BOEM 2012-100

Atlantic Well Folio: Georges Bank Basin

Lydonia Canyon Block 410 No. 1 Well

Erin T. Elliott
Paul J. Post

U.S. Department of the Interior
Bureau of Ocean Energy Management
Gulf of Mexico OCS Region
Office of Resource Evaluation

1.3. Lydonia Canyon 410-1

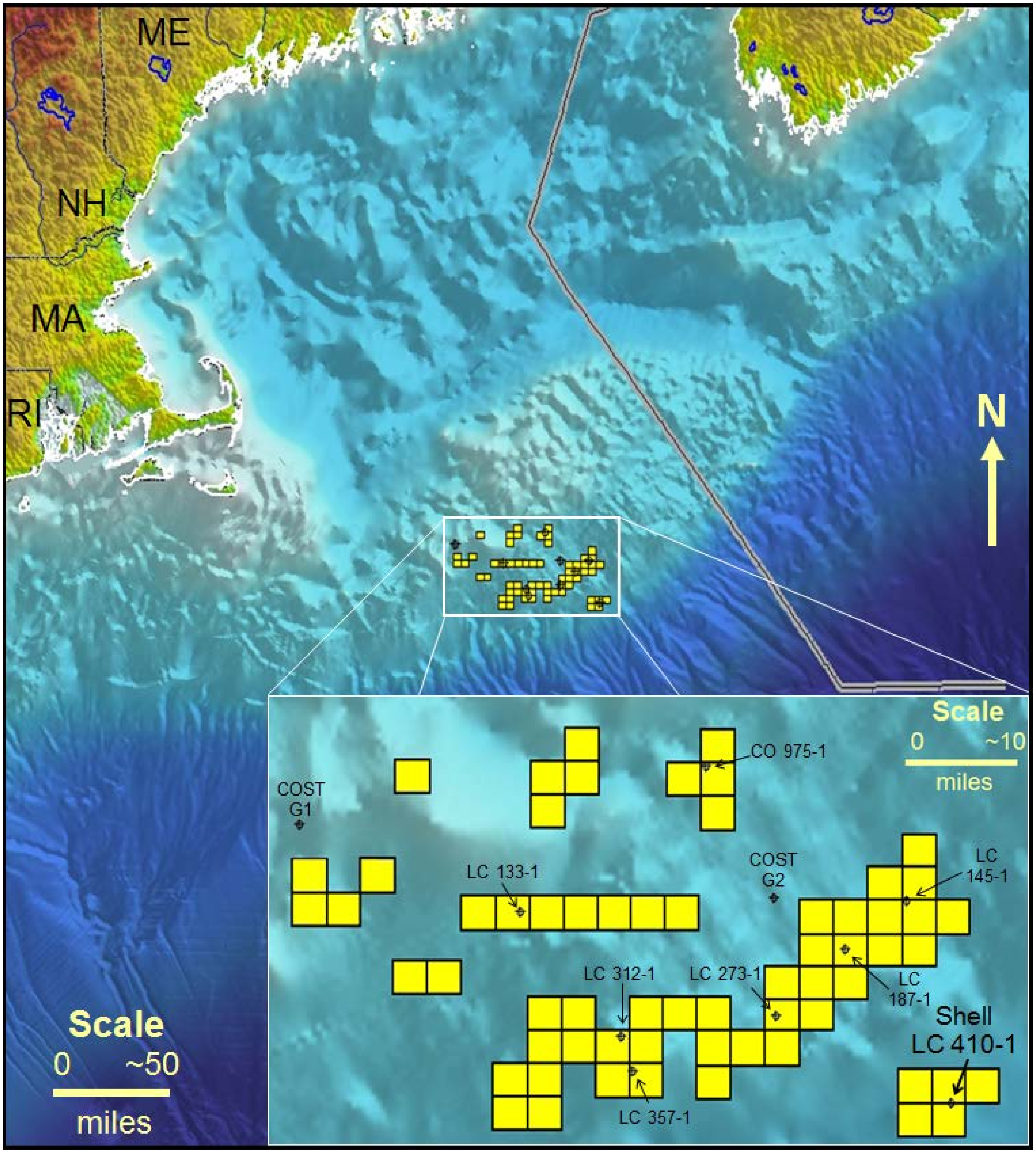

Figure 1. Location map of Georges Bank basin, offshore Massachusetts, USA. Well locations are indicated with ⌖. Leases previously held in the area are shown in yellow.

On July 27, 1981, Shell Offshore Inc. (37%) spudded Lydonia Canyon (LC) 410-1, the third industry exploration well and fifth well drilled in Georges Bank basin (GBB) (Figure 1, Table 1). LC 410-1 was the most seaward of all the wells drilled in the GBB, located 25 miles southeast of COST G-2 in 381 feet (ft) of water. Shell contracted the *Zapata Saratoga* to drill the well. Total Depth (TD) of 15,568 was reached March 18, 1982. The well was plugged and abandoned as a dry hole without significant hydrocarbon shows on March 31, 1982.

Table 1. Wells drilled in Georges Bank basin

Well	Date	Target	Actual
COST G1	1977	n/a	n/a
COST G2	1976	n/a	n/a
LC 133-1	1981	Callovian Reef	Volcanic Sequence
CO 975-1	1982	Bathonian porous shelf carbonate	Evaporite Lens
LC 410-1	**1982**	**Porous Jurassic Limestone, Structural Closure**	**Jurassic closure poor porosity and permeability**
LC 312-1	1982	Callovian Reef	"Tite" micritic Limestone
LC 187-1	1982	Jurassic age Limestones and Dolomites	Reservoir of poor porosity and permeability
LC 145-1	1982	Jurassic Porous Shelf edge Calcarenites and Carbonates	"Tite" micritic Limestones
LC 273-1	1982	Four way closure, Jurassic oölitic and bioclastic limestones	"Tite" micritic Limestones
LC 357-1	1982	Simple structural closure in Limestone, Dolomite, and anhydrite	"Tite" micritic Limestones

1.3.1. Objectives and Concepts

The objective was an interval of interpreted porous, Jurassic-age carbonates within structural closure between estimated measured depths (MD) of 12,000 to 16,000 ft (Figure 2).

