International Journal of Innovative Research and Advanced Studies (IJIRAS)
Volume 5 Issue 4, April 2018

ISSN: 2394-4404

Regional Stratigraphy And Hydrocarbon Potential Of The Jurassic Abenaki Basin

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***Abstract:** Sedimentation in the Jurassic Abenaki Sub-Basin located North-East Offshore Scotian Basin was predominantly influenced by the structural arrangement of the Paleozoic Continental Basement, the existence of the Sable Island Paleo-delta that submerged carbonate production and by local variation in relative sea-level. Salt movement gave rise to local variations in the way carbonate sediments was deposited and produced paleohighs that entrappedpre-Jurassic deposits*

Deposition within this area consists of remarkable and uniqueLithofacies and Biofacies. Syn-rift deposition consists of Triassic red beds and Salt deposited in graben structures which are overlain by infill of Early Jurassic dolostones, sandstones and shales. The Abenaki Formation is divided into four lithological distinct parts beginning with a basal laterally continuous shallow water oolithic limestone facies overlain by deep water shales facies. By Mid Jurassic up until Early Cretaceous much of the basin was filled with reefal limestones facies containing coral stromatoporid packstone and boundstone. The overall succession was capped by deeper foreslope limestone filled with argillaceous limestones, silt and very little pure limestone.

The overall stratigraphy represents third order stratigraphic sequences containing excellent reservoir source and seal facies. Reservoir rocks in the Abenaki include leached oolithic packstones, grainstones and dolostones. Porosity includes vuggy limestones and dolostones and is fabric destructive. Deepweter and Lacustrine shales serve as potential source rocks likely to feed this reservoir rocks. Petroleum traps within the Abenaki are both stratigraphically and structurally enhanced. These traps are mounds, reefs, post-depositional folds,uncoformities and diagenetically influenced.

The key to achieving a successful exploration programme lies on the ability to figure out areas where secondary porosity has been preserved in reservoir rocks that was subjected to fracturing and late burial diagenesis.

I. INTRODUCTION

The Abenaki Sub-basin is located North-East of the Canadian margin. It is part of the offshore Scotia Basin, a basin that covers a total area of almost 300,000Kilometre square. The Scotian Basin formed around 250Ma ago as a result of separation of North-America and African plates. The basin contains nearly 1.5 Km thick succession of Jurassic to Early Cretaceous Sediments lying overlain by the Sable Island delta system. The tract of Jurassic carbonates extends over a large area of approximately 2500 km from the Grand Banks into Florida.

Initial exploration efforts that focused on this carbonate platform were dry. Earlier discoveries were on sand draped structures of Upper Cretaceous age that produced about 44 million barrels. However, a recent economic discovery on the deep Panuke Gas Field contains in excess of 1 TCF of gas. Hydrocarbon production from this Jurassic reef reservoir has motivated added attention on the Abenaki Sub basin. So far a total of 28 exploratory wells have been drilled on this carbonate platform.

Mound shaped structures containing reef bearing carbonate sequence within the Scotian Basin were initially discussed in the published works of (Eliuk, 1978; Harvey and MacDonald, 1990; Jansa and Wade, 1975; McIver, 1972; Wierzbicki et al., 2002). This study reviews the internal stratigraphy of the basin. It is necessary to re-evaluate the basin Stratigraphy to better understand controls on sedimentation, lateral and vertical facies distribution, palaeography and the hydrocarbon potential within the basin.

Regional 3D seismic data of poor to fair resolution spanning a total area of approximately 89 $km^2$and two keywells namely Penebscot B-41 and L-30 have been provided for this study with the aim of determining stratigraphic ages and the petroleum potential of the basin. The datasets were obtained from the publicly available Canada-Nova Scotia offshore petroleum board directory and interpretations were done using Schlumberger Petrel software. Key objectives to be obtained from the study are highlighted below

- ✓ Record the stratigraphic evolution of the Abenaki sub-basin through large scale mapping of the Jurassic carbonate sequence and locating their positions
- ✓ Identify potential Jurassic reservoir facies, determine their temporal and spatial distribution, and possible controls that influence their quality and distribution

Identify possible trap styles and source rocks within the Jurassic and their implications to hydrocarbon exploration.

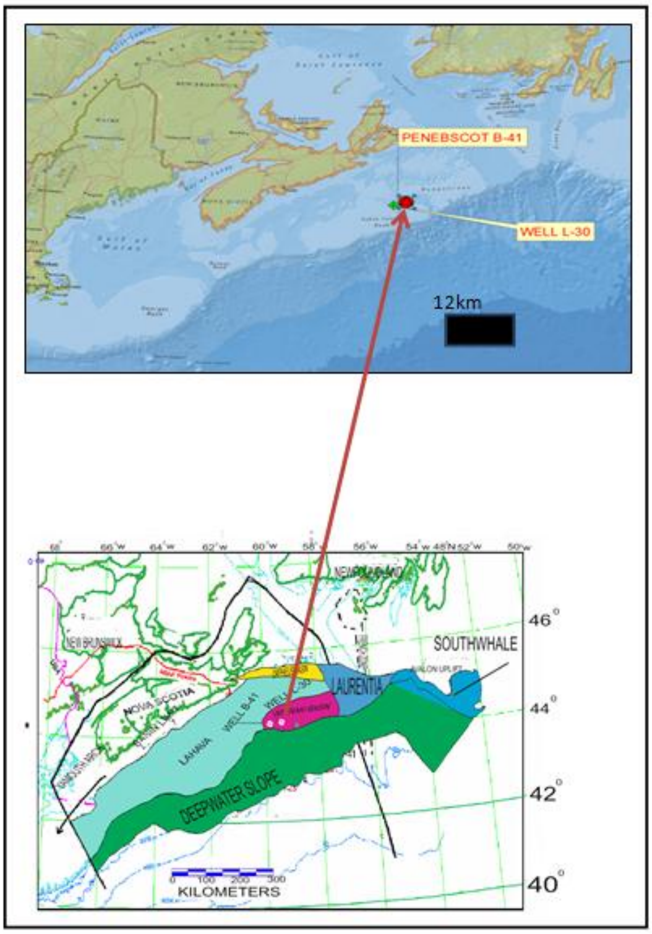

Figure 1: Location basemap of the Scotian basin showing the various sub- basins and the well locations modified from (Kidston et al., 2005)

A. HISTORY OF PETROLEUM EXPLORATION IN THE ABENAKI BASIN

Hydrocarbon exploration on the Abenaki carbonate platform began as far back as 1970 when Shell drilled the Oneida 0-25 well looking for sand draped structures. Several other wells were subsequently drilled on various positions on the platform, from the platform interior, bank edge and even on fore-slope. These wells include Demascota G-32, Cohaset L-97 and Acadia K-62 etc.

Exploration on this Carbonate platform has been through different phases of drilling inactivity, mostly during periods when the industry focused more on the American Atlantic margin. The rate of exploration success on the bank margin is quite low within the Abenaki platform, with a total of 28 wells drilled so far on the platform with just only one successful discovery and the rest being just shows having little or no porosity. This success was as a result of recent exploration on the bank margin after a long time of inactivity where the deep Panuke gas field was discovered containing in excess of 1TCF of gas.

It is believed that the current drive for natural gas as a choice of hydrocarbon in America today is likely to give extra attention to the Panuke gas field, thereby reviving the interest in the search for hydrocarbon producing from bank edge play. Several other wellsdrilled after this Panuke discovery at different positions around the segment were abandoned. However, the quantity of hydrocarbon discovered on the segment could be the needed drive required in re-examining the whole petroleum system within the Abenaki.

B. PREVIOUS WORK

The earliest set of subdivisions done on the Scotiian Basin stratigraphy were put forward by (McIver, 1972a) using sub-surface data from more than 18 wells. Research interest in hydrocarbon exploration was a key drive in the search for Mesozoic carbonate platforms that were identified from large scale dredging and other geophysical data (Jansa et al., 1979; Sheridan, 1974).

Initial discussions about sedimentation patterns, hydrocarbon system and basin fill succession on the Abenaki Formation were done by (Given, 1977) using six key wells that penetrated deep into the stratigraphic succession. (McIver, 1972) divided the Abenaki Formation into three members as observed in (**Error! Reference source not found.**), these are the limestones of the Scatarie Member, the Misaine shale Member, and limestones and minor dolomites with shallow and deep-water build-up of the Baccaro Member.

However the most spectacular contribution done so far on the Abenaki Formation has been the published thesis of (Eliuk, 1978). His research thesis was centred more on the geological evolution of the Abenaki formation where he used an integrated data set of seismic, wells, cores and cuttings in making a comprehensive analysis of the lithostratigraphy, biostratigraphy and internal facies description.

Jansa and Wade (1975); Sherwin (1973), Ellis (1985), Eliuk and crevello (1985),Adams (1987), Welsink et al. (1989), Harvey and MacDonald (1990), Wade et al. (1995), Mukhopadhyay et al. (1995), Kidston et al. (2002); Wierzbicki et al. (2002), Weissenberger et al. (2006) Kidston et al. (2011), have provided extremely useful details on the Jurassic carbonate platform in the Scotian basin.

(Sherwin, 1973) through his paper in the Energy and Mines Resources Canada was the first to discuss about the hydrocarbon prospectivity in the Scotian Shelf and Grand

Banks. His work contributed in understanding the paleogeography and basin fill within the Scotian Shelf.

