OPG's DEEP GEOLOGIC

REPOSITORY

FOR LOW & INTERMEDIATE LEVEL WASTE

Analogue Study of Shale Cap Rock Barrier Integrity

March 2011

Prepared by: T. Engelder

NWMO DGR-TR-2011-23

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EXECUTIVE SUMMARY

Ontario Power Generation (OPG) is proposing the development of a Deep Geologic Repository (DGR) at the Bruce nuclear site in the Municipality of Kincardine, Ontario for the long-term management of Low and Intermediate Level Waste (L&ILW) from OPG owned or operated nuclear generating facilities. This report presents evidence to show that gas prone, organic rich shales from the Appalachian-Ouachita stratigraphic system serve as suitable analogues to demonstrate the long-term integrity of a 212 m thick Ordovician shale sequence, which will act as the primary cap rock seal for the proposed DGR horizon.

Suitable analogues exist across the Appalachian-Ouachita stratigraphic system since the Blue Mountain Formation shale, which forms the lower portion of the seal rock at the Bruce nuclear site, correlates across the Appalachian and Michigan Basins with a number of formations that include the Utica, Antes, Pleasant Point, Reedsville and Martinsburg Formations. The Blue Mountain shale was deposited during the Ordovician Taconic Orogeny when the eastern margin of Laurentia was tectonically loaded during a period of continental collision. This tectonic loading depressed the continent to the east, creating accommodation space that was subsequently filled in by a thick marine clastic succession. Rapid downflexing of the continent created a starved sedimentary sequence into which a significant volume of organic material was preserved. This starved sequence is characteristic of a transgressive systems tract (TST) indicating a rapid eustatic sea level rise that can be amplified by a tectonically induced (i.e., non-eustatic) sea level rise.

Another suitable analogue is the organic rich Marcellus Shale with a total organic content (TOC) of >12%. The Marcellus shale was also deposited in response to a tectonically induced sea level rise and underwent continued Paleozoic subsidence and burial, which allowed these rocks to achieve thermal maturity and generate hydrocarbons. These hydrocarbons subsequently became trapped beneath formations that have acted as seals since the end of the Paleozoic. Seal longevity is evident from the recognition of regional overpressures in the northern Appalachian Basin and underpressures in the southern Appalachian Basin. The Ordovician shales at the Bruce nuclear site are underpressured, signalling the long-term existence of a similar stratigraphically-controlled cap rock seal.

Total organic content (TOC) at the Bruce nuclear site is typically less than 2% with an isolated peak in the upper portion of the Collingwood Member of the Cobourg Formation recorded at 2.5%. Limited hydrocarbon maturation at the Bruce nuclear site is a result of subsidence that reached a total burial depth of approximately 1.5 km and certainly no more than 2 km, creating temperatures that only marginally crossed the oil generation window (60ºC). This lack of thermal maturity in combination with low organic content has resulted in the generation of a very limited occurrence of commercially unexpolitable hydrocarbons at the Bruce nuclear site.

Gas generation in the Appalachian Basin has lead to extensive and pervasive natural hydraulic fracturing (NHF) and three analogs to the Bruce nuclear site seal rock (i.e., Utica, Marcellus and Geneseo shales) contain extensive NHF. These are common in the underpressured portion of the Appalachian Basin where large volumes of gas were generated during maturation of source rocks. In contrast, the seal rock at the Bruce nuclear site does not contain closely spaced NHF as indicated by extensive coring. In this regard the integrity of the cap rock seal was protected by a lack of maturation with the relatively low TOC insufficient to drive extensive NHF.

The lack of hydrocarbons, maturation related fracturing, high clay content and the existence of underpressured compartments at the Bruce nuclear site demonstrate that long-term integrity of the Upper Ordovician shales can be maintained for geological time periods.

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1. INTRODUCTION

Ontario Power Generation (OPG) proposes to construct a Deep Geologic Repository (DGR) for Low and Intermediate Level Waste (L&ILW) at OPG's Bruce nuclear site in the Municipality of Kincardine, Ontario. The proposal is to excavate underground emplacement rooms at a depth of about 680 m below the surface within the lower member of the Ordovician Cobourg Formation.

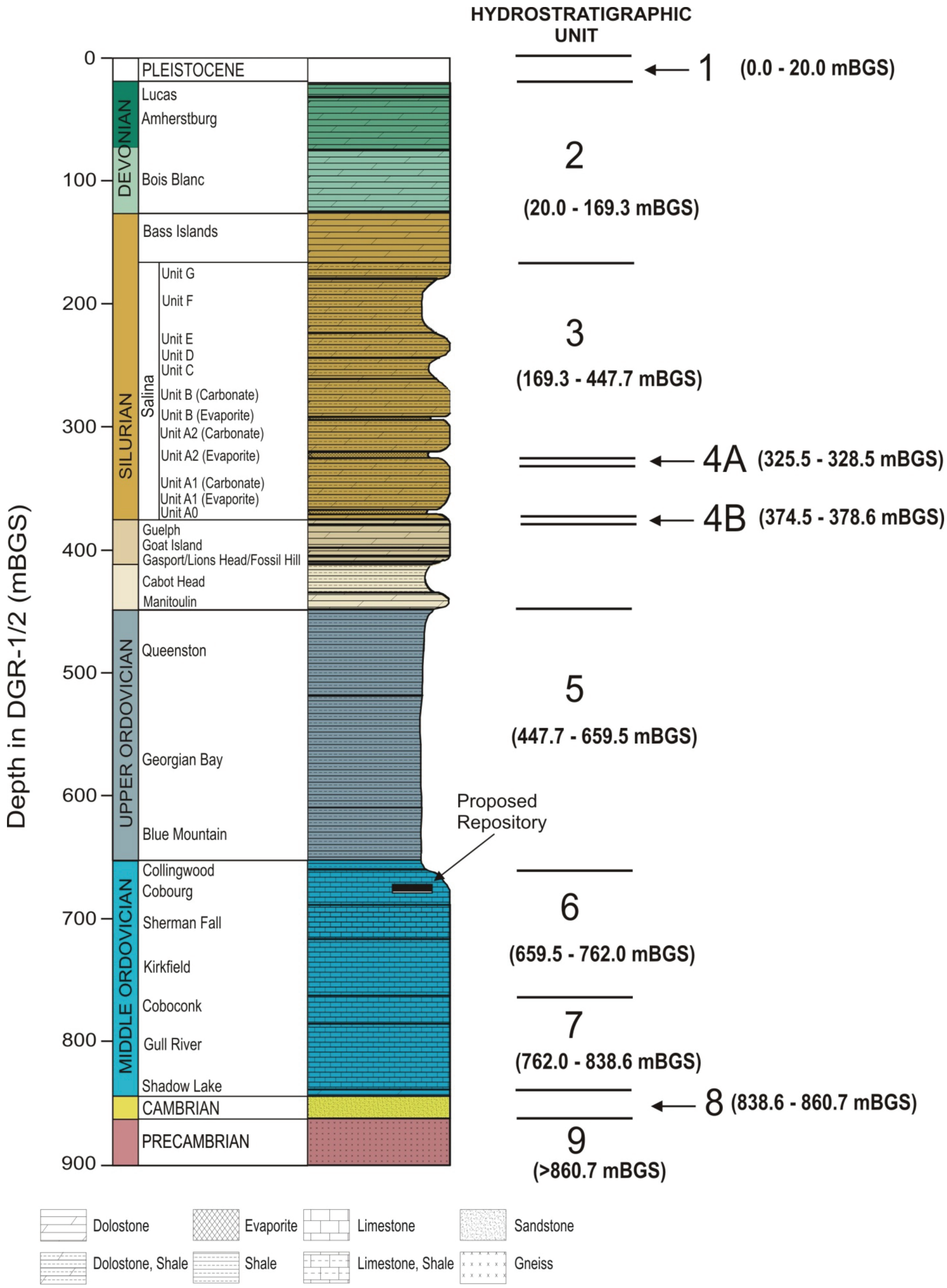
The cap rock at the Bruce nuclear site is defined as the package of rocks from the top of the Queenston Formation to the base of the Collingwood Member of the Cobourg Formation, these formations form hydrostratigraphic unit (HS) # 5 (Figure 1.1). Cap rock integrity is the long-term ability of a rock to maintain a very low bulk permeability despite being penetrated by either joints or small faults. It is known that argillaceous or evaporitic rocks are most likely to remain impermeable even when disrupted by minor brittle structures. The cap rock at the Bruce nuclear site consists of several geological layers including Upper Ordovician red shales, greenish to bluish shales with interbedded limestone, and non-calcareous shales grading downward to a Mid Ordovician black shale (Armstrong and Carter 2010). The basal portion of this 212 m thick cap rock will act as a primary seal for the DGR. The Collingwood Member is a dark grey to black, organic rich, calcareous shale with very thin, fossiliferous bioclastic interbeds (Armstrong and Carter 2010).

The Upper Ordovician seal rocks at the Bruce nuclear site (i.e., the Queenston-Georgian Bay-Blue Mountain-Collingwood stratigraphic package), particularly the basal portion of this package, are equivalent to the Coburn limestone to Antes (Utica) black shale transition in the Ordovician section of Pennsylvania (PA), the Marcellus Shale in the Devonian section of PA and the Point Pleasant and Utica (Blue Mountain) organic-rich shales in Ohio (Obermajer et al. 1999a). These units comprise petroleum systems that are both source and reservoir rock (Curtis 2002, de Witt et al. 1993, Drozd and Cole 1994, Engelder et al. 2009, Milici 1993, Milici et al. 2003, Roen 1984; Ryder 2008, Ryder et al. 1998).

The recent focus of industry on black shales brings an increased understanding of them as a petroleum system. Many of these black shale reservoirs are overpressured and, hence, effective seal rocks and possible analogs for the seal rock at the Bruce nuclear site (Curtis 2009, Energy Information Agency 2009, Engelder et al. 2009).

Field measurements of horizontal hydraulic conductivity (K_h), formation pressure, and hydraulic head tests were conducted in six wells, which were drilled into the cap rocks of the Bruce nuclear site (INTERA 2011[1]). Within the cap rock aquiclude (HS Unit #5, Figure 1.1),formation average horizontal hydraulic conductivities range from $3x10^{-14}$ in the Queenston Formation to $2x10^{-14}$ m/s in the Collingwood Member of the Cobourg formation (INTERA 2011). Abnormally high formation pressures were observed in the Silurian Goat Island, Gasport and Lion's Head Formations. Hydraulic head tests show that the hydraulic gradient converges within the Mid Ordovician in the Blue Mountain shale (Figure 1.2). A number of mechanisms may cause underpressured shale including poroelastic response to glacial unloading, poroelastic response to Cenozoic erosional exhumation; capillary pressure effects due to a separate gas phase, and/or chemical osmosis (Neuzil 1993, Neuzil 2000).

[1] Currently known as Geofirma Engineering Ltd.



Note: From INTERA (2011).

Figure 1.1: Stratigraphic Column Showing Hydrostratigraphic Units at the Bruce Nuclear Site

The hydraulic head tests at the Bruce nuclear site lead to the conclusion that the Ordovician shale of the Georgian Bay and Blue Mountain Formations have a formation-scale permeability (k) of less than 10^{-20} m^2 ($K_h < 10^{-13}$ m s^{-1}) (INTERA 2011). This lithological package is ideal for maintaining long-term integrity with the hydraulic head data suggesting that HS#5 will serve as the cap rock.

1.1 Report Objectives

The objective of this report is to answer the following questions: 1) Do gas shales from known petroleum systems in the Appalachian and Michigan Basins provide natural analogs for the long-term behaviour of seal rock at the Bruce nuclear site, 2) Is there the potential for commercially exploitable hydrocarbon occurrences within the vicinity of the Bruce nuclear site?. Because the seal rock at the Bruce nuclear site is underpressured (Figure 1.2), the objective can be reduced to an exercise in comparing and contrasting seals in the Appalachian-Ouachita stratigraphic system (A-OSS), some of which are overpressured rather than being underpressured. In this report, the rocks of the Michigan and Illinois Basins are considered part of the greater A-OSS.

These objectives can be answered through four specific tasks:

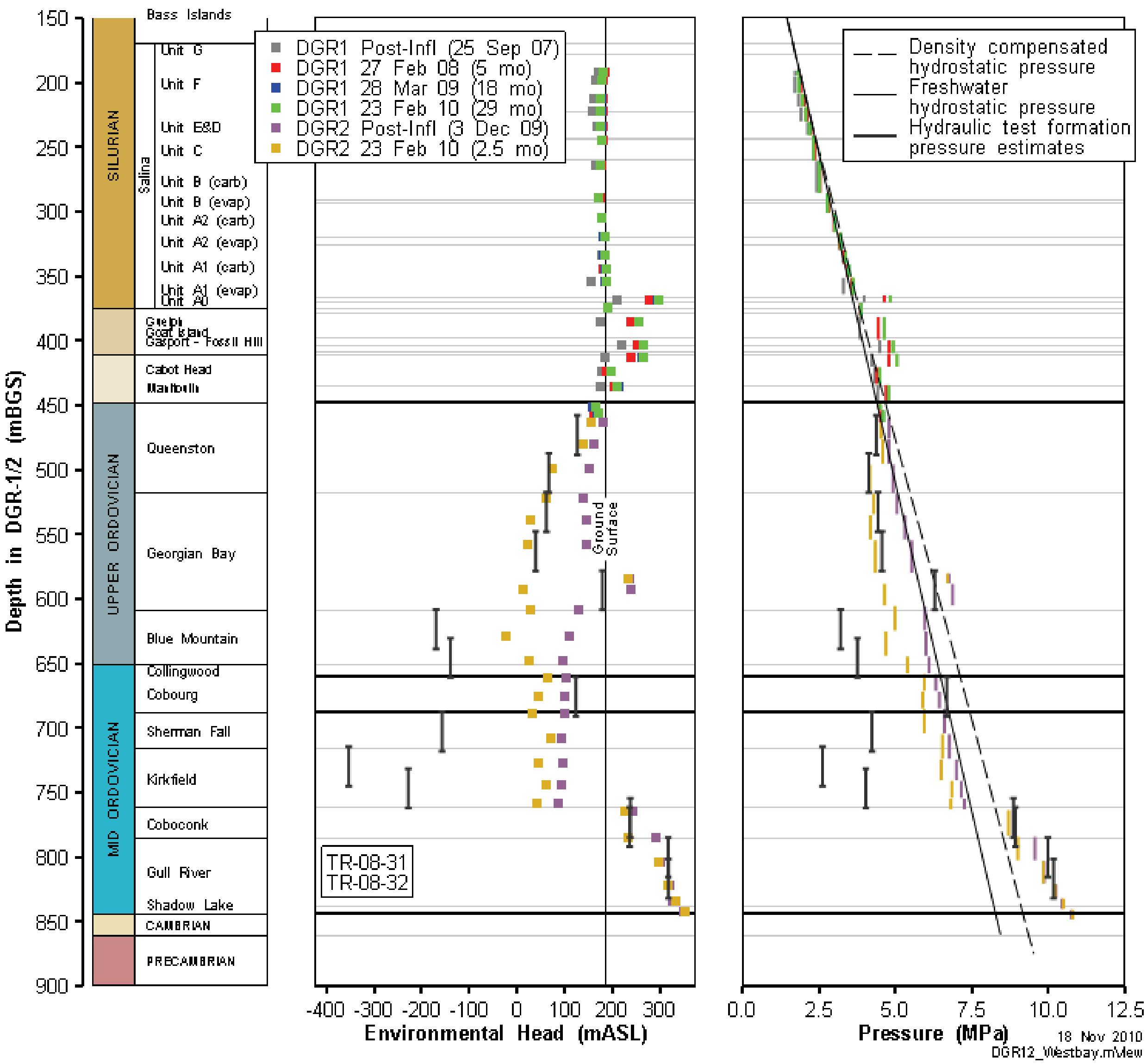
Task I: Examine the structure of Ordovician hydrocarbon reservoirs and sealing mechanisms throughout the Michigan and Appalachian basins in order to build a natural analog case for the Ordovician cap rock integrity at the Bruce nuclear site.