Included with Shell's 1981 Plan of Exploration (POE) and Application for Permit to Drill (APD), submitted to the United States Geological Survey (USGS), were the original pre-drill interpreted seismic lines and structure maps. These, in addition to post-drill well logs, cores, and test results submitted by the operator and relevant literature, were used in compiling this report.

Structure maps from Shell's APD (Figure 3) show, with a limited scope, that the prospective upper and base Jurassic horizons exhibit less than 300 ft of structural relief. The original seismic data, acquired and processed in 1979, shows the target Jurassic closure in a blue bracket between 1.7 and 2.7 seconds two-way travel time (TWTT) (Figure 4). Shell's structural interpretations indicated that the Jurassic interval represented the best level of closure, and therefore offered the most likely prospect for hydrocarbon accumulation (Shell, 1981). There was no information available on the type of hydrocarbon accumulation (oil, gas, or both) expected.

1.3.2. Results

Drilling

Oölitic Limestone and mudstone with interbedded sandstone were encountered at approximately 5,600 ft MD. Microcrystalline limestone and coarsely crystalline dolomite characterized the interval between ~13,000 ft and 15,221 ft MD (Figure 5). The well encountered sandstone and minor siltstone and anhydrite from 15,221 ft MD to 15,568 ft (TD).

Two conventional cores were cut from 9,738 ft to 9,768 ft MD and from

15,229 ft to 15,234 ft MD. Core analyses indicated that both porosity and permeability were low in these intervals.

Sidewall cores were cut between 13,060 ft and 15,484 ft MD (Figure 5) with recoveries ranging from 0.01 to 1 inch. Sidewall core analyses indicated poor permeability, which ranged from .07 to 26.5 millidarcies (mD). In the target interval, below 12,000 ft MD, permeability averaged less than one mD (considerably below the threshold for a reservoir).

Porosity ranged between 3.7% and 13.5%. The average porosity in the target interval was < 10 % (the minimum cutoff for a reservoir in this frontier area). A lithologic description of the conventional cores was not available. The geochemical reports for the sidewall cores contained short descriptions of the lithology, e.g. coal, limestone. No other core-based lithologic descriptions were available for these intervals.

Seismic Interpretation

Shell's pre-drill 2D time-migrated seismic interpretations (Figure 4) show a Jurassic age structure overlain by a thinner interval expected to contain porous carbonates. This interval appears to thin across the top of the Jurassic-age structure. A full explanation and definitive details of the objective was not originally provided with the documentation submitted by Shell.

Figures 6 and 7 show 2D seismic lines, recently depth-converted and time-migrated (d-c, t-m) by Fugro Robertson (GeoSpec), that are in close proximity to the LC 410-1 well. The south-to-north seismic line in Figure 6 is located approximately 1,500 ft west of the well. Between 12,000 and 16,000 ft, the target interval for the well, the base Bathonian and younger horizons are relatively flat-lying and exhibit no structure. The base Jurassic dips slightly south in the southernmost portion of the profile and the Jurassic interval begins to thicken. The west-to-east seismic line in Figure 7 is approximately 750 ft north of the well, just north of the northern edge of block LC 410. This seismic line shows that the Jurassic interval is of uniform thickness and exhibits no structural relief. Because the BOEM does not have access to the original seismic data used by Shell, these two seismic lines were selected to best depict the structure drilled.

Two structure maps and one isopach map were created by gridding 24 d-c, t-m 2D seismic lines in the vicinity of the leased blocks (yellow blocks, Figures 8, 9, and 10). The structure maps in Figures 8 and 9 show that the well was drilled on the flank of a structural high seen in both the Bathonian and base Jurassic structure maps. Figure 10 is a regional isopach map of the Jurassic interval (the contoured thickness between the base Bathonian and base Jurassic horizons in Figures 8 and 9). Taken together, these maps show that LC 410-1 was drilled in an isopach thin. Shell may have interpreted this to indicate the location of a possible high-energy (wave-base impingement) environment on the flank of a Jurassic structure where a zone of porous carbonates were most likely to occur. This could be why the well was drilled in an off-structure position. Post-drill analyses provide no conclusive support for this interpretation.

Biostratigraphy and Palaeoenvironment

Biostratigraphic and palaeoenvironment information were compiled from Carpenter (1984) and Edson et al. (2000). The reliability of biostratigraphic data is questionable, especially in the Jurassic, because of the possible re-deposition of indicator fauna in the shallow environment of deposition (Edson et al., 2000).

Most of the sediments encountered in the LC 410-1 well were deposited in an inner to middle shelf environment (Table 2). Paleo-water depths were generally less than 300 ft, averaging approximately 110 ft

(Edson et al., 2000). Present-day water depth is ~381 ft.

1.3.3. Operations and Costs

The LC 410 prospect encompasses five OCS blocks (Figure 8). Shell Offshore Inc. (37%), Phillips Petroleum Co. (24%), Cities Service Co. (24%), and Louisiana Land and Exploration Co. (15%) leased Block LC 410 in 1979 (Sale 42) for a high bid of $34,733,000.00 (Carpenter, 1984), approximately $115.8 MM in 2012 dollars (HBrothers, 2012). This consortium also leased block 367 for ~$33.7 MM. Exxon (100%) leased blocks 365 (~$214,000) and 409 ($5.4 MM). Texaco Inc. (90%) and Reading & Bates Petroleum Co. (10%) leased block 366 for $27.8 MM. The total bonus for all prospect-related leases was ~$101.9 MM or ~$339.6 MM in 2012 dollars (Hbrothers, 2012). The total well cost for LC 410-1 was estimated to be $31 MM (Carpenter, 1984 citing an undated Oil and Gas Journal article) equating to approximately $81.1 MM in 2012 dollars (HBrothers, 2012). No cost breakdown was available. Total drilling time was approximately 251 days (from spud date to completion) including ~69 days for significant operational problems (abandoned first hole, blowout preventer (BOP) repairs, mooring system problems, and milling operations). Drilling operations were also halted for 35 days due to severe weather (Carpenter, 1984).

