

**BOEM 2016-028**

# **Atlantic Well Folio: Georges Bank Basin**

## **Lydonia Canyon Block 357 No. 1 Well**

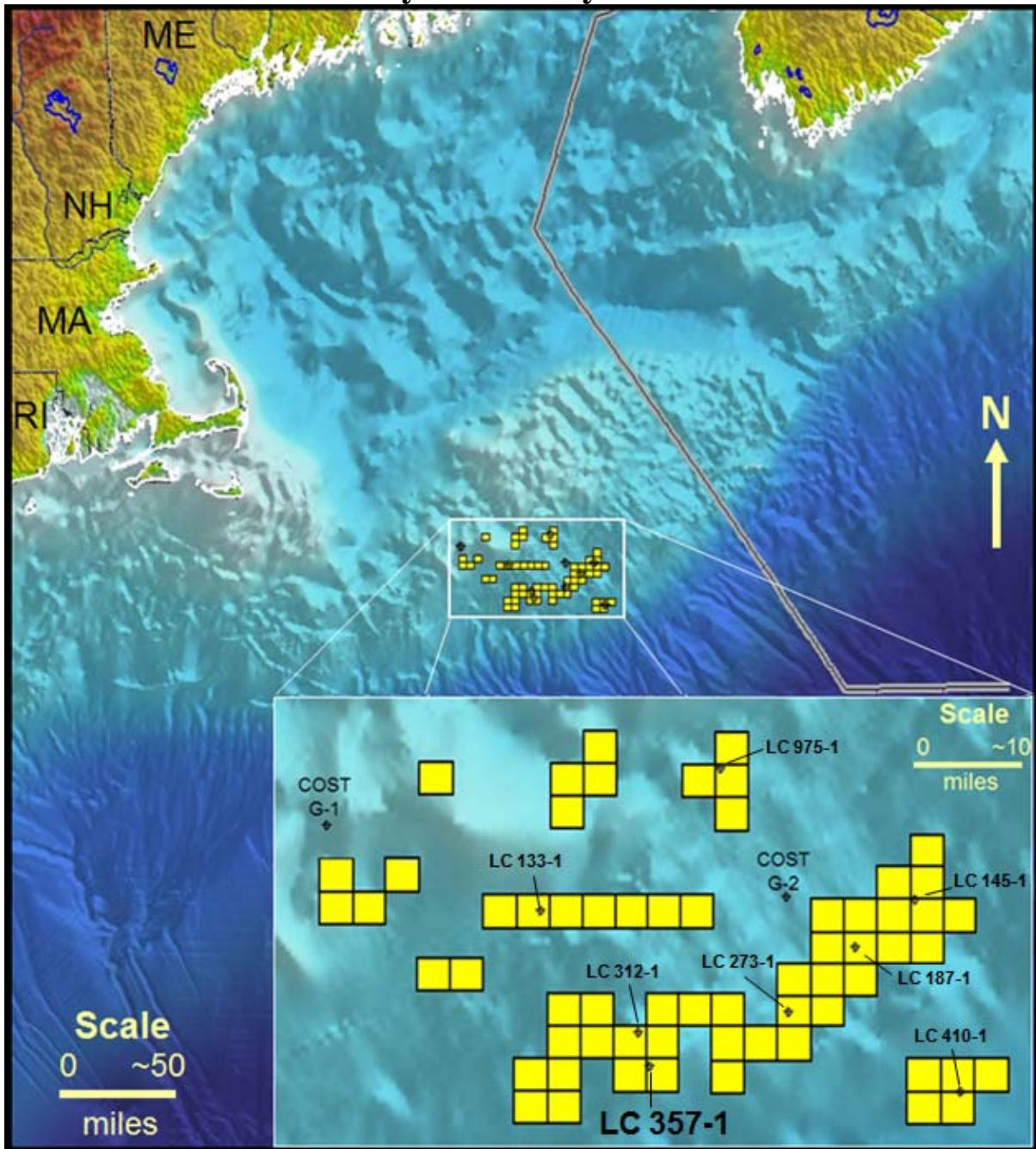
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**BOEM**  
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## 1.6. Lydonia Canyon 357-1



**Figure 1.** Location map of Georges Bank Basin (GBB), offshore Massachusetts, USA. Well locations are indicated by the symbol  $\oplus$ . Leases previously held in the area are shown in yellow.

Lydonia Canyon (LC) Block 357 was leased by Shell Oil Co., Phillips Petroleum Co., Cities Service Co., and The Louisiana Land & Exploration Co. at OCS Sale 42 in 1979. The semi-submersible *Zapata Saratoga* spudded the first new field wildcat well on the block on April 14, 1982 in 265' of water to evaluate a structural anticline prospect with carbonate reservoir objectives. Permitted to 20,000', the well reached a total depth (TD) of 19,427' and was completed on September 27, 1982 (Shell Oil Company, 1982a). (All depths in this report are measured depth unless otherwise specified.) LC 357-1 was the 6<sup>th</sup> industry well spudded in the Georges Bank Basin (GBB) (Fig. 1), but the last to be completed due to taking 167 days to drill and complete. The second Continental Offshore Stratigraphic Test (COST) well in GBB, COST G-2, is approximately 20 miles northeast of LC 357-1. COST G-2 provided predrill information for LC 357-1, including an estimate of reservoir parameters (MMS staff, 1984). The decision to lease and drill was based on good quality 2-D seismic coverage. LC 357-1 was located at latitude 40° 36' 51.196" N and longitude 67°44' 40.419" W (Shell Oil Company, 1982b) or ~18 miles from the present-day shelf edge (Edson, *et al.*, 2000) near seismic line gb\_75-16.

LC 357-1 was unsuccessful because anticipated carbonate reservoirs had low porosity and permeability, and the total organic carbon (TOC) content of the mature strata drilled was too low to constitute viable source rocks for the expulsion of commercial volumes of hydrocarbons. The lease expired on January 31, 1985 (Edson *et al.*, 2000).

### 1.6.1 Objectives and Concepts

In the APD, Shell Oil Company (1982c), stated: "Hydrocarbon trapping in Block 357 is believed to exist in a simple structural closure occurring especially in carbonate horizons at the Jurassic level. The anticlinal structure appears to be an expression of a deeper positive feature which possibly is a salt pillow diapir." These Late and Middle Jurassic carbonate reservoirs (Table 1 and Fig. 2) were expected between ~15,700' and ~19,800' (Fig. 3); and the anticlinal closure, only part of which is on LC 357, is depicted in Figure 4. The target intervals are labeled JII and JIII on the submitted seismic line (Fig. 5). JII is just below the BOEM interpreted base Bathonian, or Sequence Boundary (SB) 2, and JIII is about halfway between the "pre-mid Jurassic" (SB1) and SB2 (Figs. 5 and 6). The Minerals Management Service (MMS), a BOEM precursor organization, presale tract evaluation was 0 hydrocarbons for the resource/reserve estimate (MMS staff, 1984).

### 1.6.2 Results

#### *Drilling*

Located 140 miles southeast of Nantucket, MA (MMS staff, 1984), LC 357-1 was essentially a straight hole (Shell Oil Company, 1982a). There was a significant mud log gas show of 1,375 units in a thin interval between 18,760' and 18,770', identified as a silt-filled, limestone fracture zone (MMS staff, 1984). There were several other indications of gas seen on the mud log; however, they were insignificant, the largest shows averaging just a few units each. No well tests (formation, production, or drill-stem) were made (MMS staff, 1984).