Task II: Analyze structural styles of reservoir faulting and the mechanisms and nature of fault propagation into the overlying Ordovician Shales. Here joints are considered the most likely brittle structure to disrupt seal integrity of a shale seal largely because of the extent to which they pervade black shale source rocks.

Task III: Investigate the occurrence of shale gas within the Michigan and Appalachian basins to constrain the potential for commercial shale gas within the Ordovician Shales in the Bruce area of Ontario.

Task IV: Utilize data from the Bruce nuclear site drilling program, which includes porosity and permeability data, TOC measurements, pore pressure data and pore fluid compositions for assessment of Ordovician shales in the Bruce area as a potential commercial source of unconventional hydrocarbons.

These four tasks have been integrated into this report, which stems from the driving question paraphrased as, “Do gas-prone, organic-rich rocks of the Appalachian and Michigan Basins serve as appropriate analogs in predicting the long-term behaviour of the Ordovician stratigraphic section immediately overlying the proposed Deep Geologic Repository?”



Note: From INTERA (2011).

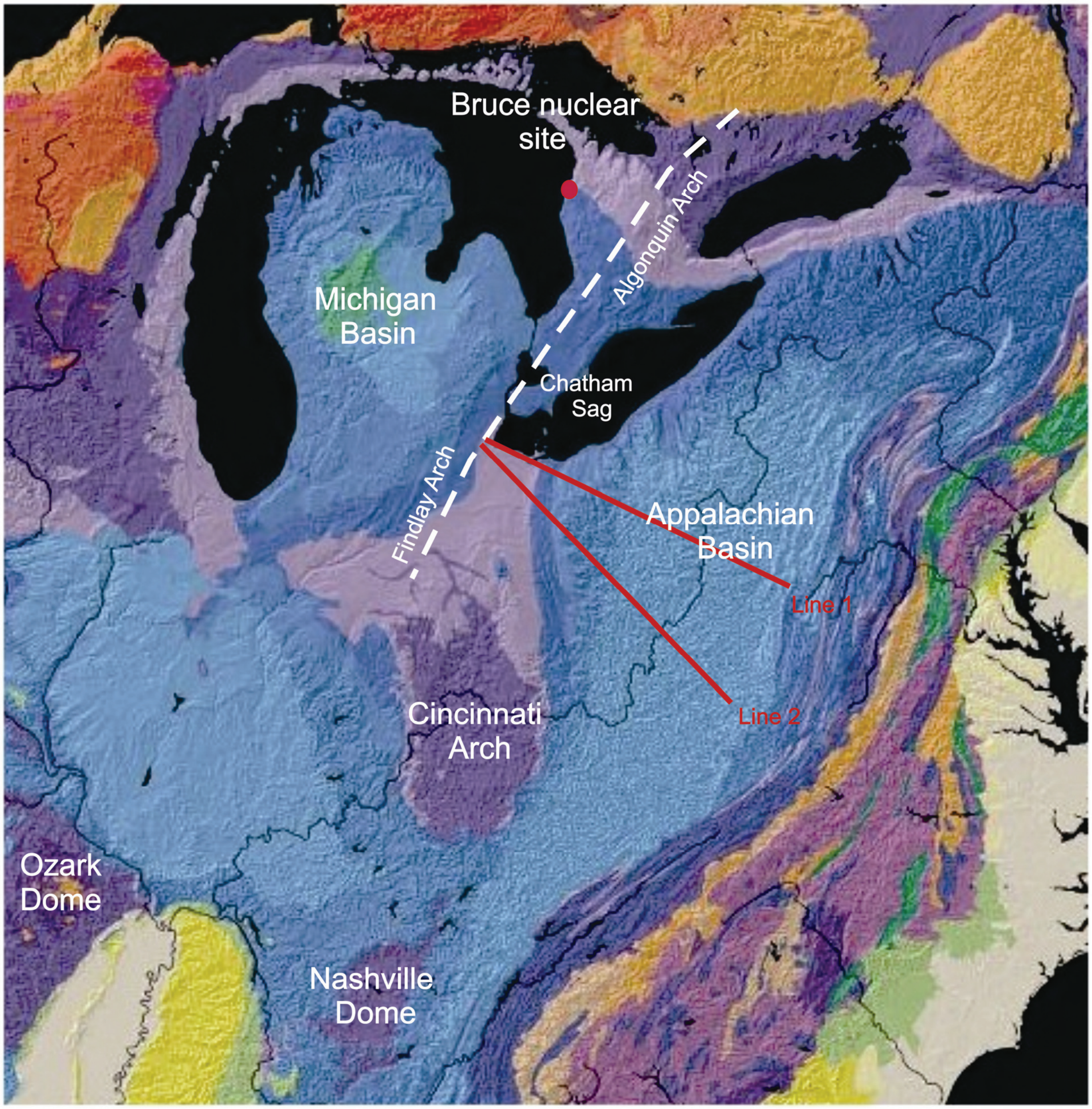
Figure 1.2: Composite Profile of Formation Pressure, Fresh Water Head and Environmental Head

2. BACKGROUND

Rocks of the Appalachian-Ouachita stratigraphic system (A-OSS) including the Michigan Basin date from the breakup of the supercontinent, Rodinia. The basal portion of the A-OSS is a classic rift-to-drift sequence of sedimentary rocks deposited on the southeastern margin of Laurentia, the early Paleozoic predecessor of North America. In modern geography the A-OSS extends from the Appalachian Basin across the Algonquin and Findlay Arches into the Michigan Basin. The A-OSS covers the Cincinnati Arch and Nashville Dome and extends as far west as the southern side of the Ozark Dome and into the Oauchita and Marathon Mountains of Oklahoma and Texas (Figure 2.1). Because the focus of this report is on the question of the long-term integrity of seal rocks at the Bruce nuclear site, we must study paleoseals in parts of the A-OSS to gain confidence that seal rocks at the Bruce nuclear site, situated on the western flank of the Algonquin Arch, have properties in common with their counterparts in the A-OSS. To establish that components of the A-OSS were paleoseals, we first need to lay out the rationale for presuming that any rocks of the A-OSS: 1) may have been overpressured; and 2) that a pressure seal may have been present within argillaceous sections of the A-OSS. Bear in mind that exhumation, particularly to outcrops, has relieved whatever overpressuring may have once been present in these rocks.

The Bruce nuclear site is located just to the west of the Algonquin Arch in Southern Ontario (Figure 2.1). Because of its location, the seal rocks at the Bruce nuclear site are logically considered part of the Michigan Basin petroleum system (Swezey et al. 2005). In this report, the Michigan Basin along with rocks of the Algonquin Arch are incorporated into the greater A OSS. A total petroleum system (TPS) consists of petroleum source, reservoir, seal, and overburden rock with the essential elements of a conventional petroleum system distinguished in the same manner (Magoon and Dow 1994, Ryder 2008). Unconventional gas shales of the A-OSS act as a TPS with the first three elements, source, reservoir and seal being the same rock. The total petroleum systems of the Appalachian and Michigan Basins are further discussed in detail in chapter three of this report. In order to understand the factors that may affect integrity of the primary seal for the Bruce nuclear site (i.e., the Ordovician Blue Mountain-Georgian Bay section), it is appropriate to review the deposition of black shales and their development into source rocks as a source for natural gas in the Appalachian-Ouachita stratigraphic system (A-OSS). Exploration and production of gas in the Appalachian Basin lead to the discovery of extensive areas exhibiting abnormal pore pressure over large reaches of the Appalachian Basin. The extent of this abnormal pore pressure regime is the primary evidence that seal rocks, mainly the black shales, maintained long-term seal integrity. The paradox is that these same seal rocks are pervasively fractured, largely with the propagation of natural hydraulic fractures (NHF) (Engelder et al. 2009). Long-term seal integrity in the presence of pervasive fractures requires a mechanism for self-sealing the system.

The Ordovician seal rocks at Bruce nuclear site are underpressured. Regions of the A-OSS in the Appalachian Basin are also underpressured. Presently, it is not clear what geological conditions lead to a regional stratigraphic system that house both states of pore pressure. While the geological history of the A-OSS must vary along strike to allow for both states of pore pressure, it is presumed that common rock properties allow both states. An analysis of conditions, particularly those that yield long-term seals, for abnormally high pore pressure are applicable and relevant to understanding long-term seals for rocks containing abnormally low pore pressures, such as those found at the Bruce nuclear site.



Note: Transect lines are discussed in Section 4.6 (Rowan 2006).

Figure 2.1: General Regional Geology of the Appalachian-Ouachita Stratigraphic System

Given the abnormally low pressures, if Ordovician rocks in the vicinity of the Bruce nuclear site are cut by ancient minor brittle faults, these faults are self-sealed. A rock is said to be self-sealing if it is cut by faults that have not allowed invasion of pore fluids to restore hydrostatic pressure. Lessons learnt from fracturing in overpressured environments within the Appalachian Basin may be applied to the self-sealing of discontinuities, if they exist, at the Bruce nuclear site.

A common characteristic across the Taconic Basin is the transition from carbonate to black shale. The transition starts with a calcareous shale and grades up into a more siliceous shale. The black shale tends to be mature in the proximal regions and immature in the distal regions; total organic content (TOC) falls in the range of 1% to 3% across the basin. The seal rock at the Bruce nuclear site is the distal part of the Taconic Basin (Figure 2.2). The major difference being that the proximal black shales were deposited several million years before a gradual deepening allowed the deposition of black shale in the distal reaches of the Taconic foreland.

In looking for the basis upon which the Ordovician seal rocks of the Bruce nuclear site may have analogs in the A-OSS, two general geological questions emerge: 1) What are the properties of a seal, particularly ones that involves black shales that later mature to become gas shales and 2) what are the characteristics of fractures, the major structure that can disrupt the integrity of a seal?

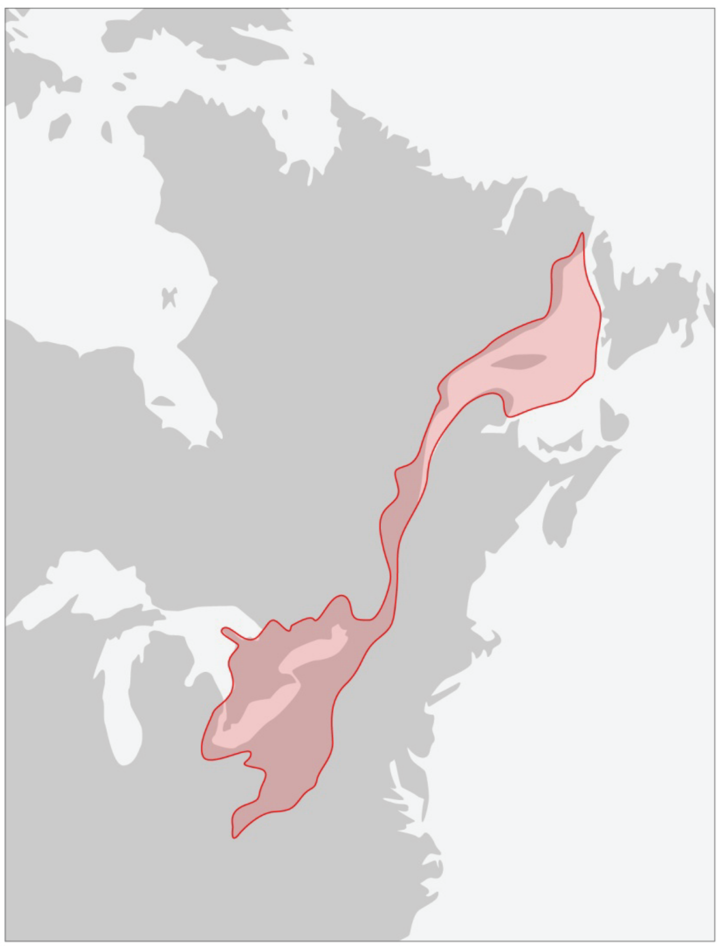
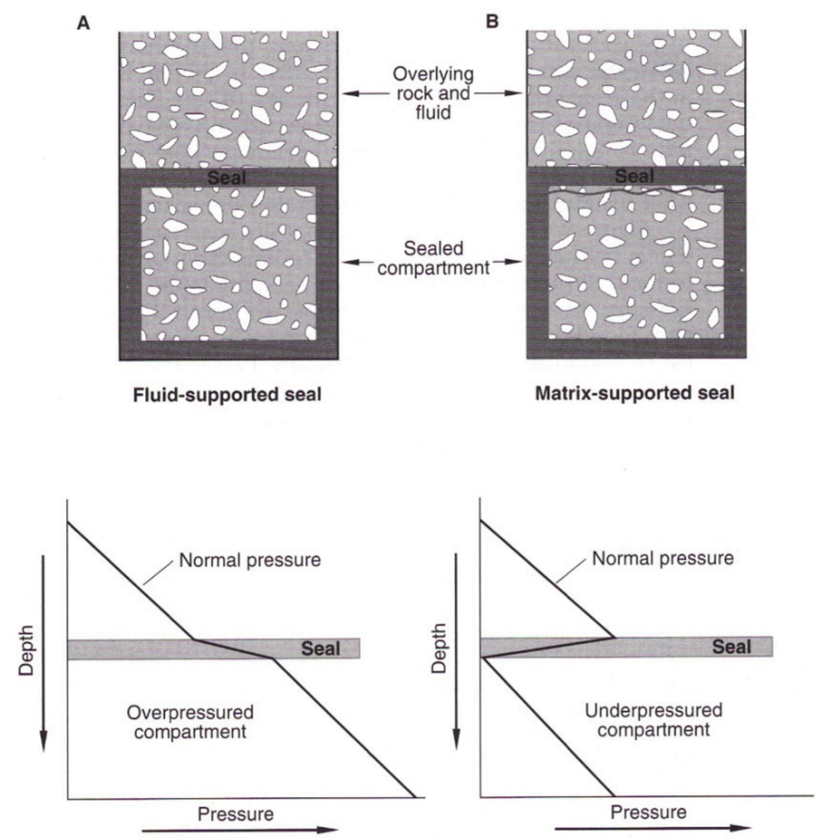


Figure 2.2: Extent of the Taconic Basin from the Proximal Utica to the Distal Blue Mountain Formations

2.1 Characteristics of a Seal Rock

A seal is any rock with a low enough permeability to prevent the upward flow of buoyant fluid. The classic conventional hydrocarbon trap is a seal below which immiscible fluids have separated with the least buoyant component at the top of a stack of petroleum-related fluids. A good seal rock is capable of maintaining a gas-pressure differential against hydrostatic (pressure in a free column of water) for geological time scales. Commonly this stack consists of gas over petroleum over water, trapped for a long enough time that equilibrium is established with each fluid at its own hydrostatic gradient. By buoyant forces, the pressure at the top of such a stack follows a hydrostatic gradient that is greater than water pressure at comparable depths outside the trap. When the trap is sealed at its bottom and the spill of hydrocarbons is not taking place, a pressure compartment has formed with seals on all sides (Figure 2.3).



Notes: (A) Pressure/depth gradient from normal pressure to overpressure across the hydraulic seal surrounding the overpressured rock section. (B) Pressure/depth gradient from normal to underpressured rock across the hydraulic seal surrounding the underpressured rock section (after Hunt 1996).

Figure 2.3: Fluid Compartments in the Petroleum and Natural Gas Environment

Seals present the possibility of abnormal pressure generation (Swarbrick and Osborne 1998; Swarbrick et al. 2002). The mechanisms causing abnormally high pressure are commonly grouped into three categories. These mechanisms include:

1. Stress-related mechanisms (compression leading to pore volume reduction):
   - Disequilibrium compaction (vertical loading stress);
   - Tectonic stress (lateral compressive stress);

2. Fluid volume increase mechanisms:
   - Temperature increase (aquathermal pressuring);
   - Water release due to mineral transformation;
   - Hydrocarbon generation;
   - Cracking of oil to gas;

3. Fluid movement and buoyancy mechanisms:
   - Osmosis;
   - Hydraulic head; and
   - Buoyancy due to density contrasts.