Table 2. Biostratigraphy and probable palaeoenvironment of sediment intervals in LC 410-1

Depth	Age	Lithology	Depositional Environment
0	Unknown	Insufficient wireline log data	Unknown
1050	Miocene to M. Eocene	Banquereau Fm: Green silty mudstone	Shelf (clastic, sand prone)
1670	Campanian to Cenomanian	Dawson Canyon Fm.: Gray calcareous siltstone, chalky limestone, unconsolidated sand beds	Shelf (mixed clastic & carbonate)
2720	Cenomanian to Aptian	Logan Canyon Fm.: Limestone unit overlying Gray silty mudstones interbedded sandstones (Naskapi Fm.)	Mud dominated shelf
4050	Aptian to Hauterivian	Roseway Unit: Limestones, mudstones and calcareous sandstones overlying limestone.	Shelf (mixed mud & carbonate)
5650	Berriasian-Tithonian		Shelf (carbonate dominated)
6930	Tithonian to M. Jurassic	Abenaki Fm.: Predominately limestone	Shelf (carbonate dominated)
12680	L. to M. Jurassic*	Mohican: Limestone	Mud dominated shelf
15221	L. to M. Jurassic*	Iriquois: Limestone with minor dolomite overlying sandstone with mudstone and anhydrite	Shelf (mixed clastic and carbonate)

E. – Early M. –Middle L. –Late

*Sediment interpreted as being reworked; therefore, age interpretation considered unreliable.

1.3.4. Petroleum System Analysis

Magoon and Dow (1994) defined a petroleum system as “a natural system that encompasses a pod of active source rock and all related oil and gas and which includes all the geologic elements and processes that are essential if a hydrocarbon accumulation is to exist.” Petroleum is defined as biogenic or thermal gas located in a reservoir or as naturally occurring surficial condensates, asphalts, and crude oils (Magoon and Dow, 1994).

Essential geologic elements are: source rock, reservoir rock, seal rock, and overburden rock (a thick enough rock column above the source rock interval to result in burial sufficient for temperatures to result hydrocarbon generation). Our guidelines for source, reservoir, and seal elements are shown in italics in Table 3.

Essential processes include trap formation and hydrocarbon generation, as well as hydrocarbon expulsion, migration, accumulation, and preservation (Magoon and Dow, 1994).

The essential processes must act on the geologic elements at specific times such that a reservoir and trap exist, hydrocarbons are generated, expelled from the source rock, migrate into the trap, become entrapped and retained in the trap (Magoon and Dow, 1994). Not all processes will occur in all areas; *i.e.*, when there is no hydrocarbon generation and expulsion, there can be no migration or accumulation.

Table 3. Petroleum System Elements

Element	LC 410-1 Lithology
Source rock *(>1% TOC)*	Limestones in the interval 13,000 ft- ~15,000 ft
Reservoir rock *(>10 % ϕ >1 mD k)*	Aptian and Albian sandstones (~25% – ~31% of generally mudstone-rich interval). Hauterivian sandstones (70% of mudstone-rich interval)
Seal rock *(10^{-3} mD k)*	Shale, impermeable Limestones
Overburden rock	~13,000 ft above deepest source rock interval

Geochemistry

Rock-Eval Pyrolysis is the most widely used technique to establish the maturity of organic matter and its petroleum potential. This technique involves heating a sample in a helium atmosphere (Pimmel and Claypool, 2001). The thermal maturation of a sample is determined by T_{max}, "the temperature at which maximum release of hydrocarbons from cracking of kerogen occurs during pyrolysis" (Pimmel and Claypool, 2001). Thermally mature rocks for oil generation are those that reach a T_{max} of ~435 ^{o}C (incipient/early mature for oil generation) and remain at or below 470^{o}C (post-mature for oil generation). For gas generation, T_{max} values must exceed 470^{o}C. Four basic products are obtained from Rock-Eval Pyrolysis: S1, S2, S3, and T_{max} (Pimmel and Claypool, 2001).

Instead of using standard Rock-Eval Pyrolysis, Shell developed the Pyrolysis-Flame Ionization Detector (P-FID) to monitor the hydrocarbon generation capacity of a heated rock sample by recording the distillable (~S1) and pyrolyzable (~S2) hydrocarbons. This technique involves heating a small sample in a nitrogen atmosphere, piping the hydrocarbon vapors into the flame ionization detector (FID), and recording the signal. The percent hydrocarbon yield is calculated by calibrating the FID signal with a petroleum wax. T_{max} can be approximated by subtracting 25 to 29 degrees from the recorded pyrolizable hydrocarbons. Consequently, only 3 values are obtained from P-FID: S1, S2, and an estimated T_{max} (Burkley and Castaño, 1985).

Total organic carbon (TOC) is typically determined using the sample remaining after Rock-Eval Pyrolysis. The organic matter in the sample is oxidized in a 600 ^{o}C LECO induction furnace and the residual organic carbon is measured. The TOC is then calculated by adding the residual organic carbon to the pyrolized organic carbon measured by Rock-Eval Pyrolysis (Pimmel and Claypool, 2001). A good source rock will contain TOC between 1% and 2% and a very good source rock will have TOC > 2%. However, while TOC values of 1–2% are source rocks and will generate hydrocarbons, those hydrocarbons are typically not expelled from the source rocks. Source rocks with higher TOC and S2 values generate and expel hydrocarbons, which then migrate into traps, or escape to the depositional surface via migration conduits.

