

**EA Ultra-Deep Sub-Salt Hydrocarbon Exploration Targets: Dead Sea Rift Zone –  
Implications from Ultra-Deep U.S. Gulf of Mexico,  
Anadarko, Permian, and Tarim (China) Basins Successes\***

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### **Abstract**

Ultra-deep exploration targets in the Dead Sea Rift (DSR) are underexplored, but share similarities in stratigraphic, structural, and salt tectonic history with established productive ultra-deep areas of North America and China. U.S. is among the world leaders in petroleum daily production going from 4.5 mbopd to nearly 12 mbopd over the past decade. A major increase of daily U.S. petroleum production is attributed to unconventional and conventional petroleum technological advances.

### **U.S.A.**

The offshore Gulf of Mexico is contributing significantly to the production numbers. Recently ultra-deep drilling has added significant gas reserves for Shell, Chevron and Total in the deep water of the Gulf of Mexico. Shell has announced 6 new discoveries in a Jurassic age aeolian dune sand long thought to be only present onshore. In the 1970's ultra-deep gas (19,000 ft, 5790 m) was produced onshore from the Norphlet Formation in Mobile Bay Alabama (7.7 Tcfg). The hydrocarbon sourcing is believed to be the Upper Jurassic Smackover Formation, an organic rich carbonate which also serves as a reservoir, an oolitic

carbonate in the onshore which overlies the Norphlet Formation and Luann Salt. Offshore deep-water wells have penetrated up to 1400 feet of net pay sands ([Figure 1](#) and [Figure 2](#)). Wells were drilled to 29,000 ft (8840 m). Seismic profiles demonstrate anticlinal folds associated with the Louann Salt mobilization ([Figure 3](#)).

Norphlet Formation reservoir studies in the Gulf of Mexico suggest facies selective, the rocks with the best reservoir properties being grainstones. Sandstones demonstrate early diagenetic calcium carbonate precipitation and cementation supporting the sandstone infrastructure during compaction. The calcite was later dissolved with the simultaneous dissolution and migration of hydrocarbons. In most major reservoirs chlorite coating inhibited silica cementation and authigenic quartz growth ([Figure 4](#) and [Figure 5](#)). These are the high-performance reservoirs. Changes in pH aqueous concentrations created the diagenetic conditions derived from salt-related brines. With continued burial, thermochemical sulfate reduction leads to destructive oxidation of the hydrocarbons to yield carbon dioxide, hydrogen sulfate and continued dissolution of calcium carbonate ([Figure 6](#)), corresponding to a vitrinite reflectance of 1 to 1.3 Ro.

Ultra-deep drilling sub-salt onshore U.S. Gulf of Mexico (25,000 ft - 35,000 ft) has discovered the occurrence of viable petroleum reservoirs at depth with significant methane gas from Cretaceous (Tuscaloosa) and Paleogene age rocks ([Figure 7](#)). The large ultra-deep structures were interpreted on regional 2-D seismic data, on pre-stack (PSTM), 3-D seismic, and on proprietary reprocessed pre-stack depth-migrated (PSDM) 3-D seismic. Evacuation and allochthonous flow of the Louann Salt due to sedimentary loading has a dramatic influence on the petroleum geology. The primary reservoir objectives were the deep-water sandstones from the ancient Mississippi River system ([Figure 8](#)). Hydrocarbon source rocks are believed to be shales of Cretaceous to Paleogene age. E-logs indicate the Tuscaloosa sandstones lack feldspars and are clean, containing primary porosity ([Figure 9](#)). Diagenetic factors, including dissolution of feldspars, are essential in the Wilcox and has demonstrated good pay sand thicknesses (200 ft). The Blackbeard ultra-deep was drilled to 33,000 ft (10,000 m) and publicly announced the occurrence of hydrocarbon bearing Oligocene sandstones preserving the reservoir during burial. McMoran Oil & Gas LLC drilled the Highlander prospect inland of the Louisiana Gulf Coast (29,500 ft TD, 9000 m). The main ultra-deep objectives were sub-salt and was noted during drilling announcements. The well encountered 150 feet of net pay, with sandstone porosities of 24 percent and, attained a 75 mmcf/d on a 42/64<sup>th</sup> inch choke, with 10,300 PSI flowing tubing pressure. The well has produced over 50 BCF of gas since January 2015, and it can be noted that the perforated interval is more than 5000 feet (1525 m) deeper than any other producing well in Louisiana. Ultra-deep Gulf of Mexico risked potential may approximate 30 Tcfg.

Historically, studies done by the U.S. Department of Interior, USGS. and Oklahoma State University reported that up until 2002 ultra-deep drilling in the United States of 1676 wells exceeding 20,000 ft (6100 m), 974 (58%) are producing, of which 847 are

gas wells. The production rates of the Oklahoma deep wells average depth 17,500 ft (5330 m), produce 11 times more output of gas than wells drilled to less than 15,000 ft (4570 m) ([Figure 10](#)). Ultra-deep drilling in the Anadarko Basin (30,000 ft, 9100 m), and the Permian Basin (23,000 ft) ([Figure 11](#)) contain dolostones with porosities of up to 10 percent and are due to mesodiagenetic dolomitization, with onset at 12,000 ft (3660 m) corresponding to a vitrinite reflectance of .55 ([Figure 12](#)). Xenotopic textures result in the carbonates at ultra-deep depths ([Figure 13](#) and [Figure 14](#)). Petrophysical studies of the Anadarko Basin's Hutton Group (Lower Paleozoic) demonstrate good reservoir properties with moderate porosities (5.2-6.9%) and moderately sized pore throats (2.6-8.8  $\mu\text{m}$ ). Higher porosity rocks containing moldic and vuggy porosity dolostones have lower mercury-recovery efficiencies (RE). Thus, mesodiagenetic dolomitization creating intercrystalline porosity is optimal for economic reservoir flow rates. The simultaneous reactions of organic and inorganic chemistry creates the ideal sequence of source and reservoir rock timing events. The Paleozoic ultra-deep reservoirs produce primarily gas.

## **China**

In China, the ultra-deep drilling (24,000 ft, 7300 m) resulted in the discovery of giant oil discoveries in the Tarim Basin ([Figure 15](#)). The basin contains four separate salt deposits (Paleozoic-Neogene) which during burial and salt mobilization has created numerous structurally related traps, subsalt, synsalt and suprasalt. The primary ultra-deep reservoir is a Paleozoic age intercrystalline dolomite with vuggy porosity (.9-9%) ([Figure 16](#)). Source rocks are lagoonal carbonates and mudstones. The Paleozoic reservoir contained oil preserved due to a regional low geothermal gradient. The basin underwent rapid subsidence of 2 km in the past 5 million years. Geologists attribute the short duration in reaching its current high temperature to lack of cracking. The departure of thermal maturation organic geochemical relationships due to extremely rapid recent burial may also occur in the DSR where extreme recent subsidence occurred. Ultra-deeply buried Cretaceous sandstones (21,000 ft, 6890 m) contain excellent porosities and are productive. Jurassic age source rocks are proposed for the sourcing in the Mesozoic clastics.

## **Eastern Europe**

Most recently, a major study evaluating the ultra-deep hydrocarbon potential of the Dnieper-Dontes Basin, a Paleozoic salt depression and major petroleum province in Eastern Europe, has concluded forecasting wet-gas accumulations between 7 and 10 km. The basin reaches depths of 20 km. Thus, other basins worldwide with mature petroleum fields are being explored.

## Israel

The drilling activity in onshore Israel is significant with over 500 wells drilled. Petroleum geologic studies have been numerous on the organic geochemistry of the hydrocarbons discovered. Unlike the highly productive Mesozoic rocks of the Tethys Sea to the east, insignificant quantities of petroleum has been discovered. We recommend reading Kashai (1988) A Review of the Relations between the Tectonics, Sedimentation and Petroleum Occurrences of the Dead Sea-Jordan Rift Zones, Gadosh and Tannenbaum (2014), and Coleman and Brink (2016). There are numerous other published articles in AAPG, Tectonophysics, and the JGR concerning the DSR.

The primary sourcing from the DSR hydrocarbon is believed to be the rocks of Campanian-Maastrichtian Menuha and Ghareb formations, identified as a regionally important source rock from Egypt's Western Desert to Southeast Turkey ([Figure 17](#)). The geothermal gradient of the DSR is low (1.14° F/100 ft). Higher geothermal gradients (2.0° F/100 ft) exist locally drilled into the salt. The Dead Sea demonstrates extreme subsidence rates (8724 ft/my, 2506 m/my) during the last 1.5 million years, with hydrocarbon generation modeling of the Sedom Deep 1 well suggesting onset at 12,000 feet ([Figure 18](#) and [Figure 19](#)). When comparisons are made to basins in North America, Mexico, Cuba, and Bahamas (656-1640 ft/my, 200-500 m). The Dead Sea is over 5 times greater in respect to subsidence rates. Hydrocarbon generation modelled in those basins occurred during the Mesozoic. The South Caspian Basin demonstrates petroleum systems with drastic subsidence of 10 km in the past 6 million from the Pliocene and contains a low geothermal gradient (1.20° F/100 ft) ([Figure 20](#)). Hydrocarbon basin modeling suggests onset at 33,000 ft (10,060 m) ([Figure 21](#)). The hydrocarbon maturation may not be in true equilibrium due to the rapid burial in a cold basin and the calculated hydrocarbon burial depths may be deeper than thought. Other factors affecting the thermal maturation modelling are mineral catagenesis and thermochemical sulfate reactions.

Two areas where hydrocarbon exploration successes have as yet been elusive are the U.S. offshore east coast, the Baltimore Canyon, and the Bahamas. Those deep basins have low geothermal gradients and potentially mature source rocks were never encountered. We have recommended ultra-deep drilling strategies in those basins in search of efficient seals and diagenetic traps.

Other comparisons have been made of the DSR to the pull-apart basins of the U.S. west coast. Along the coast of California, the Neogene basins produce significant oil (billions of bbl). The basins differ in the fact that the average geothermal gradient is up to three times greater (3.0° F/100 ft). The extremely rich deep water source rocks, the Monterey Formation is a complex

chemical mix and is a highly productive source and reservoir rock. At depth the Monterey is productive and is 1100 ft thick, resulting in economic reserves.

To the southwest of the DSR, in the Negev, regional studies correlating 18 wells encountered thick Triassic and Jurassic sandstones and carbonates, which are intercalated with marine and non-marine shales. When the Triassic age well studies of the Negev are correlated to the north thru Syria it appears a thick section should be present in the DSR ([Figure 22](#)). In the DSR, as in the Anadarko Basin, highly porous dolostones at ultra-deep depths may exist attributed to shale fluid compaction. Additionally, exposed Upper Cretaceous pinnacle reefs near the western margin of the DSR demonstrate dolomitization, a result of phreatic diagenesis.

In USGS estimates, the DSR contains, based on geophysical data, 6 km of basin fill with 4 km of pre-basin sedimentary rocks below it. The thickness estimate assumes that the basin is filled only with low density sediments (2.15 gm/cc) resting on carbonates, density 2.55 gm/cc. Note that in the low-density sediments, 2.15 gm/cc is also the density of salt making it impossible to separate the two units using only gravity data. The 10 km thickness of the DSR is contentious. If some units within the basin are found to a higher density, the 10 km thickness value would be substantially underestimated. Detection of large structural traps deep in the basin and below salt on seismic requires accurate time-depth models built on a regional to sub-regional scale with accurate well ties and rock data.

