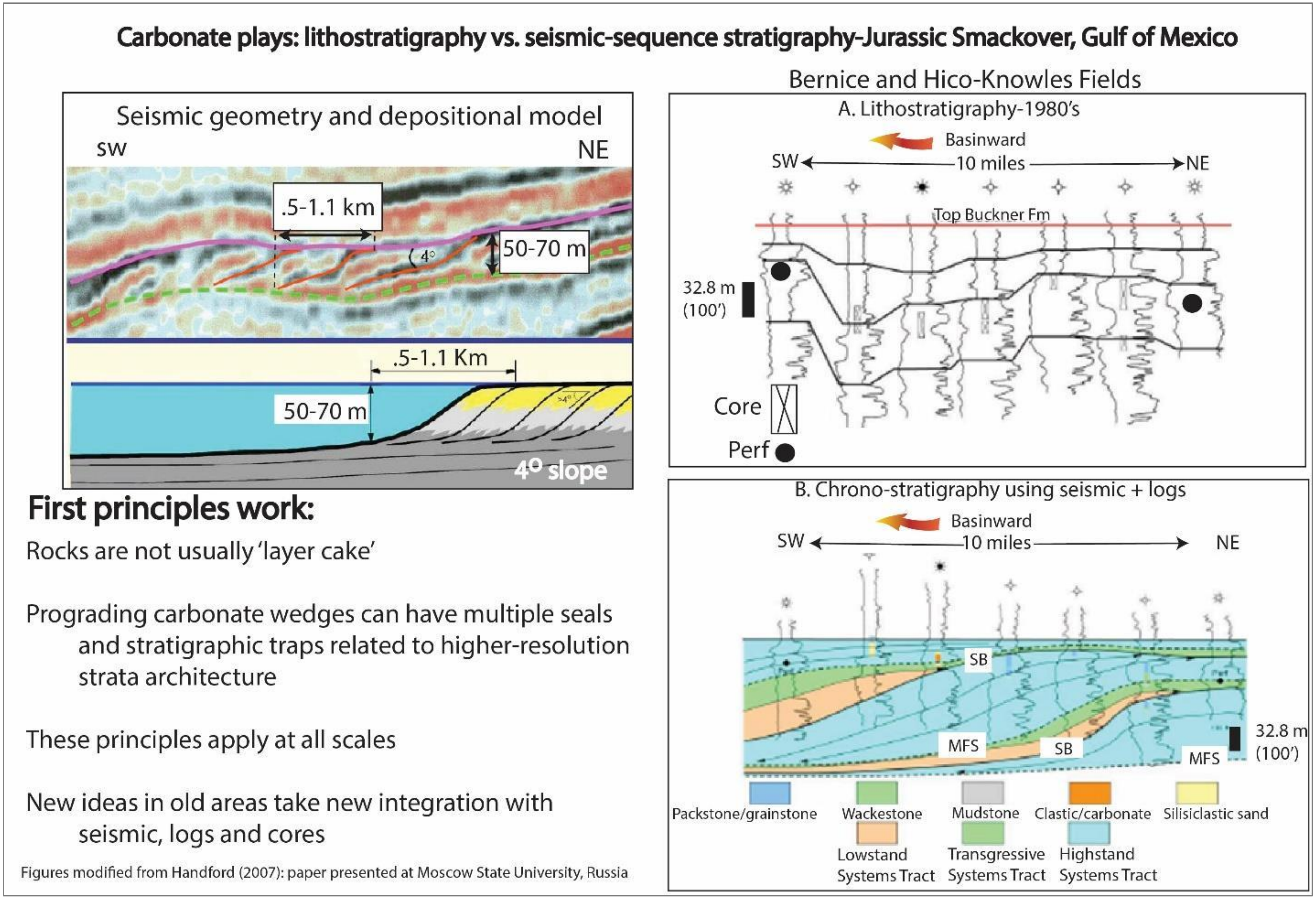


Figure 37. Carbonate plays. The same principles apply to carbonate shelf margins as those shown in the Priobskoye and North Slope progradational packages. Modified from Handford (2007).