The Collingwood Member of the Cobourg Formation is underpressured. There are five mechanisms causing abnormally low pressure ((Swarbrick and Osborne 1998, Swarbrick et al. 2002) (Figure 2.4). These mechanisms include:

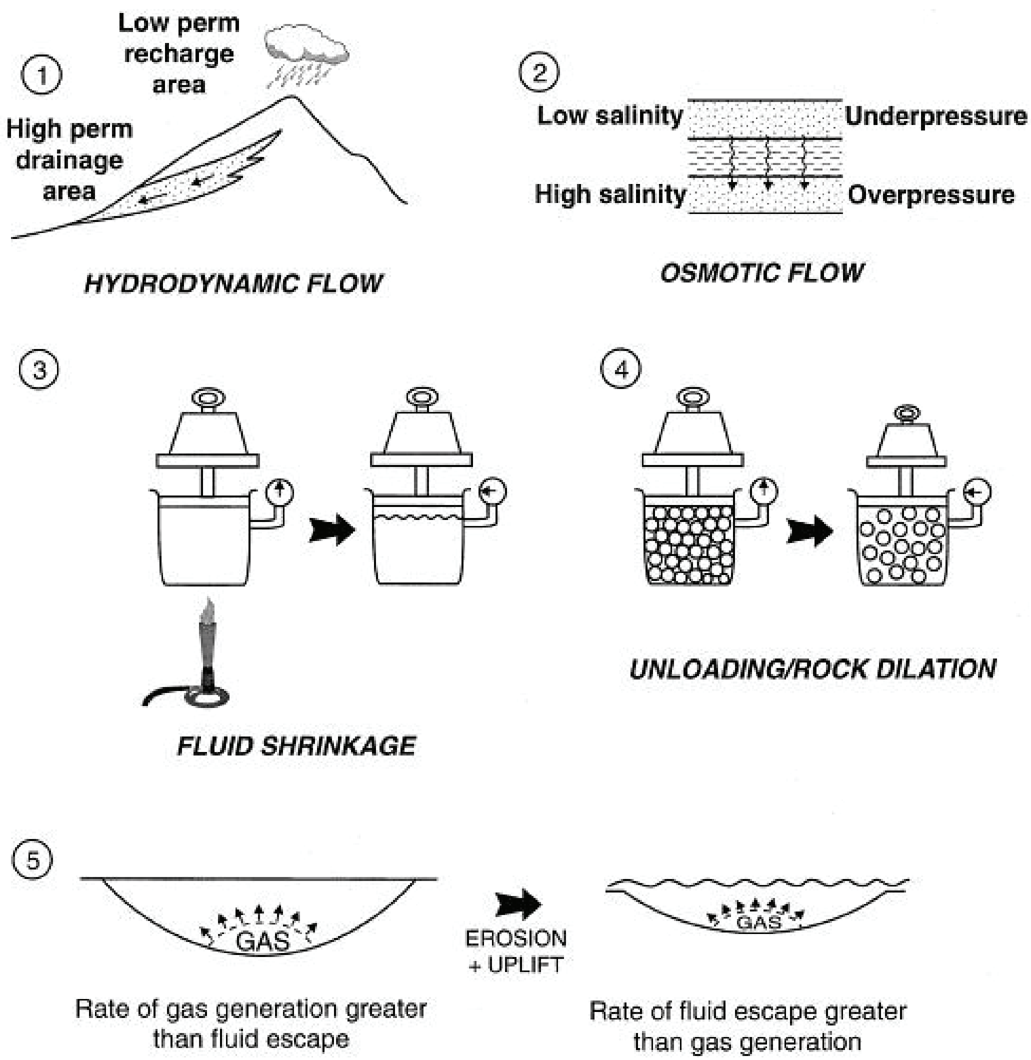
- Differential discharge of groundwater flow;
- Differential gas flow;
- Rock dilatancy;
- Osmosis; and
- Thermal affects.

2.2 Summary of Evidence for a Paleoseal

The following discussion points to twelve independent data sets that indicate a paleoseal and concomitant abnormal fluid pressure:

1. Undercompaction of shale via chlorite fabric analysis and anisotropy of magnetic susceptibility (AMS), below the lithology bearing the chemical signature for a seal;
2. Distribution of volume loss strain by pressure solution above the seal versus volume constant strain below the seal from modeling and field observations;
3. Present in situ stress profile showing evidence for poroelastic relaxation below the seal;
4. Thermal maturation of hydrocarbons increases with depth in the Appalachian Basin;
5. Fluid inclusion trapping pressures shows evidence for abnormal pressure;
6. Vertical distribution of lithologies is equivalent to that found in other overpressured basins on continental margins;
7. Density of shale: Evidence for undercompaction below the seal;
8. Surface morphology of cross-fold joints is indicative of fluid-driven joints;
9. Joint patterns (cross-fold joints better developed below the seal);
10. Joint patterns (abutting relationships change below the seal);

11. Joint patterns (070° joints found below the seal); and
12. Seal rocks are marked by a unique chemical signature.



Note: From Swarbrick and Osborne (1998).

Figure 2.4: Summary Diagram for the Major Mechanisms Thought to Be Responsible for Generating Underpressure

2.2.1 Undercompaction of Shale Based on Chlorite Fabric

Strain analysis not only provided information about tectonic deformation during the Alleghanian Orogeny but it also shed light on overburden compaction. The preferred orientation of chlorite basal planes in shales and siltstone was used to measure overburden compaction (Engelder and Oertel 1985, Evans et al. 1989b). A key assumption with this technique is that the clay grains were originally deposited with their basal planes oriented at random. During compaction and the accompanying loss of porosity, the clay develops a preferred orientation with basal planes sub-parallel to bedding. Analysis shows that compaction increases approximately linearly with depth, from 40% at the present surface to ≈ 65% at the base of the Rhinestreet (Figure 2.5). Beneath the Rhinestreet, compaction decreases to 50% in the underlying Cashaqua Formation. This type of compaction profile is consistent with compaction curves from overpressured portions of large sedimentary basins (Magara 1978). These data were also useful in first identifying the location of a regional pressure seal zone that is believed to have developed during sedimentation in the Devonian, particularly in the eastern reaches of the Catskill Delta where J_1 joints are well developed in the black shales of the Geneseo and Marcellus Formations.

2.2.1.1 Undercompaction of Shale Based on Anisotropy of Magnetic Susceptibility

If the ferromagnetic and paramagnetic components in rocks have a fabric induced by either overburden compaction or tectonic compaction, the susceptibility of the bulk sample will be anisotropic. The degree of susceptibility anisotropy will correlate with the relative strength of the fabric anisotropy. Measurements of low temperature Anisotropy of Magnetic Susceptibility (AMS), where the susceptibility from paramagnetic minerals is enhanced, shows that samples taken below the base of the Rhinestreet are relatively undercompacted (Hirt et al. 1995) (Figure 2.6).

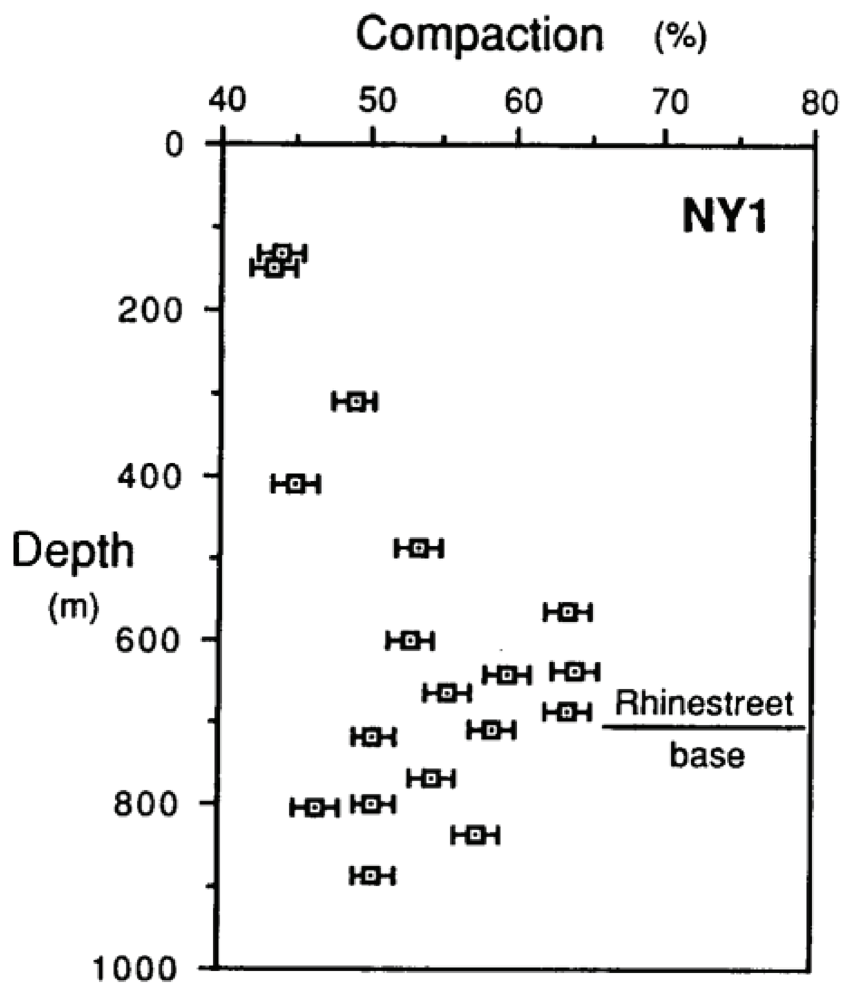
Total strain within the clastic rocks of the delta complex can be accommodated by one of three patterns, two of which are shown in Figure 2.7. In each pattern, overburden compaction is assumed to have finished before tectonic shortening took place. The effect of tectonic deformation could have caused either volume loss strain or volume constant strain. Volume constant strains include a bedding parallel stretch (type b strain) and a vertical stretch (type v strain). In contrast, uniaxial shortening (type u strain) would cause a volume loss strain.

2.2.2 Distribution of Volume Loss Strain by Pressure Solution (Modeling Results)

It is interesting to examine whether the vertical strain anomaly below the Rhinestreet (indicated by a chlorite fabric) can be explained entirely by a volume constant strain with undercompaction being a manifestation of this vertical stretching. Figure 2.8 is a predicted profile of compaction prior to the advent of Alleghanian shortening calculated based on a type v strain model. Even if type v strain took place below the Rhinestreet, we find that compaction of the lower section is still somewhat low. Hence, Evans et al (1989a) inferred that “overpressuring had developed to some degree prior to tectonic shortening”.

2.2.2.1 Distribution of Volume Loss Strain by Pressure Solution (Field Observations)

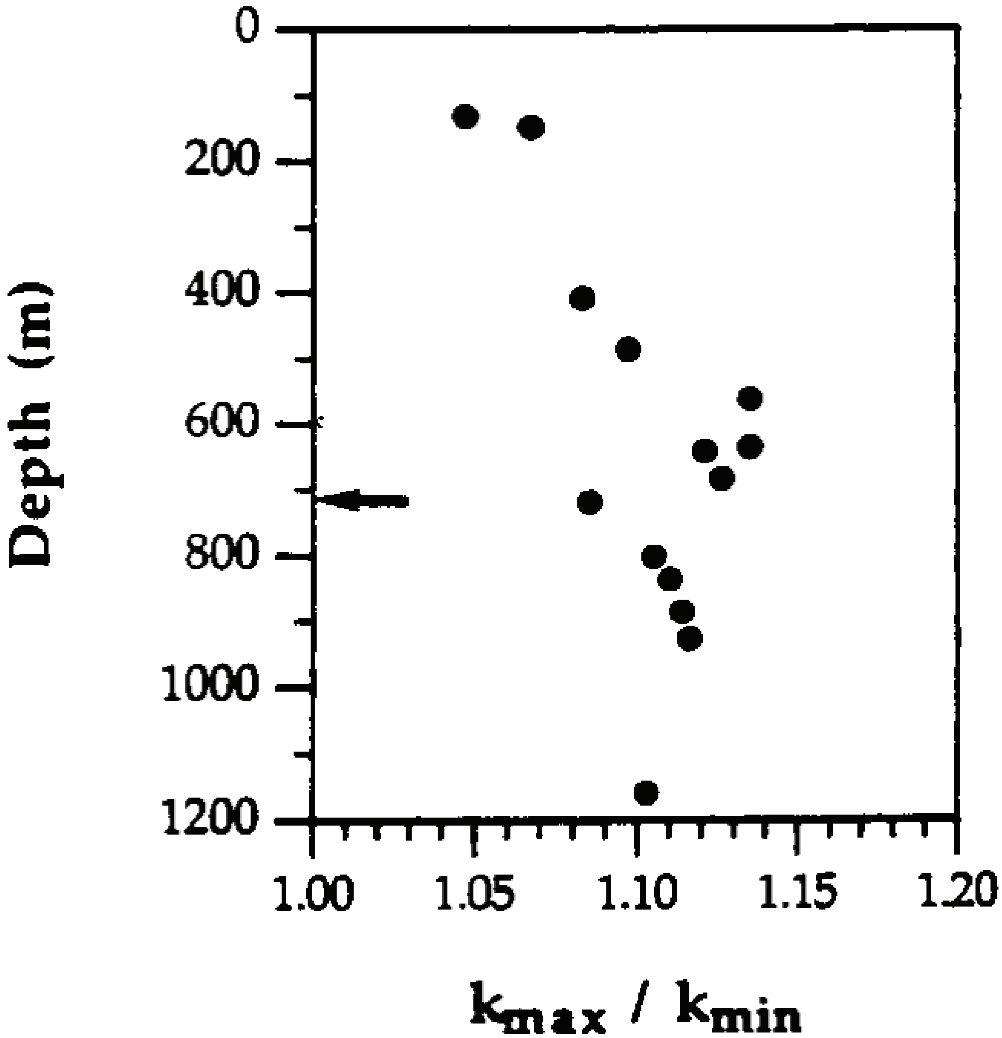
Layer-parallel shortening mechanisms including pressure solution and free-face dissolution are common within the Canadaway and West Falls Groups of the Catskill Delta but not so common lower in the section (Engelder 1979, Engelder 1984). Pressure solution and dissolution are volume loss strain mechanisms, which are more active where freely circulating water can carry dissolved components of the rock out of the local system. Restricted circulation of water favours volume-constant strain because there is no other mechanism known to remove large volumes of rock from the local system.



Note: Adapted from Evans et al. (1989a).

Figure 2.5: Compaction Estimates from Chlorite Fabric Analysis

If a seal were present during Alleghanian deformation, we would anticipate that volume constant strain would be more likely below the seal where water could not circulate freely. This appears to be the case where pressure solution is less common below the base of the Rhinestreet Formation. Although the Tully Limestone does contain well-developed pressure solution seams, deposition in local veins may account for any loss by pressure solution. Alleghanian joints of the Finger Lakes District are not filled with vein material. One interpretation of this phenomenon is that the joints were driven and then filled by a gas. The gas prevented water and concomitant minerals from filling the veins. If this was largely the case in the rock matrix as well, mass diffusion via water circulation would have been minimized and pressure solution would have taken place only along local grain boundaries. This latter condition would have favoured volume constant strain.