Porosity and permeability were measured at 38 locations on 34' of conventional core taken at two intervals

from 18,815'–18,842' and 19,399'–19,406' (Shell Oil Company, 1982d). Porosities and permeabilities were very low in both cores (Table 2). There were also 44 sidewall cores recovered between 15,189' to 18,782'. However, only at 18,762' and 16,435' were porosities reported, these being 3% and 1% respectively. No permeabilities were measured (Shell Oil Company, 1982e). Porosities determined by geohistory modeling and estimated from wireline logs, while in good agreement with one another, were higher than the core values, with discrepancies between the wireline logs and the cores being on average ~5%. Those porosities directly measured from the conventional cores are accepted as being more representative of the actual porosity of the strata. However, due to their very limited, focused locations, log estimated porosities are used where conventional cores are not available with the caveat that they are likely to be too high. The discrepancy between geohistory modeling and core porosity could be due to diagenetic cementation, mineral replacement, and/or fracture fill. The sidewall core report describes calcite recrystallization and secondary chert, along with dolomite and anhydrite fracture fill in many of the samples.

Cuttings were acquired from ~500' to TD. Sample intervals were 30' down to 13,020', and 10' for the balance of the well (Edson, *et al.*, 2000). Lithologic descriptions were made from the cuttings. The Early Cretaceous, beginning at 3,298', consists of predominately sandstone and siltstone with small amounts of limestone. The Jurassic, whose top is picked at 6,398', becomes increasingly more carbonate-rich with depth. Over 90% of the Middle Jurassic is limestone and dolomite. The dipmeter shows shallow dips for much of the well. However, from ~15,500' (near the JII horizon of Shell

*et al.*) through ~17,600' the dip steepens from ~2° to >20°, while the dip direction continues to be predominately west and southwest. The steeper values, also seen on the seismic (Fig. 6), correspond with the shallowest expression of the targeted structure.

#### *Seismic Interpretation*

Shell identified and interpreted 3 strong seismic reflectors in the Jurassic carbonate objective interval, and submitted maps on these horizons (Fig. 4). From shallow to deep the JII, JIII, and JIV were interpreted between 2.8 and 3.6 seconds two-way travel time as seen on Figure 5. Shell interpreted the top of the targeted anticlinal closure at ~2.8 seconds. With the JIII at ~3.4 seconds, the zone of interest is from ~15,700' to ~19,800'.

Four Late to Early Jurassic horizons, between 8,000' and 22,500' were mapped by the MMS when reviewing the lease bid and the proposed well. Closure was mapped on only one of the Middle to Early Jurassic horizons (MMS staff, 1984). According to MMS staff (1984), Shell's primary target, a seismic reflector at 15,872' (JII) was interpreted as a Jurassic reef, with other possible objective zones of Jurassic carbonates anticipated at 11,222' and 19,672' (JIII). Shell's publically stated objectives did not include the middle target and did not label the shallower JII as a reef (Shell Oil Company, 1982c).

Mapping completed for this folio was based on 8 sequence boundaries (SBs) initially identified and interpreted by GeoSpec, a CGG company, on GeoSpec's seismic interpretation of the U.S. Atlantic OCS (GeoSpec, 2003) and in the two COST wells and 5 industry wells in the GBB. One of the 5 wells was the LC 312-1, located ~3 miles to the north-northwest. LC 357-1 was correlated with and seismically tied to LC

312-1 to obtain the depths for the SBs used in this report.

Structure maps on the intra-Oxfordian (SB3), and “base of mid-Jurassic” (SB1), and an isochore between these were among those constructed (Figs. 7, 8, and 9) using GeoSpec’s depth-converted, time-migrated seismic data. Shell’s JII is near the SB2, a base Bathonian SB (Fig. 6), and their JIV is near SB1 (Figs. 6 and 8). The SB1 map shows closure on this more steeply dipping horizon (Fig. 8). However, by SB3, seismic events flatten as the structural relief diminishes upward in the stratigraphic section (Fig. 6), as documented by the dipmeter in the description above. Figure 9, the isochore between SB1 and SB3, also depicts the feature tested by the well.

#### *Biostratigraphy and Paleoenvironment*

The only paleontological data on the well is the report submitted by Shell, which contained a table of 17 sample depths and interpreted geologic ages; *e.g.*, Campanian, *etc.* (Shell Oil Company, 1982f). Therefore, paleobathymetry determination for geohistory modeling relied on well correlations with LC 357-1 and LC 312-1. Formation determinations were also made via wireline log and seismic correlation with LC 312-1 where formations were identified by GeoSpec. Depositional environments, as well as lithology, were based on analysis of the mud logs, neutron-density crossplots using Log Evaluation System Analysis (LESA) software (Fig. 3), sidewall and conventional core description, and GeoSpec’s work on adjacent wells (Table 3).

#### **1.6.3 Operations and Costs**

Shell Oil Company operated the LC 357-1 well with a 37% interest. Philips Petroleum Company and Cities Service

Company each owned 24%, and the Louisiana Land & Exploration Company owned 15% (Shell Oil Company, 1980). Block 357 was leased during OCS Sale No. 42 on December 18, 1979 for \$17,611,000 (Shell Oil Company, 1980), equivalent to \$61,082,000 in 2015 dollars (HBrothers, 2015). Our mapping indicates the prospect interpreted to have been tested by LC 357-1 (orange outline in Figs. 7, 8, and 9). Bonus bids for prospect blocks LC 356 (\$8,797,000), LC 357, and LC 313 (\$15,392,000) totaled \$41,800,000 in 1979 or \$144,980,000 in 2015 dollars (HBrothers, 2015).

Total well costs were unavailable. However, LC 410-1 in GBB was also drilled using the *Zapata Saratoga*, and its daily average rig costs were \$123,505 (MMS staff, 1984), \$336,042 in 2015 dollars (HBrothers, 2015). Using this daily rate and the 167 drilling days it took for LC 357-1, \$56,119,014 would be a reasonable estimate for the total drilling and completion costs for the well in 2015 dollars (HBrothers, 2015).

#### **1.6.4 Petroleum Systems 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 includes thermal or biogenic gas ... or condensates, crude oils, and asphalts found in nature (Magoon and Dow, 1994).

Petroleum system elements are: source rock, reservoir rock, seal rock, and overburden rock (a thick enough rock column above the deepest source rock interval to result in burial sufficient for temperatures to initiate hydrocarbon generation). Our guidelines for source,

reservoir, and seal elements are shown in italics in Table 4.

Petroleum system processes include trap formation and hydrocarbon generation-expulsion-migration-accumulation (Table 5), and preservation (modified after Magoon and Dow, 1994).

Timing is paramount in petroleum systems; *e.g.*, a reservoir in a sealed trap must exist when hydrocarbons are generated, expelled from the source rock, and most importantly migrate into, become entrapped and subsequently 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.

### *Geochemistry*

Shell conducted Rock-Eval pyrolysis, measuring  $T_{max}$  (a maturity indicator),  $S_1$  (a measure of free hydrocarbons), and  $S_2$  (a measure of hydrocarbons released upon heating and cracking of the kerogen) on samples from the LC 357-1 well. With these data, production index, a ratio of  $S_1$  to  $S_1$  plus  $S_2$ , and hydrogen index (HI) ( $(S_2/TOC) \times 100$ ) were calculated and used in the geohistory models and to estimate cumulative hydrocarbon volumes.  $S_3$  was not measured (Shell Oil Company, 1982g). Therefore, the oxygen index (OI) ( $(S_3/TOC) \times 100$ ) needed to create a pseudo van Krevelen diagram identifying kerogen kinetic types using pyrolysis data, in which OI is plotted against HI, could not be plotted. However, an  $S_2$  vs. TOC plot can also be used to characterize kerogens from pyrolysis data. This was done and used (Fig. 10).