(Jansa, 1993) described Early Cretaceous carbonate successor facies to the extensive Jurassic carbonate platform complex. He described the facies distribution, and platform geometries in extensive detail.

II. REGIONAL GEOLOGIC SETTING

TheAbenaki sub-basin is an integral component of the Nova-Scotian basin, a typical Atlantic type Continental margin that began initially as a rift basin up until late Triassic. Three distinc phases mark the basin evolution from Late Triassic up until Earliest cretaceous.

A pre-rift phase characterized by areas of platforms and depocentres. The platforms are the La Have Platform and Banquereau Platform while the basins are the Shelburne Subbasin, Sable and Abenaki Subbasins, Orpheus Graben and Laurentian Subbasin (Figure 1). The boundaries of these platforms and basins may have been defined by regularly-spaced oceanic fracture zones that extended landward onto continental crust (Welsink et al., 1990).

During riftingthe Canadian eastern border was situated near the equatorial region, however since the Jurassic the North-American plate has moved northward thus moving the Nova-Scotian eastern passive continental margin to 20^0 N(Sheridan, 1974).Rifting lead to deposition of continental red beds and evaporates (**Error! Reference source not found.**) in half grabensunder post Triassic conditions which were fully marine. (Given, 1977) During the final phases of rifting, the hanging wall subsidience and footwall uplift created basins that were filled with dolomite and sandstone beds(Jansa et al., 1979).

Renewed tectonism in the central rift basin during the Early Jurassic (mid-Sinemurian) is recorded by the complex faulting and erosion of Late Triassic and Early Jurassic sediments and older rocks. This phase of the rifting process resulted in the formation of a Break-Up Unconformity (BU), which coincided with the final separation of the North America and Africa continents, the creation of true oceanic crust through volcanism, and opening of the proto-Atlantic Ocean. As a result of the BU, the heavily faulted, complex terrane of grabens and basement highs along the Scotian margin underwent a significant degree on peneplanation (Jansa et al., 1979)

In the study area, these features have been identified on the basis of thickness maps of the units that make up the Abenaki Platform. Evidence of the transformation from a low angle to a steep profile of the platform can be observed clearly on seismic (Eliuk, 1978; Jansa, 1981). Sedimentationtrends in the Abenaki Formation are locally affected by extensional faults, regional uplift and salt movement. Such controlling factors could result in having low energy lithofacies deposited down dip and higher energy lithofacies deposited up dip. Also it is quite possible for huge sands to be deposited as delta lobes (**Error! Reference source not found.**) and complexes shifts their direction in reaction to rates of changing sediment supply and the associated growth faults (Given, 1977). Several analogue basins with almost similar type of basin evolution and facies type exist for this basin, such as the Baltimore Canyon Trough, George's Bank Basin, Offshore Mauritanian Basin, Gulf of Mexico, Western Canada Sedimentary Basin(Kidston et al., 2005)

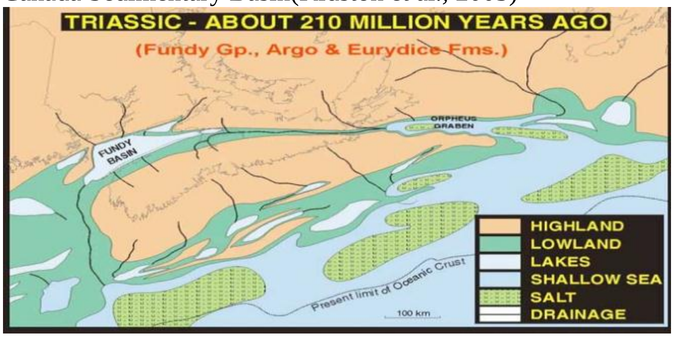

Figure 2: Late Triassic (Rhaetian) Ca. 210 Ma. Paleo-Geographic Reconstruction Of The Scotian Basin Showing Initiation Of Salt Deposition.From Wade And Jansa (1990)

Figure 3: Late Jurassic ca. 150 Ma paleo-geographic reconstruction of the Scotian Basin marking final stage of the Abenaki carbonate margin which was overwhelmed by a large delta system. The evolution of the morphology of the margin from a ramp-like feature seen in the Sable and Laurentian deltas to a reef profile observed in other areas. Wade and Jansa (1990)

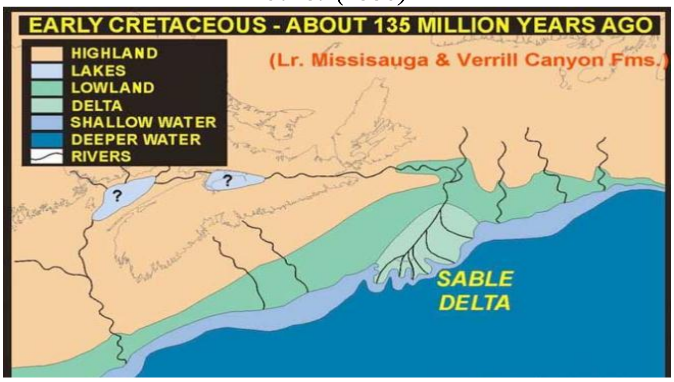

Figure 1: Early Cretaceous 135 Ma paleo-geographic reconstruction of the Scotian Basin.Showing a shift in deltaic sedimentation from the East to the Sable Sub-basin. Also rapid sedimentation led to the creation of many syn-sedimentary growth-fault structures and resultant over-pressure conditions. from Wade and Jansa (1990)

A. STRATIGRAPHY

The stratigraphy of the Abenaki sub-basin is shown in the **Error! Reference source not found.**. The contact between

 ISSN: 2394-4404

the Jurassic and the underlying Triassic strata is marked by a regional unconformity that is quite prominent and can be traceable to a large extent when mapped on seismic. The contact is erosive and characterized by redbeds of sand, silt and clay underlyinginter-bedded dolomite mudstones and anhydrite beds.

In the study area, the Jurassic has been subdivided into 3 Formations which are the Iroquois, the Mohican and the Abenaki Formation shown in

PERIOD	GROUP	FORMATION	MEMBERS	THICKNESS
JURASSIC	WESTERN BANK GROUP	ABENAKI	Artimon member	60m
			Abenaki 6	120m
			Abenaki 5	
			ABENAKI 4	1.5km
			ABENAKI 3	
			ABENAKI 2	
			Misaine shale	
			Abenaki 1 or Scatarie	
		MOHICAN		200m
		IROQUOIS		150m

Table *1*. Given (1977), observed from well Shell Argo F-38 that the Iroquois Formation contains a maximum thickness of approximately 800m. The Iroquois formation is characterized by sandstones and shales with anhydrite and dolomite. Lithofacies of the Iroquois Formation were interpreted to have been deposited under restricted shallow marine conditions(Adams, 1987).

PERIOD	GROUP	FORMATION	MEMBERS	THICKNESS
JURASSIC	WESTERN BANK GROUP	ABENAKI	Artimon member	60m
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			ABENAKI 4	1.5km
			ABENAKI 3	
			ABENAKI 2	
			Misaine shale	
			Abenaki 1 or Scatarie	
		MOHICAN		200m
		IROQUOIS		150m

Table 1: showing subdivisions that make up the Jurassic Stratigraphy of the Abenaki basin and their thickness

The Mohican Formation follows with a sharp contact above the Iroquois Formation. The Mohican is characterized by sand and shale beds with the highest recorded thickness of nearly 400m. Observation from seismic data shows that the Formation is laterallyquite extensive and traceable for upto 5km along dip direction. The Mohican Formation on the Penebscot L-30 well in the study area is predominantly shaly and has a measured thickness of about 200m.

The Abenaki Formation consists of seven stratigraphic subdivisions and contains a maximum thickness of approximately 2kilometers. it represents a second order stratigraphic sequence controlled by relative sea level changes and deposited within a time interval of 30ma(Eliuk, 1981).

Sedimentation begins with the deposition of the Scatarie Member (Abenaki 1), an oolithic limestone dominated by grain supported texture and deposited in relatively moderate-high energy environment. It exhibits a gradational contact to underlying Mohican Formation. The Scatarie shows three shoaling upward cycles in the Penebscot L-30, totalling 120m. itis characterized by very low gamma ray and an oolite character which could be indicative of facies deposited under higher current energy.Eliuk (1978) observed from cores from over 25 wells of at least four Lithofacies types. The lithofacies types observed where massive oolithic limestone facies, cyclic and non-cyclic limestone facies.

The Misaine Member consists of a calcareous shale with minor laminated limestones having thickness of about 150 meters. It formed in relatively deeper water. The contact to the underlying Scatarie is conformable. Wade et al. (1995)describes the Misaine Member shale to be of Oxfordian age and indicates possible drowning of the underlying Scatarie Formation. The Lithofacies represent lower energy neriticfacies most probably indicating a global eustatic sea level rise.

The Baccaro member consists of Abenaki 2-5 sequences and is the thickest member of the Abenaki Formation. It record saggradational and progradational sedimentation patterns

The Baccaro member is quite distinctive and is dominated by a number of Lithofacies each reflecting a particular depositional environment from lagoonal, shoal, reef and reef margin and slope facies (Eliuk, 1978). The approx. imatethickness of the Baccaro is about 1500 meters.

