Sequence stratigraphy and hydrocarbon potential of Upper Cretaceous limestone units, offshore Nova Scotia

R. Andrew MacRae, John W. Shimeld, and Hans J.B.W. Wielens

Geological Survey of Canada (Atlantic), Bedford Institute of Oceanography

P.O. Box 1006, Dartmouth, Nova Scotia B2Y 4A2

Natural Resources Canada / Ressources naturelles Canada

ABSTRACT

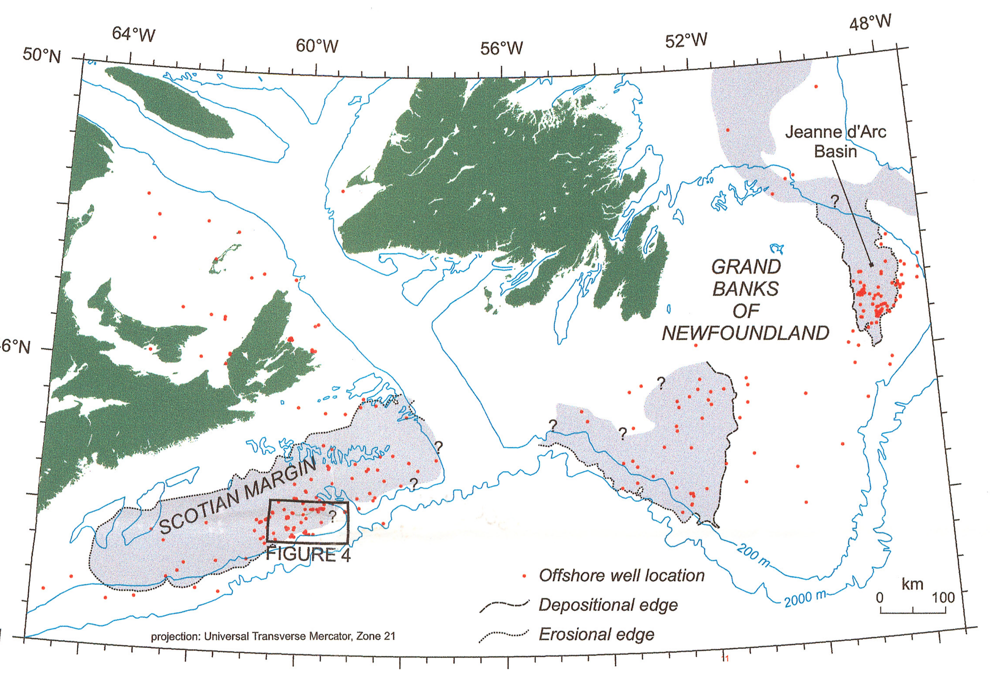
Two regionally widespread, Upper Cretaceous limestone units form important seismic markers beneath the Scotian Margin and Grand Banks. These units, the Upper Turonian-Coniacian Petrel Member of the Dawson Canyon Formation and the Upper Santonian-Maastrichtian Wyandot Formation, are typically composed of intensely bioturbated, fine-grained, coccolith-dominated limestone (chalk) with minor amounts of sandstone, calcareous mudstone, wackestone, and packstone. Thicknesses range from a few metres up to 400 metres, but they are absent along the southern edge of the Scotian Margin and part of the southeastern Grand Banks. This poster focuses on the Wyandot Formation in the central and eastern Scotian Shelf, where the Wyandot is the thickest and best-sampled of the two units.

Information about the Wyandot Formation comes primarily from drill cuttings, seismic, and wireline data. Conventional core is available only from four wells drilled on the Scotian Shelf: Eagle D-21, and Primrose F-41, A-41, and 1A A-41. Based upon the cores, trace fossil assemblages are dominated by *Zoophycos*, *Thalassinoides*, and *Chondrites* of the *Cruziana* ichnofacies. Inoceramid bivalves are also present. The Wyandot Formation in this area was deposited in a deep shelf environment below storm wave base, an interpretation that also appears applicable to the Petrel Member.

Given the significance of similarly-aged chalk reservoirs worldwide (e.g., the Austin Chalk in the Gulf of Mexico and the Chalk Group of the North Sea), the hydrocarbon potential of these units as reservoirs and source rocks warrants careful evaluation. On the Scotian Shelf, significant gas was discovered at the Primrose and Eagle structures in the Wyandot Formation. Additional gas shows were tested in the Wyandot Formation in the Sable Island E-48 well, and there are wireline indications of potential hydrocarbons in the same interval in other wells. Available organic geochemistry data, although sparse, indicate total organic carbon as high as 14% in the Wyandot Formation (South Venture O-59) and hydrogen indices ranging from negligible to as high as 493 (Louisbourg J-47). Data from the Petrel Member are less promising. At some well locations (e.g., Venture B-43 and Venture B-52), vitrinite data indicate that both units are in the oil window. Oxygen indices are generally high in both units, suggesting that the kerogens may be oxidized – an interpretation consistent with the degree of bioturbation observed in core.