TOC and vitrinite reflectance ( $\%R_o$ ) were measured on samples from LC 357-1.  $\%R_o$  is a maturity indicator, measuring under a microscope the percentage of

incident light reflected from a polished surface of vitrinite (U.S. Dept of Interior BLM, 2014). Visual Kerogen Analysis (VKA) is visual, microscopic determination of various kerogen types present in a sample with a percentage of each type estimated. Objectivity and consistency between samples is a priority for both of these inherently subjective methodologies. There were 56 usable  $\%R_o$  values for geohistory modeling that resulted in the oil and gas window depths (Shell Oil Company, 1982g).

Shell's Geochemistry Report contains 62 TOC values measured from cuttings and 10 from core, reported here as present-day values (Shell Oil Company, 1982g). Sixteen (16) TOC data points were removed due to the values being higher than reasonable (16.7% or greater), and attributed to coal, as trace and occasional lignite is commonly seen in the mud logs from 2,100' down to 13,800'. These coals have not been established as source rocks for conventional petroleum accumulations on the U.S. Atlantic Margin. TOC values between 1 and 2% are common in the shallow half of the well (Shell Oil Company, 1982g). However, below ~10,000' the values are very low, averaging 0.22% after values attributable to coals are removed. If these coal-related TOCs are not removed, the measurements below 10,000' still average a low 0.47%. The main gas generation window ( $\%R_o > 1.3$ ) is near the bottom of the well at 17,200' (Shell Oil Company, 1982g).

VKA was performed on 47 cutting samples from 1,330'–18,310'. Shell's visual kerogen analysis strongly disagrees with the more objective Rock-Eval pyrolysis data and the  $S_2$  vs. TOC graph. The VKA suggests that Type III kerogen comprises 51%, Type I 42%, and the balance Type IV (6%) and Type II (1%) for the well from 1,330 to 18,817'. We believe the Rock-Eval data to be more accurate, determining the

most significant aspect of kerogen characterization, their kinetic behavior under thermal stress. The derived HI values, which are quite low, show the kerogens to be largely gas-prone (Peters and Cassa, 1994). This would indicate that the percentage of Type III kerogens is significantly higher, and that Type I kerogens, if present, based on their kinetics are very minor. Kerogens fitting the VKA results and Rock-Eval predictions were both modeled separately. It was only when modeling with the higher Type III percentages that hydrocarbon generation fit the gas shows documented in the mud log.

#### *Exploration Implications*

1. TOC values between ~1.4 and ~2.0% occur in immature Cretaceous Campanian–Aptian units above ~4,500'. Between ~6,500' and ~10,000', TOC values above 1% are found in Late Jurassic Tithonian–Kimmeridgian strata. This interval is modeled to be in the early maturity oil generation stage; *i.e.*, %R<sub>o</sub> 0.5–0.7, within which hydrocarbons may be generated. However, the low level of maturity and the gas-prone nature of the kerogens, results in source rocks from which limited hydrocarbons have been generated, and none expelled (Katz, 2012). From ~10,000' to TD, the TOC values are very low (~0.2% average). Only a few TOC values reach or exceed 1%, and these are likely due to contamination from uphole cavings and lignite (Shell Oil Company, 1982g). The HI values and S<sub>2</sub> vs. TOC crossplots (Fig. 10) indicate that all the kerogens encountered in the well are gas-prone. Depths at and below ~17,200' are within the gas generation stage of maturity (%R<sub>o</sub> >1.3). However, this section is organically lean. Consequently,

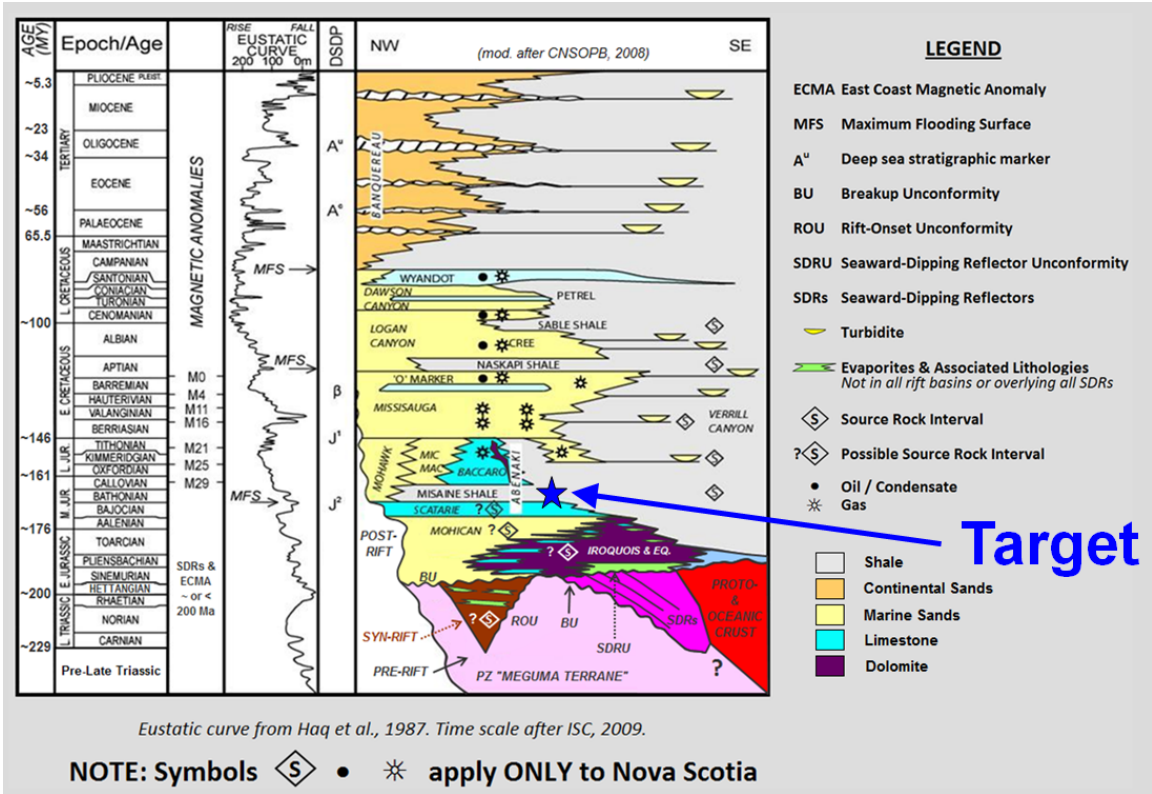
modeling indicates that although hydrocarbon generation has occurred, expulsion has not. Table 6 cites these deficiencies in the post-drill results section.

2. While better than some of the other wells in GBB, the reservoir porosity and permeability below ~14,000' (Middle Jurassic Bathonian–Bajocian), and through the target reservoir interval, are generally less than 5%, and where not fracture-enhanced, <1.0 mD, respectively. Porosity averages 1.2% from the conventional cores covering 18,815'–18,842' and 19,399'–19,406'. The best reservoir rock is in Jurassic and Cretaceous strata above 12,000' (Shell Oil Company, 1982d). The shallowest measured porosity available is from a sidewall core at 16,435' with a value of 1% (Shell Oil Company, 1982e). Geohistory modelling suggests that the depth-related porosity reduction of the Middle Jurassic Carbonates may be due to more than just compaction. Pore space occlusion due to diagenetic fluids depositing cements, and/or low primary porosity from the increasingly microcrystalline carbonates may explain the poor reservoir qualities at target depths.