Shell established the amount of TOC in a sample using an in-house method. The acid soluble portion of a sample is removed using hydrochloric acid. The remaining sample is then combusted in an oxygen stream and the CO_2 produced is measured. These readings are used to establish the weight percent of TOC in the original sample, typically referred to as the non-carbonate carbon (NCC) (Burkley and Castaño, 1985).

Vitrinite reflectance data are used to determine the thermal maturity of a sample. It provides a measure of the organic metamorphism applicable to different coal ranks or level of organic metamorphism (LOM). The T_{max} from the P-FID provides an estimate of the level of organic metamorphism (LOM) but is not as accurate as measured vitrinite reflectance (Burkley and Castaño, 1985).

Shell's in-house P-FID method does not measure hydrogen index (HI) or oxygen index (OI). HI corresponds to the quantity of pyrolyzable organic compounds or "hydrocarbons" (HC) from S2 relative to the TOC and can be used to indicate the kerogen type and richness (Peters, 1986). OI corresponds to the quantity of CO_2 from S3 relative to the TOC, and can be used in conjunction with HI to determine kerogen type (Peters, 1986).

An analysis of Shell's geochemical data in BasinMod® *Classic* shows that the majority of the converted T_{max} data points above ~11,000 ft are unusable due to either large temperature variations within a very small depth range or the samples may be from re-cycled material, providing erroneously high T_{max} values. The interval below 11,000 feet contains T_{max} data that are not only in a reasonable range to generate hydrocarbons, but are also in agreement with the vitrinite reflectance data. These T_{max} values cluster between 440 ^{o}C and 480 ^{o}C, a mature level for a Type III kerogen derived oil or a possible gas condensate.

TOC values for the LC 410-1 well ranged from 0.23% to ~43.5%. The highest values, over 3% TOC, were documented to correspond with coal seams encountered while drilling, based on the sample descriptions in the geochemical reports. TOC values above 1% were sampled in several formations throughout the well, and TOC values above 1.5% were recorded in the Late Cretaceous Coniacian, Early Cretaceous Hauterivian, and the Middle Jurassic Callovian. In the Callovian, below ~13,000 ft MD, the TOC values cluster between 1% and 2%. A few TOC values were above 2% in the Callovian, making this interval the most likely source interval in the well.

Table 4. Petroleum System Processes

<table>
<tr><td>Onset hydrocarbon generation</td><td>~11,000 ft MD based on T_{max} data.</td></tr>
<tr><td>Expulsion</td><td rowspan="3">Although the Callovian Limestones below 13,000 ft MD contains sufficient TOC (~1 to >2%) to generate hydrocarbons, there are no significant shows in reservoir lithologies; only in the source rock intervals. This indicates that TOCs are too low to result in expulsion (supported by BasinMod® Classic modeling) and/or a lack of vertical cross–stratal or other migration conduits to facilitate hydrocarbon expulsion, migration, or accumulation.</td></tr>
<tr><td>Migration</td></tr>
<tr><td>Accumulation</td></tr>
</table>

Exploration Implications

The exploration implications derived from LC 410-1 are the following:

1. The reservoir element of the petroleum system was inadequate. The limestone reservoir objectives were of lower porosity and permeability than previously thought.
2. The source rock element was inadequate: source rock richness (TOC) was generally insufficient to allow the expulsion of hydrocarbons from the source rock. Based on our analysis and interpretation of the mud log, geochemistry, and modelling, hydrocarbons are retained in the source rock. This explains the relatively minor mud log shows while drilling the interval below 6,800 ft MD.
3. In conjunction with the low permeability of the prospective reservoirs and an apparent absence of migration pathways, any possible *in situ* hydrocarbons would have been unable to migrate to better quality, shallower reservoirs. Reservoir quality rocks were sandstones of Hauterivian or younger age.

Table 5. LC 410-1 Target Summary

Pre-Drill Interpretation	
Target	~12,000-16,000 ft MD Interpreted porous Jurassic carbonates
Trap Type	Structural-Stratigraphic
Hydrocarbon Expected	Oil or gas
Post-Drill Results	
Target Interval	At ~6,250 ft MD Jurassic carbonates were encountered. Sufficient T_{max} and TOC for hydrocarbon generation were encountered below 11,000 ft MD.
Hydrocarbon Shows	No significant shows of either oil or gas. Some gas recorded on the mud log while drilling through carbonate source rocks below 6,800 ft MD.

Acknowledgements

The support of BOEM management and staff: R. Poling, M. Wilson, M. Celata, and D. Cooke, are gratefully acknowledged. We also thank R. Poling whose review and comments significantly improved the clarity and readability of the paper, and E. Klocek for her peer review. We are grateful to Fugro Robertson (GeoSpec) for allowing the publication of their reprocessed, depth-converted, time-migrated seismic data and derivative maps produced by BOEM staff from this data. The assistance of J. Danford and M. Paton of Fugro Robertson (GeoSpec) is greatly appreciated.