Like other Upper Cretaceous chalk-rich units around the world, the Petrel Member and Wyandot Formation have been interpreted by several authors as the product of primarily pelagic carbonate sedimentation during stages of maximum transgression and minimal siliciclastic input to shelf environments. While much of the evidence is consistent with this interpretation, lateral variations in thickness and lithofacies from well and seismic interpretation also suggest the development of significant unconformities within and immediately above the limestone units. Depending upon location within the basin, mappable seismic horizons may correspond either to a maximum flooding surface, an erosional surface developed during relative sea-level lowstands or due to local salt uplift, or an amalgamation of surfaces when the thickness between them falls below the limit of seismic resolution. This situation complicates the use of the Upper Cretaceous limestone units for regional correlation, but even so, there are some consistent stratigraphic patterns. For example, the limestone units appear to be coeval, in part, with siliciclastic units that prograded across the shelf of both the Scotian Shelf and Grand Banks, forming distinctive clinoform geometries. Sandstones within these siliciclastic units are also potential hydrocarbon reservoirs.

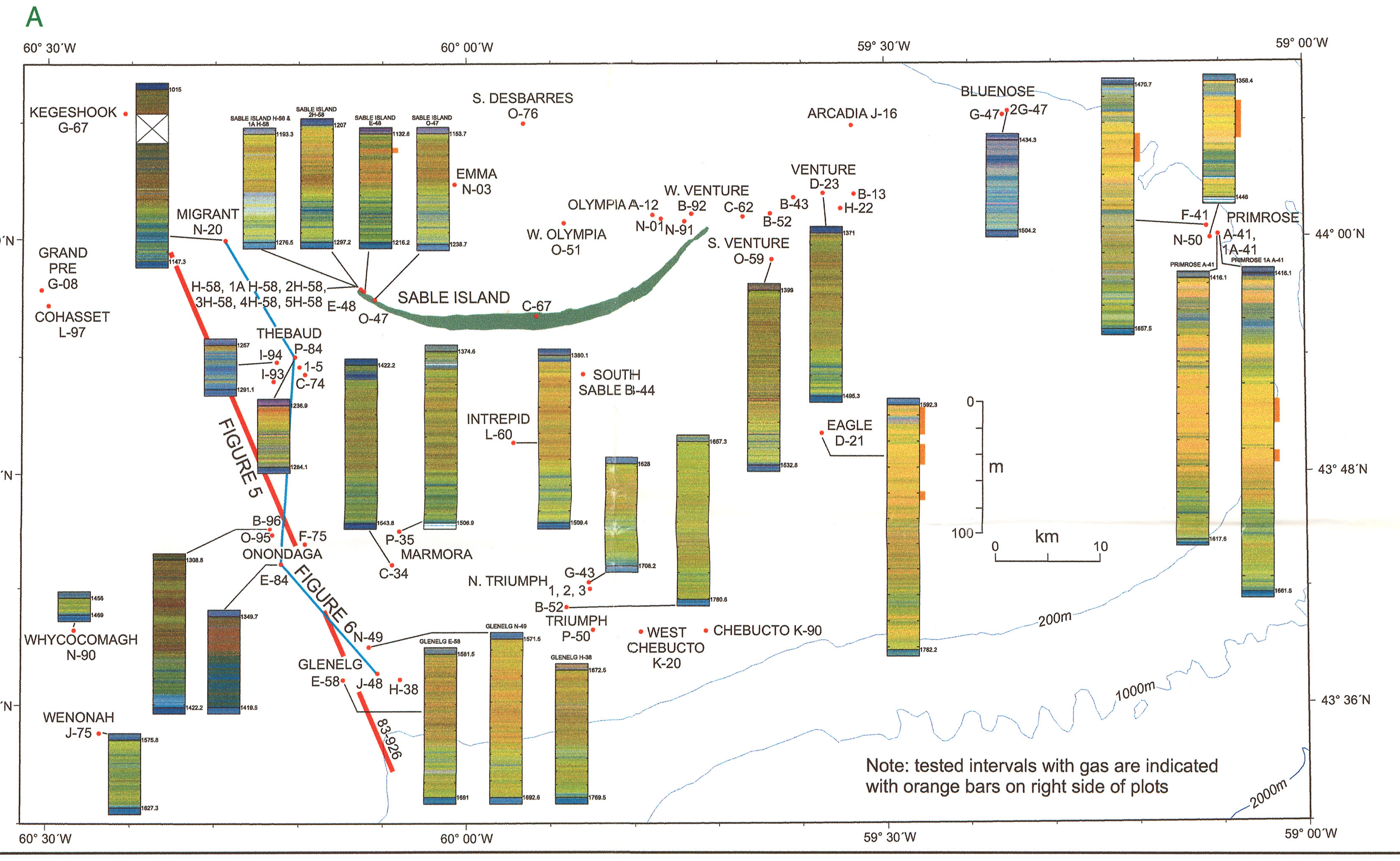
FIGURE 3: DISTRIBUTION OF UPPER CRETACEOUS LIMESTONE UNITS OFFSHORE EASTERN CANADA