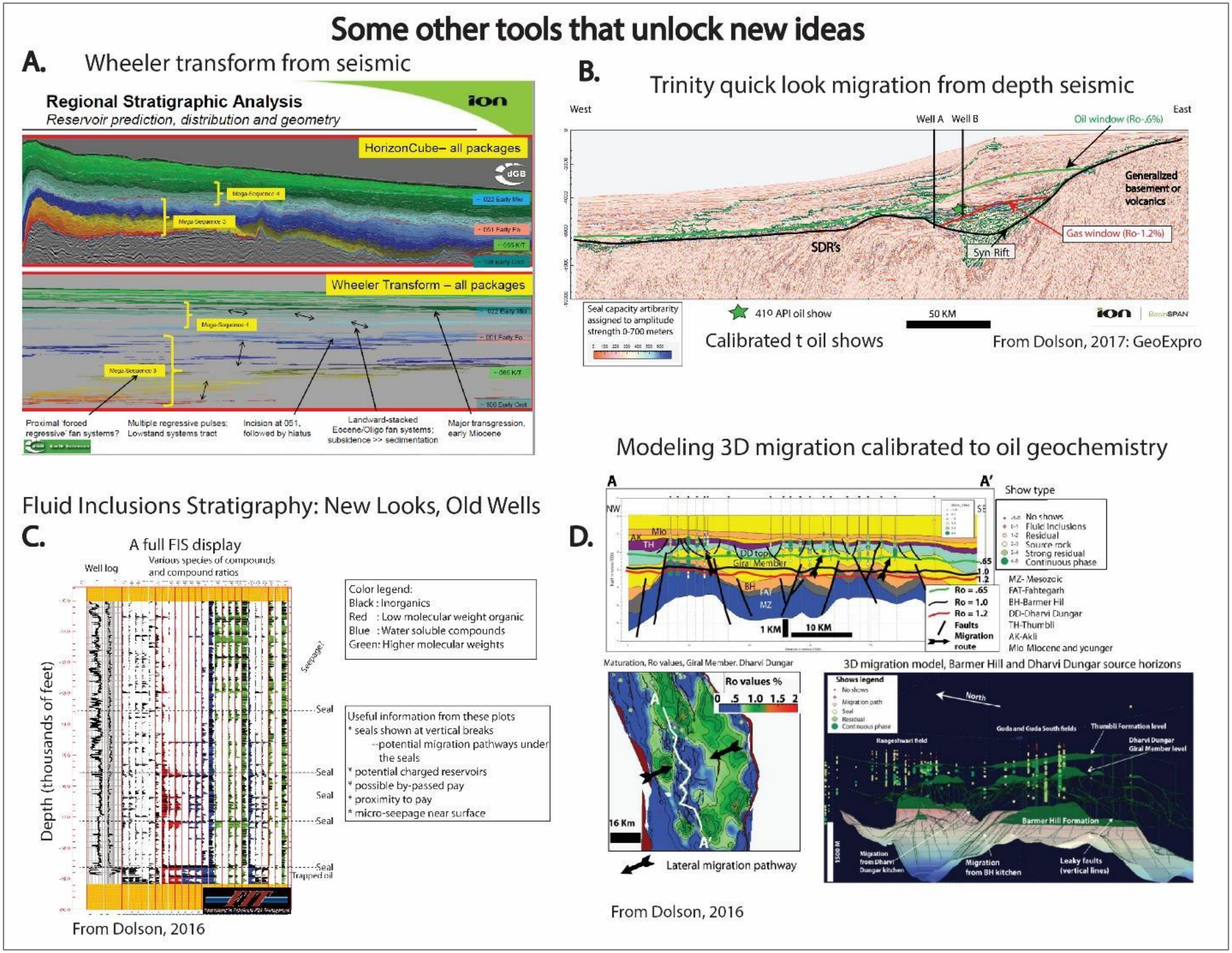


Figure 38. Other tools to generate new ideas.