Structural deformation creating petroleum traps are absent at the Mesozoic levels of the DSR. The Syrian Arc structural trends running sub-parallel to Israel ceases in maps of the DSR ([Figure 23](#)). Clay structural models of pull-apart basins of California, an area compared frequently to the DSR, demonstrate en echelon fold and fault patterns between the master faults ([Figure 24](#)). Onshore and offshore geophysical detailed mapping confirms the modeling in California. Thus, in the DSR, we propose fault and folds created during Neogene deformation and during the Cretaceous exist but due to the ultra-deep depths below sub-basin fill have not been mapped using seismic data. The timing of trap formation would precede hydrocarbon generation in the last million years to present.

Exploration in the DSR (15 wells) targeted Mesozoic and younger clastics and carbonates in six structural traps ([Figure 25](#) and [Figure 26](#)). The deepest well drilled in the DSR is the Sedom-1 to a depth of 21,156 ft (6450 m) near the master-faults of the western southern DSR. Seismic profiles suggest the well drilled sub-salt bottomed in Miocene age rocks, basin fill ([Figure 27](#)). Workers have estimated 900 m of salt lining the DSR basin's center in the Sedom Formation. Carbonates and siliclastic comprise the pre-basin Paleozoic and Mesozoic rocks, products deposited from the Tethyan Shelf. Hydrocarbon producing

intervals are the Triassic Raaf Limestone and Gevanin Sandstone, the Jurassic Inmar Sandstone, Zohar, and Sherif Limestone and the Lower Cretaceous Judea Limestone. The Sedom Deep 1 well, drilled in 1992, targeted the Miocene Hazeva Formation, an eolian, fluvial, and lacustrine sandstone, at shallow depths is poorly consolidated and has high porosity (20-30%). In the Sedom Deep 1 well porosity of the Hazeva sandstone at depths of 15,000 ft-18,000 ft. (4770-5490 m), were significantly reduced due to cementation as described by Gardosh. The Hazeva sandstone could be the chronostratigraphic equivalent of the Oligocene-Miocene age Tamar sandstone, the highly productive reservoir offshore Levant ([Figure 28](#)). The offshore sandstone is 450 ft (137 m), and contains 25% porosity. The pre-basin fill deposits were never penetrated in the DSR basin center. There exists significant untested potential below the total depth of the Sedom-1 well. Two wells encountered Mesozoic rocks, Aminiz-1 TD (15,104 ft, 4603 m) and En Gedi-1 TD (9072 ft, 2765 m). Light oil was encountered in two Triassic age dolomites and sandstones. Gas was produced from fields at the graben margins.

### **Conclusions**

Exploration targets are in the central southern portion of the DSR at a depth of 32,000 ft (10,000 m) where the master-transform faults are absent and limited migration of hydrocarbons and salt. The oil and gas windows may be difficult to calculate due to the extremely rapid burial and subsidence since the last 1.5 million years and the presence of sulfur and pyrite suggesting thermochemical reactions. Seismic sections demonstrate sedimentary rocks below graben fill. However Syrian Arc anticlines have not been identified in the sub-basin fill Mesozoic rocks. An ultra-deep well is needed to accurately model and process the seismic data and may unveil unidentified anticlines. At depth, primary reservoirs would be high porosity sandstones and dolostones below the Neogene salt. The trapping mechanisms would be stratigraphic traps diagenetically controlled or yet identified subtle structures. Due to the ultra-deep geological conditions, exploration wells that are successful typically are of high economic impact financially.

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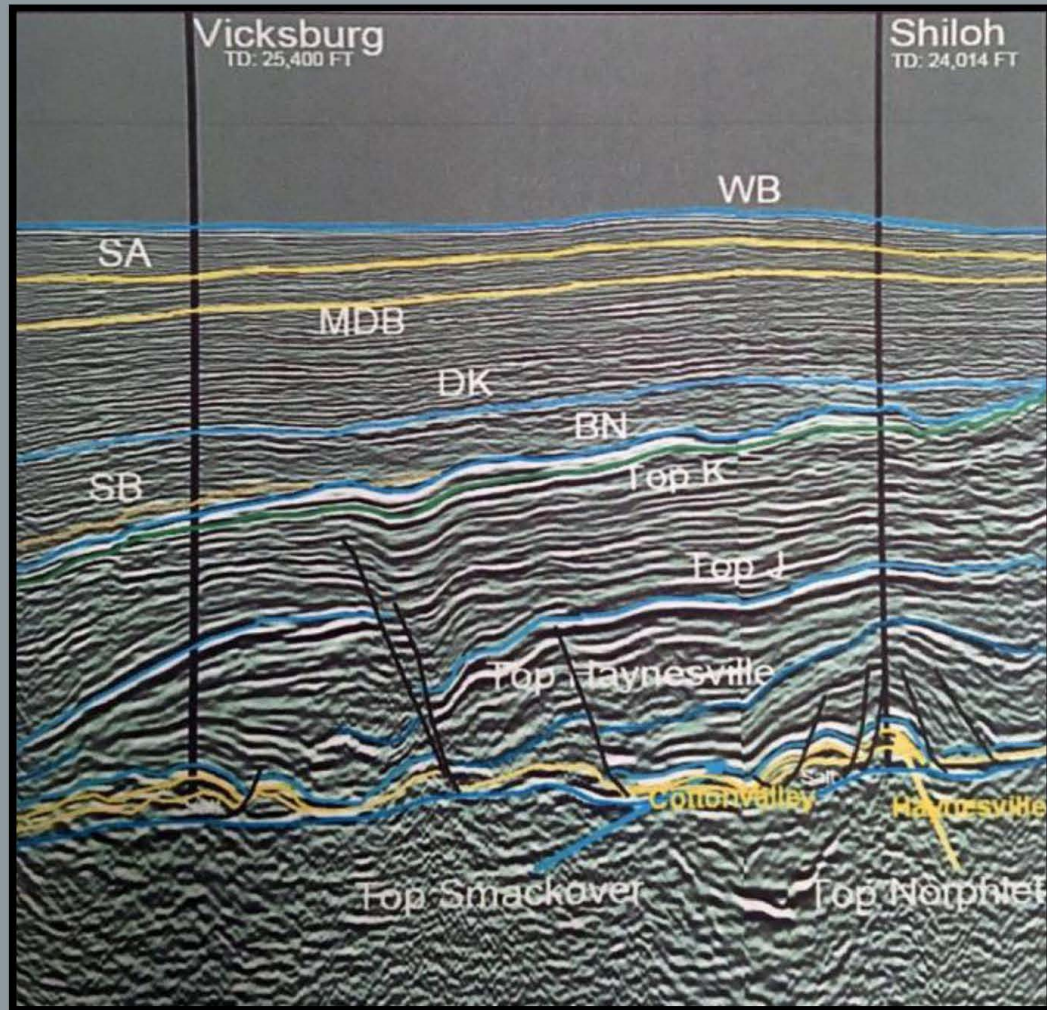


Figure 1. Seismic profile through Norphlet trend in the eastern Gulf of Mexico. The line is in time-depth, and represents the Norphlet Formation at 22,000 feet (6705 m); distance between wells 15 miles (33 km) (Chowdhury, 2009).

## Onshore GOM Hydrocarbon Genesis Pathway

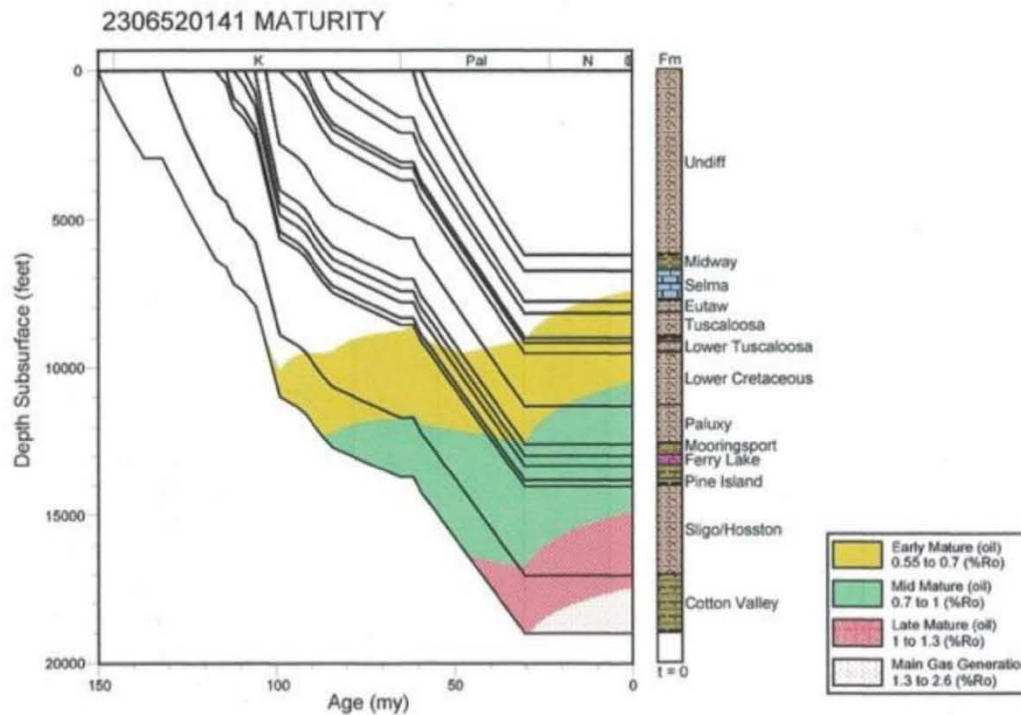


Figure 253. Thermal maturation profile for well 2306520141, Mississippi Interior Salt Basin.

Figure 2. Typical onshore Gulf of Mexico thermal maturation history (Mancini et al., 2012).