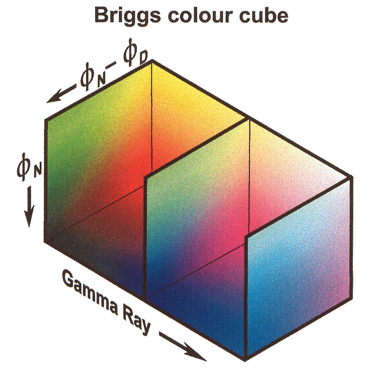
The distribution of the Petrel seismic horizon, offshore Eastern Canada, is plotted on the map above. The outlines are based on interpretations by Wade and MacLean (1990) for the Scotian Margin, and unpublished maps created for the Grand Banks by A. Edwards (1990), and north of the Grand Banks by A. Grant (pers. comm., 1999). The Wyandot horizon has a similar distribution but is less widespread on the southern and eastern Grand Banks.

FIGURE 4: WYANDOT FORMATION ELECTROFACIES ON THE SCOTIAN SHELF

A



B



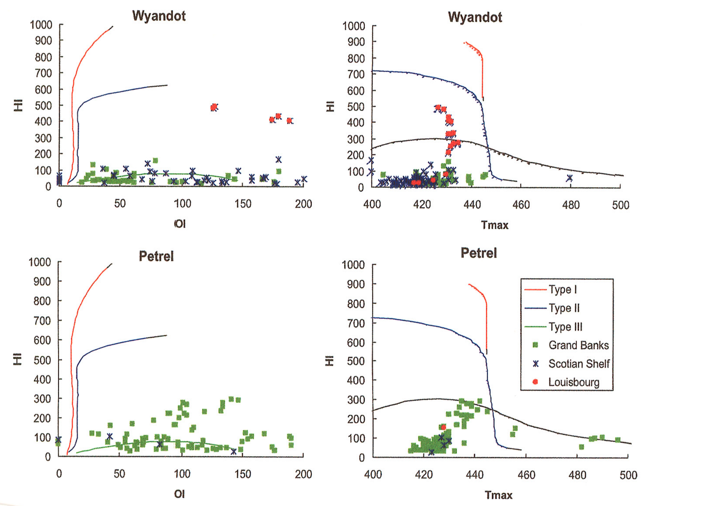
Briggs (1985); Collins and Doveton (1986)

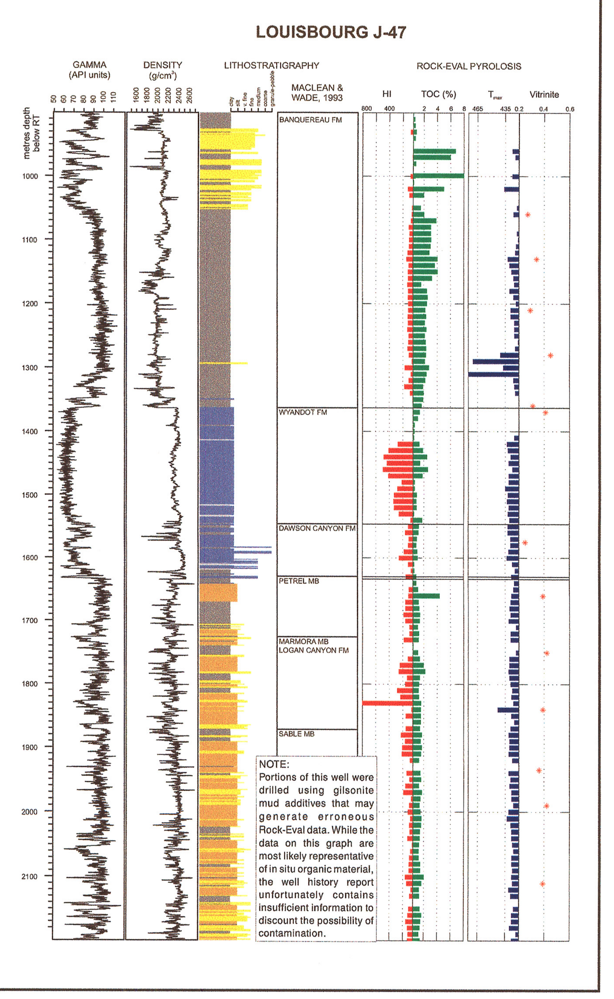
"Briggs plots" of electrofacies in the Wyandot Formation summarize the variability in gamma ray, neutron porosity (ϕ_N), and the difference between neutron porosity and density porosity ($\phi_N - \phi_D$). The range of each parameter is converted to a gradient of colours in a red-green-blue (RGB) colourspace (Figure 4B). In this plot style, increasing gamma ray is increasingly blue, decreasing neutron porosity is increasingly green, and increasing difference between the neutron and density porosity is increasing red. Calibration of the typical colours to the lithofacies seen in core (Figure 2) allows interpretation of probable lithofacies patterns. This technique is not a substitute for detailed petrophysical analysis, but serves as a useful "first look" tool.