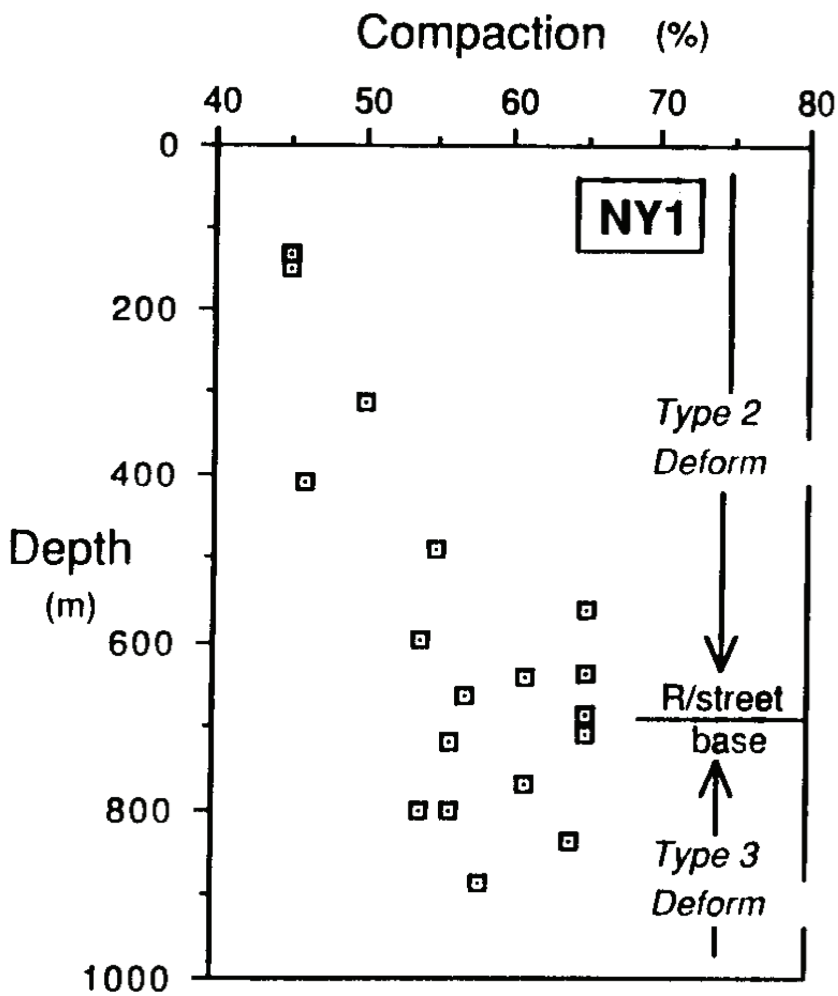


Note: Adapted from Hirt et al. (1995).

Figure 2.6: AMS Fabric Measured at Low Temperature where Paramagnetic Minerals Are Most Susceptible to a Magnetic Field

2.2.3 Present In Situ Stress Profile

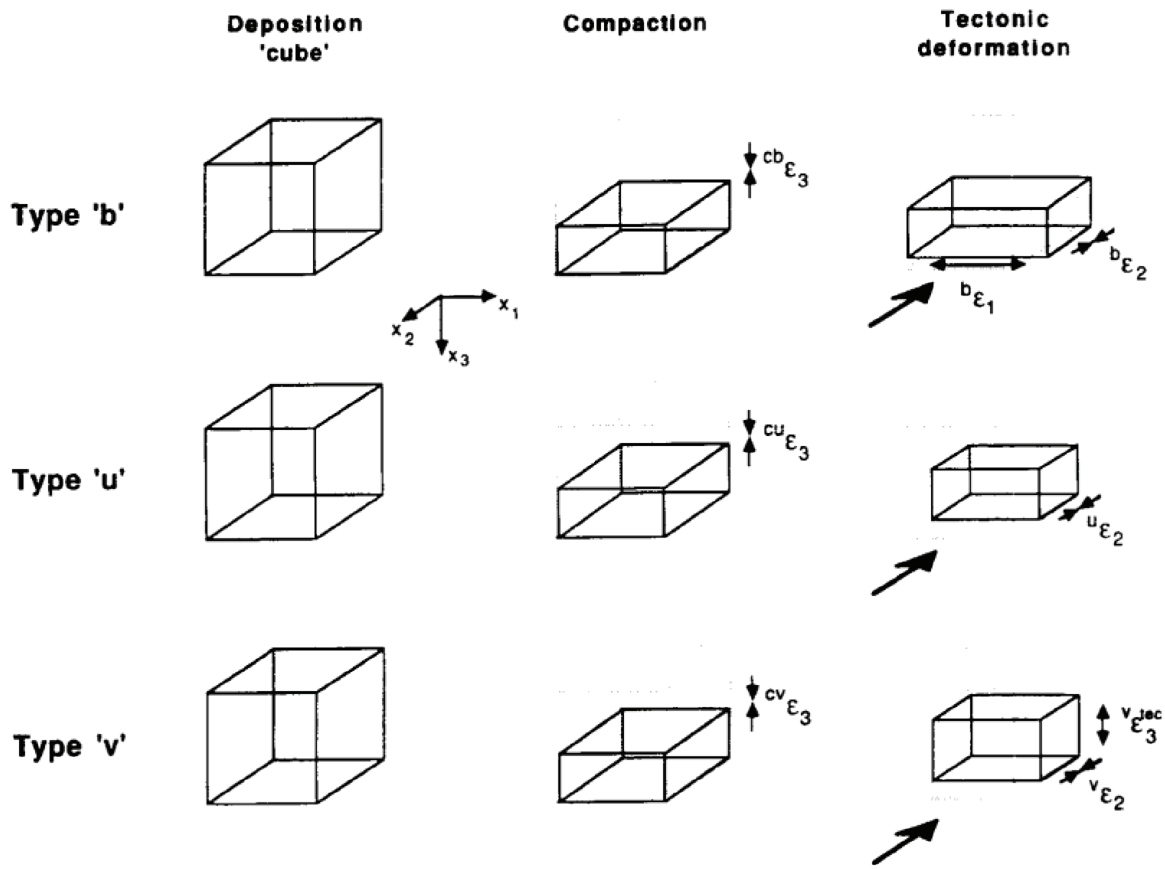
A detailed three-dimensional description of in situ stress in the section above the Hamilton Group from the Catskill Delta was obtained by conducting a series of hydrofracture measurements in three uncased 200 mm-diameter boreholes (Evans et al. 1989a). Each well shows three stress regimes (Figure 2.9): an upper regime with instantaneous shut in pressure (ISIP) on a lithostatic trend so that S_h (horizontal stress) is at least as great as S_v (vertical stress); a transition zone where S_h declines below S_v but S_h in the sandstone layers remains at least as great as the S_v; and a lower regime where S_h is significantly less than S_v. This stress offset corresponds to the base of the Rhinestreet where fabric data indicate shales are undercompacted. The stress discontinuity is consistent with drainage of an abnormal pore pressure in the sub-Rhinestreet section. If so, the stress drop is a consequence of a poroelastic relaxation of the sub-Rhinestreet section. Such a case for poroelastic relaxation is consistent with the pattern of undercompaction during Devonian sedimentation rather than layer-parallel shortening during the Alleghanian. Although Alleghanian deformation did not overprint the depositional fabric, the distribution of high fluid pressure was more extensive during the Alleghanian as indicated by the development of joints in the siltstones and gray shales throughout the Devonian section and, in particular, above the Devonian pressure seal.



Notes: To estimate overburden compaction the chlorite strain had to be normalized for the type of layer-parallel shortening developed during Alleghanian shortening. Type 2 layer-parallel shortening deformation is uniaxial parallel to bedding (type u) whereas Type 3 layer-parallel shortening deformation is volume constant strain (type v). Adapted from Oertel et al. (1989).

Figure 2.7: Overburden Compaction Based on the Analysis of Chlorite Fabric

In siltstone-gray shale sequences such as the Ithaca Formation (Genesee Group) field evidence indicates that jointing initiated in siltstone layers during the Alleghanian Orogeny. This means that S_h was low in the siltstone layers relative to shale layers. One of the interesting puzzles concerning the Alleghanian Orogeny, a compressional event, remains how S_h in the siltstone stayed low relative to the shale. The answer to this question is probably tied to the tendency for shale to compact more than siltstone under layer-parallel shortening.



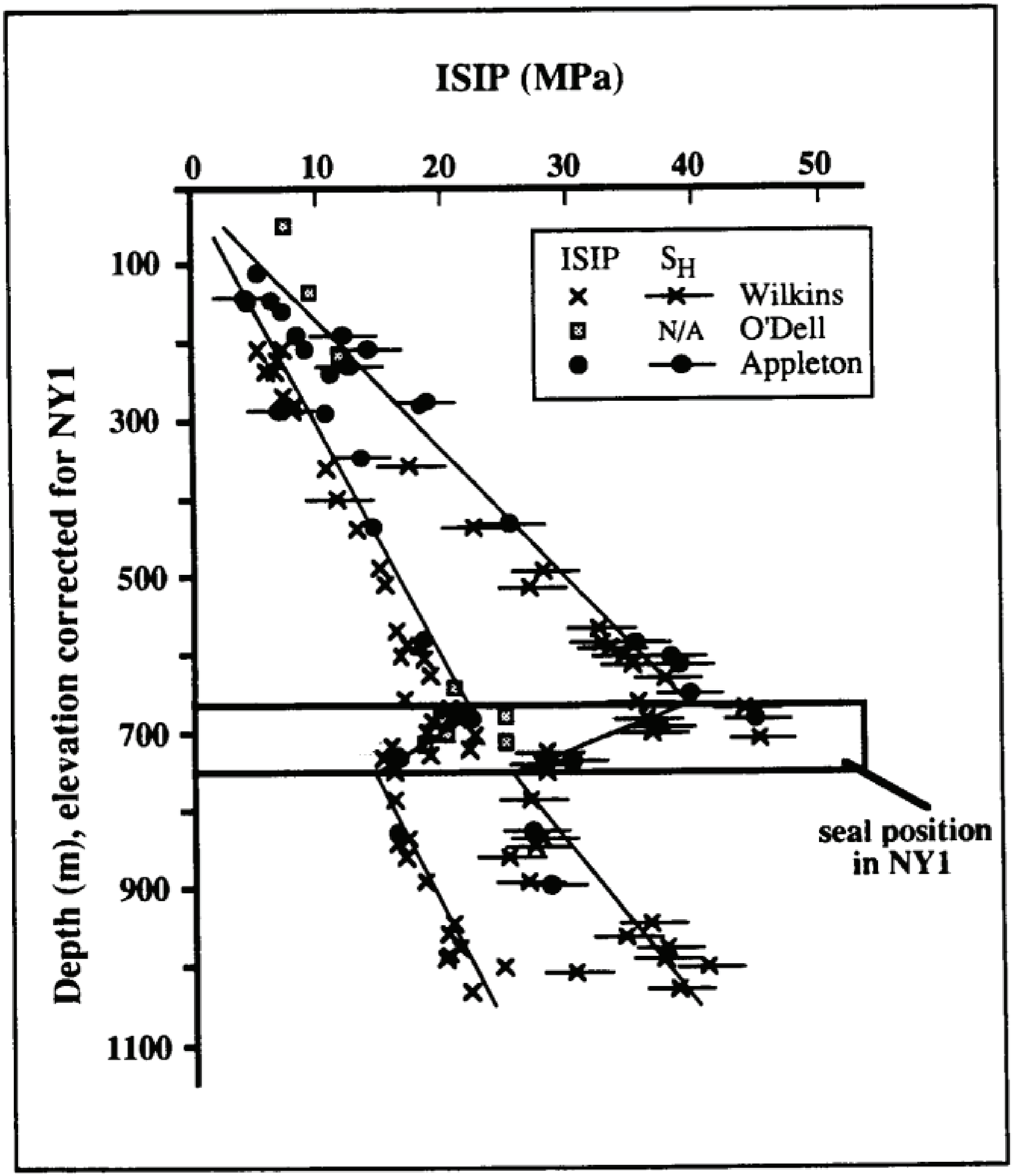
Notes: Distribution of volume loss versus volume constant strain. Adapted from Evans et al. (1989).

Figure 2.8: Tectonic Deformation Patterns Considered to Represent the Kinematic Response of the Devonian Clastic Section to Alleghanian Compression

2.2.4 Thermal Maturation of Hydrocarbons

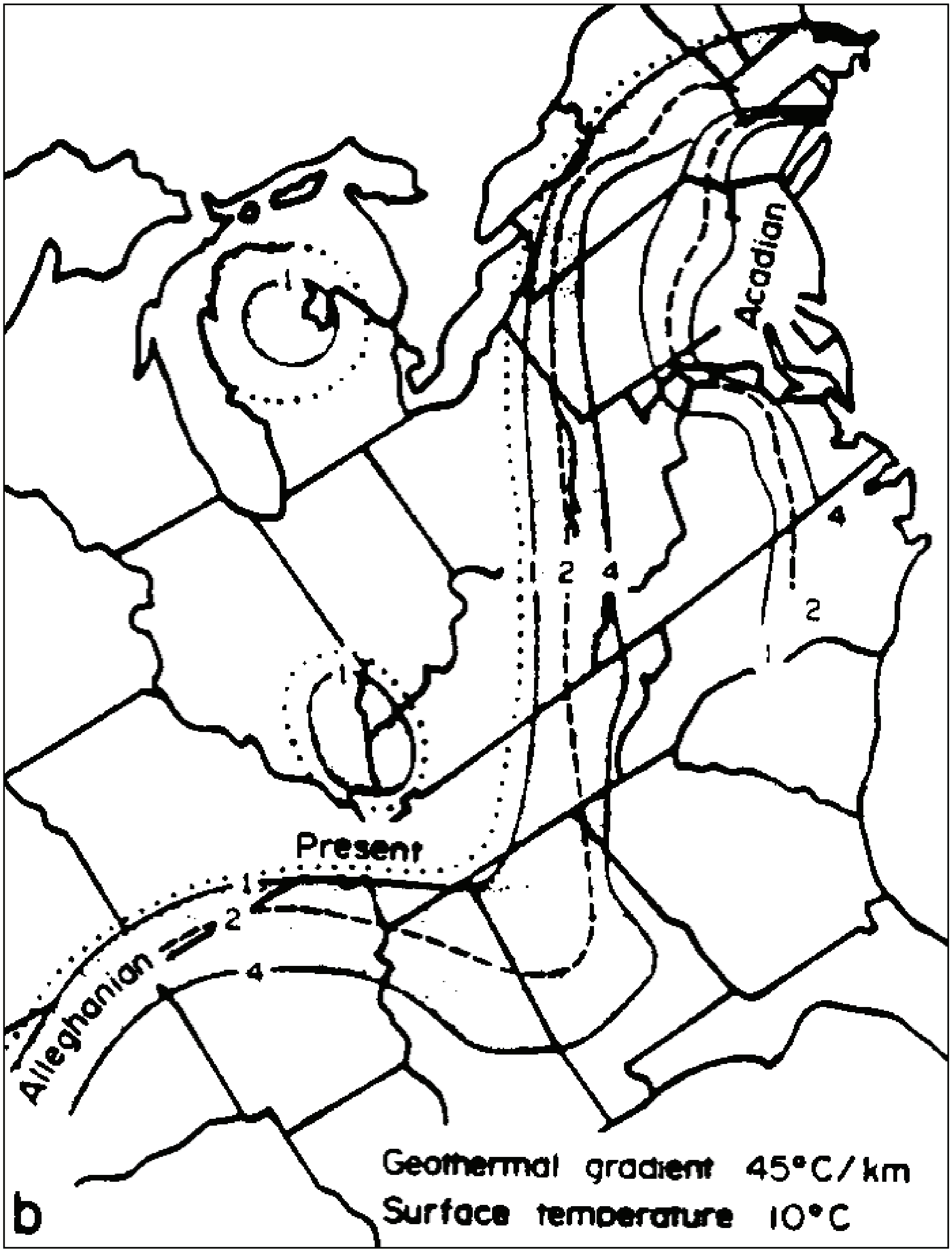
Maturation of hydrocarbons and the timing of oil and gas generation depend primarily on the time-temperature history of the sedimentary basin. The appropriate time-temperature history for Paleozoic source rocks in the Appalachian foreland basin was investigated by coupling the model burial history with the geothermal gradient to predict the time-temperature index of maturity - the TTI in Figure 2.10 (Beaumont et al. 1987). The modeling used a paleogeotherm of 45°C/km in central New York State approximately 40 Ma after the end of the Alleghanian

Orogeny which is quite compatible with the present geothermal gradient in an equivalent location in the Alberta Basin approximately 40 Ma after the Laramide Orogeny (Beaumont et al. 1985).



Note: Adapted from Evans et al. (1989a).