## Luann Salt Mobilization Offshore GOM

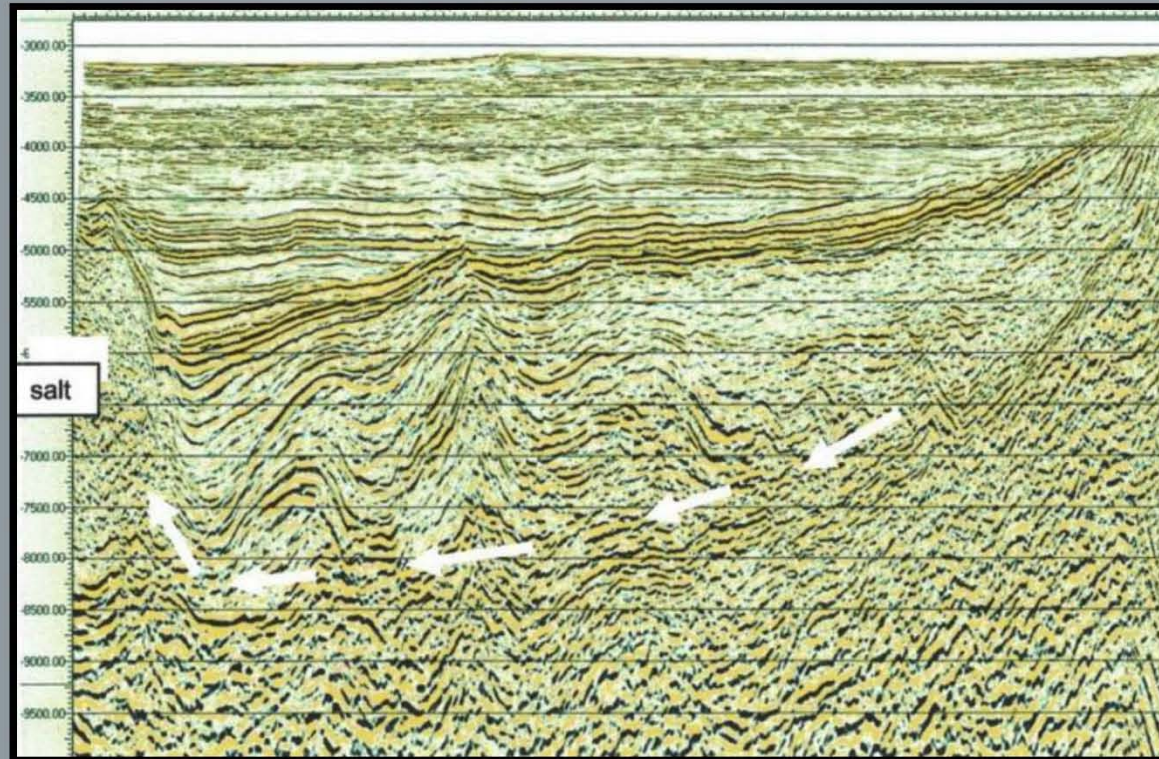
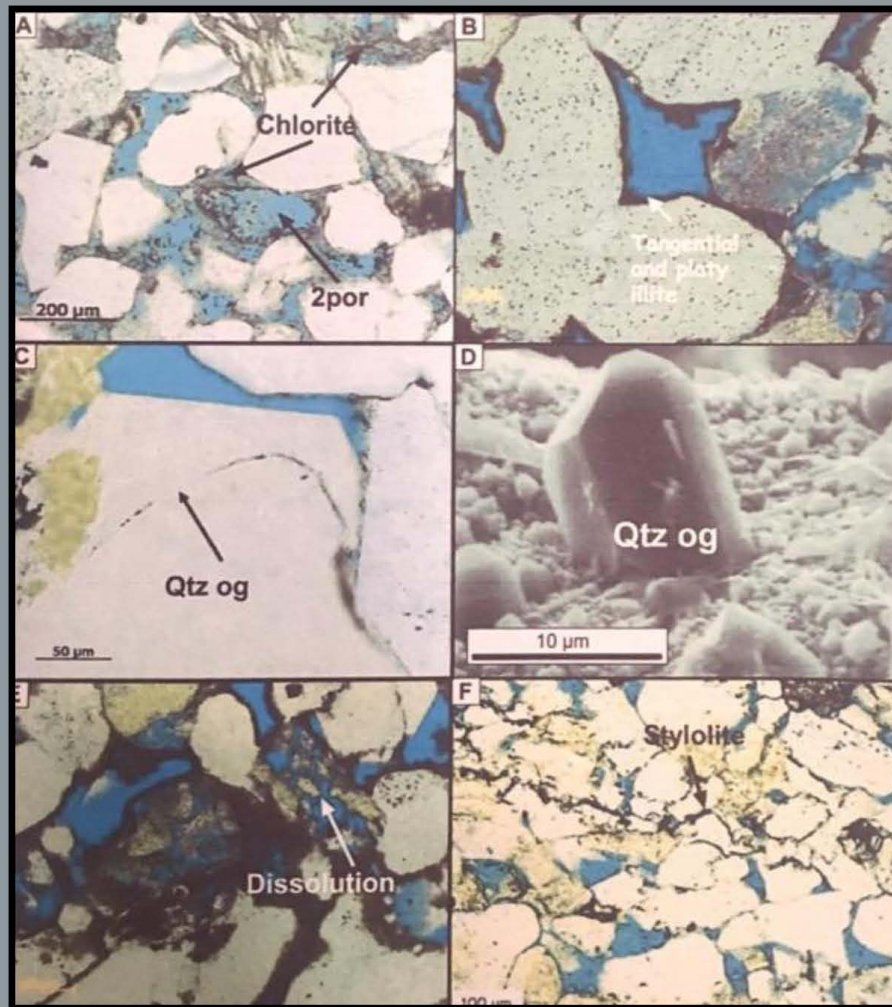


Figure 3. Gulf of Mexico offshore. PDSM section showing Jurassic Louann Salt movement and expulsion creating structures trapping hydrocarbons (Douglas, 2010).



Norphlet  
Diagenesis  
GOM

Figure 4. Photomicrographs showing Norphlet Formation in the Gulf of Mexico showing porosity (blue), chlorite coatings, quartz grains, authigenic quartz growths and dissolution (Douglas, 2010).

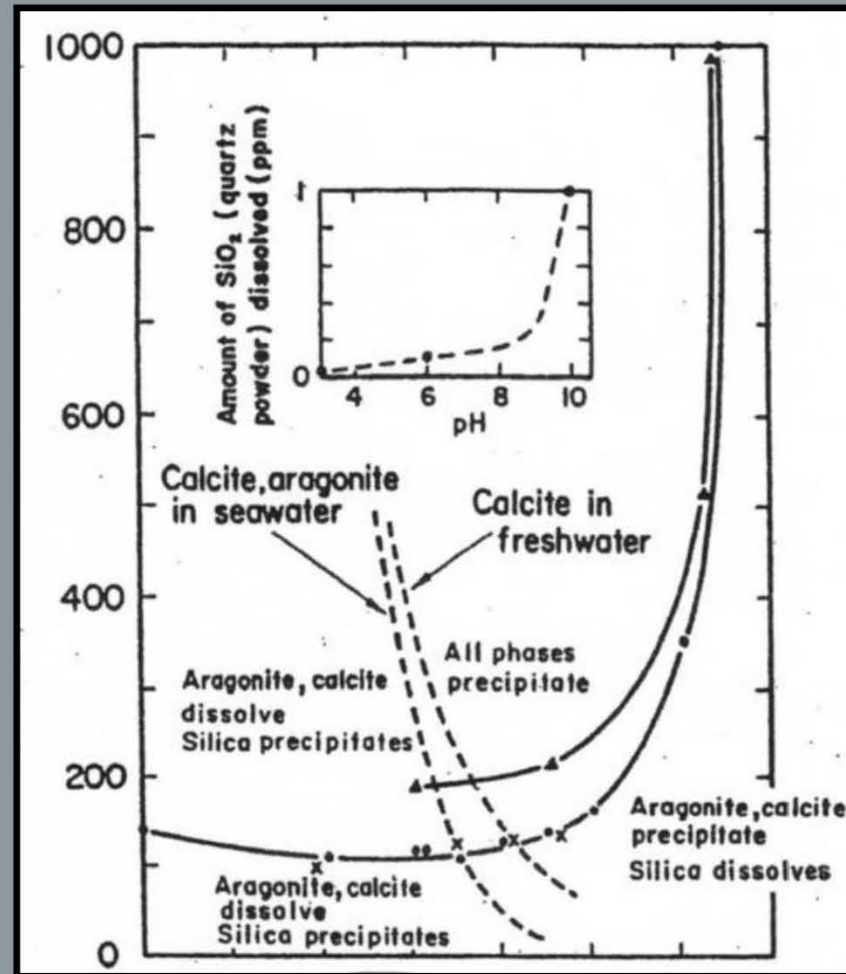


Figure 5. The relationship between calcium carbonate precipitation and simultaneous dissolution of silica, as a function of pH (Epstein and Friedman, 1982).