Based upon electrofacies correlations, the Wyandot Formation in this area characteristically has a gradational base, with probable interbedded marlstones and chalky lithofacies grading upwards to greater proportions and thickness of chalk. The greatest development of chalky lithofacies is apparent in the upper half of the formation, as are indications (orange-yellow) of gas presence. The upper contact of the formation tends to be sharp, and is erosional at many localities, according to biostratigraphy.

Intervals with formation tests that yielded gas are indicated with an orange bar on the right-hand side of the Briggs plots.

FIGURE 7: HYDROCARBON POTENTIAL IN THE WYANDOT FORMATION AND PETREL MEMBER





On a global scale, widespread deposition of organic-rich shale and chalk units occurred during approximately the same Late Cretaceous time intervals in which the Petrel Member and Wyandot Formation were being deposited. Thus, careful evaluation of not only the hydrocarbon reservoir potential but also the hydrocarbon source potential of these units is warranted. To date, clear evidence of source rocks has not been documented within either unit. However, the presence of source rocks is certainly feasible especially within the most distal and deeply-buried facies.

Available organic geochemistry data, while sparse, indicate the organic matter is dominantly Type III (terrestrial origin) with possibly some Type II (marine origin) input (refer to the graphs above). Total organic carbon reaches 14% in the Wyandot Formation (South Venture O-59) and 5% in the Petrel Member (Hibernia B-27 – Grand Banks). Hydrogen indices range from negligible to as high as 493 in the Wyandot Formation (refer to the example, at right, from Louisbourg J-47) and 293 in the Petrel Member (East Rankin H-21 – Grand Banks). At some well locations (e.g., Adolphus D-50, Adolphus 2K-41, Heron H-73 – Grand Banks; Venture B-43, and Venture B-52 – Scotian Shelf), vitrinite maturity data indicate that both units are within the oil window; regions where the Wyandot Formation and Petrel Member are most deeply buried, and therefore more likely to be mature, have not been sampled. Oxygen indices are generally high in both units, suggesting that the kerogens have been oxidized. This is consistent with the intensity of bioturbation in intervals of conventional core (see Figure 2).

CONCLUSIONS

Upper Cretaceous limestone units are widespread across the Scotian Margin and Grand Banks and are potentially important both as hydrocarbon reservoirs and as source rocks.

While much of our data are consistent with existing interpretations of the Petrel Member and Wyandot Formations as the product of pelagic deposition during relative sea level maxima, lateral variations in thickness, lithofacies, and biostratigraphic age suggest significant diachroneities at formation contacts and development of unconformities during and immediately after their deposition. Some of the unconformities are probably related to salt diapirism, others appear to be due to more regional tectonic or eustatic events. Diachroneity is probably also present as a result of interfingering relationships with coeval siliciclastic deposition (mudstones and sandstones) that form distinctive prograding clinoform units.

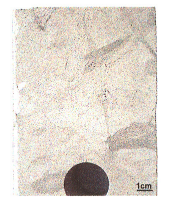
Depending upon location within the basins, mappable seismic horizons may correspond either to a probable maximum flooding surface, erosional surfaces developed during relative sea level lowstands, erosional surfaces due to localized uplift, or the amalgamation of any of the three when the thickness falls below seismic resolution. Despite the challenges, careful integration of wireline, lithostratigraphic, biostratigraphic, and seismic data can resolve these complex relationships.

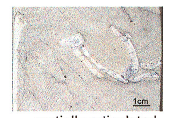
Future work will include further seismic and biostratigraphic interpretation to address some of the following questions:

- Was resedimentation of the chalk an important process?
- What is the nature of the sandy lithofacies associated with the deposition of coeval clinoforms, and what is their hydrocarbon potential?
- What influence did salt tectonics have during deposition of the limestone units?
- What effect did shelfal depositional patterns and development of local and more extensive unconformities have on the delivery of sediment to the Scotian Slope in the Late Cretaceous?
- Are incised channels present on limestone-related seismic markers as seen in the Jeanne d'Arc Basin in this interval?
- How does the nature of the limestone units vary regionally between the Scotian Margin and Grand Banks, and can further information about tectonic and sea level events be derived through these comparisons?