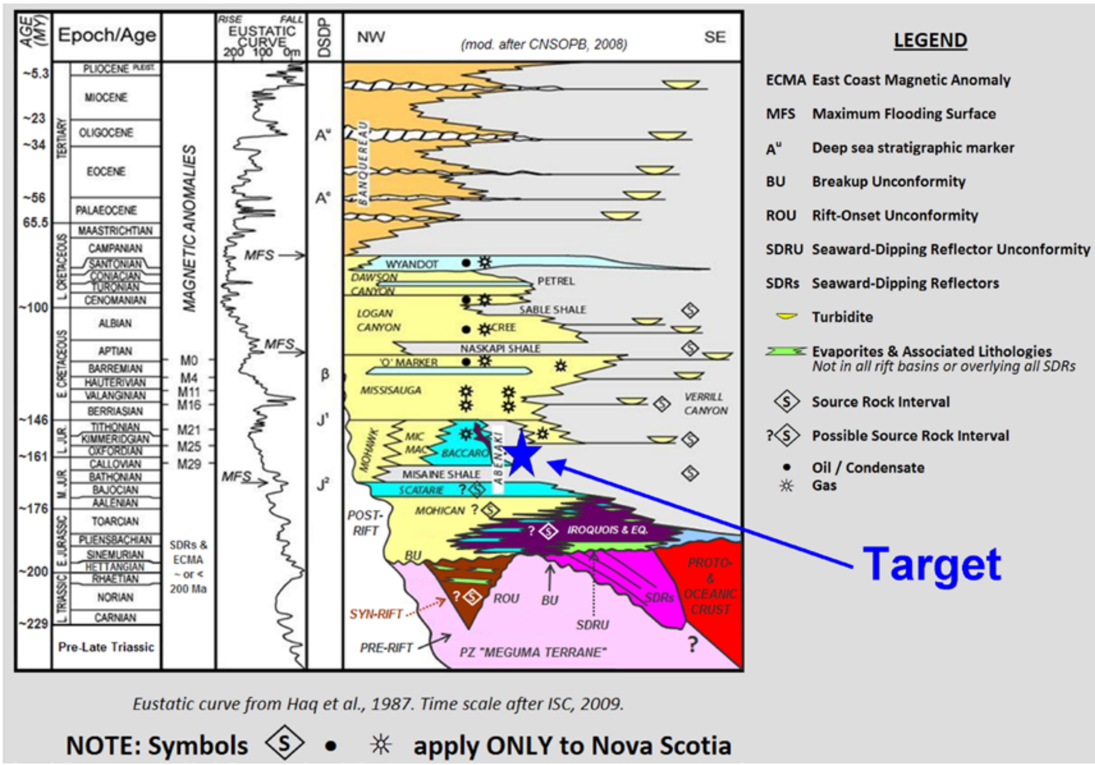

Figure 2. Stratigraphic chart showing the target interval for Shell Lydonia Canyon Well 410-1.

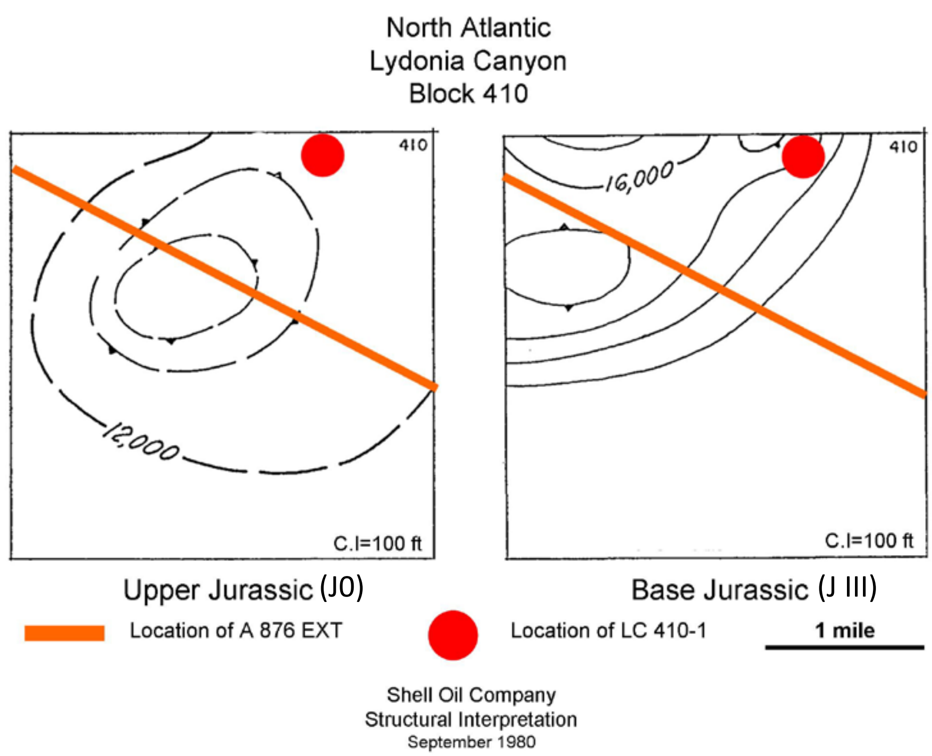

Figure 3. Shell (1981) structure maps showing the top (J0) and base (J III) of targeted Jurassic carbonates.