#### **Acknowledgements**

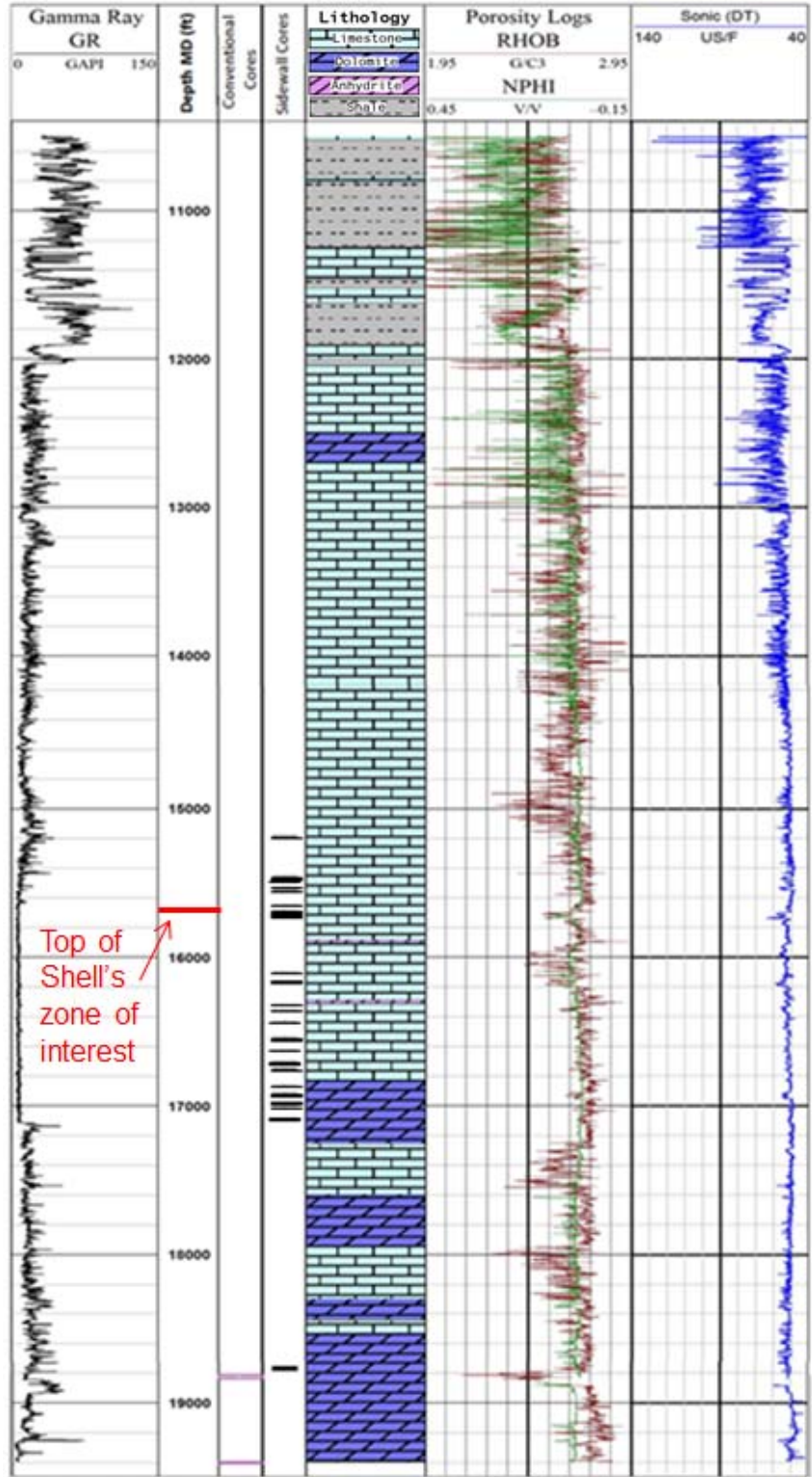
The support of BOEM management and staff: R. Poling and M. Wilson are gratefully acknowledged. We are grateful to GeoSpec, a CGG company, for allowing the publication of their reprocessed, depth-converted, time-migrated seismic data and derivative maps produced by BOEM staff from this data. The assistance of J. Danford and M. Paton of GeoSpec is greatly appreciated.