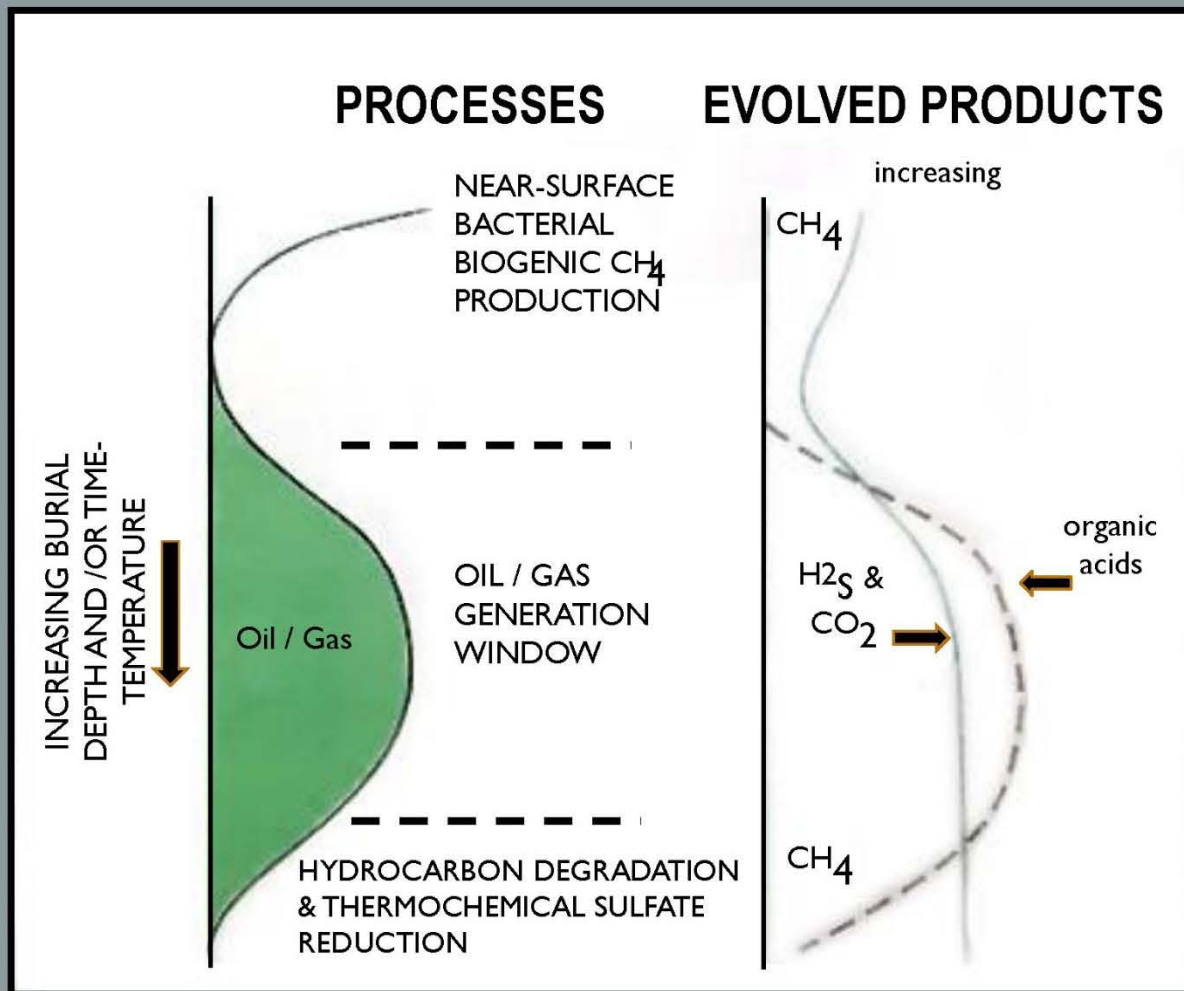


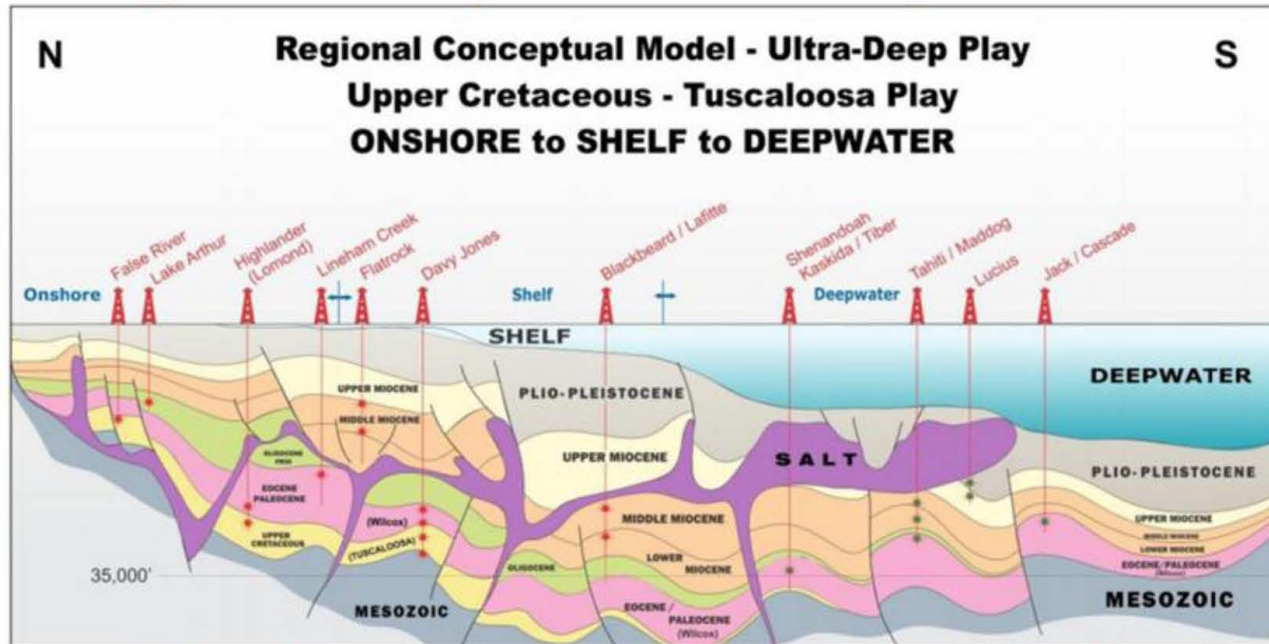
Figure 6. Relationships of thermochemical products with increasing burial.





## Conceptual Model - Ultra-Deep Play

*Recognized as Industry Leader in This New Exploration Frontier*



*Drilling activities to date have successfully confirmed geologic model and have indicated the potential for a major new geologic trend spanning 200 miles in the shallow waters of the GOM and onshore in the Gulf Coast area.*

Figure 7. Regional Gulf of Mexico cross section showing ultra-deep discoveries of subsalt sandstone reservoirs (Moffett, 2010).





## Conceptual Model – Depositional Fairways Woodbine/Tuscaloosa

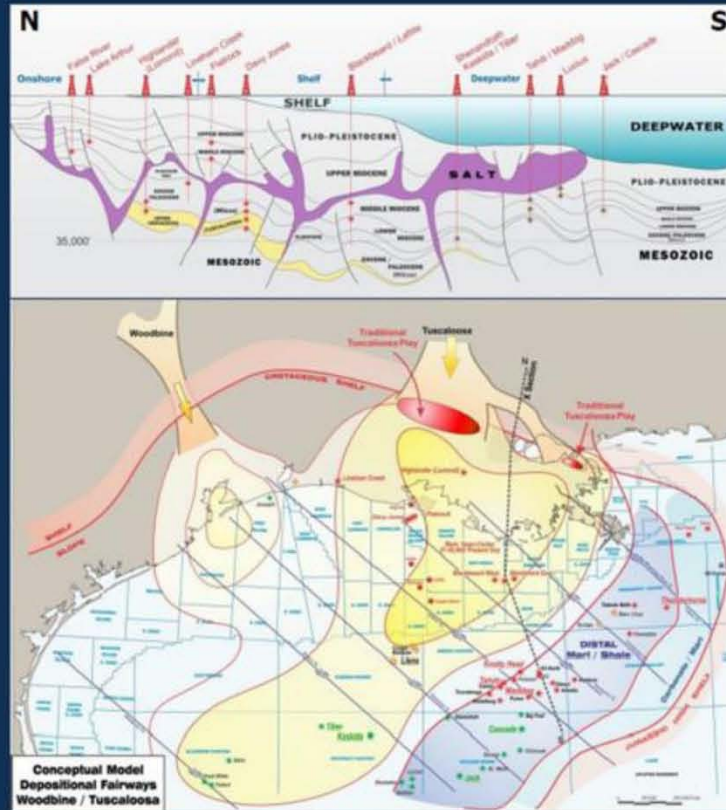


Figure 8. Ultra-deep depositional sandstone fairways Woodbine-Tuscaloosa Trend (Moffett, 2010).

## Highlander Discovery – Cretaceous Tuscaloosa

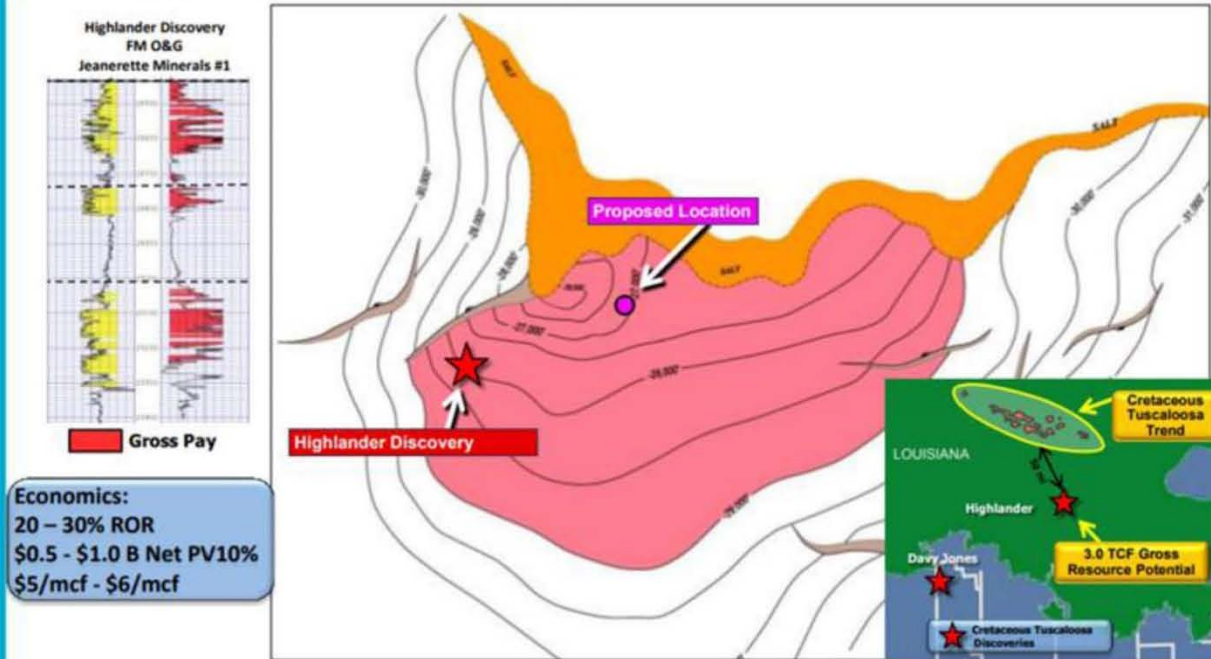


Figure 9. Onshore Cretaceous Tuscaloosa Gulf of Mexico Highlander clean sandstone discovery and associated structure map (Moffett, 2010).

## Cross-Section Anadarko Basin

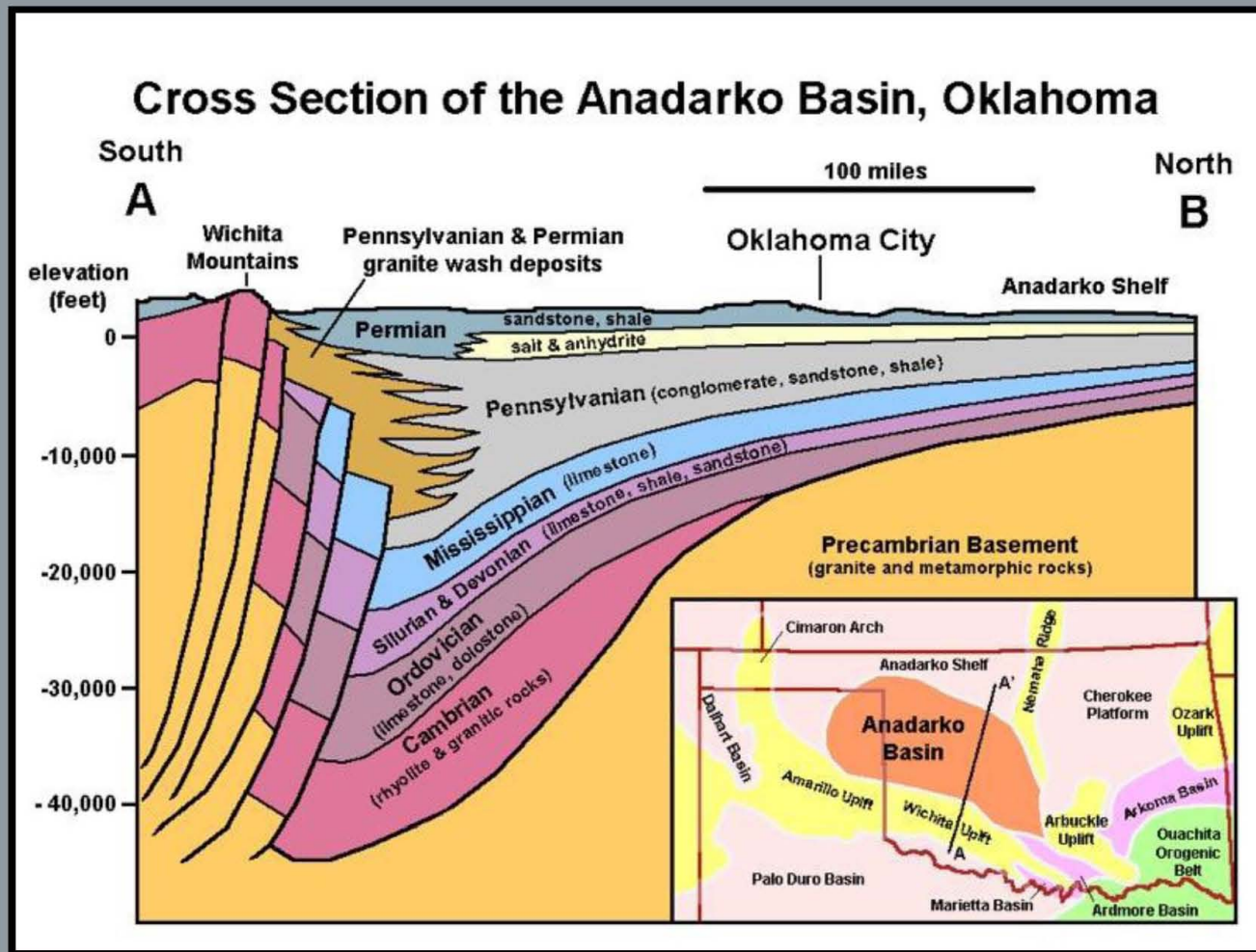


Figure 10. Regional cross-section Anadarko Basin, Oklahoma (Sternbach and Friedman, 1986)