The Artimon member as observed from cores in Cohasset D-42 was describedas sponge-bearing reef facies consisting of calcareous shale, argillaceous limestone and pure limestone. James and Macintyre (1985),Eliuk and Levesque (1988)gives facies proportions 40% shale, 50% argillaceous limestone and 10% clean limestone. The limestone contains about 2% oolitic grain/packstone, 32.7% skeletal wacke/packstone, 16% reefal (greater than 10% framebuilders and 6.1% chert-bearing. Artimon member as observed is characterized by uniform medium grey-brown sponge floatstone with an argillaceous skeletal-rich wackestone to packstone matrix.

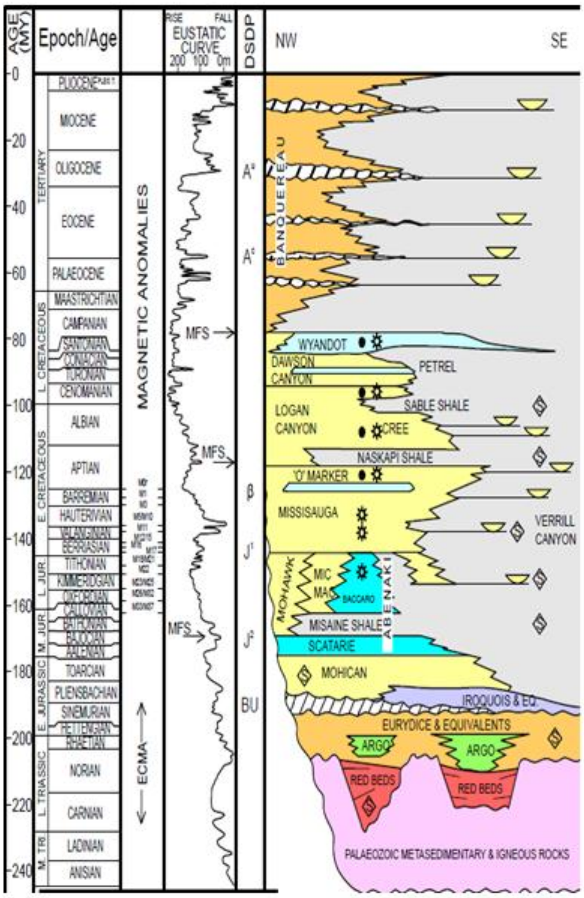


Figure 5: Generalized Stratigraphic chart for the Scotian basin Adopted from Maclean and Wade 1993

III. DATA SET AND METHODOLOGY

The data set was obtained from the Canada-Nova Scotia offshore petroleum board (CNSOPB) and it contained 3D seismic data. The study is aimed at reviewing the regional stratigraphy that was done by Weissenberger et al. (2006) in his paper 'Carbonate sequence stratigraphy and petroleum geology of the Jurassic deep Panuke field, offshore Nova Scotia, Canada'. The seismic data was integrated with the Well logs to assess the hydrocarbon potential of the Abenaki Formation. The seismic data covers an area of 89Km^2 and was primarily of poor to fair resolution.

Two exploration wells Penebscot L-30 and B-41 about 3km were used for the regional study. The wells were provided with gamma ray, density, sonic, neutron, spontaneous potential, resistivity logs and checkshot data which had to be modified for input. The initial data for the project came in an open 4dtect format and had to be converted to the Petrel seg Y format.

The project was carried out in phases, each stage was carried out according to a flowchart shown in **Error! Reference source not found.** beginning with an initial phase that involved Data management, import, storage and proper coordinate referencing. Well data import, Synthetic seismogram generation, Well-Seismictie were also carried out during this phase.

Synthethicswere generated to help identify reflections and seismic event that can be associated with a specific interface (Sheriff, 1977). The aim is to relate wave shape seen on seismic with stratigraphic feature in order to know how extensively a specific stratigraphy can be traced. The synthetic generation was done using the Schlumberger synthetic package. This was done by utilizing both wavelet generation and wavelet extraction routine. In the wavelet generation routine, a statistical wavelet was generated to evaluate frequency effects. The wavelet extraction routine estimates the wavelet from seismic based on a reflectivity curve and a reference seismic trace along the well and takes into account not only a single frequency value but a range of them which is directly detected by the original seismic section.

The Second phase of the project involves mapping important key seismic horizons that represent Stratigraphic ages within the Jurassic. In total seven horizons were picked each representing a particular stratigraphic unit. However just two of these horizons were very important Stratigraphic markers that represent Major seismic event in the Jurassic interval. They are the top of Abenaki main reef/Bacarro limestone, the Misaine shale. Each of these horizons had a peculiar seismic character in terms of reflection configuration and amplitude that aided in their picking.

A. ISOCHORE MAP GENERATION

The maps were all generated from the Petrel software, each mapped horizons was converted into a 3D surface. A velocity model was created from sonic velocity from wells to depth convert the seismic cube. Surface maps were generated to observe the structure of the platform as at deposition. Isochore maps were generated between the top and bottom of each horizon surface. The aim of these maps is to have a measure of the thickness between stratigraphic units. These maps can be used in predicting depositional environment, sedimentation pattern, and rate of carbonate growth. It can as well help in understanding depositional processes that took place during rifting in the Late Triassic.

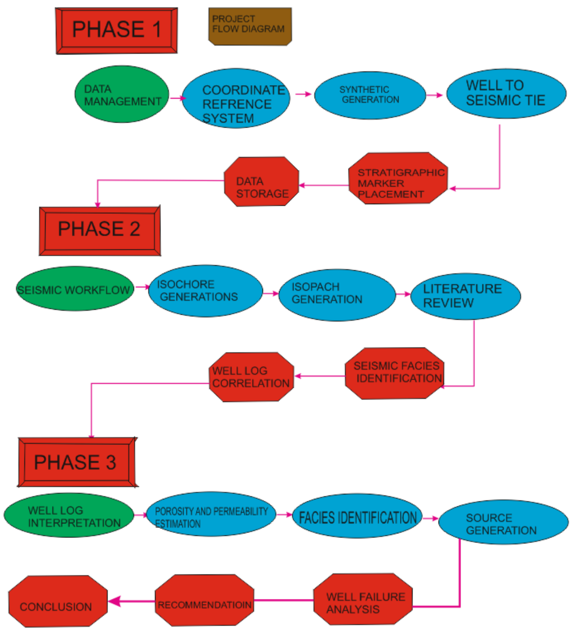


Figure 6: systemmatic flow chart for the project

B. ISOCHORE MAP GENERATION

The maps were all generated from the Petrel software, each mapped horizons was converted into a 3D surface. A velocity model was created from sonic velocity from wells to depth convert the seismic cube. Surface maps were generated to observe the structure of the platform as at deposition. Isochore maps were generated between the top and bottom of each horizon surface. The aim of these maps is to have a measure of the thickness between stratigraphic units. These maps can be used in predicting depositional environment, sedimentation pattern, and rate of carbonate growth. It can as well help in understanding depositional processes that took place during rifting in the Late Triassic.

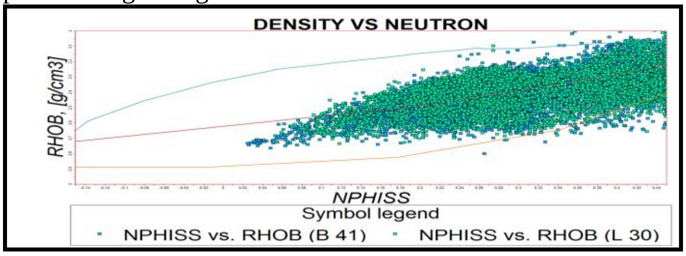


Figure 7: Generated Density vs Neutron cross plot

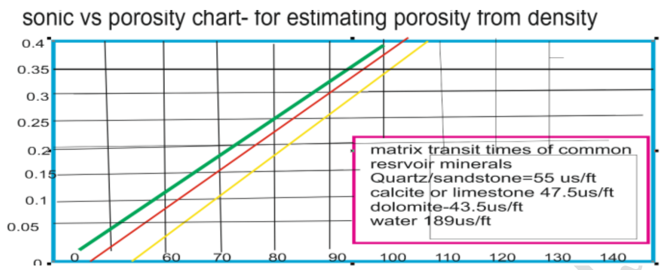


Figure 8: Derived sonic vs porosity chart used in estimating interparticle porosity

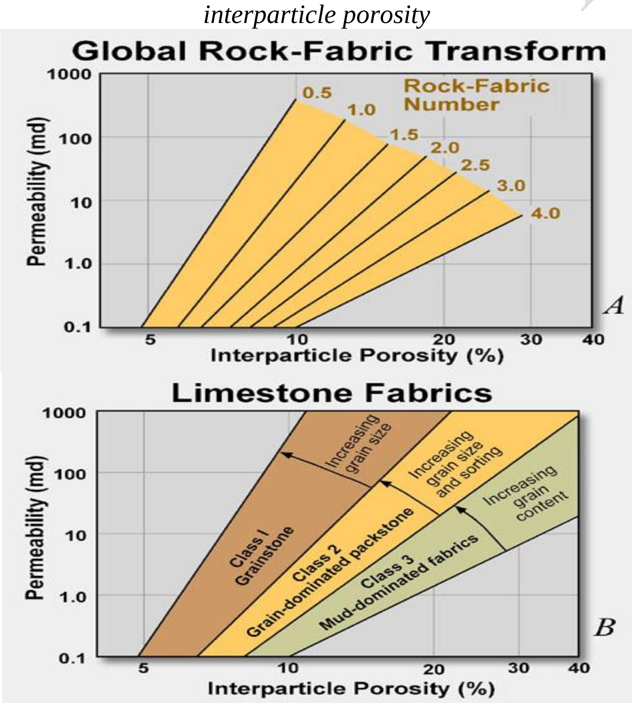


Figure 9: chart relating permeability to rock fabrics adopted from Lucia(1995)