Figure 2.9: Instantaneous Shut In Pressure and Maximum Horizontal Stress (SH) from Three Wells in the Vicinity of Canisteo, New York

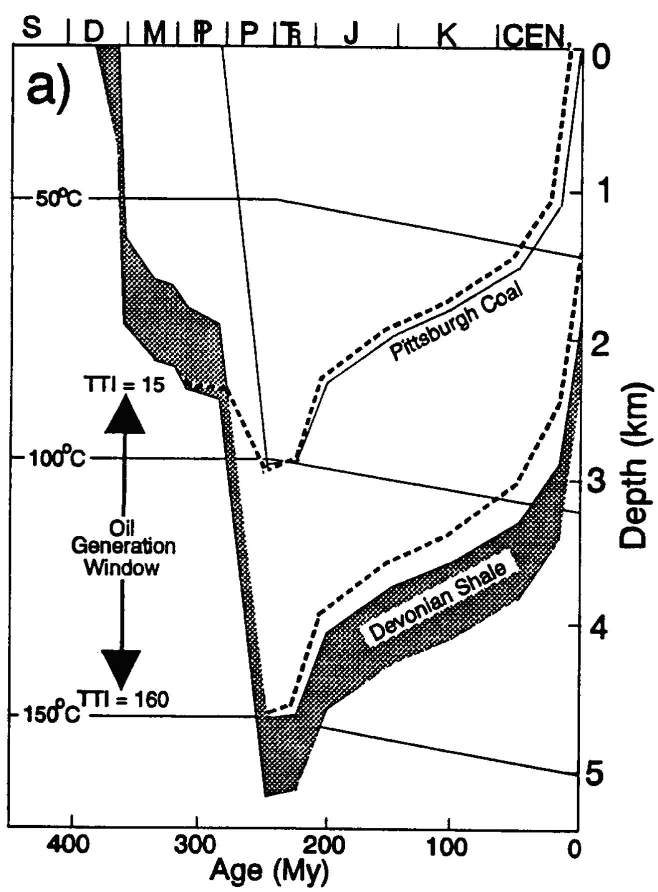


Note: Adapted from Beaumont et al. (1987).

Figure 2.10: Model Predictions of the Maturation of the Devonian Needmore Shale and Time Equivalent Unites

2.2.5 Fluid Inclusion Trapping Pressures

The trapping pressure of fluid inclusions may reflect the crack driving pressure for vein formation. If so, horizontal veins should have been driven by fluid pressures equal to the weight of overburden (Lacazette 1991). The trapping pressure in bedding-parallel veins of the Ordovician Bald Eagle Formation, Valley and Ridge of Pennsylvania, is consistent with an overburden of about 6 km. From these data we can conclude that fluid pressures approached lithostatic stress during the Alleghanian Orogeny in the Valley and Ridge. To the northwest in the Appalachian Plateau, fluid inclusion data from veins within the deeper portion of the Devonian section suggests that trapping pressures were well in excess of the hydrostatic gradient (Evans 1995). Based on the trapping temperatures and pressures, Evans (1995) derives a burial history curve for the Devonian section that shows an ultimate burial depth of 5.2 km (Figure 2.11). Of course the shale in the Finger Lakes district was never buried as deeply as that in the central portion of the basin. Never-the-less, TTI data from Devonian rocks of the eastern Catskill Mountains are consistent with a burial of 6.5 km (Friedman and Sanders 1982). These data from Devonian shales of Pennsylvania are the most direct evidence that the shales of the Finger Lakes district might also have been overpressured.

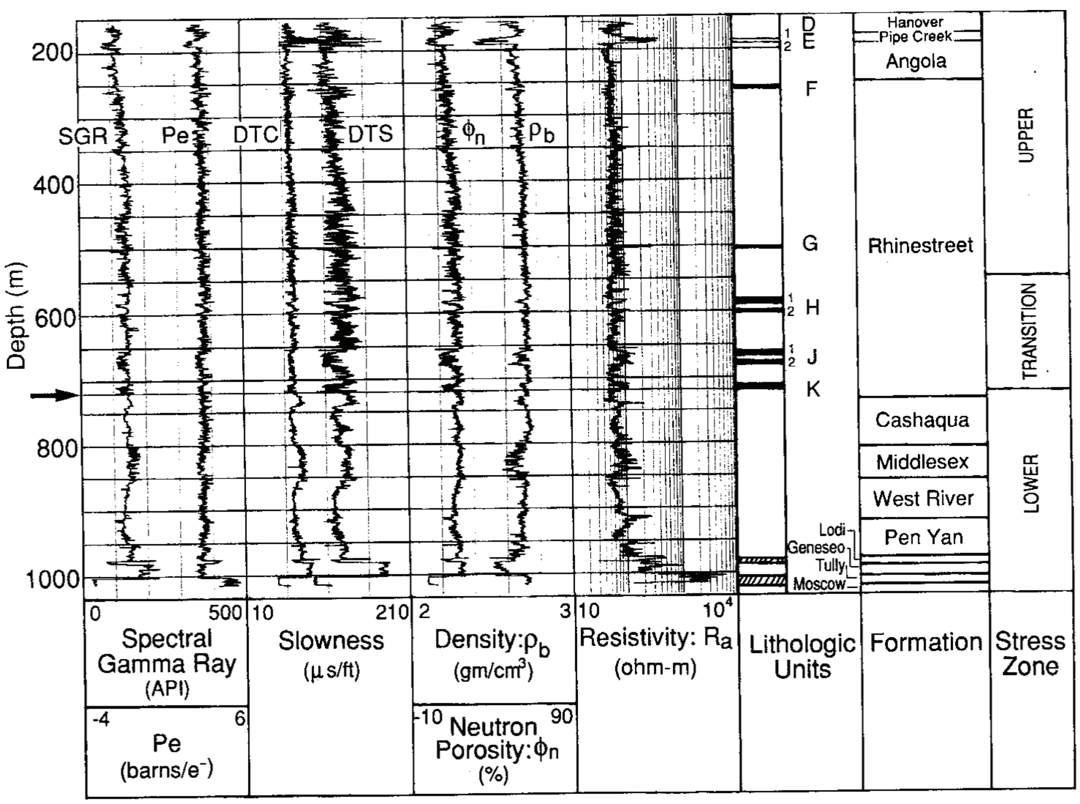


Note: Adapted from Evans (1995).

Figure 2.11: Burial History Curves for the Middle Devonian Shale Section and the Pittsburgh Coal for the Central Appalachian Plateau, Pennsylvania

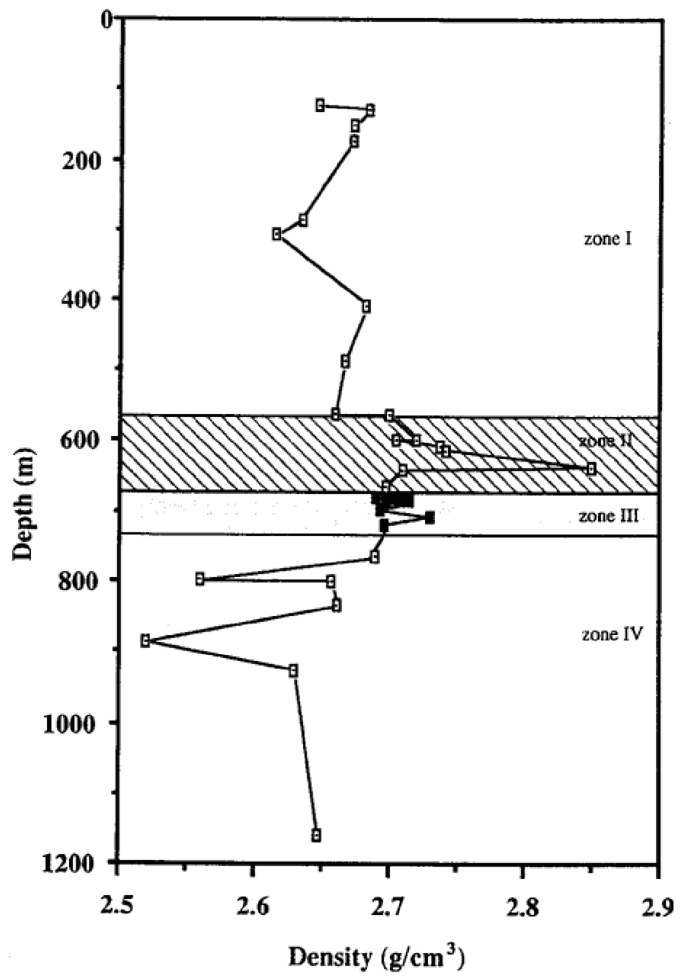
2.2.6 Vertical Distribution of Lithologies

The Catskill Delta complex of the Finger Lakes district is a typical prograding delta with regression of the shoreline to the west or southwest. Such deltas are characterized by thicker homogeneous shales at the base with interbedded sandstones and shales above. A set of geophysical logs shows just this type of a transition (Plumb et al. 1991) (Figure 2.12). In more recent delta complexes such as the Norias delta of south Texas the sequence is that of a thick shale section (Jackson and Vicksburg) under a sand-shale sequence (Frio and Miocene) (Leftwich and Engelder 1994). The transition from normal to abnormal pressure in the Norias Delta is found at the transition from sandstone-shale to dominantly shale section. Because the Catskill and Norias Deltas have a similar vertical distribution of lithology, it is not surprising that the seal and a transition to the overpressured portion of both delta complexes is found at the same lithologic position.



Notes: Key lithological units, formation names, and the three stress regimes of Evans et al. (1989a). “Sands” interbedded in shales are indicated by D-K. The Tully limestone is located at the base of the well. Adapted from Plumb et al. (1991).

Figure 2.12: Principal Geophysical Logs from the Wilkins Well



Notes: Shale densities (as measured in a heavy liquid column) peak in and above the transition zone, but decrease in the lower stress regime, indicating undercompaction of the deeper seated rocks. These data are consistent with strain measurements mentioned earlier in the text. Adapted from Albrecht (1992).

Figure 2.13: Shale Density Profile for ESGP Wells NY1 and NY4

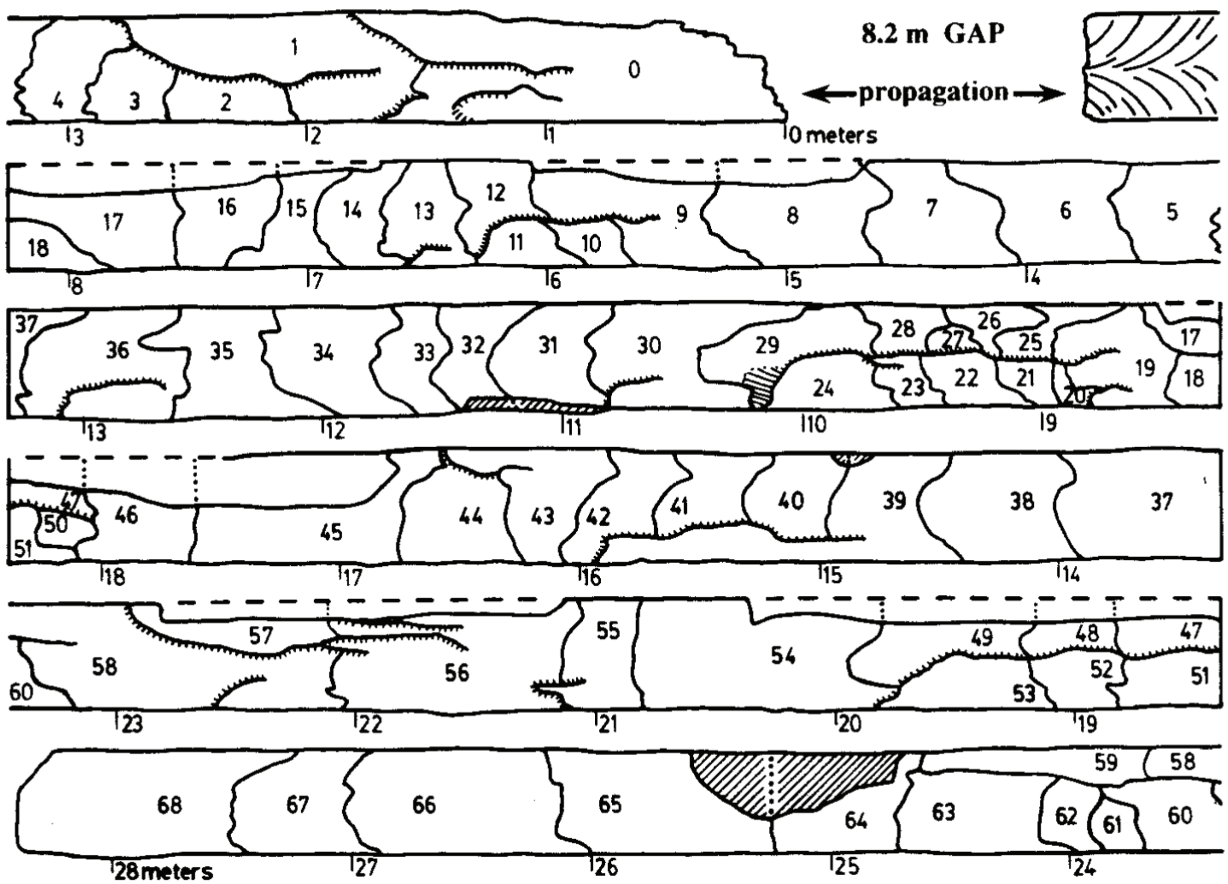
2.2.7 Density of Shale: Evidence for Undercompaction

One common electric-log signal used by industry for identifying the transition to abnormal pressure is a change toward lower resistivity shale (Hottman and Johnson 1965). This transition commonly correlates with lower shale density indicative of undercompacted shales (Magara 1978). In the Norias Delta, a transition to low density shale (as measured by mud loggers) falls near the top of abnormal pressure (Leftwich and Engelder 1994). A similar relationship between decreased density and an abnormally pressured interval is observed in the gamma and density logs at the Bruce nuclear site, at the contact between Upper Ordovician shales sequence and the adjacent units (INTERA 2011). Shales of the Catskill Delta complex show this same transition to low density shale in the vicinity of the transition zone at the base of the Rhinestreet (Figure 2.13).

It should be noted that black shales show a tendency toward lower density, as is the case for both the Geneseo and Middlesex black shales. The interlayered gray shales may be more sensitive to a density reduction during undercompaction (i.e., Cashaqua, Penn Yan, and Rhinestreet). Again, this data is consistent with other data sets revealing undercompaction which is, in turn, used as evidence for paleo-overpressures.

2.2.8 Surface Morphology Indicative of High Fluid Pressure

Some cross-fold joints contain a cyclic pattern indicative of repeated propagation and arrest, related to the mechanism of fluid driven jointing (Bahat and Engelder 1984, Secor 1965). On some joints there is a tendency for cyclic propagation events to become larger as the joint grows (Figure 2.14).



Notes: Joint propagated in discrete increments which are numbered in order of development as determined by morphological criteria, adapted from Lacazette and Engelder (1992).

Figure 2.14: Vertical Joint Contained in a Siltstone Bed That Is Isolated in Shale at Watkins Glen, New York

Given the relationship between the size of each propagation event and the growth of the joint, Lacazette and Engelder (1992) were able to estimate the compressibility of the fluid driving the joint and concluded that a gas such as methane was responsible. One caveat with this analysis is that although cyclic propagation indicates the nature of the fluid driving the joint, such morphology carries no information about the fluid pressure at the time of propagation. Still, the propagation of joints by a fluid such as methane is consistent with other evidence for overpressures in the Catskill Delta complex (Lacazette and Engelder 1992).

2.2.9 Overpressures in the Appalachian Basin

It will be argued that joints in seal rocks owe their distribution to overpressuring. There is also a suite of data will that support the thesis that a pressure seal was present within the Devonian Catskill Delta complex of the Appalachian Basin. The question remains whether the seal was anything more than thicker black shales and whether the transition zone for overpressuring was anything more than a gradual coarsening of the clastic section. Regardless of the nature of a regional pressure seal, if ever present, evidence suggests that the Catskill Delta was subject to two episodes of pressure generation. The first may have been a maturation-related event superimposed on early pressure from compaction disequilibrium. Compaction disequilibrium develops when the sedimentation rate exceeds the rate of pore fluid drainage, in which case the pore fluid carries the additional increments of overburden load thus leading to abnormal pressure. The second event may have been associated with tectonic compaction superimposed on further maturation as black shales were buried even deeper during Alleghanian sedimentation. This latter event (i.e., layer-parallel shortening during the Alleghanian Orogeny) did not affect the seal rocks at the Bruce nuclear site. With the exception of fluid inclusion trapping pressures, no single data set constitutes necessary and sufficient evidence for a paleo-overpressure in the Catskill Delta, but as a group, these data sets provide strong support for such an interpretation.