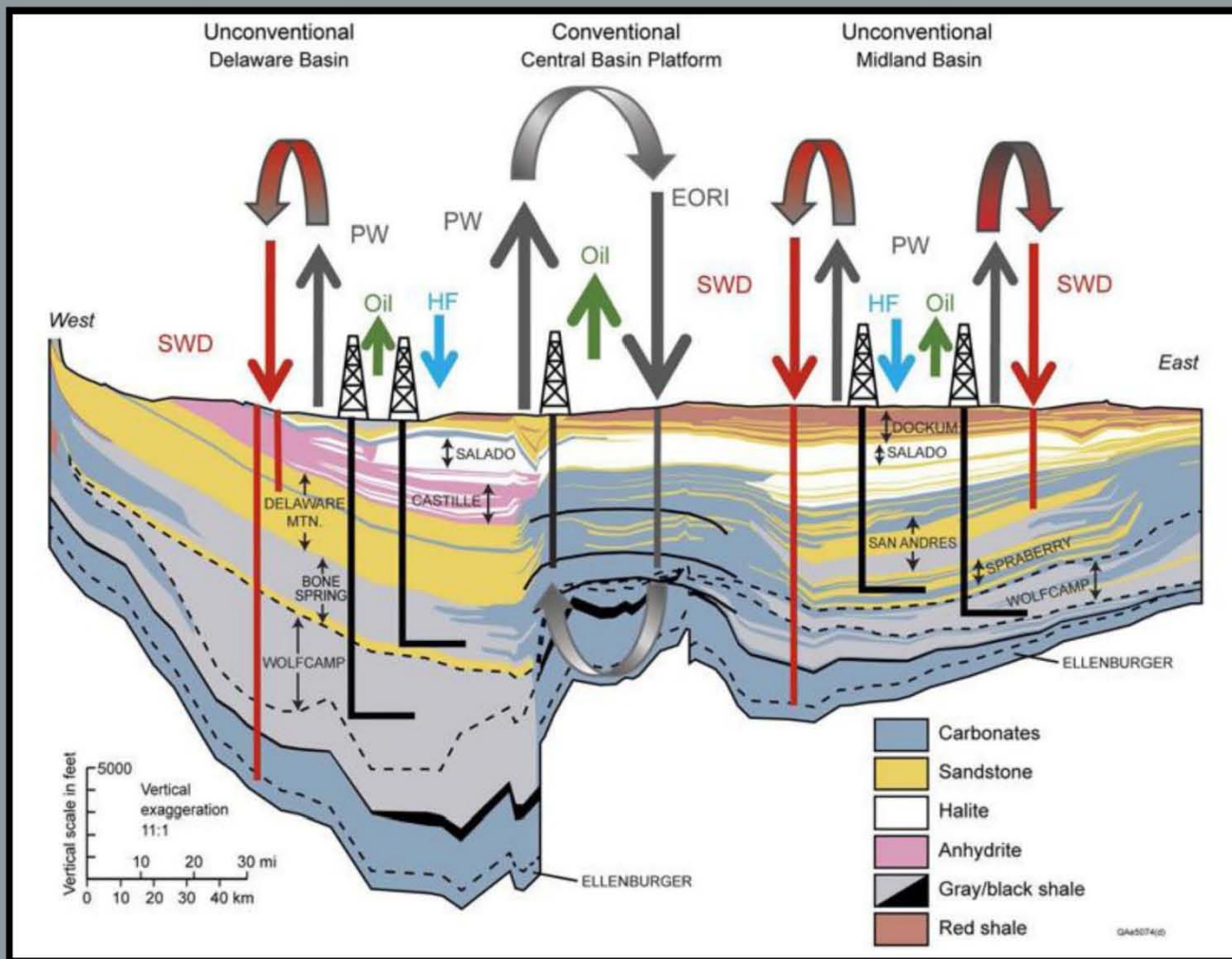


Figure 11. Regional cross section Permian Basin, Texas.



## Mesodiagenetic Burial Pathway

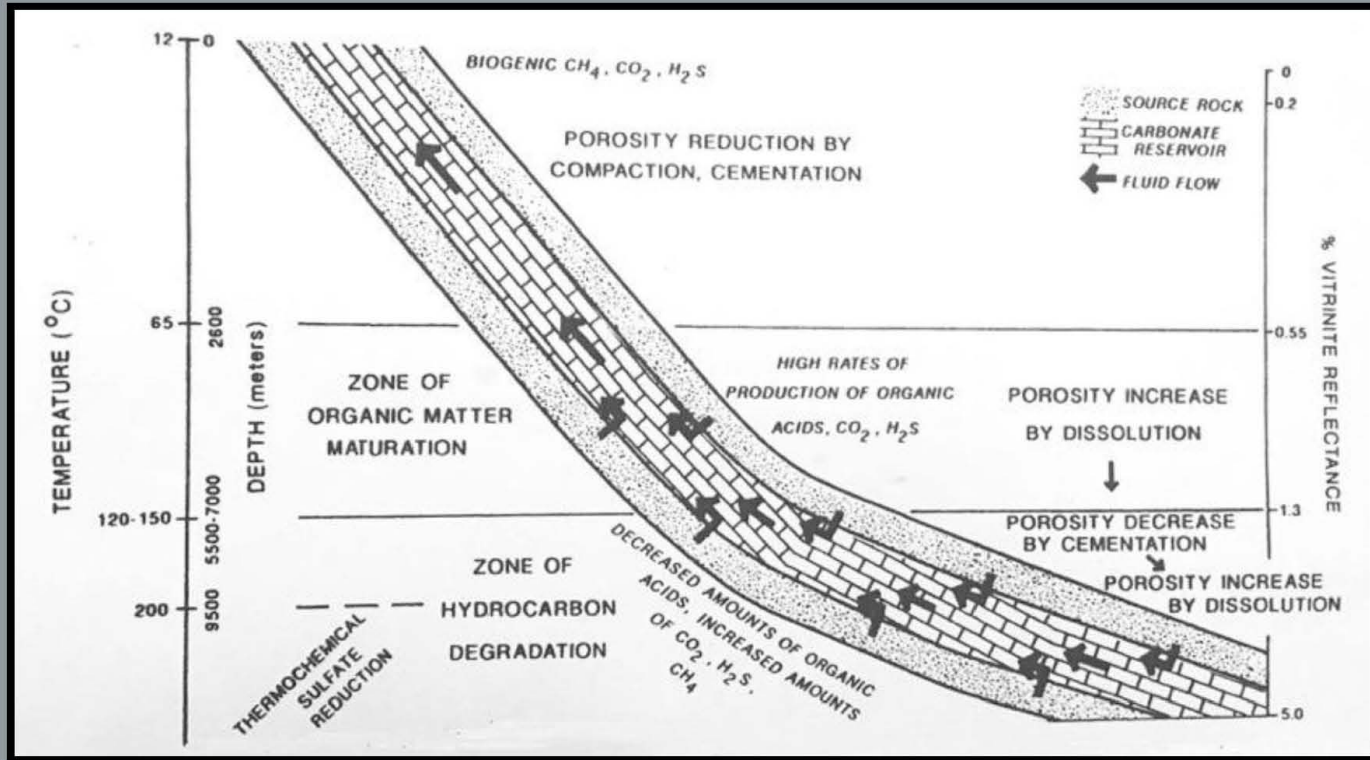


Figure 12. Model of inorganic and organic diagenesis to possible mesodiagenetic processes (Mazzullo and Harris, 1992).

### Dolomite Thin- Sections Anadarko Basin



Figure 13. Photomicrograph of iron-rich dolomites Keel Formation, Anadarko Basin. (Left) Oolitic grainstone 15,330 feet (4673 m); (Middle) Dolomites 21,259 feet (6780); (Right) 25,760 feet (7850 m) (Sternbach and Friedman, 1986).

## Ellenberger Permian Basin, Ultra Deep Dolomites

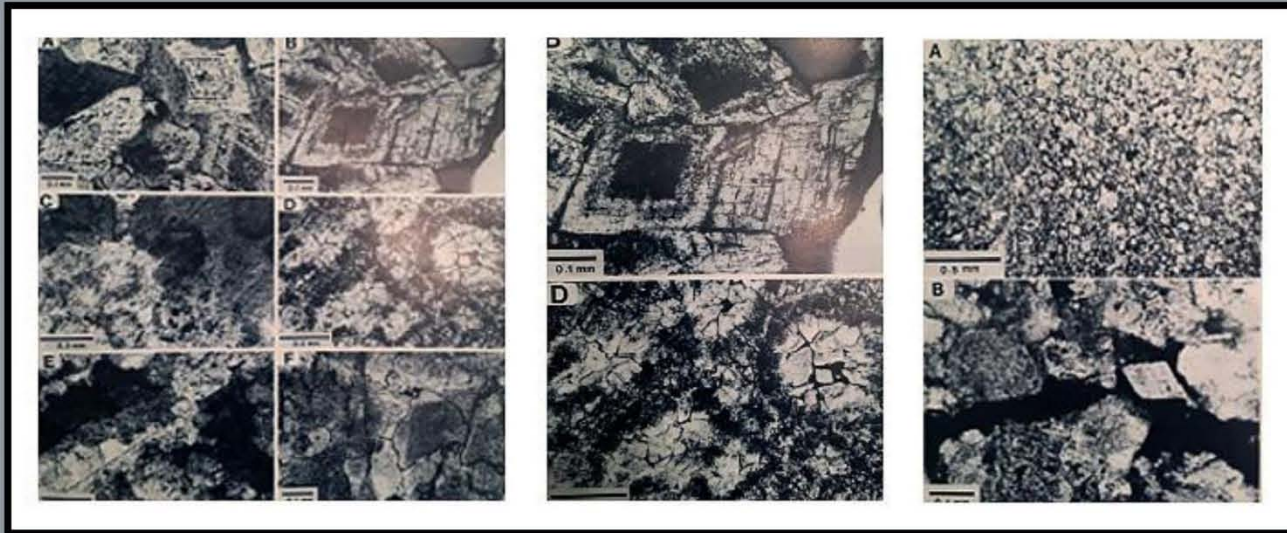


Figure 14. Photomicrograph of coarse to very crystalline dolomites, Ellenberger, Permian Basin. (A) Xenotopic textures, well developed cleavages from 22,706 feet (6920 m), (B) Dolomite from 21,264 feet, (C) Oolitic textures from 12,120 feet (3690 m), (D) Preservation Alga in xenotopic dolomite, (E) Healed microfractures from 12,152 feet (3700 m), (F) Remnants of stylolite seams in dolomite from 22,706 feet. Porosities based on logs 10% from 12,000 feet to 22,000 feet (Li and Friedman, 1987).