FIGURE 1: TYPICAL LITHOFACIES & FOSSILS AS SEEN IN CORE

Examples from Wyandot Fm., Primrose A-41 well, Scotian Shelf, cores 5 & 6





partially articulated inoceramid bivalve

Lithofacies 1: White to light grey, intensively-bioturbated chalky limestone
- fine to very fine grained, with rare mm to cm-sized shell bioclasts (mostly inoceramid bivalve fragments)
- most primary sedimentary structures disrupted by bioturbation
- stylolitic, pyrite nodules developed in some intervals
- ichnofauna dominated by *Zoophycos*, *Thalassinoides*, and *Chondrites*, with lesser amounts of *Teichichnus* and *Palaeophycus*
- deposited below normal storm wave base
- oxygenated bottom conditions
- **low** gamma ray log response

Lithofacies 2: Medium to dark grey, intensively bioturbated calcareous silty mudstone ("marlstone")
- grainsize varies from siltstone to claystone
- most primary sedimentary structures disrupted by bioturbation
- ichnofauna dominated by *Zoophycos* & *Chondrites*, with lesser amounts of *Thalassinoides* and *Teichichnus*
- also deposited below normal storm wave base
- greater siliciclastic sediment input, less carbonate production, or poorer carbonate preservation than chalky limestones
- **high** gamma ray log response

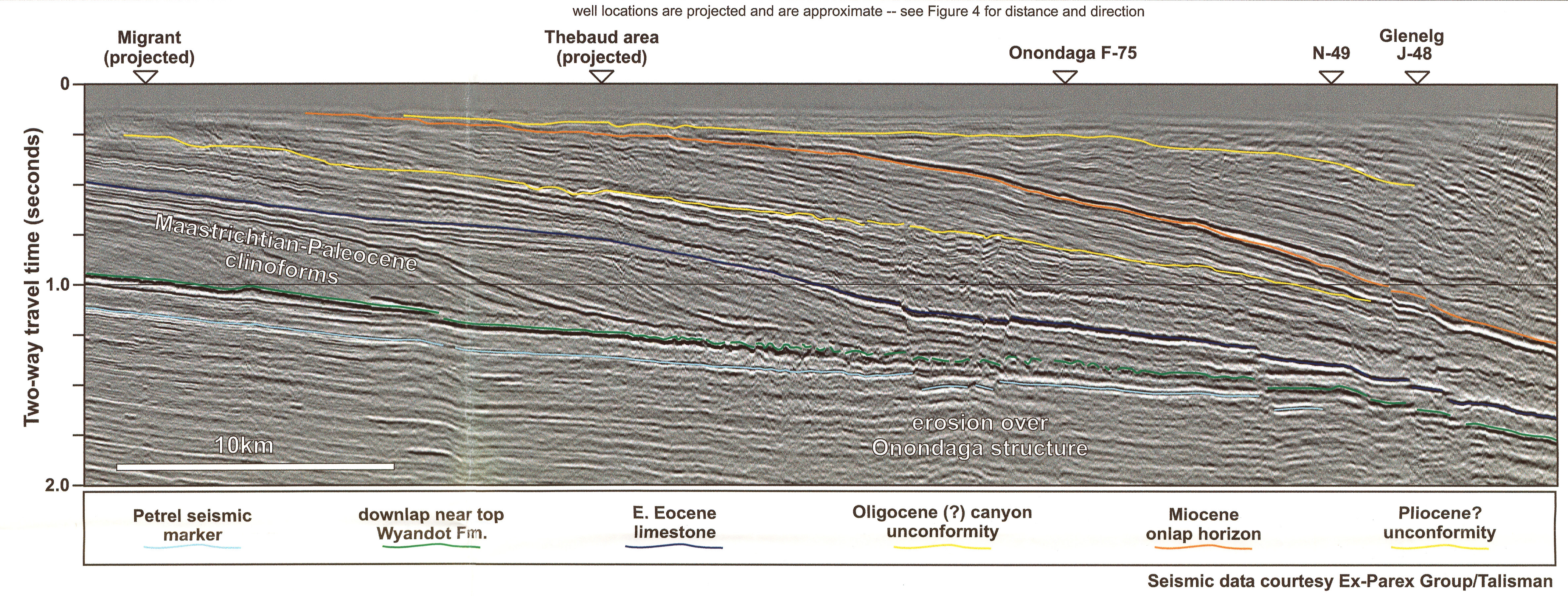
FIGURE 5: NORTHWEST-SOUTHEAST SEISMIC SECTION ACROSS THE SCOTIAN SHELF

The seismic section shown at right crosses the Scotian Shelf from northwest to southeast (see Figure 4 for location). A seismic marker approximately corresponding to the top of the Wyandot Formation (dark green) can be traced across much of the area, and often corresponds to a downlap surface for an overlying succession of prograding clinoforms (between dark blue and dark green horizons).