(Log (K)= (a-blog(rfn)+(c-dlog(rfn)logΦ)

Where A= 9.7982, B=12.0838 C=8.6711 D=8.2065 andΦ=interparticle porosity

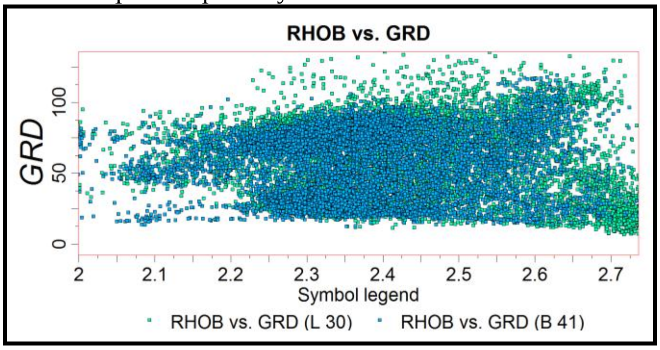


Figure 10: cross plot of Gamma ray vs Density log

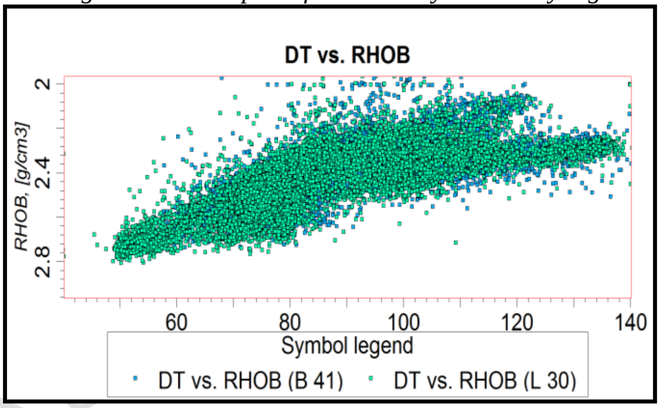


Figure 11: Cross plot of Sonic vs Density Log

IV. SEISMIC FACIES ANALYSIS AND REGIONAL FACIES DESCRIPTION

The Facies description and character were based on observations from well logs and the use of seismic facies analysis to propose a set of models of the likely depositional environments. This was done using basic contrast visible in the signature of wireline logs and from observations made from the reflection configuration seen on seismic.

A. AIMS AND OBJECTIVE

The aim of seismic interpretation is to have a very deep knowledge of the depositional environments and to know how laterally extensive each unit can be mapped across the area. Seismic facies analysis is useful as it provides good observations which are made by following reflections, noting their amplitude and reflection character. This could give first-hand information about the likely depositional environments.

This was achieved by first performing a seismic-well tie in order to place recognized correlated stratigraphic tops from well data at their correct two way travel time on seismic data. This allowed each of these stratigraphic tops to be mapped as horizons, from which maps were generated for each unit.

B. SYNTHETHIC GENERATION/SEISMIC –WELL TIE

In order to bridge the gap between the well data and seismic data, a synthetic seismogram as shown in **Error!**

International Journal of Innovative Research and Advanced Studies (IJIRAS)
Volume 5 Issue 4, April 2018

ISSN: 2394-4404

Reference source not found.was generated from the sonic and density logs from well L-30 as shown in **Error! Reference source not found.**. Wavelets had to be extracted using the statistical method to enhance the degree of reliability of the synthetic generated. The generated synthetic seismogram was tied to the seismic data at a confidence level 0f 60%, below are the results of the generated well ties along with their stratigraphic markers (**Error! Reference source not found.**).

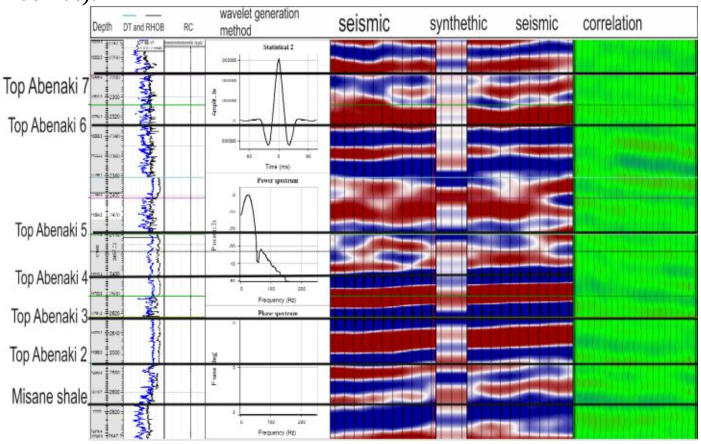


Figure 12: Well to seismic tie process with the well tops

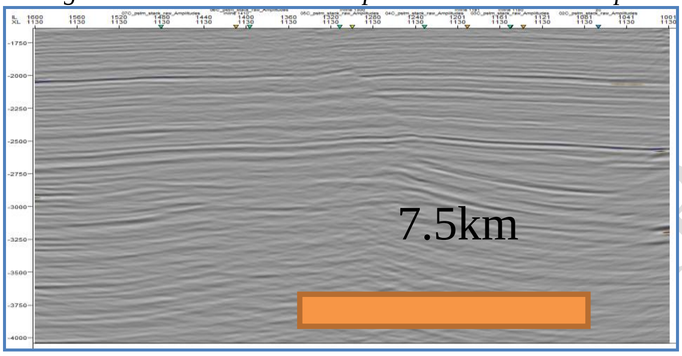


Figure 13: Raw seismic dip line of the survey at line 1130

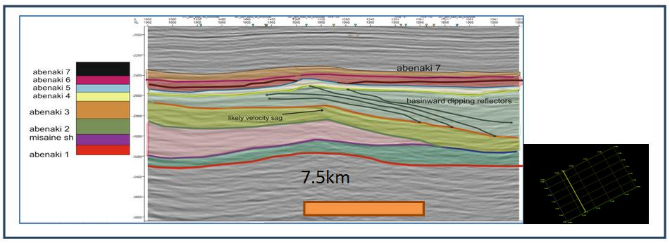


Figure 14: Raw seismic dip line of the survey at line 1130 showing interpreted horizons (C) at right shows position of the line on basemap

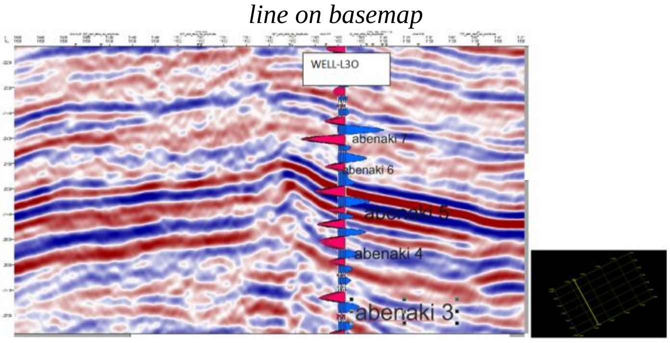


Figure 13: seismic to well tie using Well L-30

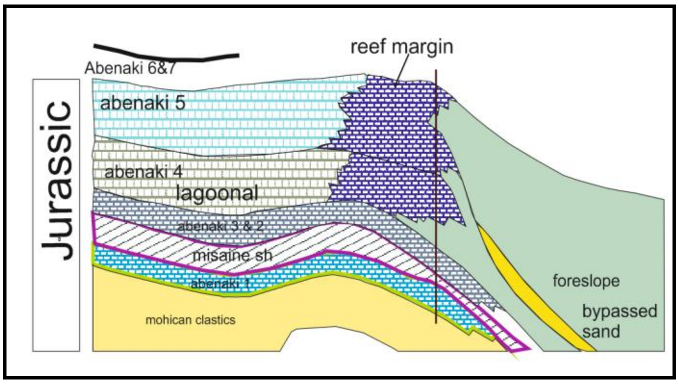


Figure 14: Schematic interpretation of the interpreted dip line 1130

HORIZON	AMPLITUDE	ACOUSTIC IMPEDANCE	CORRELATI ON
Top ABENAKI 7	moderate (variable)	Moderate	Good
Top ABENAKI 6	negative	Decrease	Poor-fair
Top ABENAKI 5	positive	Increase	Good
Top ABENAKI 4	positive	Increase	Fair-good
Top ABENAKI 3	positive	Increasing	Good
Top ABENAKI 2	Positive/moderate	Increasing	Fair-good
Top MISAINE Shale	negative	Increasing	Good
Top ABENAKI 1	positive	Increasing	Poor-fair

Table 2: Horizon character showing Amplitude, Acoustic impedance and degree of correlation

C. OBSERVATIONS AND INTERPRETATION

a. ABENAKI 7/ARTIMON MEMBER

The Artimon member or Abenaki 7

PERIOD	GROUP	FORMATION	MEMBERS	THICKNESS
JURASSIC	WESTERN BANK GROUP	ABENAKI	Artimon member	60m
			Abenaki 6	120m
			Abenaki 5	1.5km
			ABENAKI 4	
			ABENAKI 3	
			ABENAKI 2	
			Misaine shale	
			Abenaki 1 or Scatarie	
		MOHICAN		200m
		IROQUOIS		150m

Table *1* as observed exhibits horizontal onlap, characterized by strong parallel and continuous reflectors. It is above the whole Abenaki sequence. It indicates the possible end of the reef growth or the possible drowning of the Baccaro limestone by relatively deeper water probably related to slope environment. This could possible as a result of a pronounced rise in relative sea level and a relatively lower carbonate production leading to drowning of the platform.

b. ABENAKI 6

The Abenaki 6 is characterized by draped onlap reflection as with sometimes parallel internal reflections still onlapping. They were likely derived from a backstepping carbonate platform as a result of accommodation space created outpacing carbonate production causing a retreat of the carbonate platform.

c. ABENAKI 5

The Abenaki 5 is characterized by high amplitude and highly continuous reflection at shelf. At the margin it is characterized by concordant reflectors on the underform, having a toplap termination at the upper sequence boundary and a downlap at the lower sequence boundary. There is anoverall aggradational natureof the carbonate platform which is evident on the cross line 1300**Error! Reference source not found.**.