## Regional Cross-section, Tarim Basin, China

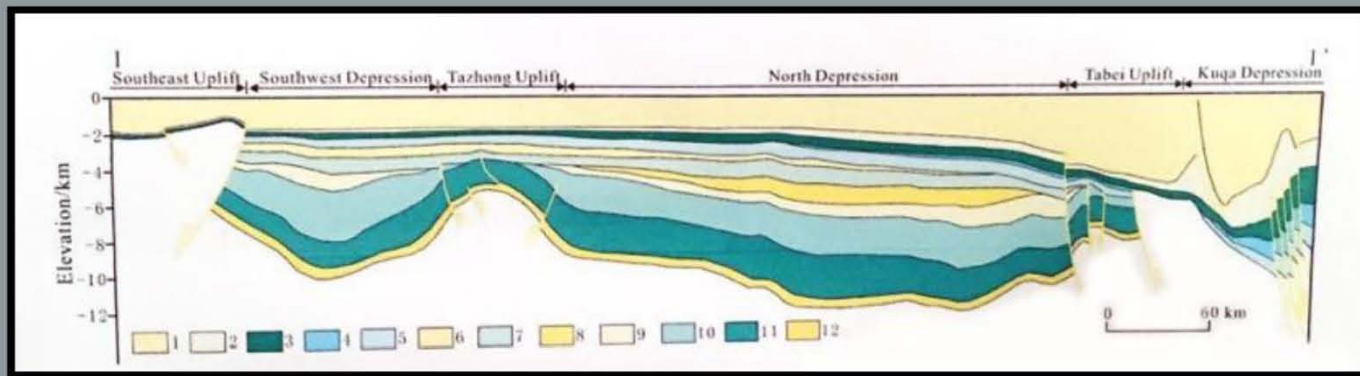


Figure 15. Geologic cross section ultra-deep Paleozoic in Tarim Basin, China (Yu, Yang, Tang, Huang, Qiu, and Li, 2014.)



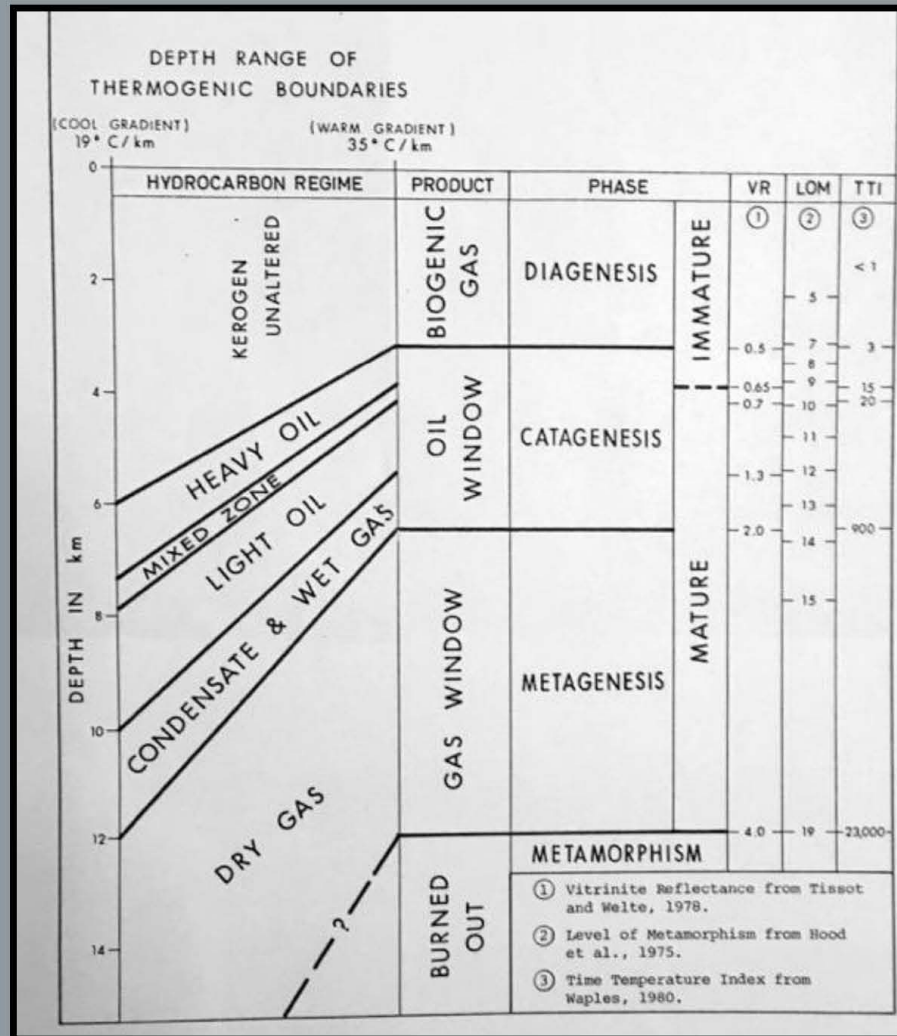


## Cambrian Dolomites, Tarim Basin

Figure 16. Photomicrographs of deep dolomites, Cambrian carbonates, Tarim Basin, China (Jiang, Worden, Cai, Shen and Crowley, 2018).

	EGYPT- WESTERN DESERT			EGYPT		SINAI - ISRAEL		JORDAN	LEBANON	SYRIA - NW IRAQ		SE TURKEY
	MELEIHA UMBA- RAKA AREA	ABU GHARA- DIG BASIN	ALAMEIN AREA	GUF OF SUEZ	NILE DELTA	NE SINAI SW ISRAEL	SE ISRAEL DEAD SEA	AZRAQ BASIN	ONSHORE	PALMYRA EUPH- RATES	NE SYRIA NW IRAQ	
Pliocene												

Figure 17. Regional hydrocarbon occurrence correlations Western Desert, Egypt to southeast Turkey showing important Campanian-Maastrichtian Menuha and Ghareb formations (Nadel, 2014).



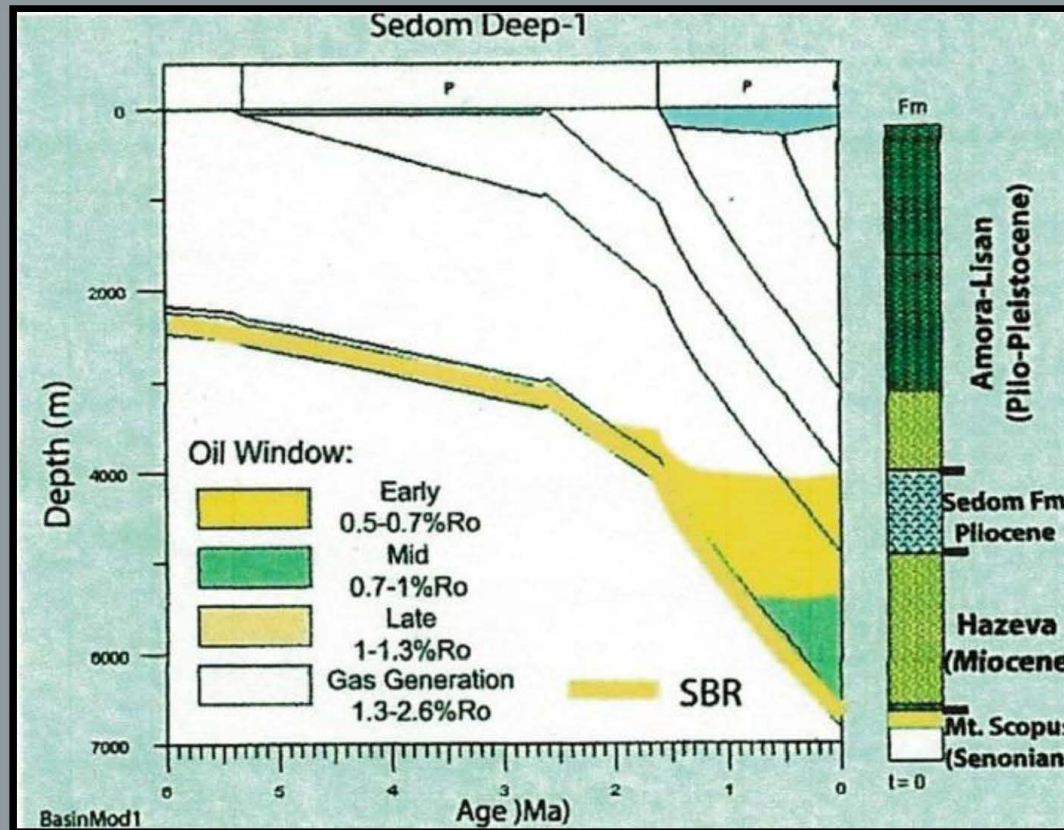
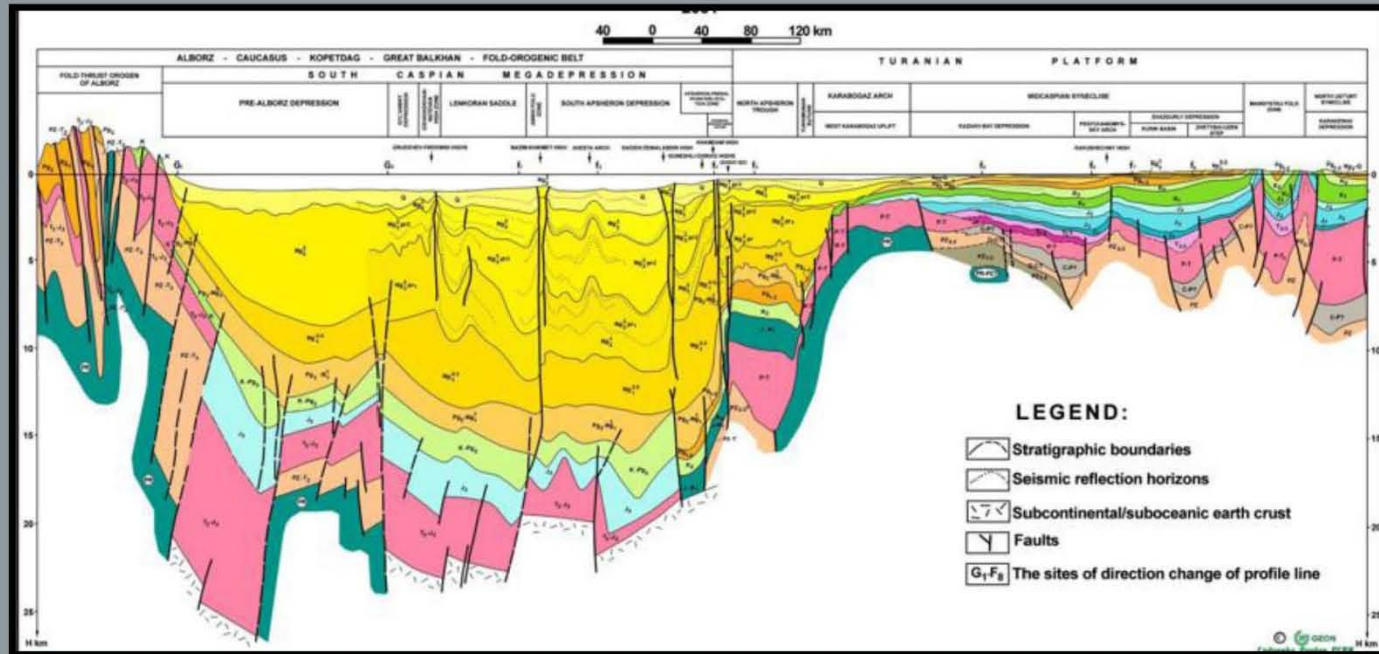