2.2.9.1 Fractured Shale-Gas Systems in the A-OSS

In a review of fractured shale gas systems some time ago, the major gas shales of the A-OSS were the Antrim and Ohio (Huron) shales (Curtis 2002). In principle, the New Albany black shale may be considered part of the A-OSS largely because of the correlation with other Upper Devonian black shales A-OSS.

2.2.10 Fracture Generation

There are two general classes of fracture: shear fractures (i.e., faults) and joints (i.e., extension fractures, cracks, etc) (Engelder 1987, Nelson 1985). The former are always local (Stearns 1972) whereas the latter can be pervasive throughout a region (Nickelsen and Hough 1967, Pollard and Aydin 1988). The former require a high differential stress and one that is not sustainable in a crust whose stress is controlled by the frictional strength of rock (Byerlee 1978, Zoback and Healy 1984). High differential stresses are largely tectonic in origin and occur where the fault is either locally folded or faulted to begin with. The latter are not dependent on the generation of a differential stress and, in fact, are not the product of a high differential stress as is consistent with Mohr-Coulomb theory (Engelder and Marshak 1988). Joints are solely dependent of the generation of a tensile effective least stress, σ_3.

The Antrim is populated with two joint sets that are similar to J_1 and J_2 of the Appalachian Basin (Apotria et al. 1994). The Antrim is an Upper Devonian shale equivalent to the New Albany and Chattanooga shales and is an anomaly relative to most gas shales in the A-OSS because present production is biogenic or microbial gas, generated during infiltration of groundwater during recent glaciation (Magoon and Dow 1994, Martini et al. 1998). According to Curtis

(2002), the association of recent gas generation with Pleistocene glaciations logically extends both to trap formation by the overlying till and to fracturing induced by ice-sheet loading/unloading (Clark 1982). This assessment is incorrect on two counts. First, the gas is adsorbed and produced by drawing down hydrostatic water pressure on the reservoir and, thus, has nothing to do with till as a seal. Second, there is no mechanism for generating two sets of cross cutting joints by glacial loading and unloading (Engelder et al. 2009). Rather, the hypothesis of Apotria et al. (1994) seems the most probable, which is that thermogenic gas was responsible for driving fractures allowing the invasion of bacteria-bearing groundwater during glaciation.

The New Albany black shales in the Illinois Basin contain the same style of jointing that is found in other black shales of the A-OSS. Gas produced from the New Albany shale, like its neighbour in the Michigan Basin, the Antrim, is considered to be biogenic (Walter et al. 2000).

In his discussion of the Ohio black shale, Curtis (2002) recognized differences between it and both the Antrim and New Albany shales. First, the Ohio shale contains thermogenic gas. Second, it was deposited at the margin of Laurentia whereas both the Antrim and New Albany were basin centered. Third, many but not all of the Ohio shale wells required stimulation. In searching for analogs for the seal rock at the Bruce nuclear site, the Marcellus and its sister black shale, the Geneseo shale are more appropriate analogs to the Ordovician Utica shale, at least based on the mechanism for the generation of accommodation space. Chapter 4 of this report develops these details.

The Appalachian Basin has gas traps below the Marcellus that reach more than 70% of the overburden stress. The Marcellus black shale is also overpressured throughout the northern Appalachian Basin, leaving no doubt about its effectiveness as a regional seal. In the southern portion of the Appalachian Basin gas shales are underpressured, as is the Upper Ordovician seal rock at the Bruce nuclear site. Gas generation leads to extensive and pervasive natural hydraulic fracturing (NHF).

The pattern of jointing in the Catskill Delta complex suggests that the distribution of overpressure during an early phase joint propagation (J_1 joints) was different from the distribution of overpressures during a later phase of joint propagation (J_2 joints) when the Alleghanian Orogeny was taking place. The more local development of early-Alleghanian joints (J_2) suggests the presence of a regional seal near the base of the Rhinestreet Formation in the West Falls Group. Although Alleghanian jointing extended above a regional pressure seal it was weaker except in association with maturation-related jointing in black shales further up section and toward the distal parts of the delta (Lash and Engelder 2009).

2.2.10.1 Joint Patterns (Cross-fold Joints)

There are three characteristics of the regional joint patterns which suggest a difference in behaviour of the sub-Rhinestreet section relative to rocks above the Devonian seal zone. First, the quantity and quality of development of cross-fold joints is markedly higher in the lower section. Secondly, the cross-fold joints above the seal do not show the tight clustering of orientation data found below the seal (Figure 2.15). It is the sub-Rhinestreet section that contains cross-fold joints with the cyclic joint surface morphology and it is also the section characterized by the lower stress regime based on in situ stress measurements. Thirdly, the lower section is characterized by fluid-driven joints (Engelder and Oertel 1985).

2.2.11 Natural Fractures in the Appalachian Basin

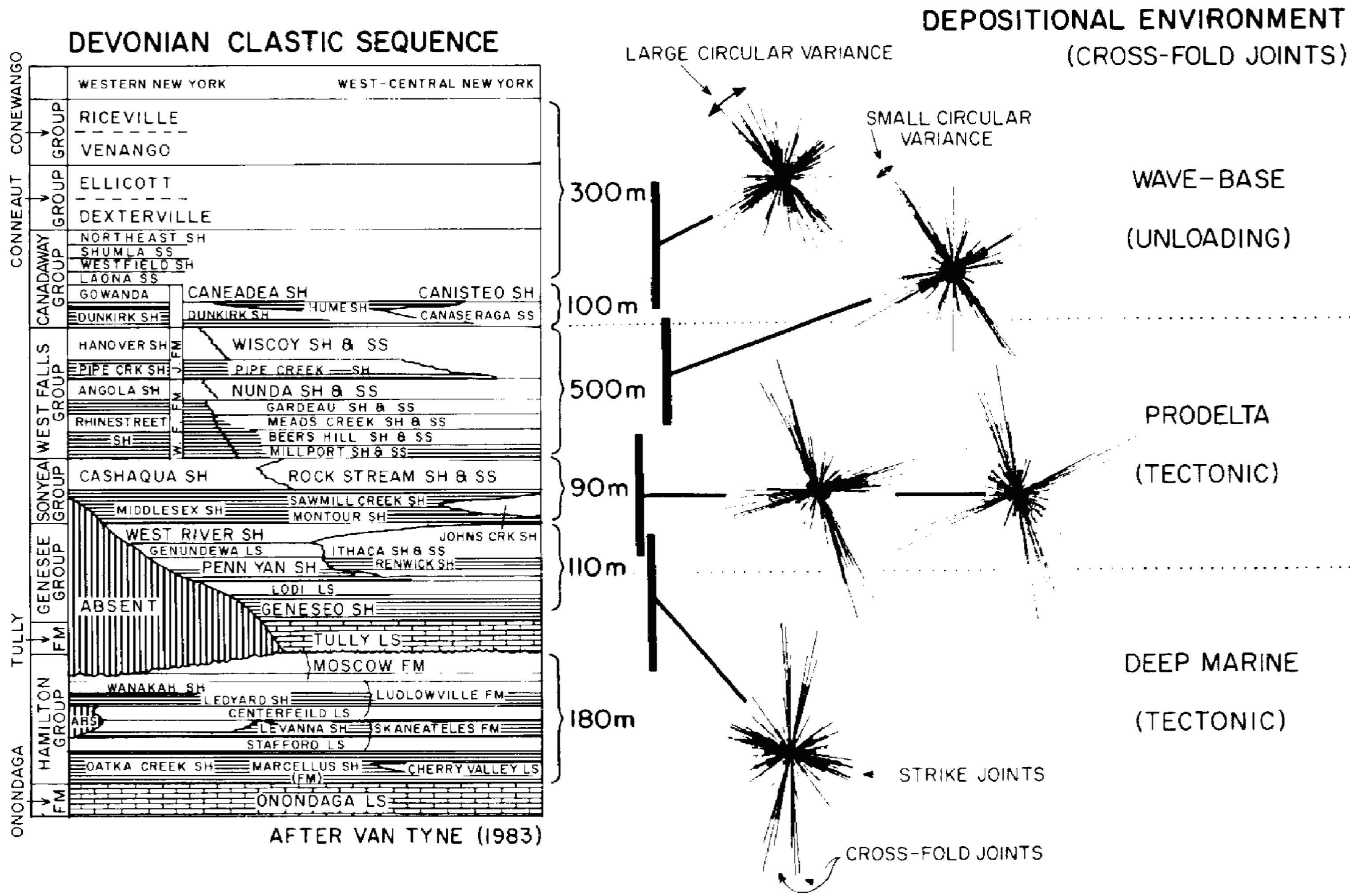
Rock fracture occurs either by rupture in shear or rupture in tension. Rupture in shear yields faults (Handin and Hager 1957) whereas rupture in tension leads to the propagation of joints (Pollard and Aydin 1988). At depth in basins where stress is compressive, tension is an effective stress and joints are natural hydraulic fractures (Engelder and Lacazette 1990, Secor 1965). Faults are rarely systematic and are invariably concentrated in zones associated with a master fault or fold (Aydin and Johnson 1978) whereas joints are frequently systematic and may be pervasive over large regions (Hodgson 1961). Industry has established that in the Appalachian Basin, joints of one systematic set in particular – the ENE set – are crucial to the success of horizontal completion techniques (Gerber 2008). Systematic ENE joints have been observed in core recovered from the Upper Devonian Dunkirk-Huron black shale as part of the Eastern Gas Shales project (EGSP) (Figure 2.16).

The similar orientation of J_1 joints in black shales of the Appalachian Basin and the maximum horizontal strain (S_{Hmax}) of the contemporary tectonic stress field lured many authors to the conclusion that all ENE-striking joints were *de facto* neotectonic and therefore related in some way to processes involving the contemporary tectonic stress field, including Tertiary exhumation or Pleistocene glaciation (Clark 1982, Dean et al. 1984, Engelder 1982, Engelder and Gross 1993, Gross and Engelder 1991, Hancock and Engelder 1989).

It is now known that the early J_1 joints were folded along with bedding, clear evidence of a pre- or early Alleghanian propagation history (Engelder 2004). Finally, it was understood that a pre- or early Alleghanian joint set, the J_1 set, occupies nearly the same orientation as Appalachian neotectonic joints and S_{Hmax} of the contemporary tectonic stress field (Engelder 2004, Engelder and Whitaker 2006, Lash and Engelder 2000, Pashin and Hinkle 1997). The presence of early joints in black shale of the Appalachian Basin and their orientation relative to first the Alleghanian and then the contemporary tectonic stress fields give rise to three geological conundrums.

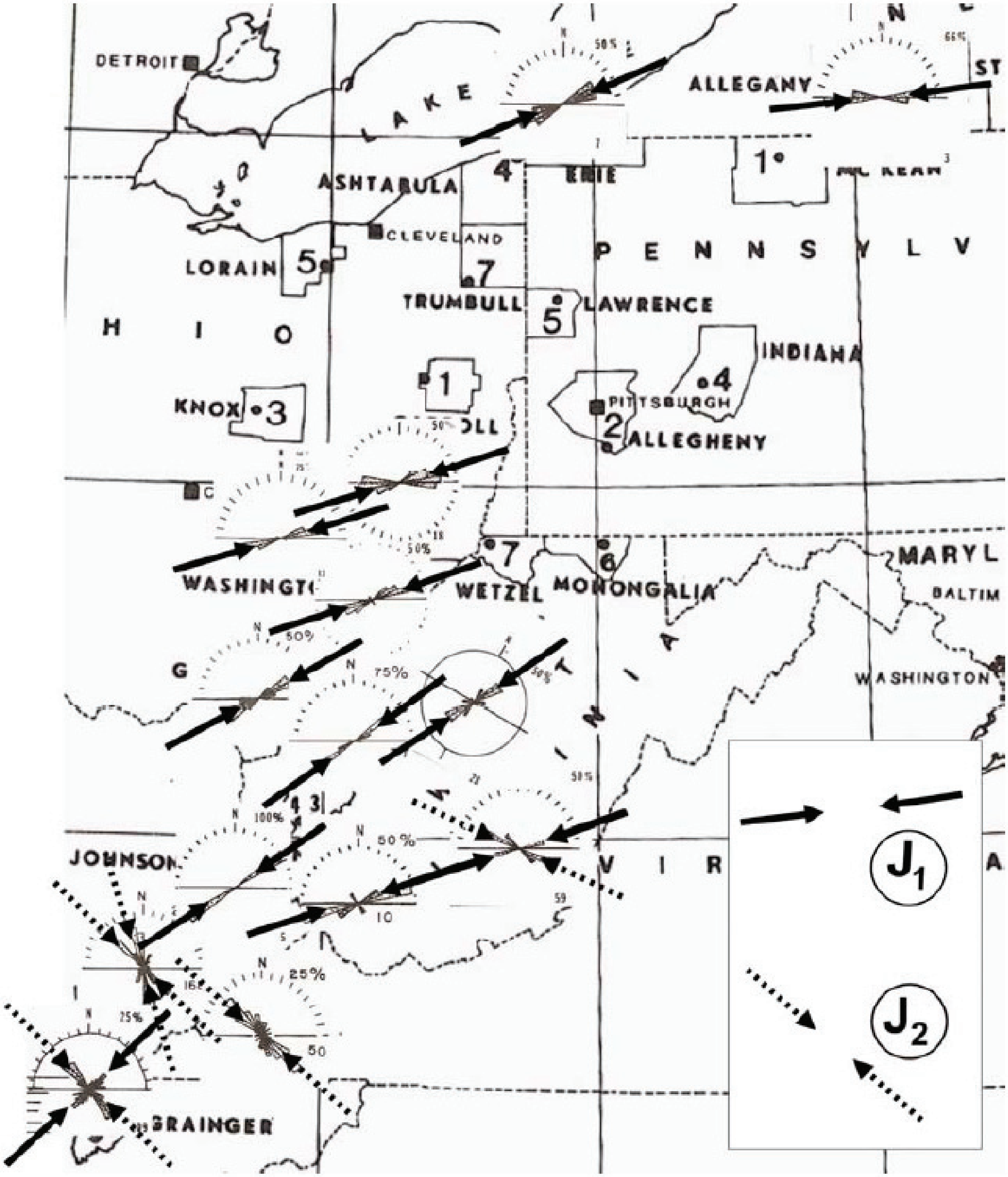
The first conundrum involves extrapolation of outcrop data for the purpose of predicting the orientation of unhealed joints within black shale at depth. Such extrapolation assumes that geologists are able to distinguish between joints that formed in the near surface as geomorphic phenomena and joints that formed close to or at maximum burial depth and persisted through exhumation. Drawing a distinction between early- and late-formed joints in the Appalachian Basin is complicated by the coincidence of the strike of J_1 joints and S_{Hmax} of the contemporary tectonic stress field. Neotectonic joints (J_3) whose ENE strike is controlled by the contemporary tectonic stress field have a mean orientation that falls within the same statistical range as the J_1 set (Hancock and Engelder 1989, Lash and Engelder 2009).

The second conundrum stems from geological evidence that suggests that the J_1 set propagated before Alleghanian folding and concomitant layer-parallel shortening (Engelder 2004, Pashin and Hinkle 1997). If the J_1 set predates Alleghanian layer-parallel shortening, it survived this tectonic deformation in black shales as unhealed joints with little modification during penetrative strain, despite being subnormal to the direction of as much as 15% layer-parallel shortening (Engelder and Engelder 1977, Geiser 1988).



Notes: Each diagram is a compilation of measurements from a local region of the delta dividing according to stratigraphic position, adapted from Engelder and Oertel (1985).

Figure 2.15: Stratigraphic Column for the Catskill Delta Complex Showing Rose Diagrams of Joints



Note: From CliffsMinerals (1982).