Above the Abenaki 5 is a very high peak with reflections truncating against it. One possible interpretation for this reflection could suggest a possible 'drowning unconformity surface'. This surface can be easily mapped on the seismic and is quite extensive.

d. ABENAKI 4

The Abenaki 4 as observed on seismic is characterized by relatively moderate amplitude, moderately continuous with parallel internal reflections on the shelf. On the shelf margin it is characterized by atoplap termination at the upper sequence boundary and a concordant termination at the lower sequence boundary having internal reflections at the margin which are mounded. Reflections at the basin slope are concordant exhibiting parallel internal reflections. The overall nature of the deposition suggest both a relatively aggradational stacking pattern with some evidence of progradation

e. ABENAKI 3

The Abenaki 3as observed on seismic is characterized by a strong peak that is moderately continuous with parallel internal reflections on the shelf while it exhibits an oblique progradational geometry at the shelf margin that is characterized by an toplap termination at the upper sequence boundary and a downlap termination at the lower sequence boundary. It is however the thickest of the entire unit that makes up the third order sequences. Higher reflectors in the upper AB III are inclined near the margin where there seems to be a likely build up and can be traced upward (landward) where they appear to terminate against flat reflectors of the overlying sequence. The offlap geometry it exhibits could suggest that the available accomadation space that is created is being filled or kept up. Genarally it exhibits both an aggradational-progradational stacking pattern

f. ABENAKI 2

The Abenaki 2 is characterized by high amplitude with parallel internal reflection with relatively moderate- high continuity at the shelf area, while they exhibit sigmoid progradational clinoforms at shelf margin which usually concave upwards that are characterized by a concordant termination pattern at the upper sequence boundary and a downlap termination at the lower sequence boundary as shown in **Error! Reference source not found.**. The Abenaki 2 from observation is characterized by an extensive Misaine shale that mark the maximum flooding surface and a reef platform that progrades or downlaps onto the misaine shale. The base of the misaine shale is usually taking as the top of the Abenaki 1 sequence. This is consistent with expectedseismic geometries above an MFS; the Misaine is the interpreted MFS of the second-order depositional sequence. Reflectors higher in the sequence display flat-lying top sets on the interpreted platform, a discernable change in slope and dipping foresets at thebasin margin. Finally, the most basinward-dipping reflectors of the AB II do not appear to have anytime-equivalent top sets on the shelf.

Obviousofflap breakgeometry can be recognized that steps down basinward with the toplap geometry supporting an obvious sequence boundary on the top of the unit. This offlaping geometry could suggest that the available accomadation space that is created is being filled or kept up. This is common with shallow water limestones where rate of carbonate productivity is high.

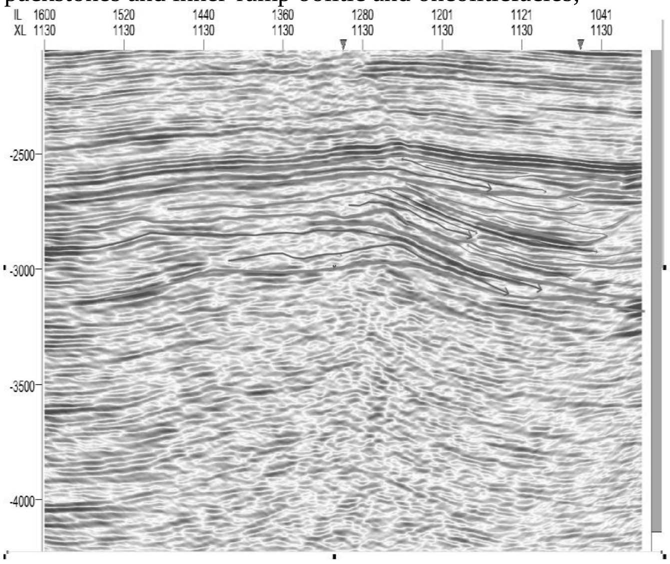
Thus the Abenaki 2 can be interpreted as the transgressive and highstand parts of the sequence and generally exhibits an aggradational-progradational stacking pattern. The Abenaki 2 consist of skeletal wackestones contain ingoolitic packstones to grainstones or reefalboundstones

g. ABENAKI 1

Abenaki1 as seen below is characterized by a high amplitude reflector exhibiting low angle slope , suggesting deposition on a broad carbonate ramp. Due to a decreased seismic resolution at that depth, interpretation of this unit cannot be concluded.

The base of the Abenaki I marks the upper part of the Mohican siliciclastics, but the poor resolution at depth does not allow this surface to be identified. The Mohican siliciclastic shelf is defined as a lowstand of the second-order sequence. Amplitude extraction made below the Abenaki 1 show a channel like structure that could serve as evidence for the underlying Mohican clastic.

Interpretations suggest Abenaki1 consist of lagoonalfacies and is interpreted as the early transgressive part of the second-order sequence. It typically has three recognizable shoaling-upward cycles, comprising outer-ramp fossil wackestones to packstones and inner-ramp oolitic and oncoliticfacies;



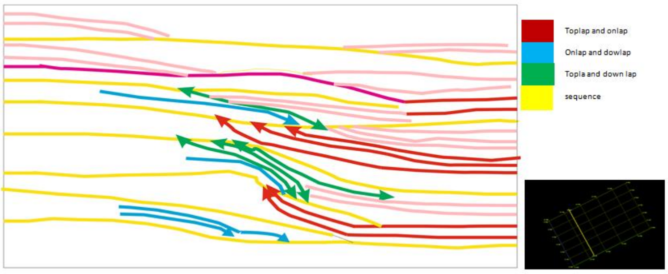


Figure 15: (A) Seismic dip line 1130 showing observed termination patterns (B) schematic diagram to seismic interpretation (C) basemap showing position of the interpreted line.

D. RESULTS AND INTERPRETATIONS

Sets of Maps were generated as results obtained from interpreting the seismic data. The maps are the structure maps and isochore maps of the interpreted horizons. The generated isochore maps represent the thickness between the top surfaces of two units. Isochore maps were produced to understand how changes in structural regime during late Triassic rifting event controlled the depositional processes of the Abenaki formation and also to have a good idea of the type of margin geometry that characterize the carbonate build-up as it will help in better understanding of the pattern of sedimentation within the platform.

The Isochore maps generated were from, Top Abenaki 5-Top Abenaki4, Top Abenaki 4 -Top Abenaki 3, Top Abenak 23-Top Abenaki 2, Top Abenaki 2-Misaine shale,

a. TOP ABENAKI 5- TOP ABENAKI 4

Thickness of this interval varies from 100-160ms. It thickens in the southwest direction towards the basin and maintains a relative thickness of 100ms in the northeast direction. See **Error! Reference source not found.** below

b. TOP ABENAKI 4 - TOP ABENAKI 3

Thickness of this interval varies from 40-240msexhibiting the same trend of thickening in the WSW direction which is basinward and gradually thins to about 40ms in the ENE. See **Error! Reference source not found.** below

c. TOP ABENAKI 3-TOP ABENAK 2

Thickness of this interval varies from 120-240ms. it exhibits uniform thickening and thinning in both northeast and southeast direction. See **Error! Reference source not found.** below

d. TOP ABENAKI 2- MISAINE SHALE

Thickness of this interval varies from 50-240ms .it thickens in the ENE direction and thins towards the WSW direction. See **Error! Reference source not found.** below

All generated thickness maps show almost similar trend of sedimentation, with the thicker deposit occurring in the ENE direction while thickness decreases towards the WSW direction. This pattern of sedimentation supports evidence on seismic of a having an aggradational and progradational margin geometry. Sediments tend to fill out towards the basin ESE while the shallow water platform tends to build out laterally and tend to accumulate over former foreslope. Sedimentation is structurally controlled as shown in **Error! Reference source not found.**