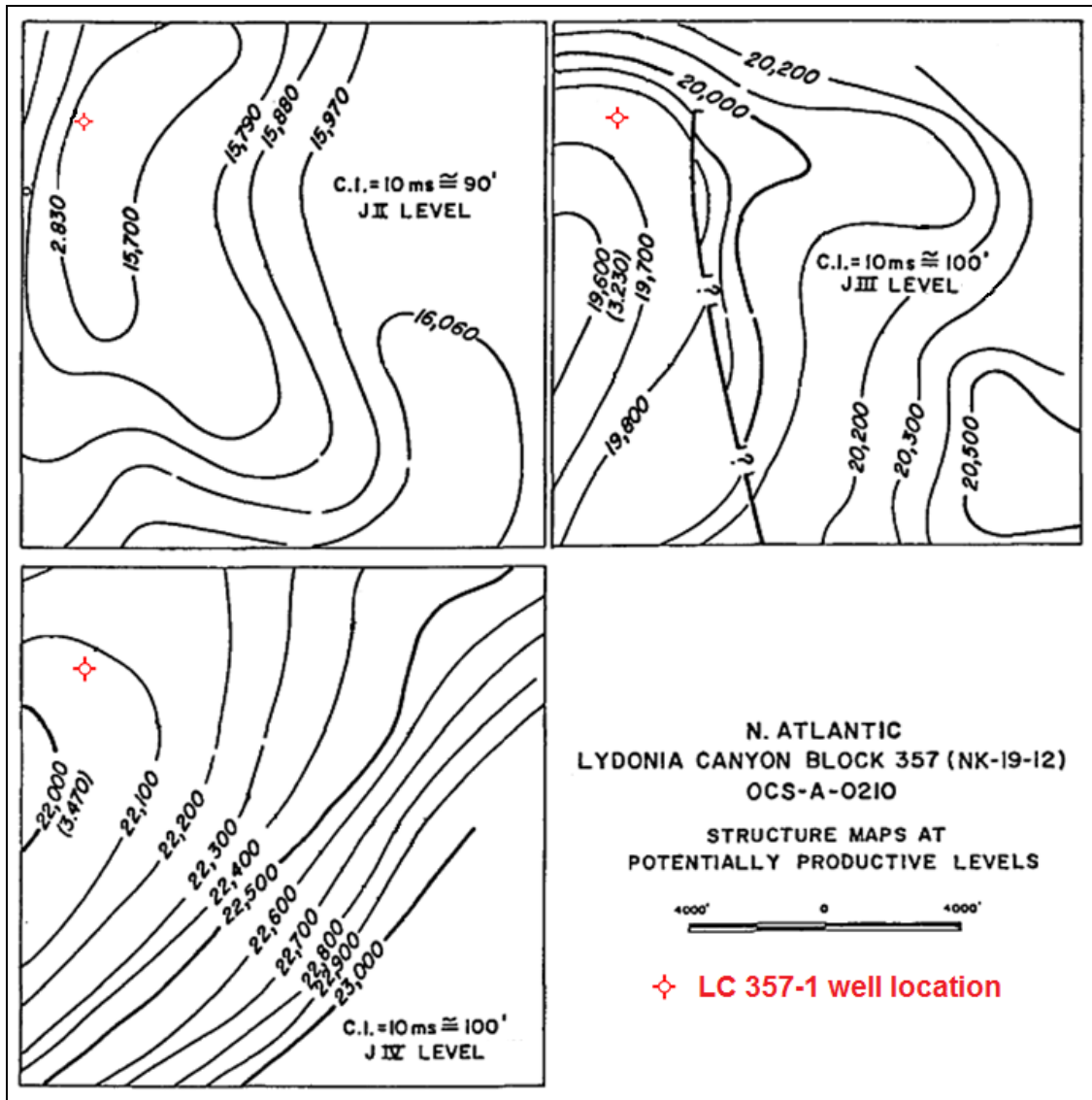


**Figure 2.** Stratigraphic chart showing the target interval for Shell’s LC 357-1.

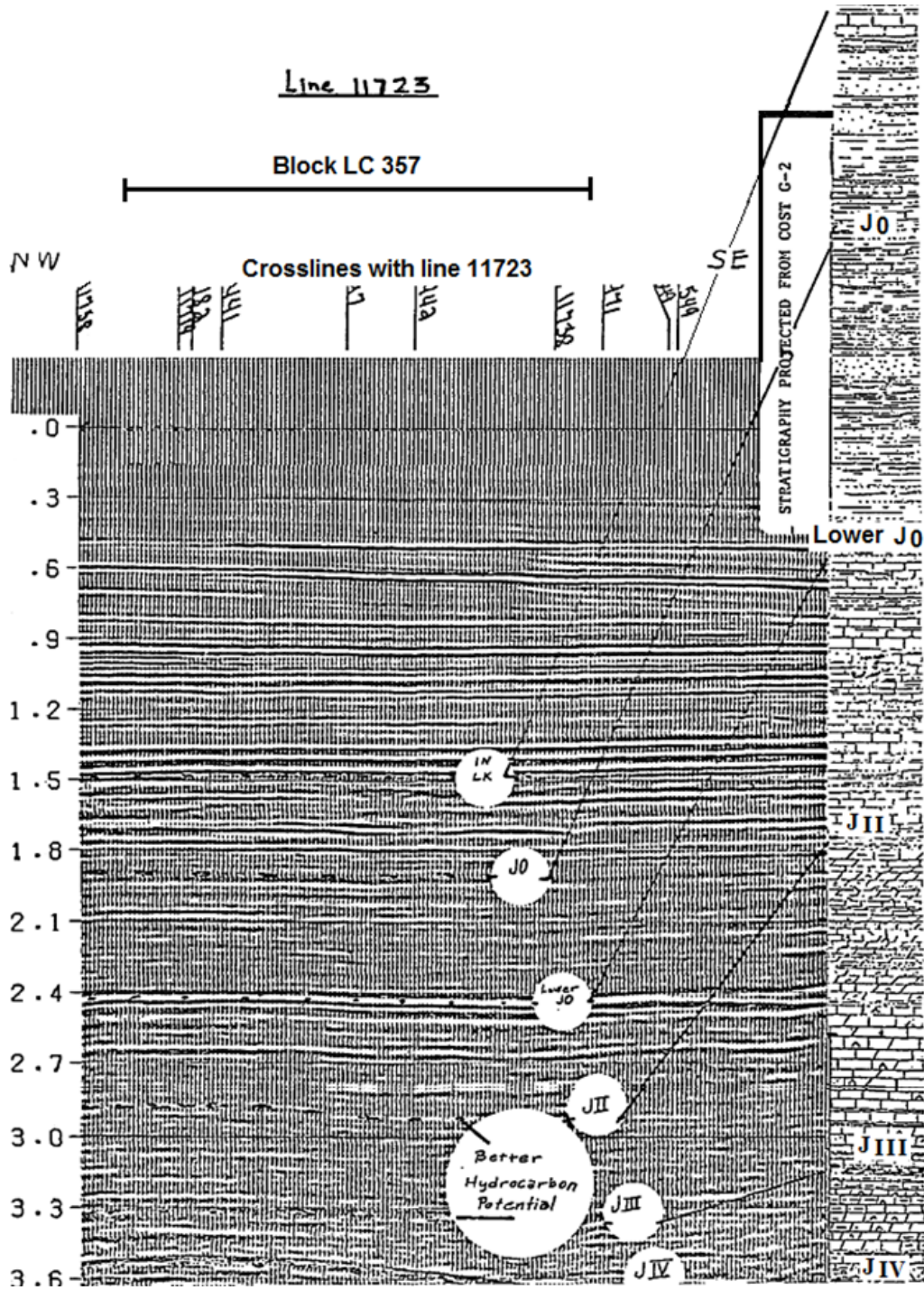




**Figure 3.** Objective zones for well LC 357-1 with interpreted lithologies based on mud logs, sidewall and conventional core descriptions, and a crossplot of neutron and density curves. Locations of conventional cores and sidewall cores are also shown.

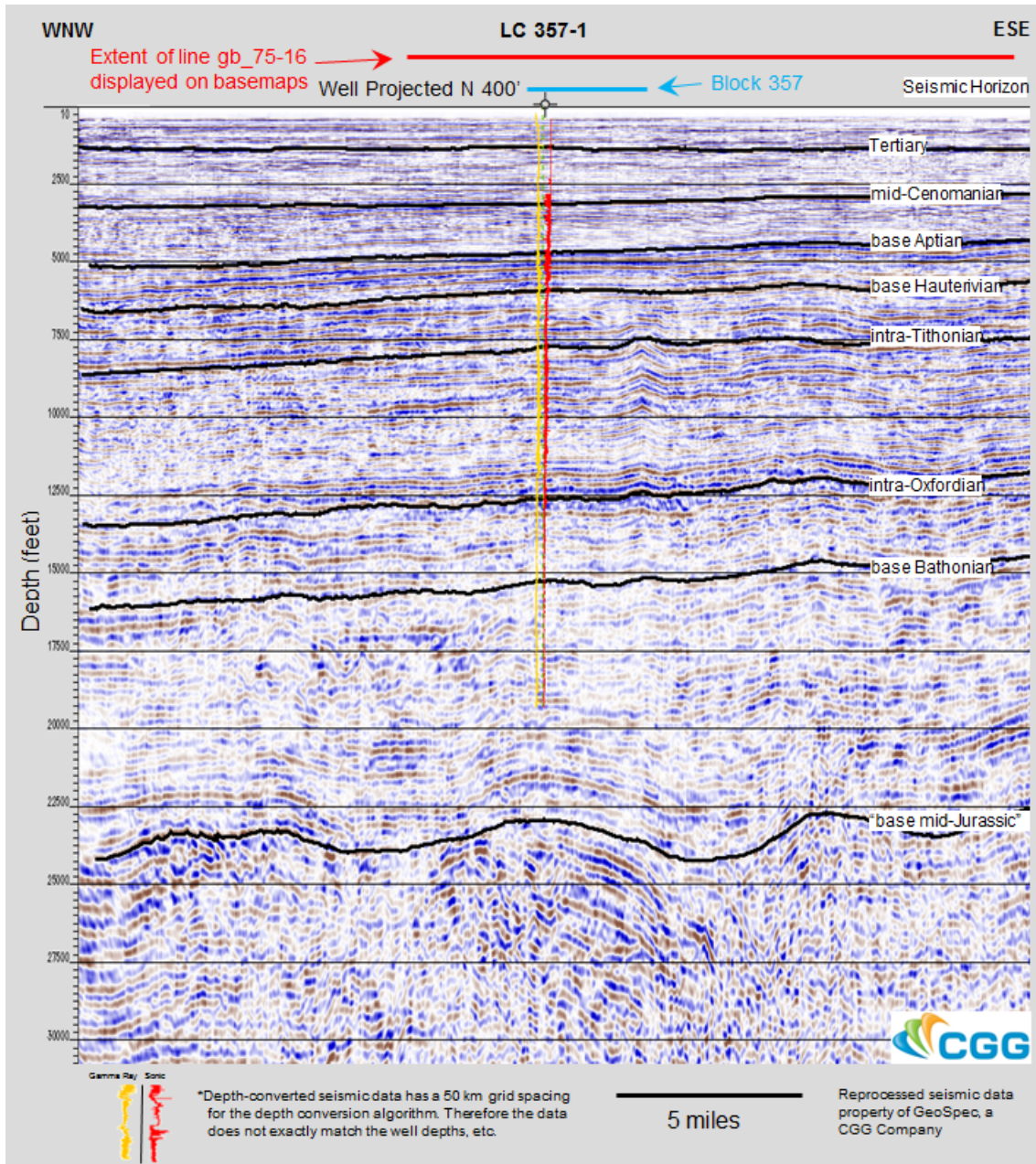


**Figure 4.** Structure maps covering block 357 showing Shell's JII, JIII, and JIV horizons (modified from Shell Oil Company, 1982c).