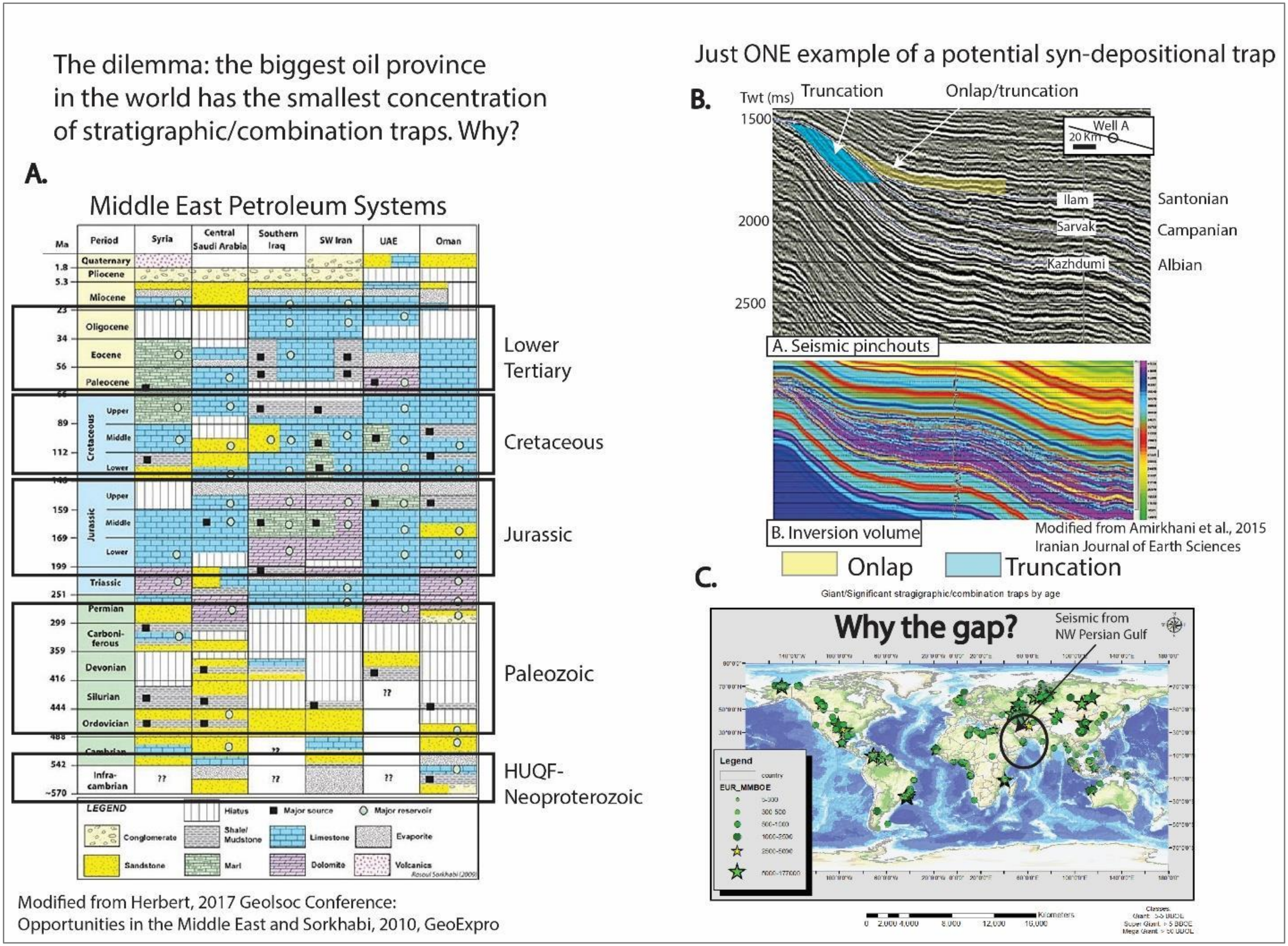


Figure 39. The middle east problem. Why are there so few giant stratigraphic traps with so many giant fields and prolific petroleum systems at multiple levels? Stratigraphic column modified from (Herbert, 2017; Sorkhabi, 2010). Seismic section modified from (Amirkhani et al., 2015).