This geometry suggests the top Wyandot seismic marker may represent a condensed section developed during maximum flooding, prior to the progradation of the overlying, probably highstand, clinoforms. However, the seismic horizon has significant lateral variations in its character. For example, it becomes irregular, lower-amplitude, and discontinuous over the top of the Onondaga salt structure. In wells at Onondaga, this interval corresponds to an unconformity surface probably encompassing the mid and upper Campanian according to biostratigraphic data (Doeven, 1983, see Figure 6 below). In addition to local development over salt structures, the top of the Wyandot Formation is commonly interpreted as erosional on the basis of biostratigraphy and truncation of reflectors towards the shelf edge (Wade and MacLean, 1990).

It is apparent that this marker is highly diachronous and represents several different types of events in a sequence-stratigraphic context.

well locations are projected and are approximate -- see Figure 4 for distance and direction



Seismic data courtesy Ex-Parex Group/Talisman

FIGURE 2: WYANDOT FORMATION LITHOFACIES AND CORRELATION TO ELECTROFACIES

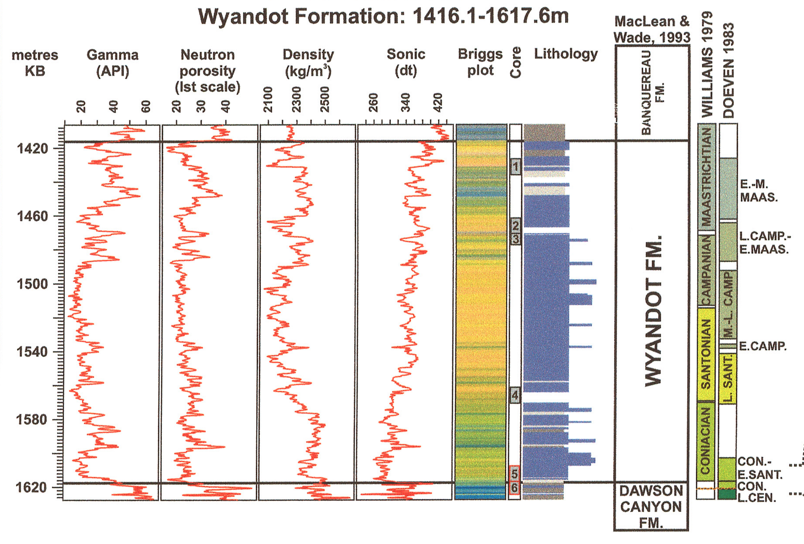
Because of the paucity of available conventional core, interpretation of the lithofacies of much of the Wyandot Formation depends upon cuttings and wireline logs. An exception is conventional cores available at the Eagle and Primrose areas on the Scotian Shelf, where calibration of the wireline logs to detailed lithofacies observations is possible.

Figure 2A shows the entire thickness of the Wyandot Formation at Primrose A-41, and Figure 2B shows an expanded-scale summary of the conventional core near the lower contact of the formation with the underlying Dawson Canyon Formation. Both logs are correlated to a colour "Briggs plot" (Collins and Doveton, 1986), a log combining gamma, neutron porosity, and the difference between neutron and density porosity tools to yield a visual summary of the variability in electrofacies (see Figure 4). At this location, the Wyandot Formation is dominated by chalky limestones (Lithofacies 1), which appear in the Briggs plot as orange, yellow, and brownish colours (low gamma, relatively large difference in neutron and density porosity). Intervals of gas shows and high porosity in the chalk correspond to the deepest orange and yellow colours, based upon observations in cores 2, 3, and 4 and formation tests. Greenish-yellow and green colours in the Briggs plot (slightly higher gamma, lower contrast between neutron and density porosity) correspond to marlstones (Lithofacies 2). Deep blue colours (high gamma) correspond to mudstones or calcareous mudstones, the dominant lithofacies of the Dawson Canyon Formation beneath, and the lower part of the Banquereau Formation above the Wyandot Formation.

These correlations can be used to infer lithofacies variations for other wells (see Figure 4). Similar comparisons were made for the cores and electrofacies of Eagle D-21, Primrose F-41, and Primrose N-50.