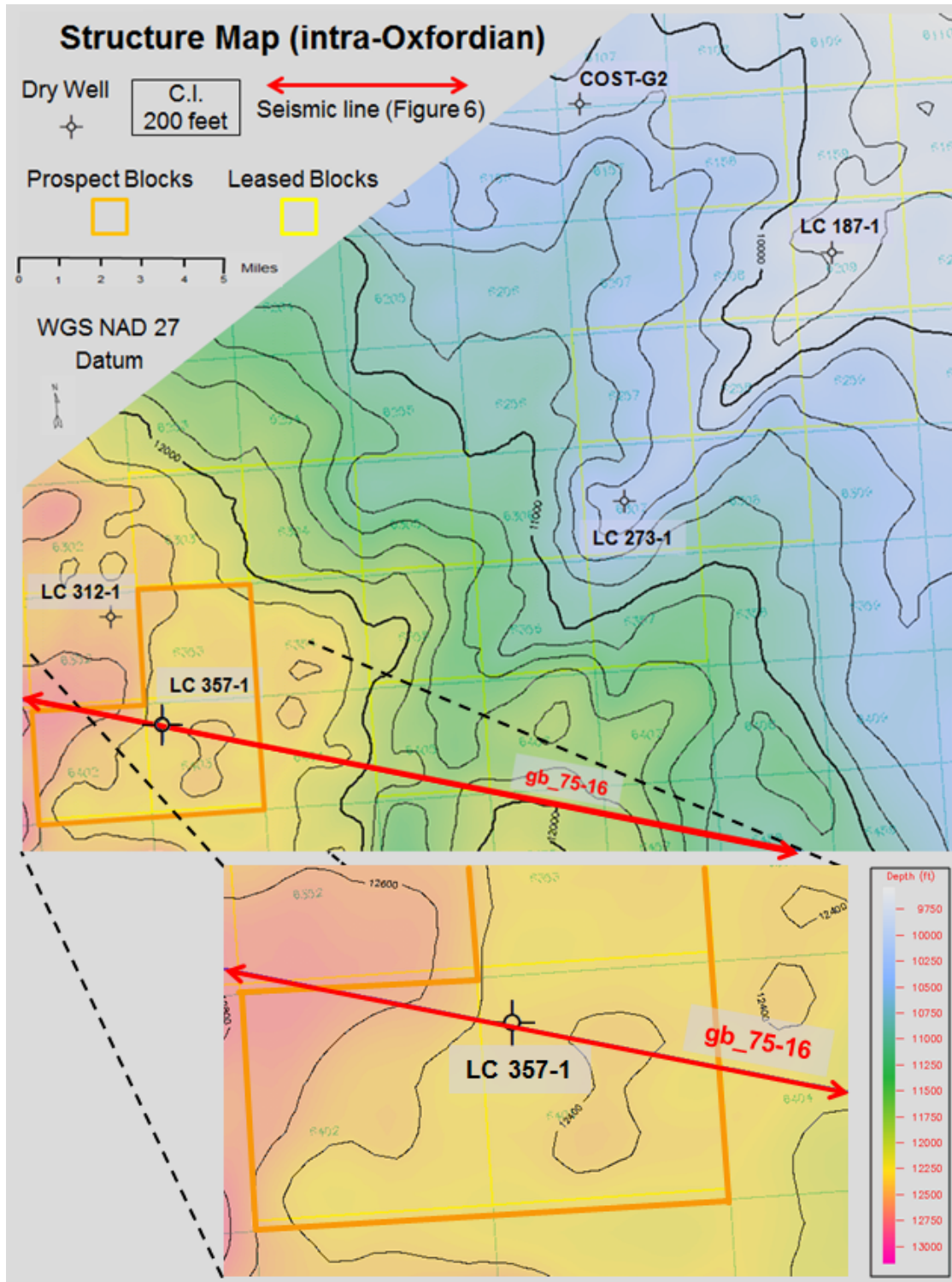


**Figure 5.** Seismic cross-section of a NW–SE trending line submitted by Shell with their APD. Shell’s horizons are marked on the seismic correlated onto their lithology chart for COST G-2 (modified from Shell Oil Company, 1982c).