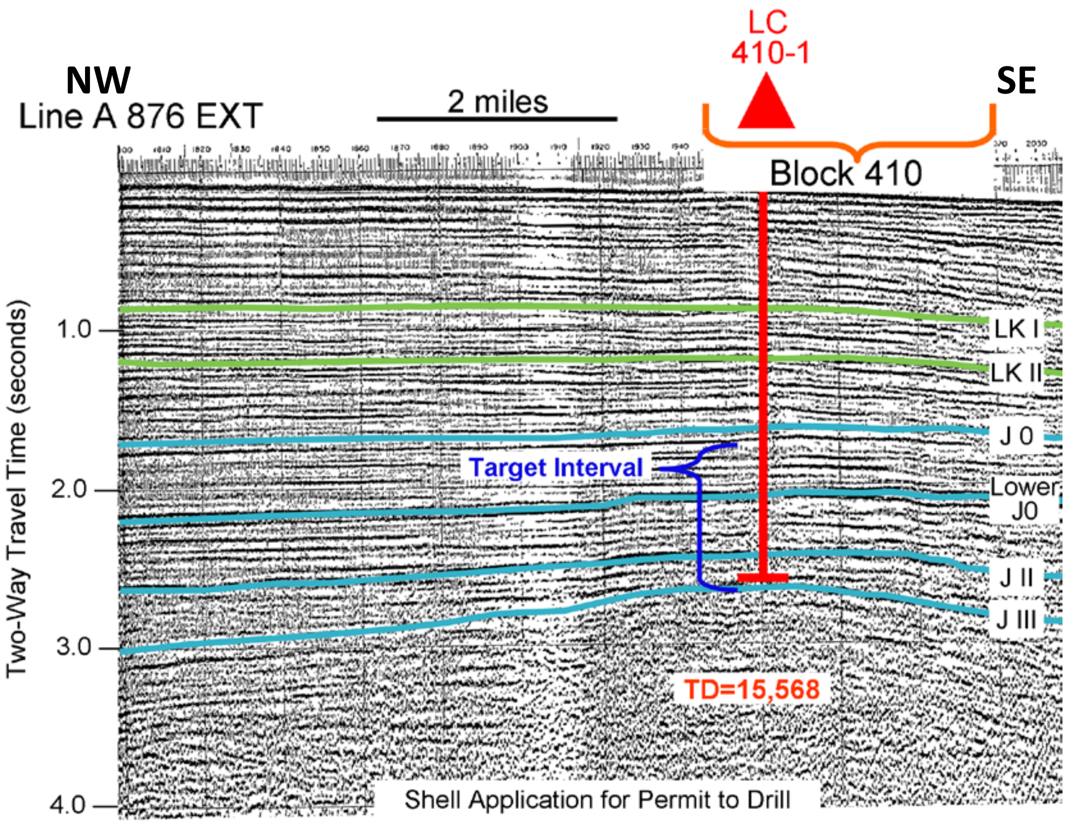

Figure 4. Shell (1981) interpreted prospective Jurassic carbonates.

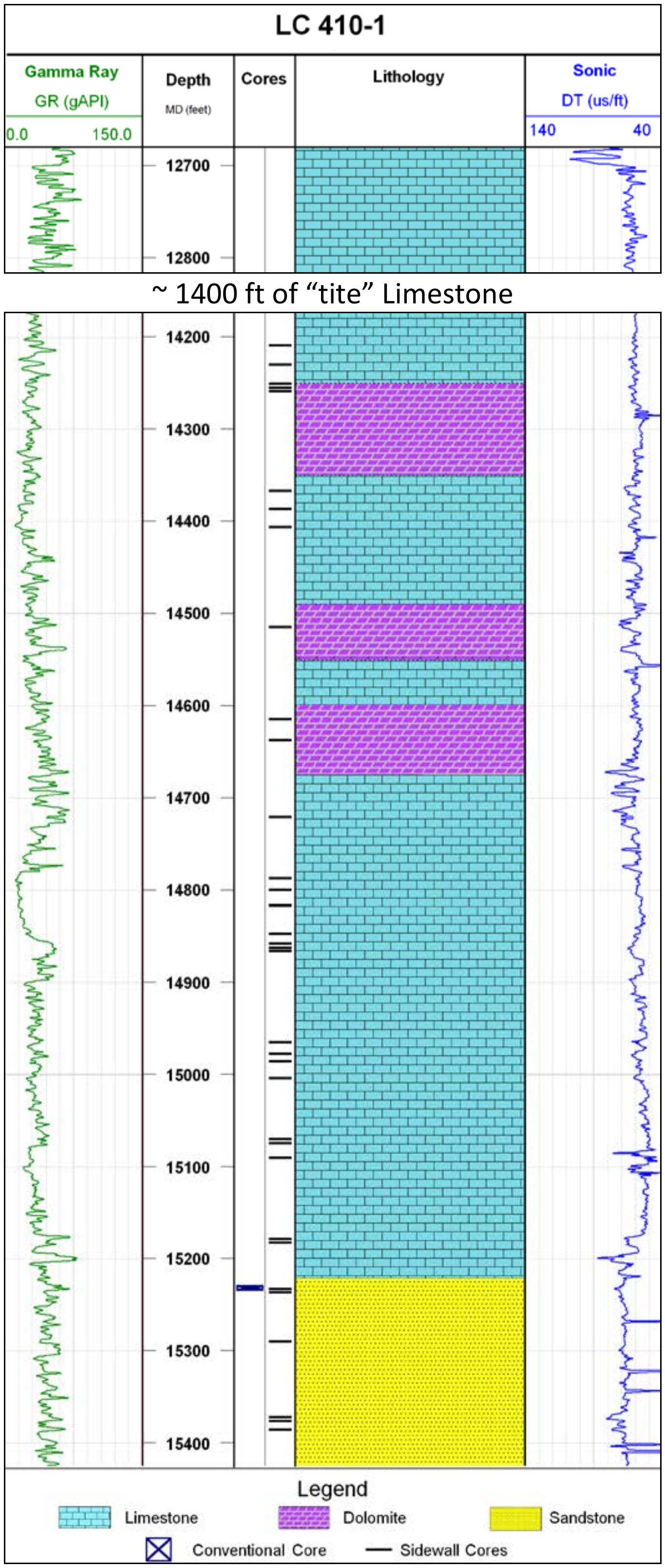

Figure 5. Well LC 410-1 target interval lithology is based on gamma ray and sonic logs, conventional and sidewall cores, and drill cuttings.