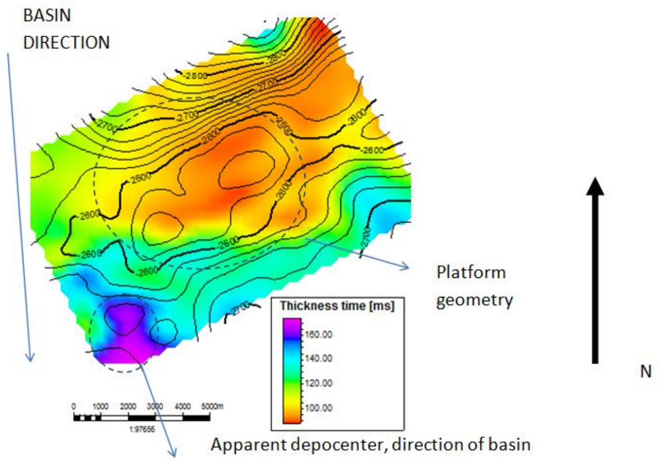


Figure 16: Thickness map between Top Abenaki 5 and Top Abenaki 4

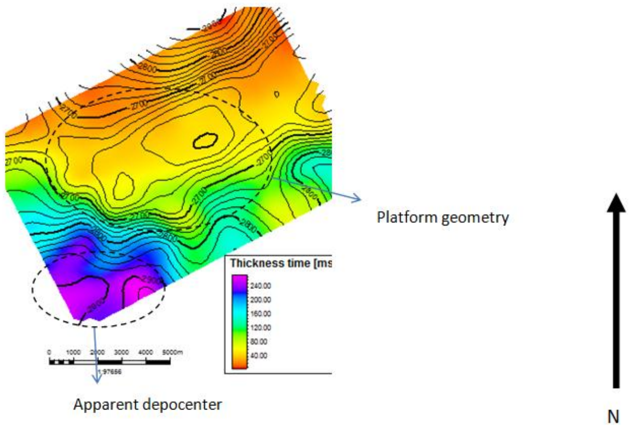


Figure 17: Thickness map between Top Abenaki 4 and Top Abenaki 3

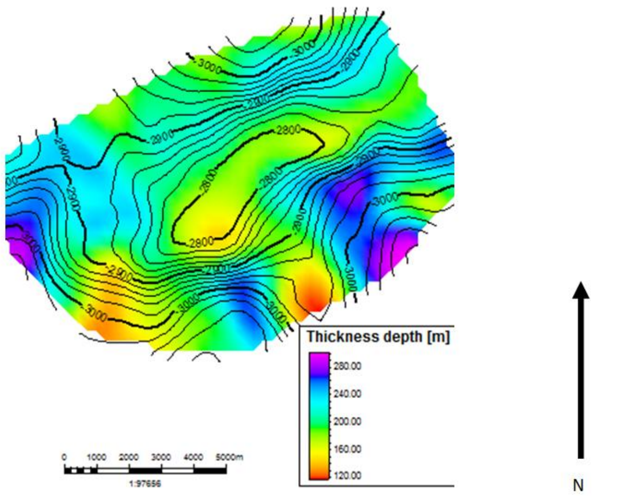


Figure 18: Thickness between Top Abenaki 3 and Top Abenaki 2

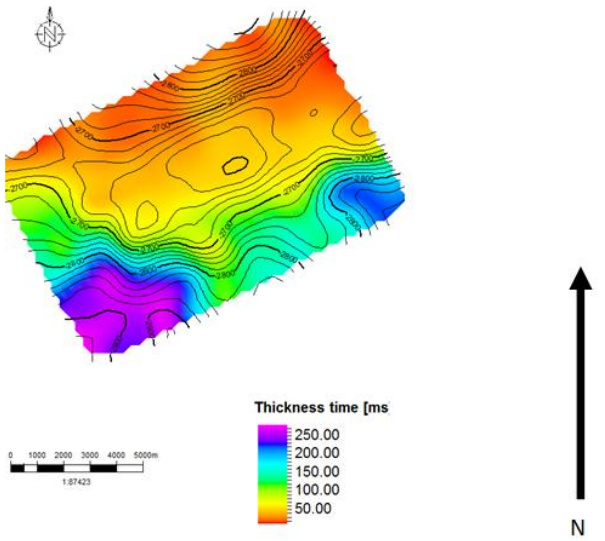


Figure 19: Thickness between Top Abenaki 2 and Misaine shale

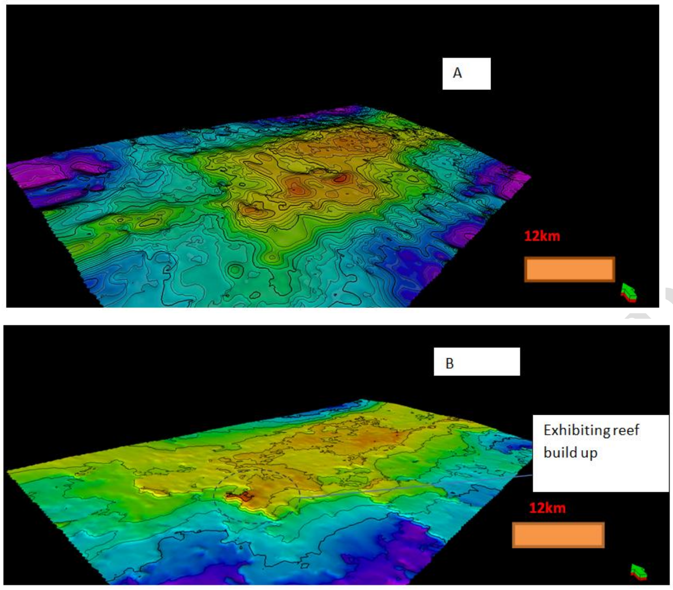


Figure 20: Time structure map of Abenaki 1 in (A) and Abenaki 3 in (B) showing margin type exhibited by the two surfaces

Time structure of TopAbenaki 1 Formation at (A) and Top Abenaki 3 structure map at (B).

The widely space isochrons at (A) could indicate a ramp type profile while the very tight isochrons at (B) could indicate a steep depositional profile. The positions of the platform margin looks similar from Abenaki 1 and 3 which reflects an inheritance of paleogeography which could possibly reflect deep structural control

V. PETROPHYSICAL OBSERVATION AND INTRPRTETATION

Geological descriptions are better quantified using information obtained from petrophysical properties. The observations obtained from well logs could depict particular lithology, depositional environment, porosity and permeability character. A suite of logs containing gamma ray (GR), density and neutron (RHOB and NPHISS), sonic (DT), spontaneous potential (SP) and resistivity have been used in analysing the character of the rocks in the Abenaki carbonate platform.

Gamma ray logs were used to infer on the possible depositional environment based on current energy. Higher gamma ray seen on logs are typified by shale, mud dominated packstones, wackestones and mudstones which infer they were deposited in a quiet environment while lower gamma ray could likely infer grain dominated packstone and grainstone that were deposited in a much higher energy environment. Lucia (1999) proposed that carbonate facies can be correlated with current energy but is a poor tool in distinguishing between rock fabrics and facies.

It should be noted clearly that grain types inferred for each depositional facies were not identified from logs rather they were inferred from geological information obtained from literatures(Eliuk, 1978).

The neutron –density cross plot was used as a better tool in identifying lithology and estimating porosity and permeability character. Sonic log was also used in estimating lithology, pore type and porosity. Porosities obtained from the sonic log were used as an input into the global permeability transform equation in estimating permeability.

A. ARTIMON MEMBER/ ABENAKI 7

The Artimon member is characterized by both a high and low gamma ray. High gamma ray could indicate deposition of sediments inlow energy environments. Such conditions will favour the deposition of mud dominated lithologies. Areas with relatively lower gamma ray plotted on the limestone axis of the density neutron cross plot, thus indicating the presence of carbonate. Observations from Wireline log indicates that this interval contain approximately 26% pure limestone, 37% shale and 37% argillaceous limestone. This unit is approximately 60 metres thick as measured from the well. Porosities range between 0.06-0.15% with computed permeability value of 0.57mD (millidarcy)

Eliuk and Levesque (1988) described the Abenaki 7 to be made up of sponge rich limestones with occasional clay minerals deposited in deeper fore-slope to basinal environment. They were formed in the more proximal part of deeper water environment. They are dominated by skeletal lime wackestone to boundstone and have only been observed in very few wells, suggesting they have been eroded or were not deposited in some areas. Several analogues that possess same similarity exist to support the interpretation of a relatively deep water setting Crevello and Harris (1984); ((Evans, 1977)); Flügel (1981). Similar sponge reef facies have been found to occur in southern Germany and morocco. These two examples are good analogues for this kind of facies.

In terms of reservoir quality this facies type are not porous. Observations from log showan increase in the percentage composition of shale at their base. Eliuk (1978) observed from cores the presence of chert, pyrite, phosphorus minerals and pervasive stylolization. He proposed the possibility of anearly submarine seafloor diagenesisaffecting the rocks. Further interpretation suggest they represent the drowning of the Baccaro limestone during a period when relative sea level overwhelmed carbonate productivity, more probably due to pronounce deepening that may have resulted in the fall of the rate of nutrient productivity(Schlager, 1981).Gradstein et al. (1975) interpreted the possibility of a major relative sea level rise capable hindering the deposition of carbonates was prominent at a time when shallow water Limestone of the Upper Baccaro was exposed. Information from biostratigraphic dating show they were deposited during Hauterivian-Valanginian age(Eliuk and Levesque, 1988).