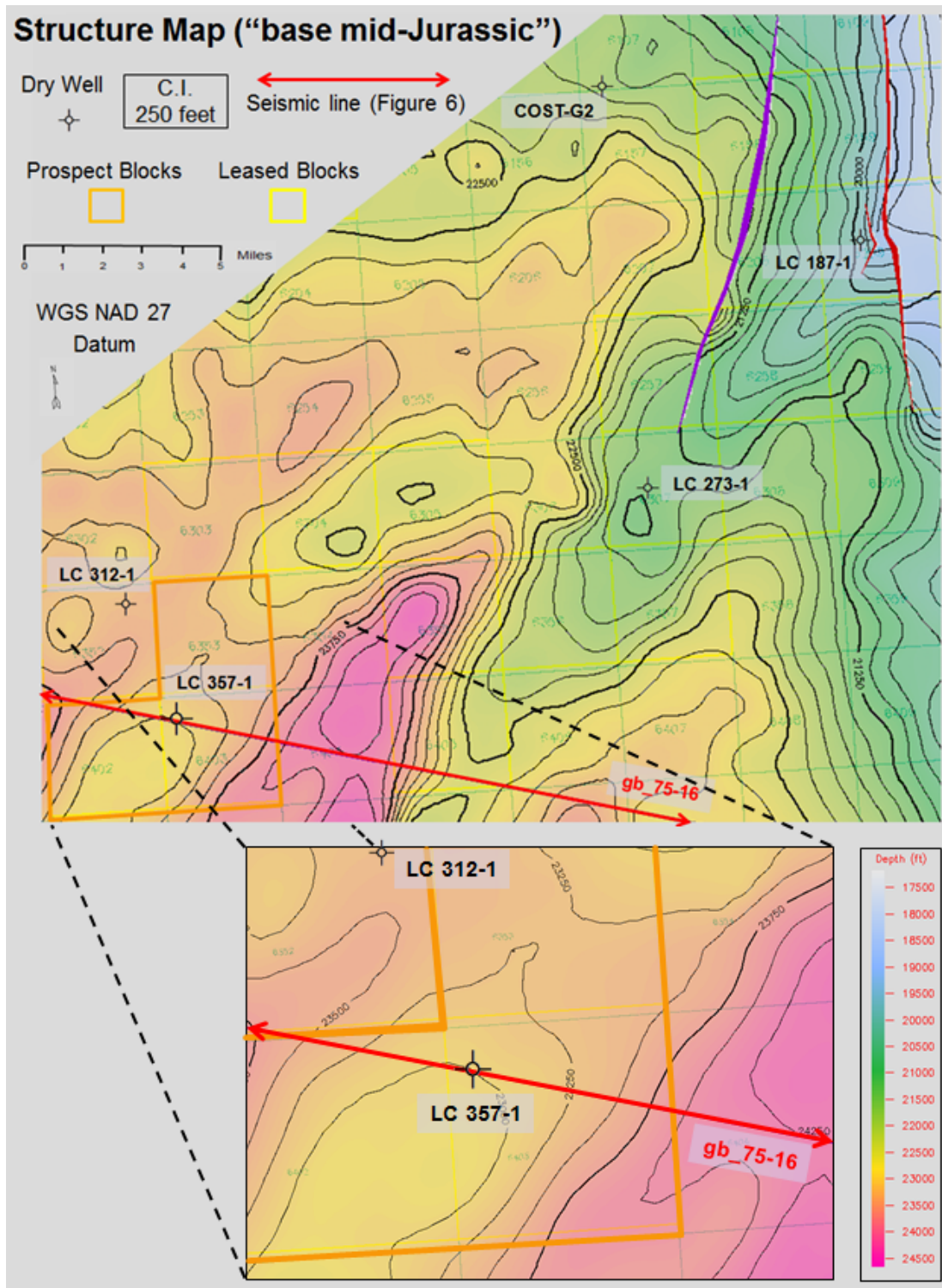


**Figure 6.** Seismic profile of line gb\_75-16 (west-northwest to east-southeast) with interpreted horizons (in black). Structure maps of the intra-Oxfordian (SB3) and “base mid-Jurassic” (SB1) horizons are shown in Figures 7 and 8. Figure 9 is an isochore between SB3 and SB1.

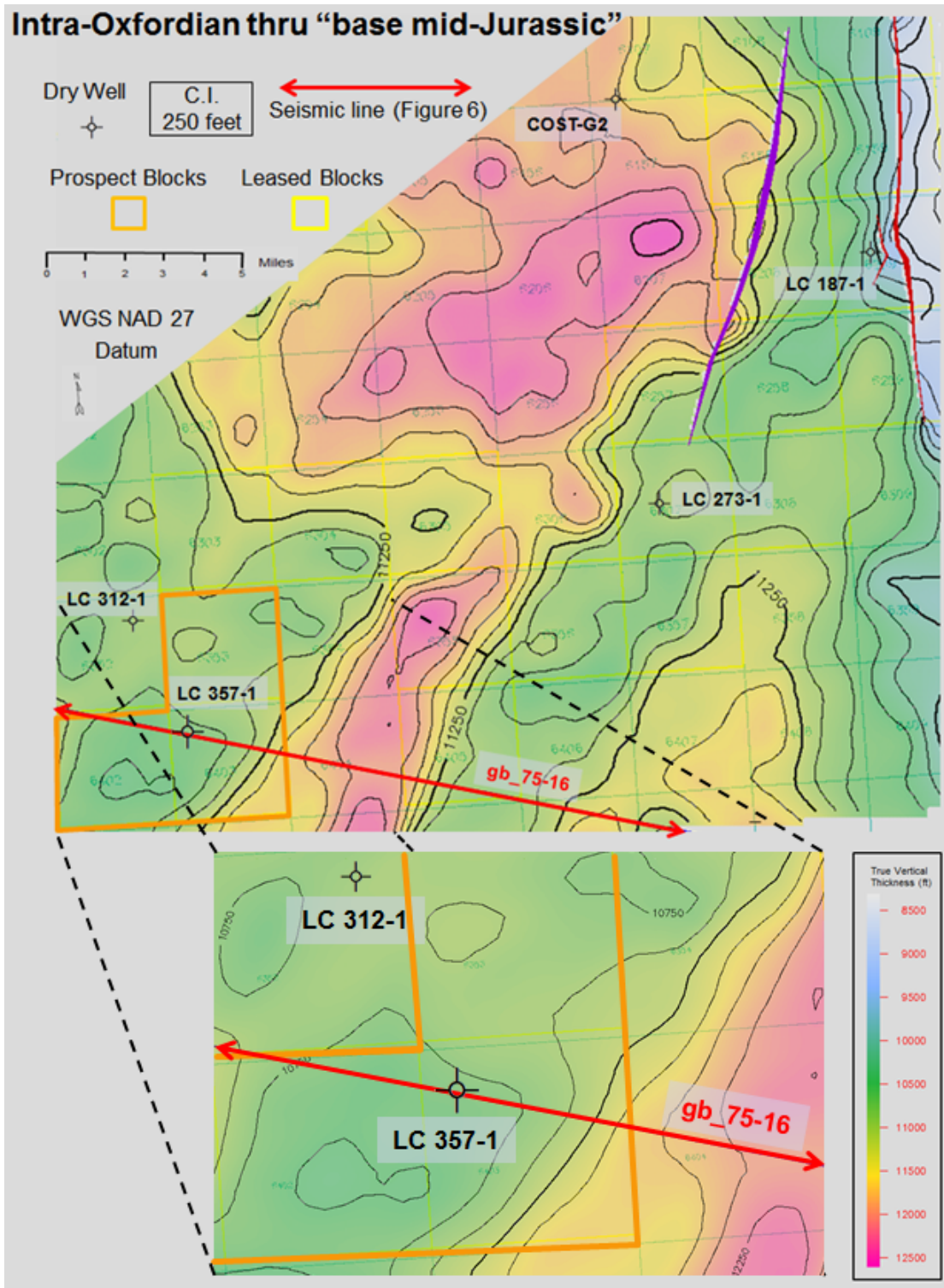


**Figure 7.** Structure map of intra-Oxfordian (SB3). Orange lines delineate the prospect LC 357-1 tested. A portion of the seismic line in Figure 6 (gb\_75-16) is shown in red.