Figure 2.16: Rose Plots Showing The Orientation of Joints in the Dunkirk/Middle Huron Interval of Cores Recovered During the EGSP Project

The third conundrum arises from consideration of the origin of J_2 joints. There remains the matter of reconciling the Andersonian stress state for foreland fold-thrust belts (i.e., the thrust fault regime where least principal stress, σ_3 is vertical) with the observed spectrum of vertical syntectonic J_2 joints in the Appalachians and elsewhere (Anderson 1951). Vertical joints imply that σ_3 was horizontal during fold-thrust tectonics.

We present data that addresses each of these conundrums thereby permitting reasonable inferences regarding the extent to which geologists may expect unhealed joints in black shales such as the Marcellus.

Outcrops of black shale within the Appalachian foreland commonly carry two systematic joint sets, herein referred to as the J_1 and J_2 sets (Engelder and Geiser 1980, Lash et al. 2004, Lash and Engelder 2007, 2009, Parker 1942, Sheldon 1912). The J_1 set is of particular interest because it strikes to the ENE and within a few degrees of the maximum horizontal compressive stress, S_{Hmax}, of the contemporary tectonic stress field (Engelder 1982, Sbar and Sykes 1973, Zoback 1992). J_2 joints generally crosscut J_1 joints when the two sets are found in the same bed. In the Marcellus and other black shale units of the Appalachian basin, the J_1 set is more closely spaced than the J_2 set (Figure 2.17). J_1 joints were recognized in outcrops from Virginia to New York and interpreted to correlate with a strong ENE-trending coal cleat in Morrowan and Desmonian coal deposits scattered from Alabama to Pennsylvania (Engelder 2004, Engelder and Whitaker 2006).

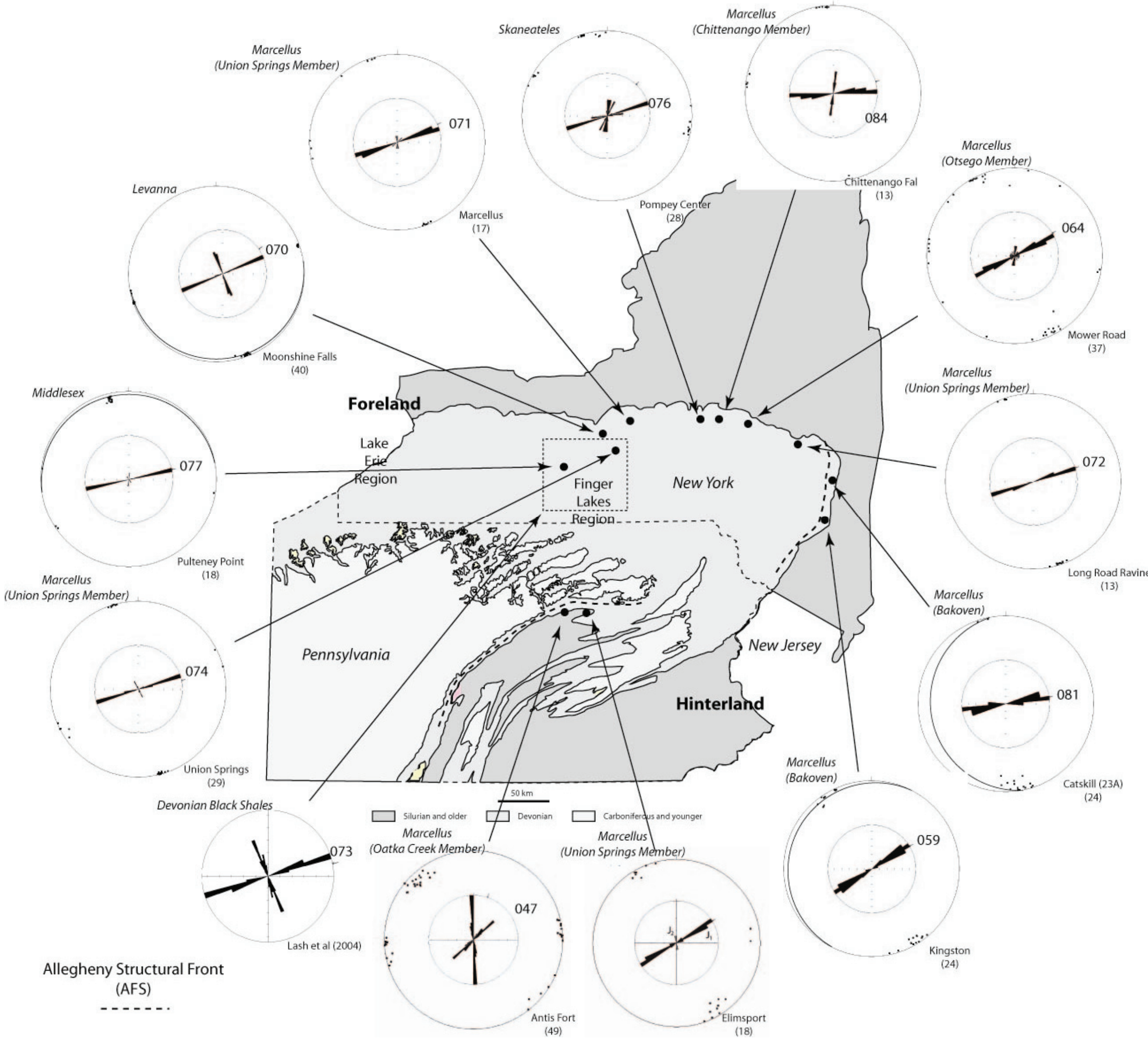
2.2.11.1 Fractures in Gas Shales

Devonian-Mississippian gas shale in the Appalachian Basin is particularly susceptible to joint growth, (Hall 1843, Sheldon 1912). Mapping of joints throughout the northern Appalachian and Illinois Basins confirmed that more than one black shale formation, including those of the Marcellus Subgroup (Ver Straeten and Brett 2006), host a similar ENE-striking joint set (Parker 1942, Campbell 1946). This points to a common post-Devonian growth mechanism within Eastern Laurentia that originated within black shale formations accumulating over more than 30 ma from the Middle to Late Devonian.

From 1821, it took industry more than a century to recognize the critical role that natural fractures played in economic gas production within fractured Devonian shale in the Appalachian Basin (Browning 1935). By the 1970s, matrix porosity was considered to exert the principal control on long-term production from black shale, thereby subordinating natural fractures to the role of high permeability pathways (Smith et al. 1979).

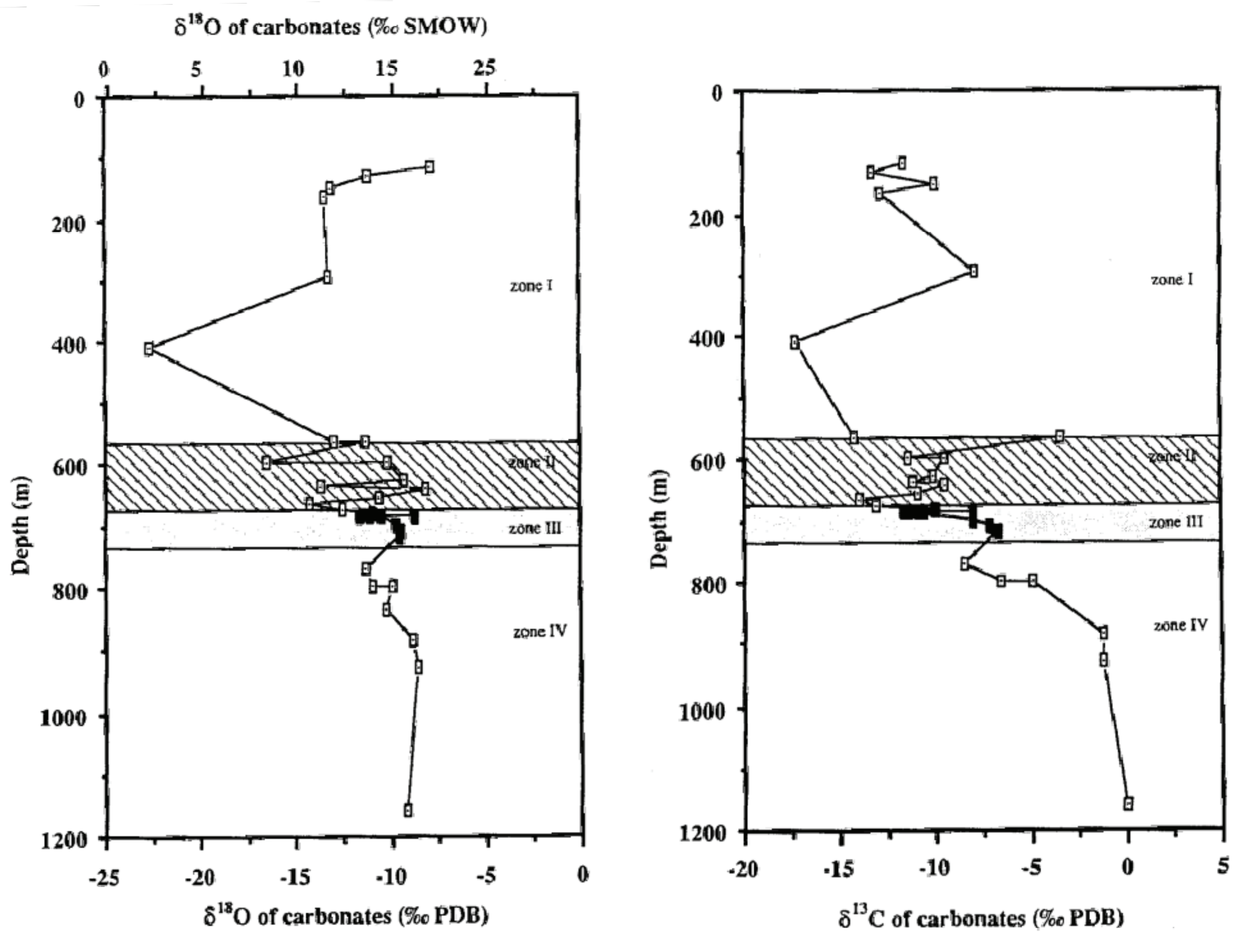
2.2.12 Chemical Signal Indicative of a Seal

Chemical characteristics of rocks in a vertical profile through the Catskill Delta complex were determined in an attempt to define a seal zone (Albrecht 1992). The seal zone (i.e., the transition zone in the stress profile) shows increased potassium, magnesium and isotopic anomalies (especially δD) indicating the formation of authigenic clays (illite, kaolinite, chlorite) at temperatures of around 70-100°C. $\delta^{13}C$ and $\delta^{18}O$ values of carbonates indicate that secondary carbonates were formed in rocks of the seal zone (Figure 2.18). Strongly depleted $\delta^{13}C$ values suggest an organic source for the carbon incorporated in secondary carbonates. In the case of the Appalachian sequence isotopically light carbon may have been locally derived from the oxidation of organic matter by sulphate-rich fluids. The precipitation of secondary calcite and authigenic clays appears to have been sufficient to significantly reduce permeability, thus indicating seal formation at temperatures between about 70 and 90°C. Most, if not all, of the preceding data can be interpreted in the context of depositional trends during the Devonian. Deformation during the Alleghanian Orogeny overprints the Devonian section to leave characteristics that are indicative of tectonic compaction during layer-parallel shortening (homogeneous strain).



Note: From Engelder et al. (2009).

Figure 2.17: Joints in Black Shales of the Appalachian Basin



Note: Adapted from Albrecht (1992).

Figure 2.18: The Variation of δ13C and δ18O of Carbonates Versus Depth in ESGP Wells NY1 and NY4

2.3 Alternative Hypothesis for Fractures within the Appalachian Basin

Concerning fractures in the Appalachian Basin, a second opinion is offered by Milici (1993). This alternative model for fracturing is closely linked to the two major structures that affect the Appalachian Basin, the Rome Trough and the sub-horizontal detachment surfaces of Alleghanian age. The Rome trough is a keel-like feature beneath the Appalachian Basin that is filled with an overthickened sequence of Cambrian siliciclastics that are correlated crudely with the Rome Formation in eastern Tennessee. The trough is a graben, associated with the rifting of the Rodenia supercontinent in late Proterozoic time. The trough was intermittently active at least into the Devonian and some have argued this Devonian movement is responsible for late-stage fractures (Shumaker 1986, 1993). Detachment-related fractures are confined to broken formations, zones of extremely fractured and brecciated rocks consisting primarily of subhorizontal shears In fact, it is the pervasive joints of the Devonian section that are far more important to gas production from the unconventional gas shale reservoirs and it is these structures that are likely to be of more relevance in questioning seal integrity at the Bruce nuclear site (Engelder et al. 2009).

2.4 Horizontal Drilling

The Devonian black shale of West Virginia (WV) was tested with high-angle or slant drilling aimed at the highest density of natural ENE fractures (CliffsMinerals 1982, Yost II et al. 1987). At about the same time, the Devonian Antrim gas shale was tested in the Michigan Basin with slant wells designed to crosscut natural fractures (Hopkins et al. 1998). Full scale development of the Huron-Dunkirk of the Big Sandy field, KY, commenced in the 2000s where one in five horizontal wells (of 80 drilled to date) flow with enough volume to forego stimulation, a clear indication of well bores crossing ENE joints (Gerber 2008). Unlike the relatively shallow Huron-Dunkirk black shales, every economic horizontal well in deeper Devonian-Mississippian gas shale requires stimulation with technological breakthroughs including slickwater fracs and multi-stage fracturing (Fontaine et al. 2008). The Marcellus black shale of the Appalachian Basin constitutes one class of unconventional reservoir from which production is optimized if horizontal drilling penetrates a systematic fracture set (Curtis 2002, Curtis and Faure 1997, Law 2002). In deeper, thermogenic black shale plays, the extent to which productivity is enhanced by stimulation of natural fractures remains a question. Here, stimulation is understood to mean the linking of natural, higher permeability pathways to horizontal well bores. The economic importance of unhealed fractures in gas shales lends exigency to an extended discussion of the present understanding of the origin, orientation, and distribution of joints in black shales of the Appalachian Basin.

3. TOTAL PETROLEUM SYSTEMS: THE MICHIGAN BASIN VS. THE APPALACHIAN BASIN VS. SOUTHERN ONTARIO

3.1 The Michigan Basin

The Michigan Basin is divided into four general petroleum systems with the Cambrian-Ordovician being the deepest of the systems (Reszka 1991). Conventional wisdom is that the Utica black shale is the seal rock element in the Trenton-Black River play. The Albion-Scipio field produces from a fault system more than 56 km long that extends vertically through the fossiliferous limestones of the Trenton-Black River formations, producing reservoirs where porosity is fracture related and dolomitized. The Albion-Scipio fields have analog gas fields in New York (Smith 2006). There is a developing consensus that the source rock for these gas fields in both the Appalachian and Michigan Basins is the Utica shale and equivalents (Laughrey and Baldassare 1998, Ryder et al. 1998). There are other reports that the Utica shale is not the source of Ordovician-type oil originating from the Trenton-Black River limestone in the Michigan Basin (Rullkotter et al. 1992). If the latter is true, the thin organic-rich beds within the Trenton sequence serve as the source for Ordovician oil. These Trenton units are equivalent to the Collingwood Member of the Cobourg Formation at the Bruce nuclear site.

The second petroleum system of the Michigan Basin is relevant to the question of long-term integrity of the Bruce nuclear site is the Devonian with a focus on the Antrim black shale. The Antrim and its counterparts in the Appalachian Basin are rich gas shales. However, Antrim methane has the isotopic signature of methanogenic bacteria rather than a thermogenic origin as is the case for most, if not all deeper Appalachian methane (Laughrey and Baldassare 1998). Although the Antrim-Kettle Point shales are not found in the vicinity of the Bruce nuclear site, their gases have an isotopic signature of interest to questions of long-term integrity at the Bruce nuclear site (See Section 4.7).