B. ABENAKI 6

The Abenaki 6 is characterizedby mixed lithologies indicating the possibility of a mixed depositional environment. Higher gamma ray is depictive of lower energy environment, while lower gamma ray could indicate deposition in higher energy conditions. Observations from Wireline log indicate they contain approximately 68.5% limestone, 24% shale and 7.5% argillaceous limestone. This unit is approximately 150m thick from the well and porosities range between 0.18-0.27% with a computed permeability value of 3mD.

Interpretations suggest they were deposited in the more distal foreslope environment and are characterized by mud-rich coral-stromat oliterudstones and floatstones, possessing features of carbonate deposited at the bank edge in a transgressive setting (Kidston et al., 2005). Information from biostratigraphic dating show they were deposited during the late Kimmeridgian age(Eliuk and Levesque, 1988),(Eliuk and Crevello, 1985).

C. ABENAKI 5

The Abenaki 5 is characterized by relatively moderate gamma ray and has anaverage density of about 2.71g/ccindicating the presence clean limestone. It is characterized by very high shallow and deep resistivity values which indicate the presence of hydrocarbon and a relatively moderate sonic. This unit was taking as the top of carbonate. Observations from well logs show that it has no porosity despite having hydrocarbon shows. Estimated porosities range between 0.016-0.078% with an estimated permeability value of 0.03mD. The measured thickness of this interval is around 32m.

Eliuk (1978) described it to be dominated by oolithic limestone facies dominated mostly by grainstones and packstones likely deposited on reef margin.Ellis (1985) described the buildup based on observations from core at depth 3730-3750m as unfossiliferous wackestone shaving very small amounts of quartz mineral.

Reservoir quality for this facies type is poor with extremely low porosity due to early diagenesis. The presence of calcite spar could have blocked pore spaces. Also occasional cements observed from cores could have contributed to the low porosity character of this facies type (Ellis, 1985). This facies type is subject to secondary porosity development mainly in areas where they have been deeply buried resulting in mouldic and vuggy porosities. Information from biostratigraphic dating show they were deposited during the Middle Kimmeridgian age (Eliuk and Levesque, 1988).

D. ABENAKI 4

The Abenaki 4 is characterized by both relatively higher and lower gamma ray. It is approximately 50m thick. Estimates of porosity range between 0.03-0.2% and has a computed permeability 2mD. Obeservations from Wireline log indicate they contain approximately 57% limestone, 29% shale and 14% silt. The lack of porosity within this unit is the same as that of Abenaki 5 and is subject to reservoir development in areas where dolomitization has created porous reservoirs. They are interpreted to reflect facies deposited on the reef margin (Eliuk, 1978).Information from biostratigraphic dating show they were deposited during the Early-Middle Kimmeridgian age (Eliuk and Levesque, 1988)

E. ABENAKI 3

The Abenaki 3 is characterized by relatively moderate-low gamma ray. The signature is moderately constant throughout the section. Density values range between 2.6-2.71 g/cc. They are also characterized by very high resistivity values which could likely be as a result of the presence of hydrocarbon. It is the thickest unit of the entire interpreted third order sequences of the Baccaro limestone and has an approximate measured thickness of 114m.Observations from Wireline log indicate they contain approximately 90% limestone, 6% shale and 4% silt. Estimated porosity values range between 0.03-0.07% and that of permeability is at 0.3mD.

Weissenberger et al. (2006) through the use of Formation MicroImager, sidewall core, and cuttings data described them to contain reefal limestone consisting of coral-stromatoporoid packstones to boundstones deposited in relatively shallow water. They are characterized by aggradational stacking pattern likely deposited on the reef or platform margin. Porosity is rare and could have been destroyed by the presence of lime-mud matrix. Information from biostratigraphic dating show they were deposited during the Early Oxfordian-Middle Kimmeridgian age (Eliuk and Levesque, 1988)

ABENAKI 2

The Abenaki 2 is characterized by relatively low gamma ray signature signifying clean carbonates. Deep and shallow resistivity values are also very high indicating the presence of possible hydrocarbon show. Observation shows it is characterized by a gamma-ray reading that is transitional with the underlying shales. The measured thickness for this unit is approximately 60m. Estimated porosity values range between 0.003-0.003% and that of permeability is at 0.7mD.

Weissenberger et al. (2006) observed from cores and drill cuttings that the Abenaki 2 consist of skeletal wackestones and overlies the Misaineshales. Some parts of the unit were identified to consist of oolitic packstones to grainstones and few reefalboundstones. Interpretation suggests the Abenaki 2 makes up the transgressive and highst and parts of the third order sequences. They were deposited within the lagoonal environment. Information from biostratigraphic dating shows they were deposited during the Callovian-Middle Oxfordianage (Eliuk and Levesque, 1988)

F. MISAINE SHALE

The Misaine member shale is characterized by relatively higher gamma ray signature with the readings suggesting they were deposited in very quiet environment. Deep and shallow resistivity values are very low and its thickness is approximately 150m within this section.

The Misaine represents a major transgression that occurred between late-middle Jurassic. This was caused by an expanding mid-Atlantic ridge system that led to displacement of water. It however holds record of the final drowning of the shallow-water Abenaki 1 limestone. This event led to series of intermittent pulses caused by relative sea level rise that resulted in cyclic sedimentation seen in the underlying Abenaki 1.

Wierzbicki et al. (2002) described the Misaine through observations made from cuttings to be dark olive-grey to grey-brown in colour. Calcareous shales were also found present with minor traces of glauconite, with an increase in the percentage of Siltstone and calcareous sandstone composition in closer proximity to the Sable Island delta. Minor traces of argillaceous limestones and oolitic textures have also been found to occur within this shale member.

G. ABENAKI 1

The Abenaki 1 is characterized by having three repeated cycles of upward shoaling sedimentation. Observation shows they have a relatively identifiable cleaning-upward profile which is evident on the gamma-ray log. Estimated porosity values range between 0.003-0.003% and that of permeability is at 0.7mD. The measured thickness of this interval 120m

Cutting descriptions where Abenaki 1 was encountered show they consist of outer-ramp fossil wackestones to packstones and inner-ramp oolitic and oncoliticfacies deposited on a large carbonate ramp. This sequence is typified by shoaling-upward cycles. Observations made by Eliuk (1978) from cores interpreted the sediments to consist of medium greenish grey, silty having clayey matrix that occurs in the medium to dark brown oolitic and oncolitic beds

The Abenaki is interpreted as the early transgressive part of the second-order sequence deposited in lagoonal environment. The Abenaki 1 is underlain by the Mohican siliciclastics which dominantly consist of shales

VI. HYRDOCARBON POTENTIAL

The search for hydrocarbon within the Jurassic Abenaki Basin is dependent on several variables which are interelated. However prospectivity within this basin could be complex based on the fact that each individual factor plays a major role in the complete petroleum system and if not present could lead to failure wherever exploratory wells are drilled. The factors are listed below

- ✓ The ability of discovering potential reservoir facies that possess good reservoir quality in terms of their porosity and permeability
- ✓ The presence of a source rock, its maturity and burial history
- ✓ The availability of charge access to allow hydrocarbon migrate up-dip into better reservoir facies
- ✓ The presence of a trapping mechanism either a structural or stratigraphic trap

A. RESERVOIR POTENTIAL

The quality of reservoir rocks in terms of porosity, types and distribution is important as it affects prospectively directly. Lack of having a porous and permeable rock as observed from well l-30 and b-41 could be a potential cause for failure of hydrocarbon prospectively within the Abenaki Basin. It becomes an utmost necessity to understand and predict correctly areas where this potential reservoir facies may have been subjected to secondary porosity development. These areas include places where the rocks have been deeply buried.

The main reservoir facies are found within the Abenaki 5 and Abenaki 3 Sequence. Within the study area, primary porosity has been destroyed mainly due to cements or in pores that have been filled by blocky calcite spar (Eliuk and Levesque, 1988). Each of these reservoir facies are subject to porosity development and tend to occur in the form of vuggy limestone or as vuggy dolostones (Wierzbicki et al., 2002).

The discovery made from the Panuke gas field, producing from secondary preserved dolomitized limestones found in the Updip Bacarro/ Abenaki 5 sequence supports the possibility of having porous rocks that have developed through time. The Abenaki 5 is characterized by coral-stromatoporoid reefallimestones containing reefal grainstones and skeletal rich wackestones. Porosity was developed in areas where partial faulting and fracturing are present.

Two obvious types of secondary porosity occur within the Abenaki, they are the vuggy limestone and vuggy dolostones. Each of this pore type exhibit a perculiar linear or curvlinear trend that follow failed normal faults along the platform margin(Wierzbicki et al., 2002) .

Porosities in the Abenaki limestone range between <1-15%, and are usually predominated by secondary vuggy and moldic pore types. Subsequent pore types are in the form of carbonate grains that have been dissolved. They are mostly micritized skeletal grains.

Secondary porosity found in limestones where mostly found to cut stylolites or are found to be preserved along them(Wang and Davis, 1992), (Mazzullo and Harris, 1992). While secondary porosity found in dolostones where attributed to the passage of hot calcium rich fluids or highly acidic pore fluids caused by deep burial condition(Murray, 1960), (Powers, 1962),(Murray and Lucia, 1967).The roles of fracturing cannot be neglected, this fractures were enhanced by leaching and are common in places that have been faulted. This fractures serve as routes that deliver diagenetic fluids that dissolve the dolomites.

a. CONTROLS ON DIAGENESIS

Understanding the timing and the factors that controlled Abenaki diagenesis is important. It provides a clearer picture on the possibility for reservoir development. The diagenesis within the Abenaki was primarily influenced by the passage of hot hydrothermal fluid. Burial diagenesis within the Abenakilimestones was affected by suturing in grainstones while stylolites acted as conduits for migrating diagenetic fluids that dissolved most cements in the matrix of wackestones and packstones (Wierzbicki et al., 2002).