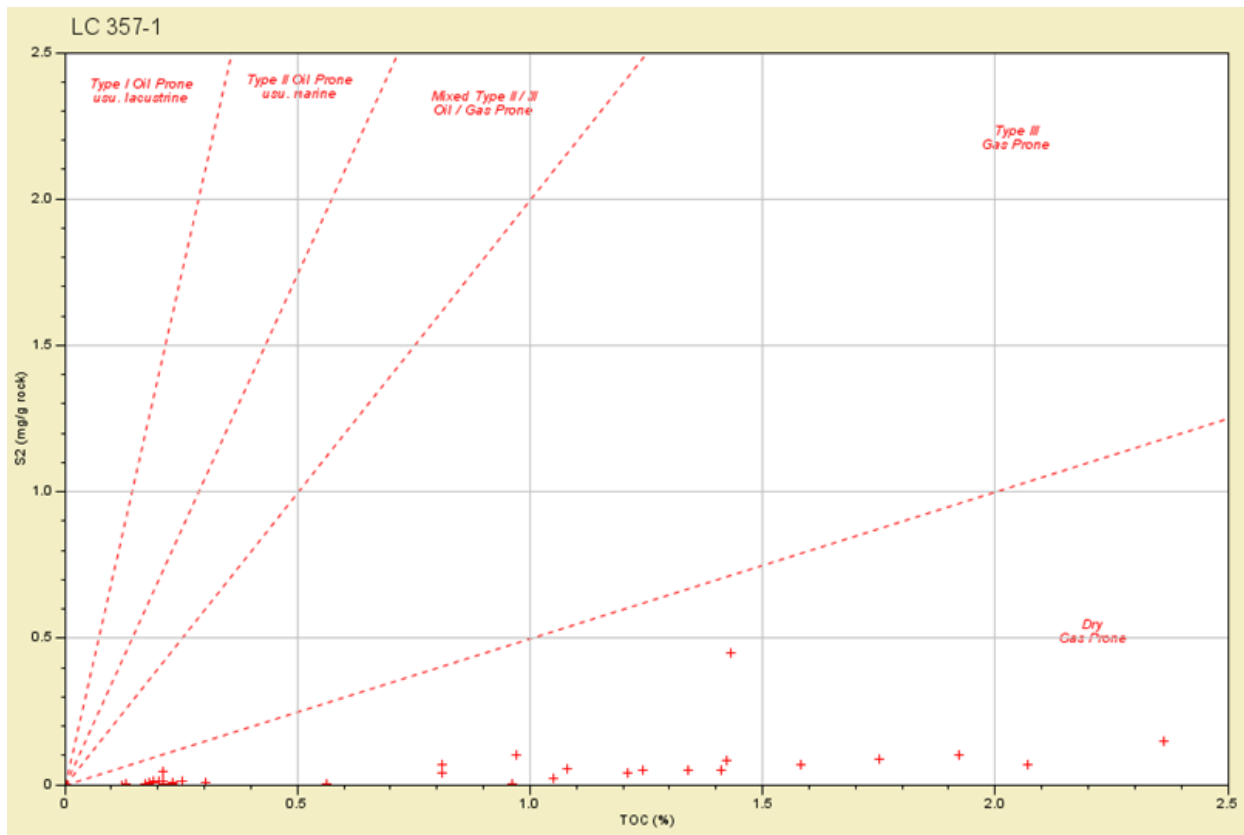


**Figure 8.** Structure map of "base mid-Jurassic" (SB1). Orange lines delineate the prospect LC 357-1 tested. A portion of the seismic line in Figure 6 (gb\_75-16) is shown in red.



**Figure 9.** Isochore map from the intra-Oxfordian (SB3) to “base mid-Jurassic” (SB1). Orange lines delineate the prospect LC 357-1 tested. A portion of the seismic line in Figure 6 (gb\_75-16) is shown in red.





**Figure 10.** S<sub>2</sub> vs TOC crossplot showing the prevalence of gas-prone (Type III) and inert (Type IV) kerogens.

**Table 1.** Wells drilled in Georges Bank Basin

<b>Well</b>	<b>Date</b>	<b>Target</b>	<b>Actual</b>
COST G-1	1977	n/a	n/a
COST G-2	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	Jurassic Closure	Jurassic Closure poor porosity
LC 312-1	1982	Callovian Reef	“Tite” micritic Limestone
LC 187-1	1982	Jurassic age Limestones and Dolomites	Reservoir of poor quality
LC 145-1	1982	Jurassic Porous Shelf edge Calcarenites and Jurassic Carbonates	“Tite” micritic Limestones
LC 273-1	1982	Four way closure, Jurassic oölitic and bioclastic limestones	“Tite” micritic Limestones
<b>LC 357-1</b>	<b>1982</b>	<b>Simple structural closure in Limestone, Dolomite, and anhydrite</b>	<b>“Tite” micritic Limestones</b>

**Table 2.** Porosities and permeabilities from conventional cores at LC 357-1

<b>Core 1</b>	<b>Porosity (%)</b>	<b>Permeability (mD)</b>
Minimum	0.2	0.007
Maximum	1.7	0.02
Average	0.95	0.009
<b>Core 2</b>	<b>Porosity (%)</b>	<b>Permeability (mD)</b>
Minimum	1.2	0.044
Maximum	3.1	61.6
Average	2.15	11.65

**Table 3.** Formation names, ages, and tops determined via wireline log and seismic correlation to wells with data from GeoSpec. Depositional environments based on data from nearby well LC 312-1. Lithologic descriptions are made from our analysis of mud and wireline logs, sidewall and conventional core descriptions.

<b>Depth</b>	<b>Age</b>	<b>Formation/Unit: Lithology</b>	<b>Depositional Environment</b>
0	Unknown	Insufficient data:	Unknown
555	Unknown	Laurentian Fm.: 3/4 unconsolidated sand with the rest being clay	Middle shelf (~250'), siliciclastic and mud-dominated
660	E. Miocene to E. Eocene	Banquereau Fm.: Clay with the bottom 100' interval as half clay and half unconsolidated sand	Middle shelf (~250'), mud and siliciclastic-dominated
1365	Campanian to Cenomanian	Dawson Canyon Fm.: Clay	Middle shelf (~150' – 400'), mud-dominated
2950	Cenomanian to Barremian	Logan Canyon Fm.: Clay comprises the upper 500' before grading into sandstone and some siltstone with a small limestone show	Shallow water (~30' – 150'), mixed mud and siliciclastic-dominated shelf
4755	Barremian to Hauterivian	Roseway Unit: Mostly sandstone and siltstone with some (~10%) limestone	Shallow water (~30'), siliciclastic dominated shelf
5460	Hauterivian to Tithonian	Mississauga Fm.: About half sandstone with the rest mostly siltstone. Small amounts of limestone and clay/shale. Limestone is below 6500' with concentrations up to 80%.	Shallow water (~30' – 150'), siliciclastic dominated shelf
6850	Tithonian	Roseway Unit: 1/3 limestone, 1/3 siltstone, 1/3 split between sandstone and clay, with the clay in the bottom 300'	Shallow water (~50'), mixed siliciclastic and carbonate shelf
8040	Tithonian to Oxfordian	Mic Mac-Mohawk Fms.: Split somewhat evenly. Decreasing percentages is siltstone, sandstone, limestone, shale	Shallow water (~30' – 150'), mixed siliciclastic and carbonate shelf
11900	Oxfordian to Bathonian	Abenaki Fm.: Overwhelmingly limestone with a few percent each of sandstone and siltstone.	Shallow water (~30'), carbonate dominated shelf
15090	Bathonian	Mohican Fm.: Overwhelmingly limestone with a few percent dolomite	Shallow water (~15' – 30'), carbonate dominated shelf
15235	Bathonian to base Middle J*	Iroquois Fm.: Overwhelmingly limestone with a few percent dolomite	Carbonate shelf and tidal flat, sabkha. Restricted shallow marine

\*Fauna are interpreted as being reworked; therefore, age interpretation considered unreliable.

**Table 4. Petroleum System Elements**

Element	LC 357-1 Lithology
Source rock ( $>1\%$ TOC) <i>However, an effective source rock has <math>\sim 2\%</math> TOC</i>	Siliclastics and carbonates 11,200' and shallower with minor, thin source intervals at greater depths
Reservoir rock ( $>10\%$ $\phi$ $>1$ mD k)	Siliclastics and carbonates above $\sim 12,000'$
Seal rock ( $10^{-3}$ mD k)	Shale, impermeable limestone, anhydrite
Overburden rock	Insufficient for those zones with higher TOC to become generative

**Table 5. Petroleum System Processes**

Onset hydrocarbon generation	Early maturity for oil (%R <sub>o</sub> 0.5) at $\sim 6,500'$ , Main gas generation (%R <sub>o</sub> 1.3) begins at $\sim 17,200'$ based on well data and modeling.
Expulsion	Overall, strata in the hydrocarbon window contain insufficient TOC to generate and expel hydrocarbons. (Katz, 2012). Modeling using BasinMod <sup>®</sup> 2012 suggests that the limited volumes of hydrocarbons generated are retained in the "source rock" ( <i>in situ</i> ).

**Table 6. LC 357-1 Target Summary**

<b>Pre-Drill Interpretation</b>	
Target	$\sim 15,700' - 19,800'$
Trap Type	Structural-Stratigraphic
Hydrocarbon Expected	Oil and gas
<b>Post-Drill Results</b>	
Target Interval	Insufficient TOC for hydrocarbon generation and expulsion. Better source rocks, with higher TOC values, are too shallow and lack sufficient overburden to be mature.
Hydrocarbon Shows	There was a single significant gas show from 18,760'–70' in an interpreted silt-filled fracture zone in limestone. There were no oil shows in the cuttings.

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