A

SHELL PRIMROSE A-41
Wyandot Formation: 1416.1-1617.6m



B

Cores 5 & 6
1607.82-1624.58m

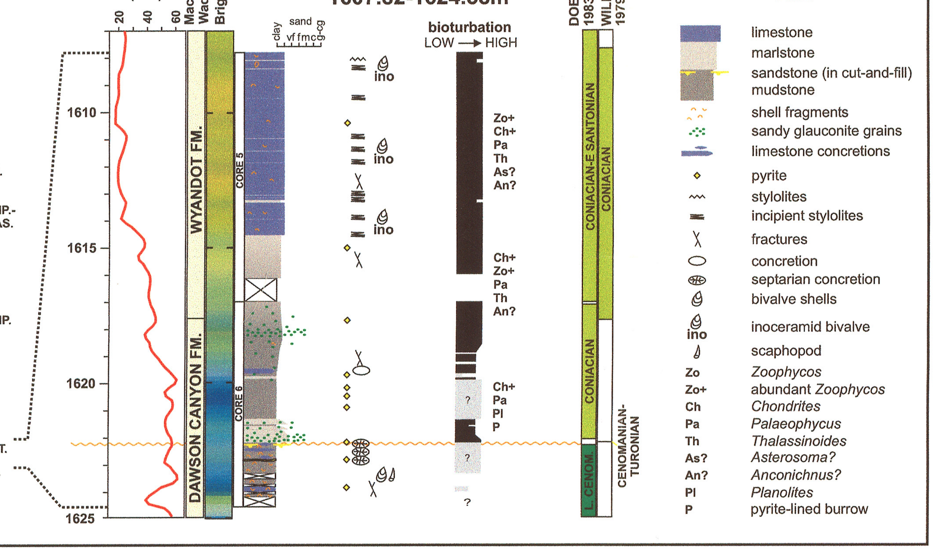
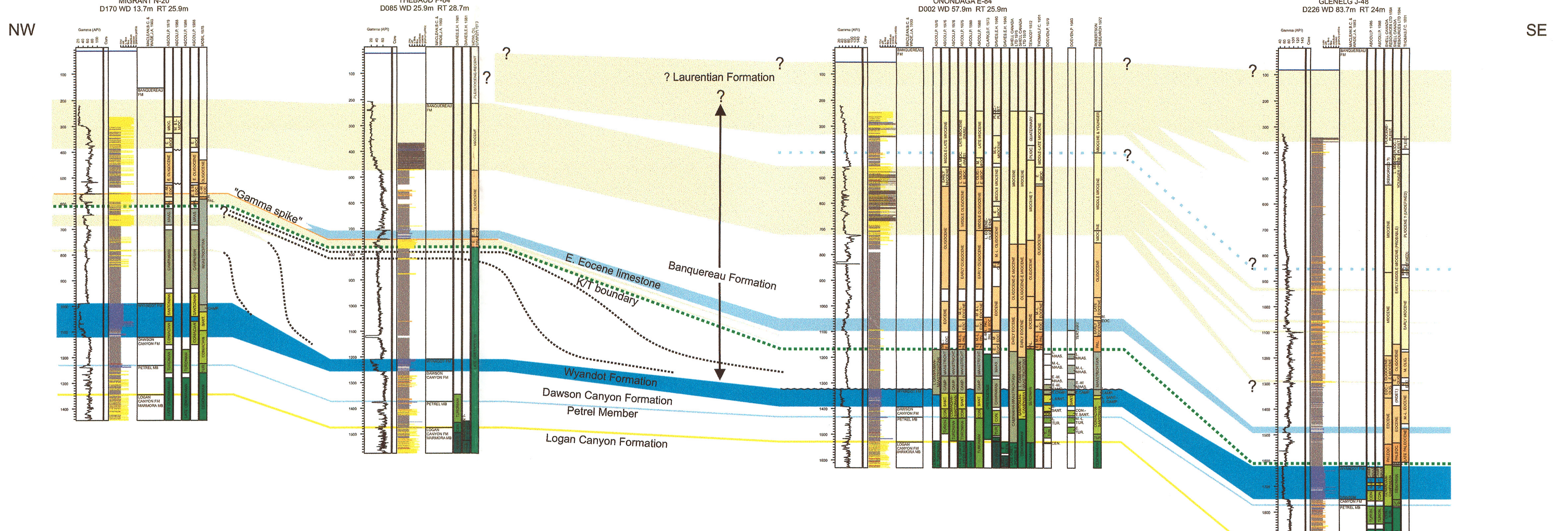


FIGURE 6: STRATIGRAPHIC CROSS-SECTION SHOWING LITHOFACIES VARIATIONS IN THE WYANDOT FORMATION AND RELATED LATE CRETACEOUS UNITS

Detailed lithostratigraphy and biostratigraphy of the Wyandot Formation demonstrates a complicated stratigraphic relationship with the overlying Banquereau and underlying Dawson Canyon Formations.