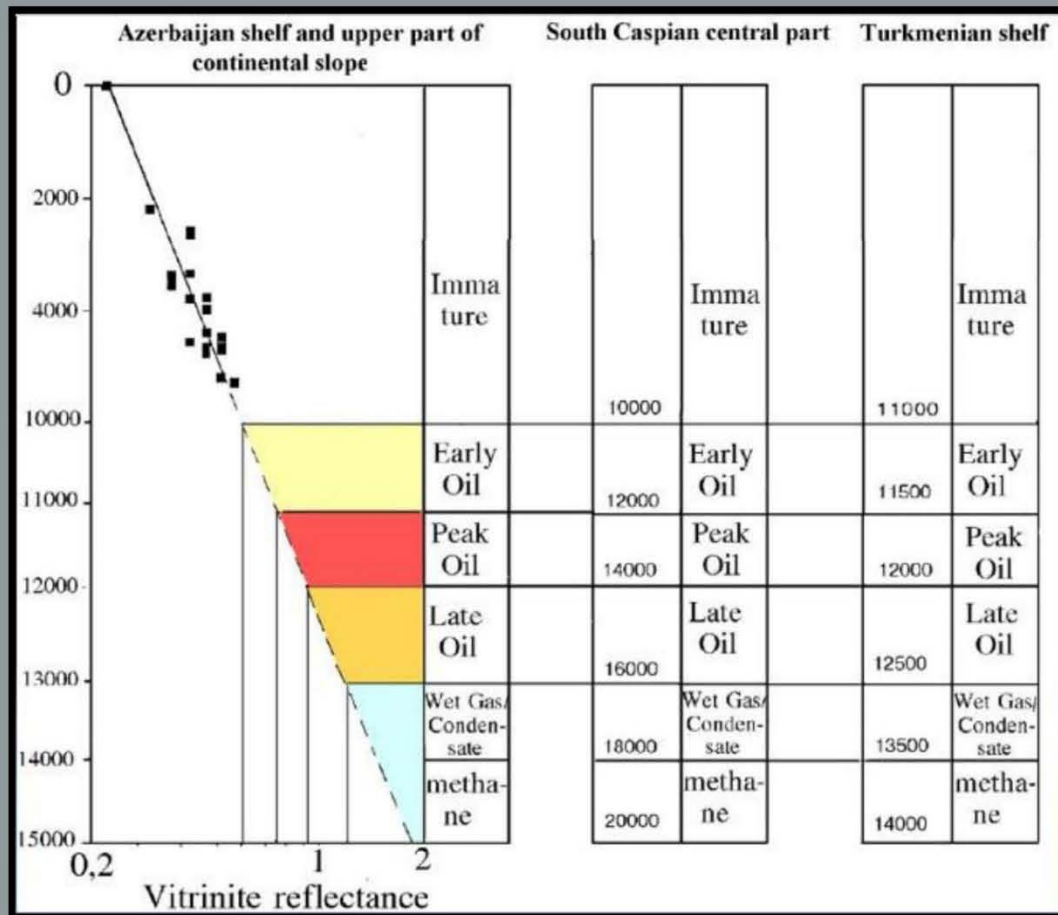
Figure 19. Basin mod Hydrocarbon Maturation. Model Sedom Deep 1 Well. Onset 4 km, main phase 5 km (Gadosh and Tannenbaum, 2014).





Typical feature:  
Due to large sediment input and rapid subsidence the sedimentary cover is as thick as 25-30 km.

Figure 20. South Caspian ultra-deep basin cross section showing 10 km of subsidence and deposition since Pliocene (Guliyev, Aliyeva, Husenov, Feyzullayez, Mamedov, 2011).



Organic matter maturity profile across the South Caspian Basin modified after Wavrek et al., 1996.

Figure 21. Thermal maturation projections South Caspian Basin, onset at 33,000 feet (10,060 m). (Guliyev, Aliyeva, Husenov, Feyzullayev, Mamedov, 2011).



Triassic  
Isopach  
Map

Figure 22. Regional Triassic Isopach map, from Syria, Jordan including southern Israel. Major study includes Druckman, 1974 (Nader, 2014).

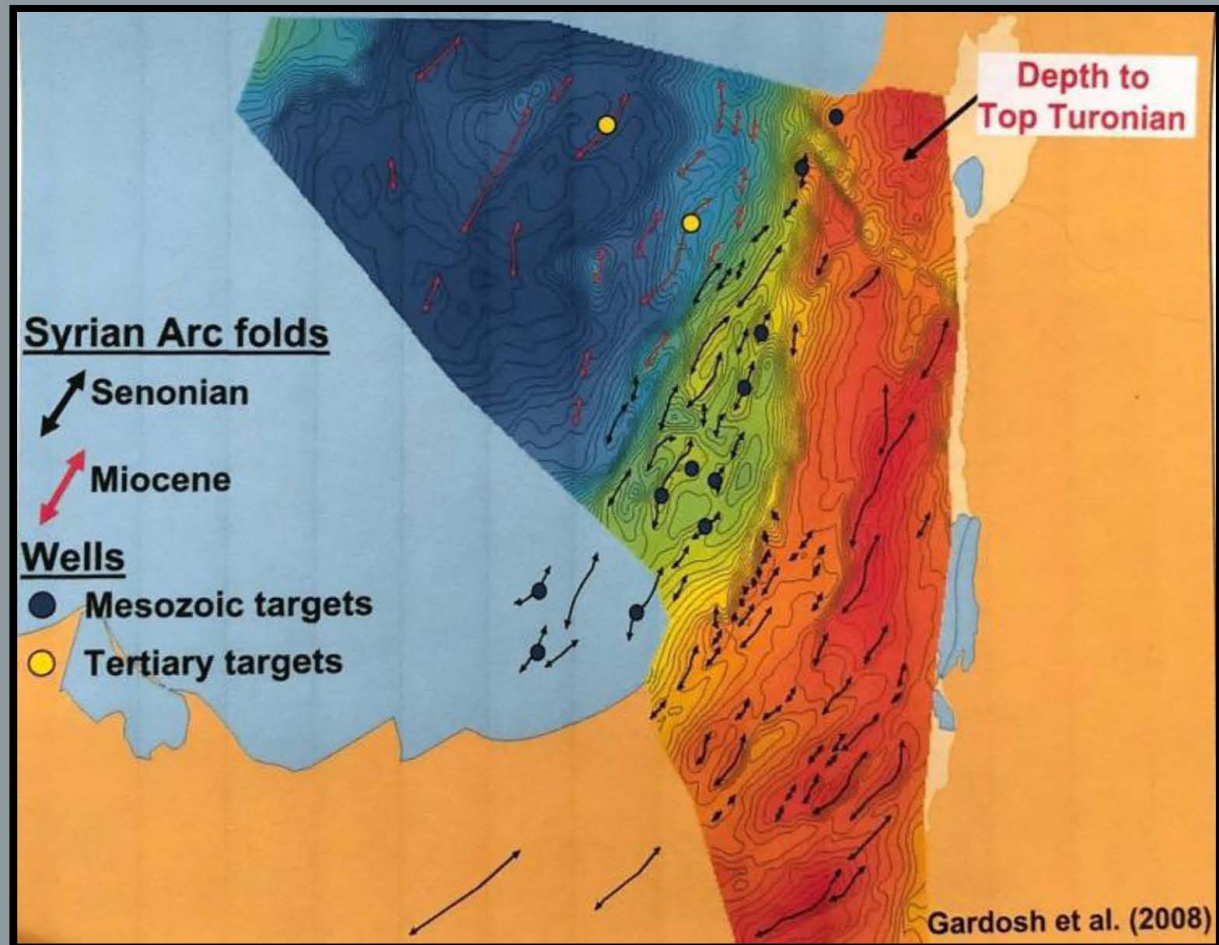


Figure 23. Onshore-offshore Israel structural trends (Gardosh, 2009).



## Pull-Apart Basin Structural Responses

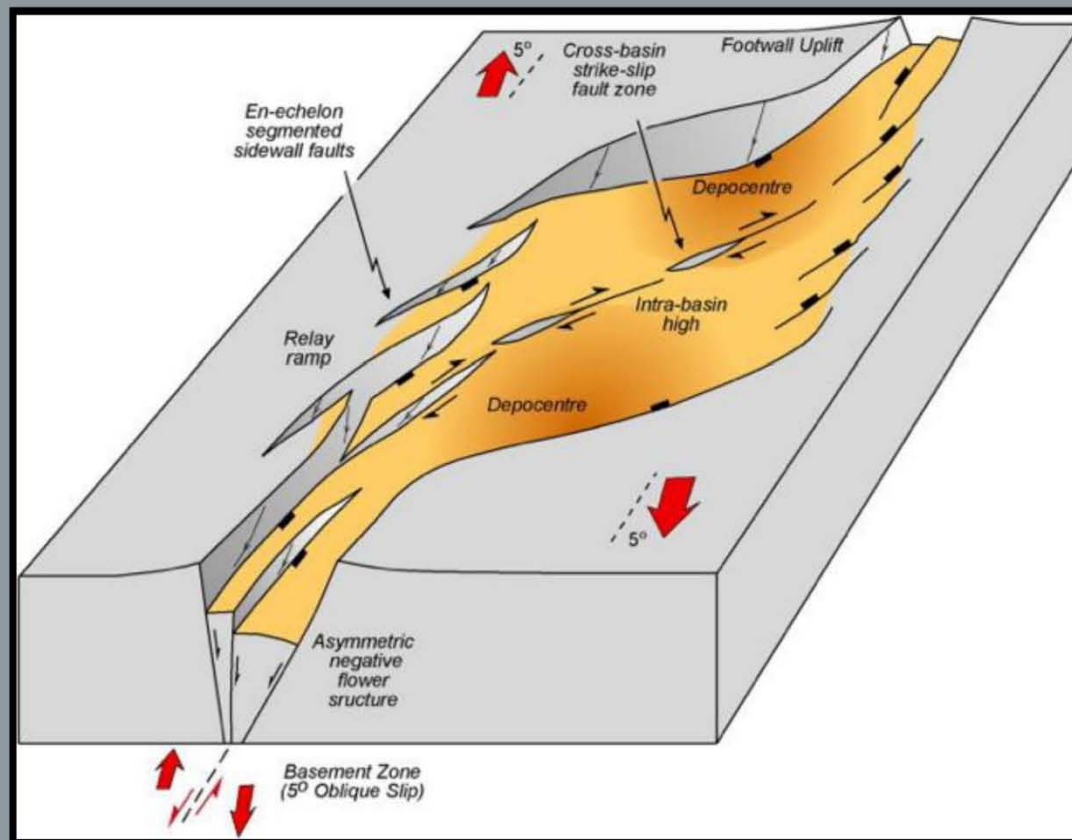


Figure 24. Fault and fold responses to strike-slip movement pull-apart basin development. Note inter-basin folds.