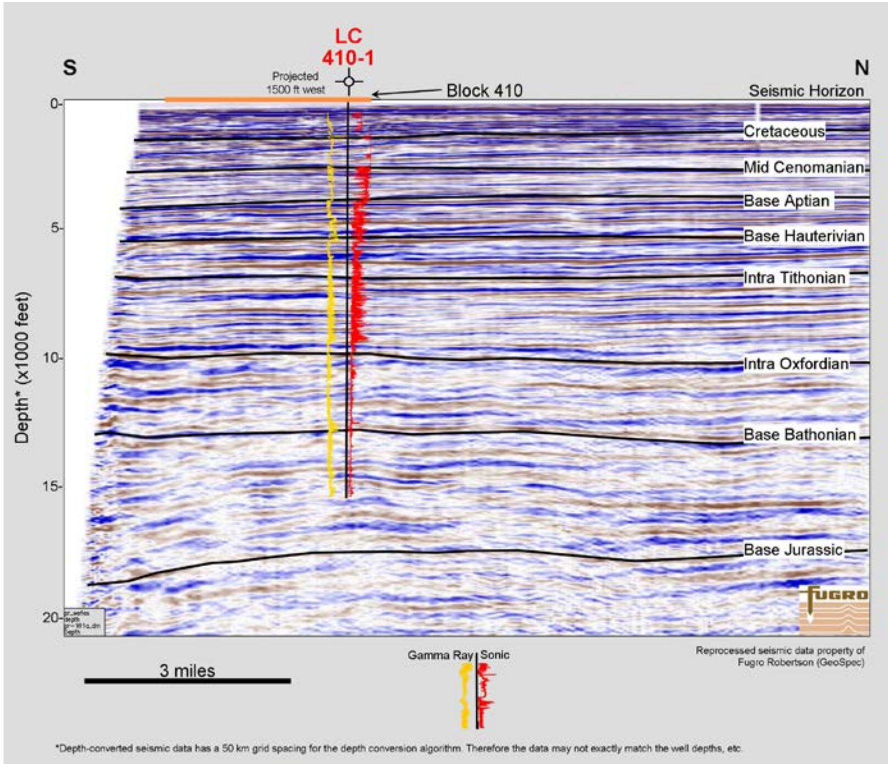

Figure 6. D-c, t-m seismic profile through LC 410-1 with interpreted horizons.

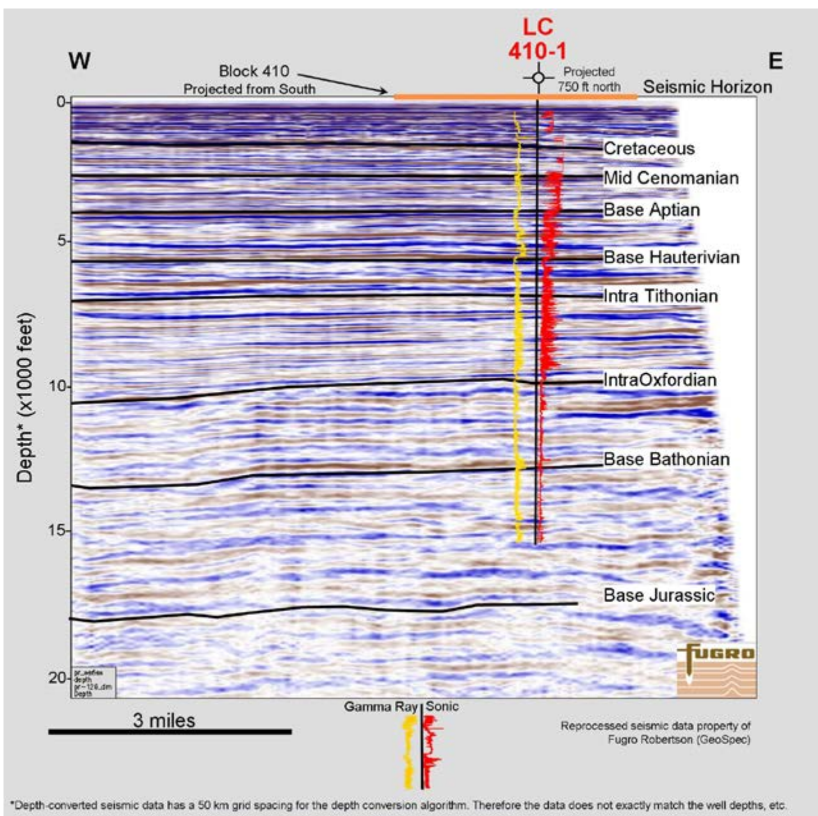

Figure 7. D-c, t-m seismic profile through LC 410-1 with interpreted horizons.

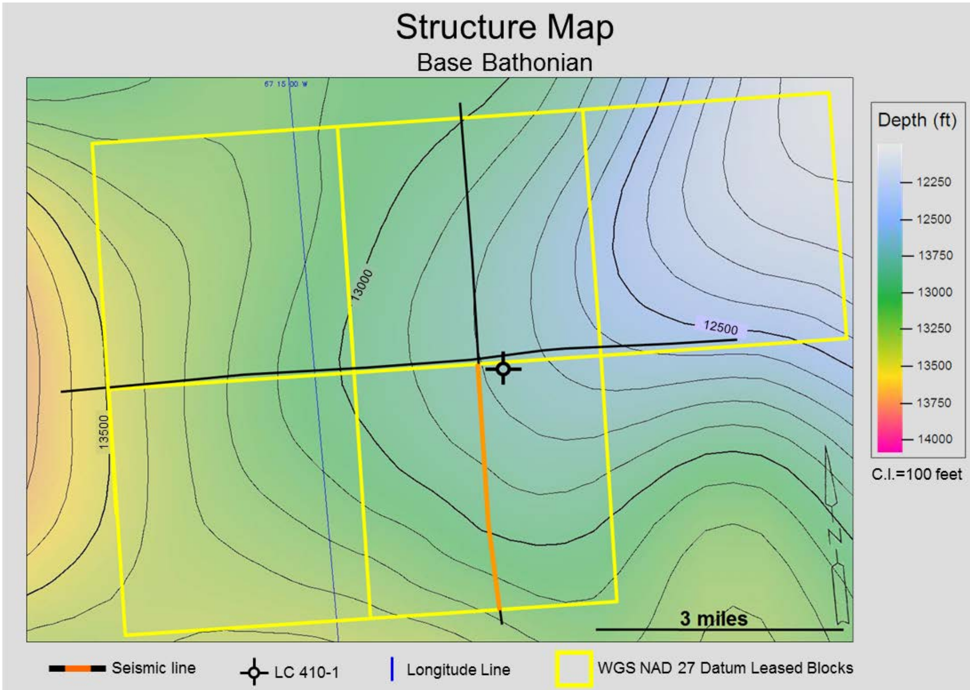

Figure 8. Structure map: datum Base Bathonian mapped horizon (Figures 6 and 7).