The Wyandot Formation spans approximately Santonian to Campanian time in most areas, but sometimes persists into the Coniacian and Maastrichtian, such as on the eastern Scotian Shelf. On the inner part of the Scotian Shelf, it is overlain by up to 400 metres of Campanian-Maastrichtian mudstones grading upwards to medium-grained sandstones as young as Lower Paleocene, assigned to the lower part of the Banquereau Formation. The sandstones capping this interval thin and pinch out distally on the shelf, and correspond approximately to the location of the topsets of prograding clinoforms seen in seismic sections (see Figure 5). A distinctive spike in gamma ray logs occurs in the area of the clinoform topsets. Towards the shelf edge, the upper contact of the Wyandot Formation is often erosional, and the Maastrichtian is absent or undetected as the mudstones and sandstones of the clinoform unit thin dramatically. Based upon biostratigraphy, the Campanian-Maastrichtian clinoform units are coeval, in part, with the upper part of the Wyandot Formation, but only where erosion of the Wyandot Formation has not completely removed the Maastrichtian.



These lithostratigraphic sections were constructed using digital data stored in the BASIN database (http://agcwww.bio.ns.ca/BASIN/) from Canstrat Ltd. and QC Data Ltd.. Lithostratigraphic picks were modified from MacLean and Wade (1993).

REFERENCES

Ascoli, P.
1976: Foraminiferal and ostracod biostratigraphy of the Mesozoic-Cenozoic, Scotian Shelf, Atlantic Canada. Maritime Sediments, Special Publication, no.1, p.653-771.

Ascoli, P.
1988: Mesozoic-Cenozoic foraminiferal, ostracod and calpionellid zonation of the North Atlantic margin of North America: Georges Bank-Scotian Basins and northeastern Grand Banks (Jeanne d'Arc, Carson and Flemish Pass Basins). Biostratigraphic correlation of 51 wells. GSC Open File 1791, 41p.

Ascoli, P.
1990: Foraminiferal, ostracod and calpionellid zonation and correlation of 42 selected wells from the North Atlantic margin of North America. Bulletin of Canadian Petroleum Geology, v.38, no.4, p.485-492.

Briggs, P.L.
1985: Color display of well logs (abstract). Journal of Mathematical Geology, v.17, no.4, p.481.

Collins, D.R. and Doveton, J.H.
1986: Color images of Kansas subsurface geology from well logs. Computers and Geosciences, v.12, no.4B, p.519-526.

Deptuck, M.
1998: Characterization and interpretation of Late Cretaceous to Eocene erosional features and submarine fans of the Jeanne d'Arc Basin, offshore Newfoundland. B.Sc. Honours Thesis, Department of Geology, Saint Mary's University, Halifax, Canada.

Doeven, P.H.
1983: Cretaceous nannofossil stratigraphy and paleoecology of the Canadian Atlantic Margin. Geological Survey of Canada, Bulletin 356, 69p.

Given, M.M.
1977: Mesozoic and Cenozoic geology of offshore Nova Scotia. Bulletin of Canadian Petroleum Geology, v.25, no.1, p.63-91.

Jansa, L.F. and Wade, J.A.
1975: Geology of the continental margin off Nova Scotia and Newfoundland in Van der Linden, W.J.M. and Wade, J.A. (eds.) Offshore Geology of Eastern Canada, Paper 74-30, volume 2, p. 51-105.

MacLean, B.C. and Wade, J.A.
1993: Seismic markers and stratigraphic picks in the Scotian Basin wells. East Coast Basin Atlas Series. Geological Survey of Canada, 276p.

Shimeld, J.W.; MacRae, R.A. and J.B.W. Wielens
2000: Sequence stratigraphy and hydrocarbon potential of regional Upper Cretaceous limestone units, offshore Eastern Canada. GeoCanada 2000, Calgary, Alberta, Abstract 784.

Swift, J.H., Switzer, R.W., and Turnbull, W.F.
1975: The Cretaceous Petrel Limestone of the Grand Banks, Newfoundland in Yorath, C.J., Parker, E.R., and Glass, D.J. (eds.) Canada's Continental Margins and Offshore Petroleum Exploration. Canadian Society of Petroleum Geologists, Memoir 4.

Wade, J.A. and MacLean, B.C.
1990: The geology of the southeastern margin of Canada, Chapter 5 in Geology of the Continental Margin of Eastern Canada, M.J. Keen and G.L. Williams (eds.). Geological Survey of Canada, Geology of Canada, no. 2, p. 167-238.

OPEN FILE
DOSSIER PUBLIC
4023
GEOLOGICAL SURVEY OF CANADA
COMMISSION GÉOLOGIQUE DU CANADA
2002

Recommended citation:
MacRae, R.A., Shimeld, J.W., and Wielens, J.B.W.
2002: Sequence stratigraphy and hydrocarbon potential of Upper Cretaceous limestone units, offshore Nova Scotia. Geological Survey of Canada, Open File 4023

Canada