The primary factor controlling secondary porosity distribution within the Abenaki is manly structural. The presence of faulting is instrumental in focusing fluids in certain parts of the platform margin. Secondary porosity development is strongly influenced by inherited textures because most porosity is secondary or partial moldic in origin. Also the reactivated basement faults contributed both in closures and also acted as conduits for hot calcium rich fluid that promoted dissolution and replacement in dolostones.

b. *TRAP STYLES*

Petroleum traps within the Abenaki are both stratigraphically and structurally enhanced. These traps are mounds, reefs, post-depositional folding, uncoformities, diagenetic and pinch outs.

B. SOURCE ROCK POTENTIAL

The two main source Facies within the Abenaki are the Misaine shale and the Mohican clastics,. from the HI/OI plot shown in **Error! Reference source not found.** below. The Mohican shale contains Kerogen type (111) terrestrially derived organic matter while Misaine shale contains kerogen type (11) B organic matter. The Misaine shale is relatively immature and is both gas and oil prone while the Mohican shale is marginally matured.

The Mohican shale is the main source for hydrocarbon in the Abenaki Basin. This shale as observed on gamma ray signature tend to be very hot with values greater than 150API.This thick Lower Baccaro Formation has an average Toc of 1.2% in which the value could have been much higher in the past, before the time of hydrocarbon generation and migration. The organic matter is gas prone derived from terrestrially organic matter(Mukhopadhyay et al., 1995) . They are also characterized by anomalously high production index >0.2.

Source potential is enhanced by pressure solution along primary laminae which concentrated kerogen along stylolites and increased the efficiency of crude oil expulsion from the source facies to adjacent reservoirs (Sassen et al, 1987). It is also enhanced as a result deep burial resulting in matured source rocks that feed into deeply buried reservoirs that provide large drainage areas for the source rocks.

Thermal maturity controls the initial generation of crude oil from kerogen, the cracking of liquid hydrocarbons into methane, and the ultimate breakdown of methane. Several factors such as geothermal gradient, chemical analysis of kerogen, vitrinite reflectance measurement need to be considered as potential maturity indicators.

The Misaine shale falls within the Type 11 (B) and has a peak vitrinite reflectance ratio of about 0.52% as shown **Error! Reference source not found.** below. Maturity increases towards the basin and decreases at the platform area. it is derived from a mixture of vitrinite and terrestrial exinite and generates oil and gas at vitrinite reflectance ratio of about 0.8% (Mukhopadhyay and Gormly, 1984), (Larter and Senftle, 1985)

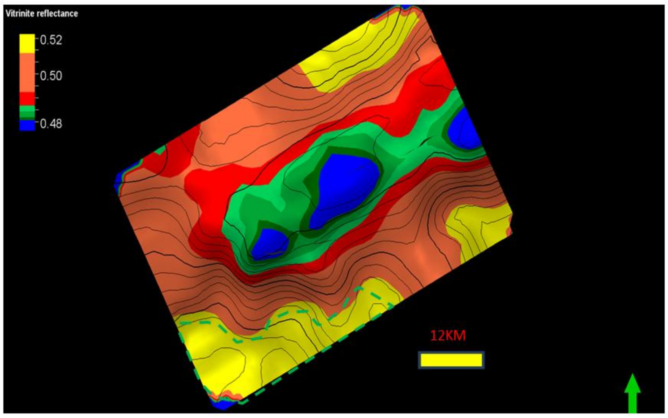


Figure 21: source facies map showing distribution of vitrinite reflectivity of the Misaine shale

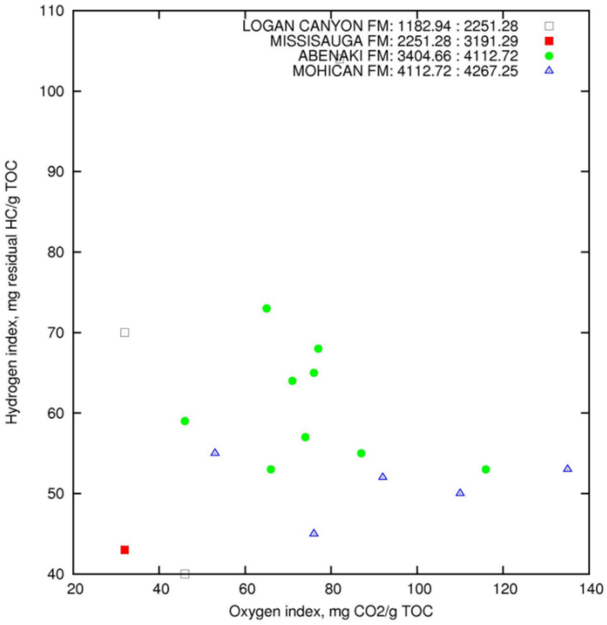


Figure 22: Hi Versus Oi Plot Of Misaine And Mohican Formation Shale

C. MIGRATION PATHWAYS

Vertical gas migration as shown in **Error! Reference source not found.** occurred around 100-150 Million years ago(Williamson and DesRoches, 1993). Major vertical faults can act as conduit for migration when pressure exerted on pore is excess. This Migration ceased around 70-80 Ma when excess pressures where released leading to resealing of the conduit at a period of reduced sedimentation. Unequal compaction of sediments and small generation of gas contributed to buildups and dissipitation of excess pressures. Generation of secondary porosity and the preservation of seals are driven by diagenesis.

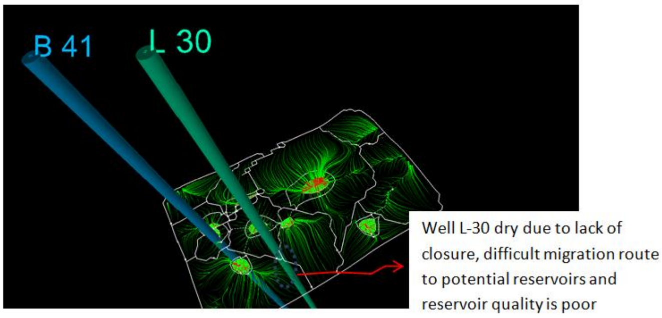


Figure 23: Generated migration pathway from Petroleum system quick look

VII. CONCLUSION, RECOMMENDATION AND SUGGESTIONS FOR FUTURE WORK

A. CONCLUSIONS

- ✓ By integrating both sub-surface data, the Abenaki Formation in northeast Canada bears similar lithostratigraphic subdivision with the Aghadir basin in morocco. Deposition of carbonate sediments were affected by paleohighs and salt movement. This salt movement could have led to the Formation of the ramp geometry in the early stages of carbonate sedimentation
- ✓ Deposition in the Abenaki is subdivided into seven Members. The Facies that characterize each of these Members signifies various depositional environments ranging from lagoon, reef margin, foreslope and deep marine.
- ✓ They contain approximately 1500m of thick carbonate sediments and show evidence of relative sealevel changes. They are classified as third order stratigraphic sequences deposited within 50Ma and hold potential for hydrocarbon prospectivity.
- ✓ Facies can be divided into 3 sections, a lowermost lithofacies characterized by upward shoaling cycles containing oolithic packstone to grainstones. The middle lithofaacies is dominated by coral-stromatoporoid packstones and boundtones deposited at water depths of less than 100m. The uppermost lithofacies are dominated by sponge reef facies dominated by argillaceous limestone, shale and very small proportion of clean limestone.
- ✓ Petroleum traps within the Abenaki are both stratigraphically and structurally enhanced. These traps are mounds, reefs, post-depositional folding, uncoformities, diagenetic and pinch outs. Reservoir rock includes fractured coral-stromatoporoid limestones containing reefal grainstones and skeletal wackestone and oolithic packstones – grainstones. Porosity types include vuggy limestone and vuggy dolostones. The Misaine and Mohican shale serve as souce rocks for the Jurassic.

The depositional pattern of the basin can help to identify locations of good reservoir facies in close proximity to source facies. The basin has good hydrocarbon potential, and exploration efforts should be channelled towards using seismic stratigraphic analysis in the search for hydrocarbon pools

B. RECOMMENDATIONAND SUGGSETIONS FOR FUTURE WORK

The dataset provided which consist of just two wireline logs in close proximity to each other is not enough for a broad facies description within the study area. Wireline datasets do not provide proper quantification of geological descriptions. They are well too limited in providing a broad facies decription. It is recommended that core data or composite logs containing lithologic descriptions should be provided. Such data will help improve the confidence of most interpretations that were inferred from literatures rather than to be backed from observations.

Detailed studies should be focused on predicting the role of diagenesis on the reservoir rocks by providing thin sections. Such studies include undergoing X-ray diffraction method, cathode luminesce studies, stable isotope analysis and X-ray computed tomography to predict accurately porosity and permeability trends, pore space characterization, mineralogy etc.

Future work should be concentrated more on seismic stratigraphic analysis in the search for hydrocarbon pools.

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