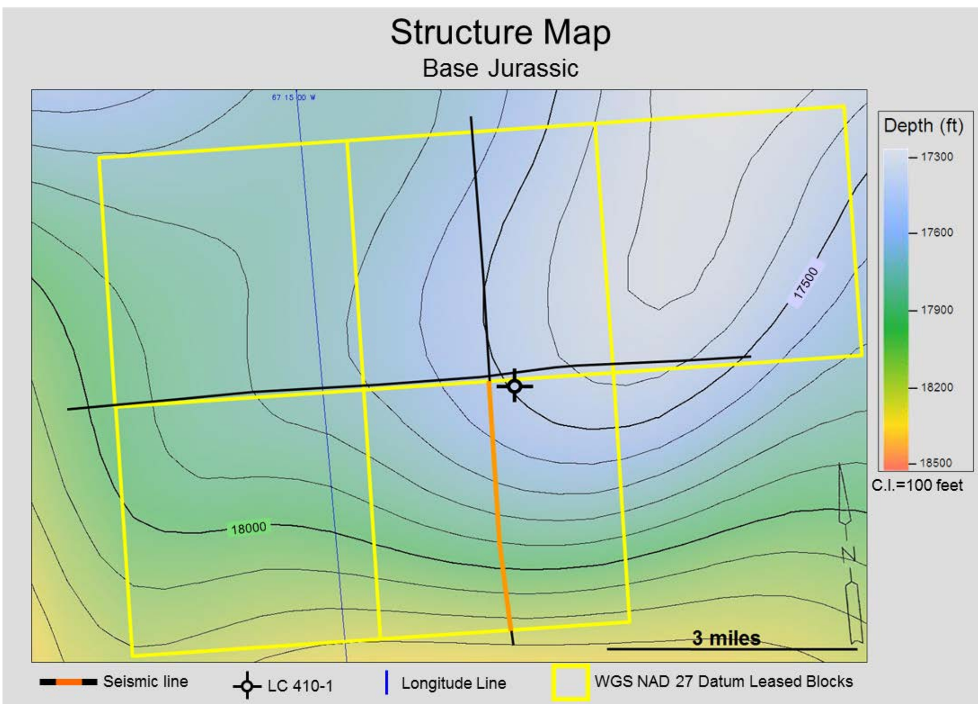

Figure 9. Structure map: datum Base Jurassic mapped horizon (Figures 6 and 7).

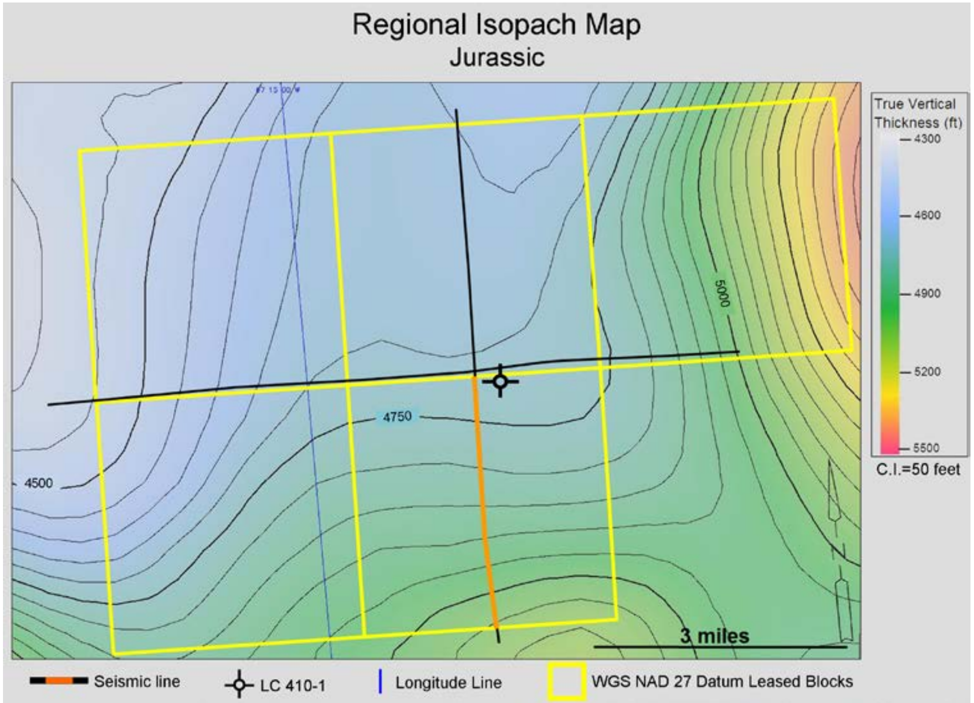

Figure 10. Regional Jurassic interval isopach map.

References:

Burkley, L.A., and Castaño, J.R. 1985. Alaska North Slope Oil-Source Rock Correlation Study in SG 20: Alaska North Slope Oil-Rock Correlation Study: Analysis of North Slope Crude. p. 95-121.

Carpenter, G., (ed.), 1984. Summary, Shell 410-1R. Minerals Management Service In-House Report, 144 p.

Edson, G.M., Olson, D.L., Petty, A.J. (eds.), 2000. Shell Lydonia Canyon Block LC 410 No. 1R Well; Geological and Operational Summary: MMS 2000-33, p. 1–58.

HBrothers. "Inflation Calculator." DollarTimes, 2012. DollarTimes. 27 July 2012. http://www.dollartimes.com/calculators/inflation.htm

Magoon, L.B., and Dow, W.G., 1994. The Petroleum System: AAPG Memoir 60, p. 3–24.

Peters, K. E., 1986. Guidelines for evaluating petroleum source rock using programmed pyrolysis: AAPG Bulletin, v. 70, p. 329.

Pimmel, A., and Claypool, G., 2001. Introduction to shipboard organic geochemistry on the *JOIDES Resolution. ODP Tech. Note,* 30. doi:10.2973/odp.tn.30.2001

Shell, 1981. Various reports submitted to the USGS including the Plan of Exploration, Application for Permit to Drill, Geochemical Reports, etc.