## Southern Dead Sea

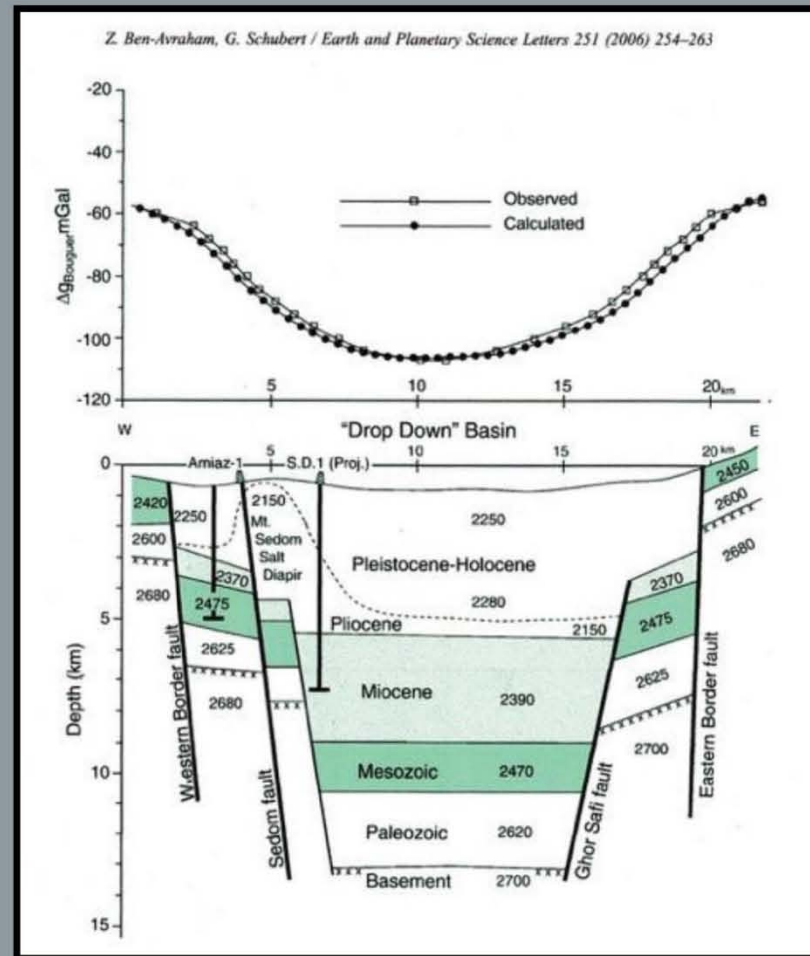


Figure 25. East-West geologic cross section of the Dead Sea based on seismic reflection, seismic refraction and drill hole data. Gravity models are shown on top using Sedom Deep drill hole (Ben-Avraham and Schubert, 2006).

## DSR Key Wells

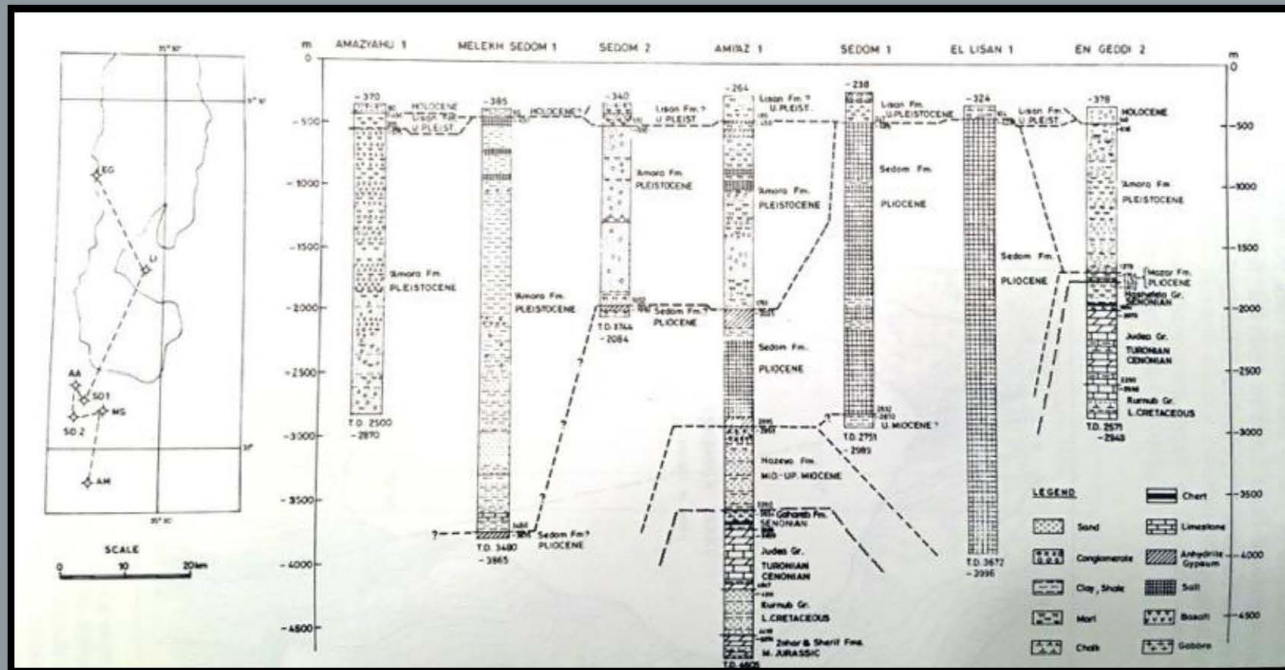


Figure 26. Condensed stratigraphic columnar sections of the significant wells drilled in the Southern Dead Sea. Note key well Amilaz 1 (Kashai, 1988).

## Seismic Southern DSR

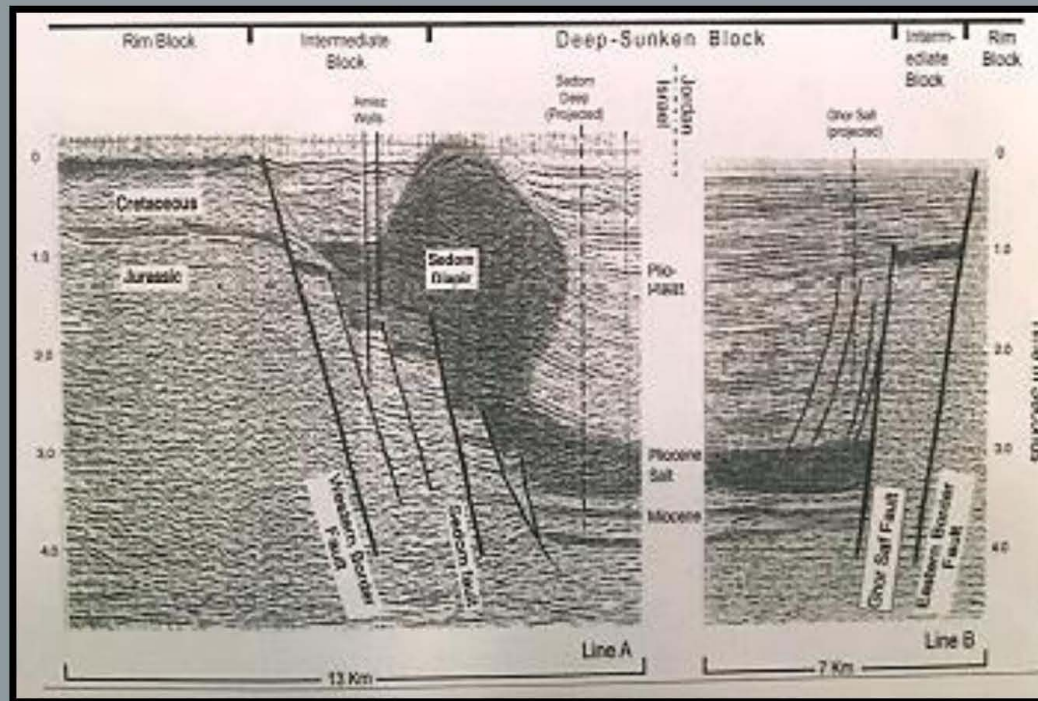
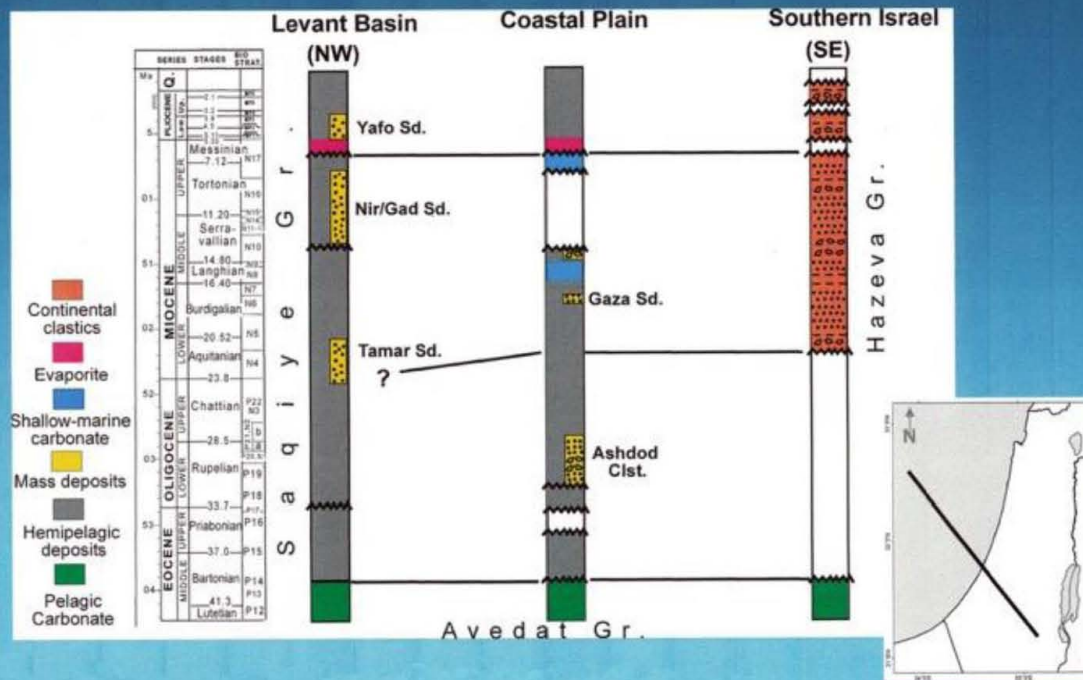


Figure 27. Seismic time-lines southern Dead Sea Basin showing deep salt interpretation (Ben-Avraham and Lazar, 2006).

# Southern Dead Sea

## Late Tertiary stratigraphy of Israel



AAPG 2009 Denver

Figure 28. Hazeva Sandstone. Chronostratigraphic equivalent to offshore Tamar Sand (Gardosh, Druckman, and Buchbinder, 2009)