3.2 The Appalachian Basin

The U.S. Geological Survey has identified a host of petroleum systems in the Appalachian Basin with the most important systems found in Utica-Lower Paleozoic and Devonian rocks (Ryder 2008, Ryder et al. 2007). The Utica-Lower Paleozoic total petroleum system (TPS) is named for its primary source rock and includes several Lower Paleozoic sandstone and carbonate reservoirs. Reservoirs include the Upper Cambrian Copper Ridge Dolomite, the Upper Cambrian Rose Run Sandstone, the Lower Ordovician Beekmantown Dolomite, the Upper Ordovician Black River/Trenton Limestone, the Lower Silurian Clinton/Medina/Tuscarora Sandstones, and the Lower and Upper Silurian Lockport Dolomite (Milici et al. 2003).

The closest analog to its neighbours in southern Ontario is the Point Pleasant-Brassfield petroleum system of eastern Ohio and just to the southeast of the Cincinnati-Findlay arch (Drozd and Cole 1994, Ryder et al. 1998). The lack of significant oil accumulations along the axis of the arch, the prevalence of stratigraphic traps on both flanks of the arch, and the significant amounts of gas in these fields all indicate that oil generated downdip and was unable to migrate freely to the axis of the arch (Cole et al. 1987). There is more than one petroleum system in the Appalachian Basin with Upper Devonian reservoir rocks of Ohio containing oil with a distinct isotopic signature characteristic of Devonian source rocks. This observation further confirms the hypothesis that long-distance migration (> 100 km) in the Appalachian Basin did not take place. Otherwise, Devonian and Ordovician oil and gas would have mixed and been indistinguishable. From this observation it is highly likely that any gas shows in the organic-rich rocks including gray shale with TOC < 1% are generated locally and did not migrate.

Petroleum systems in the Appalachian Basin are of two types largely depending on the mixture of natural gases within the system. The Devonian dry gas system is found in the deeper reaches of the Appalachian Basin where the thermal maturity is well in excess of $\%R_o$ = 1.5 (Figure 3.1). Northwest of a NE-SW line through the deeper portion of the Basin, all Devonian gas is wet, which is to say it is associated with C_2 and greater hydrocarbons. The Devonian dry-wet gas line is defined by the presence of oil fields to the NW of a line cutting McKean, Elk, Clarion, Allegheny and Washington Counties, PA. Wet gas continues right to the Algonquin arch from Central PA.

The comparable dry-wet gas line for deeper formations including Ordovician and Silurian may cut the northwestern portion of PA where deep oil fields are found (Figure 3.1). Most of the Utica shale is in the dry gas field (i.e., ‘below the oil floor’ of Drozid and Cole (1994), except for a narrow band along Lake Erie in PA and NY (Wallace and Roen 1989).

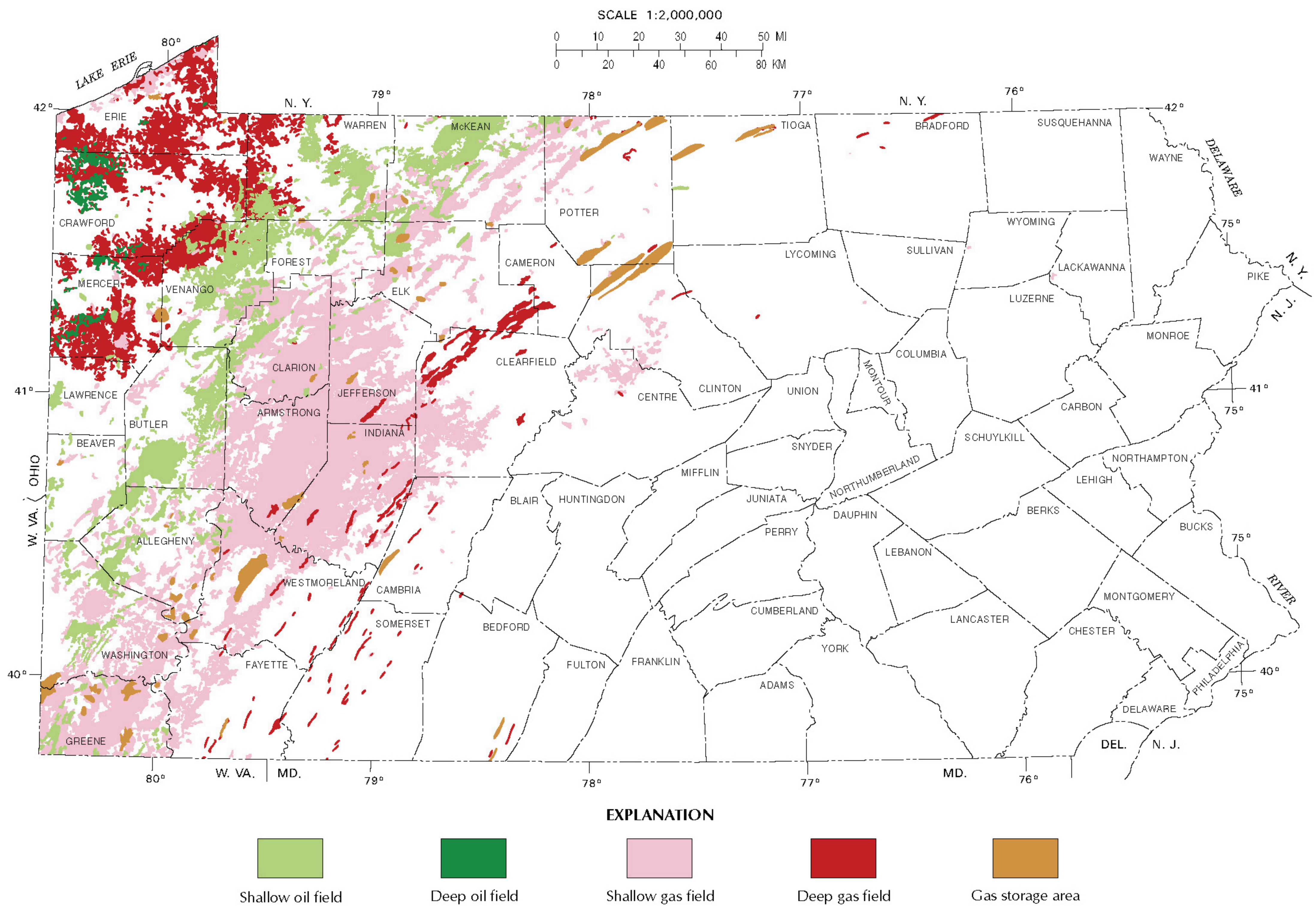
3.3 Southern Ontario

Southern Ontario including the area of the DGR hosts up to 300 separate pools or reservoirs of crude oil and natural gas (AECOM and ITASCA 2011). Within the regional study area the oil and gas pools are all found to the south of the DGR site (Figure 3.2) (AECOM and ITASCA 2011).

Natural gasses in southern Ontario are wet, with methane comprising an average of 90% of the hydrocarbon fraction (Barker and Pollack, 1984). The Lower Paleozoic sediments in southern Ontario have attained only an immature to barely mature thermal maturation and the natural gases have some characteristics of immature sources as indicated by the dominance of N_2 over CO_2 and H_2S. The ratio of (ethane/propane)/(isobutane/normal butane) does show subtle differences on either side of the trend of the Algonquin Arch (Barker and Pollack, 1984). The mechanism for this subtle difference is not understood.

In Ontario, thermal maturity, stratigraphic position, and geographic location all support the conclusion that Trenton strata including the Blue Mountain Formation are mainly self-scourced short migration pathways (Obermajer et al., 1999a). Gas in black shales has probably not migrated.

DGR boreholes found no commercially viable pools of either petroleum or natural gas (INTERA 2011). A well drilled by Texaco about 3 km from the DGR location also showed no evidence of commercially viable petroleum or natural gas. If the black shale were sufficiently rich in natural gas to yield commercial quantities, it might be presumed that small gas shows would have appeared during vertical drilling and coring through the black shale beds. There were, however, sulphurous and petroliferous odors present throughout core from the Blue Mountain Formation obtained in drilling DGR-2 (INTERA 2011). This is the seal rock at the DGR and the formation against which the petroleum systems, particularly the black shales, of the Appalachian and Michigan Basins shall be compared.



Note: Published by the Pennsylvania Bureau of Topographic and Geological Survey.

Figure 3.1: Oil and Gas Fields of Pennsylvania

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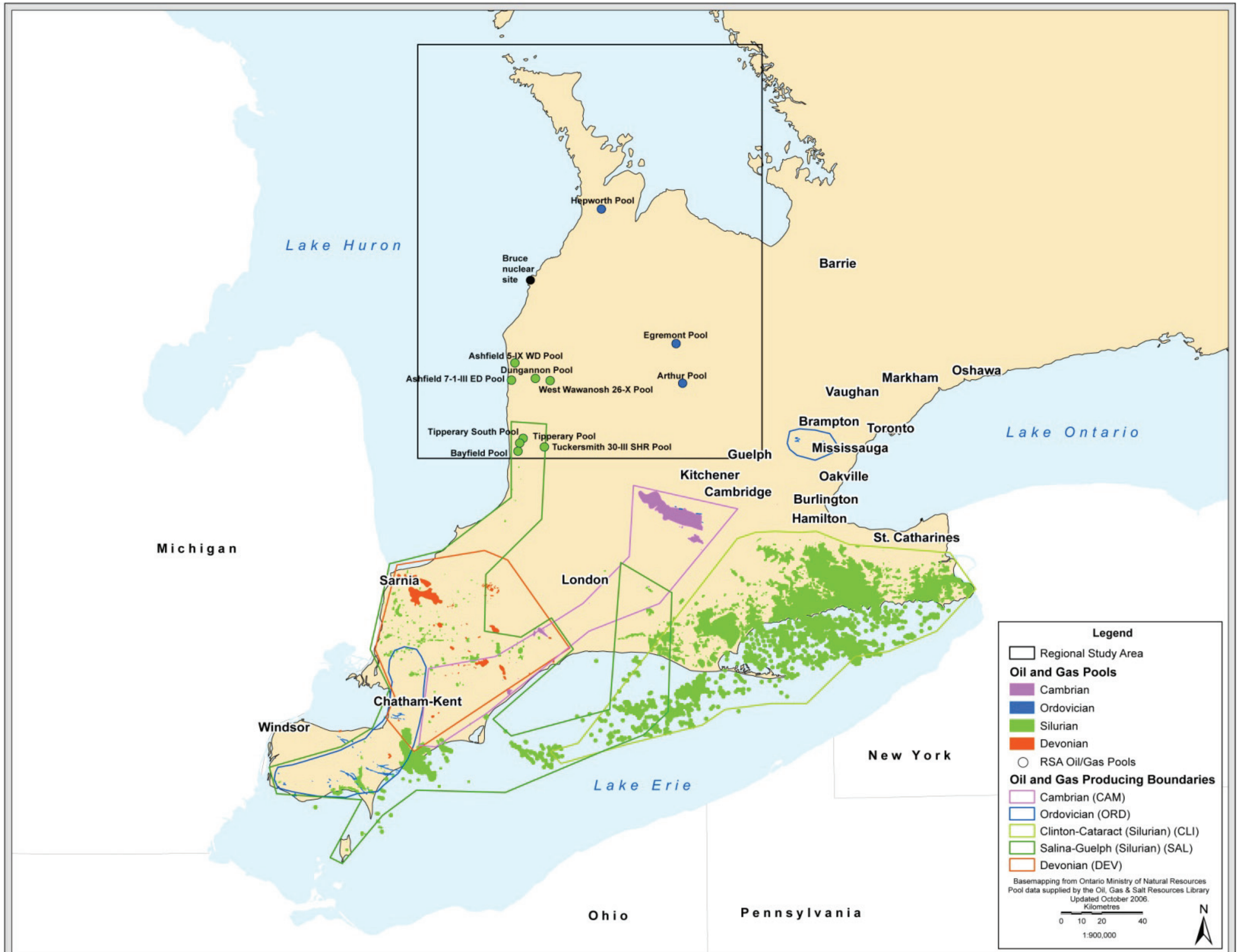

Notes: Pool boundaries are approximate. Compilation includes present and past producers. Modified from OGSR (2006) and Carter (1990).

Figure 3.2: Oil, Natural Gas and Natural Gas Storage Pools in Southern Ontario

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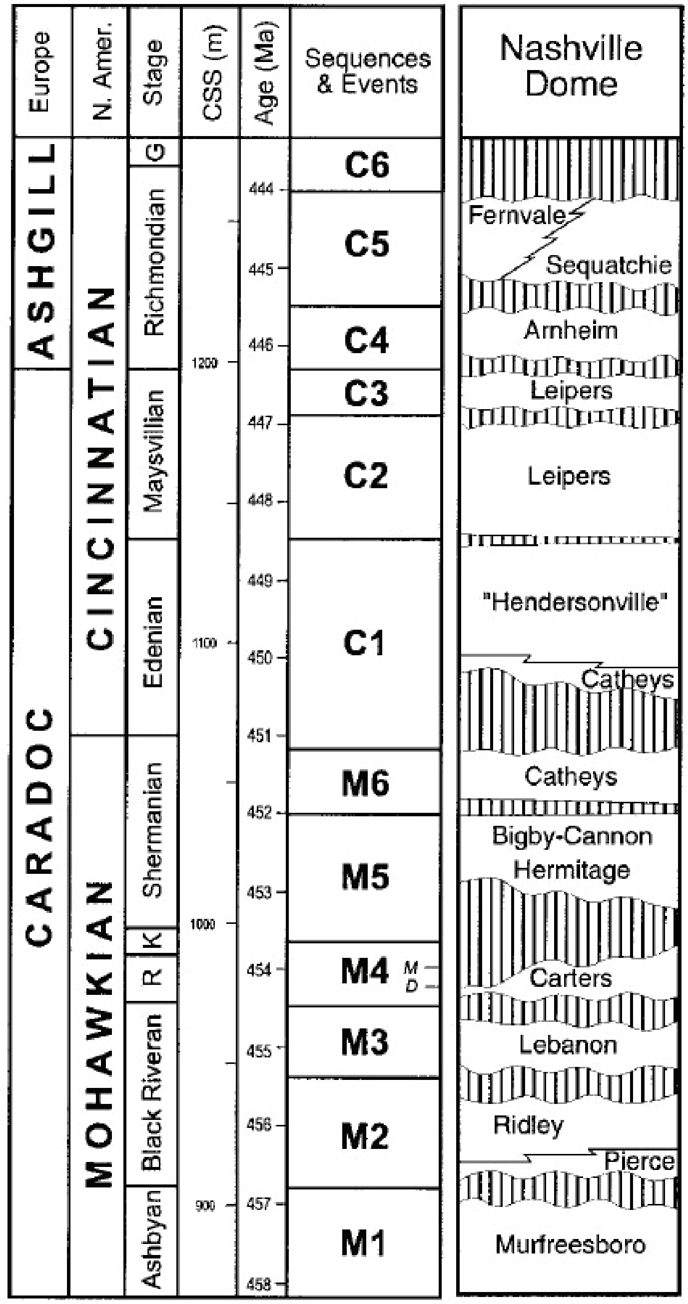
4. SEAL ROCK: BRUCE NUCLEAR SITE VS. APPALACHIAN & MICHIGAN BASINS

To predict the behaviour of the Bruce nuclear site seal rocks, an understanding of the regional characteristics of correlative rocks throughout the eastern edge (present coordinates) of the Laurentian margin is necessary. In general, the seal rock shale at the Bruce nuclear site is correlative with the Utica black shale megafacies of New York and Ontario. This black shale interval spans four graptolite zones (about 8 Ma) (Mitchell et al. 1994, Riva 1969). Other useful geological markers for this purpose include K-bentonites and conodonts. During the Ordovician one of the most extensive regional K-bentonites is the Deicke, dated at 454.2 Ma (Kunk and Sutter 1984). In the New York/Ontario region, a number of K-bentonites have been recognized and traced throughout the Mohawkian of the New York – southern Ontario outcrop area and, to a limited extent, in the subsurface (Cornell 2001). An interpolated date of 443.5 Ma is assumed for the Ordovician/Silurian boundary (Tucker et al. 1990). The North American chronostratigraphic stages shall be specified relative to graptolite zones, conodont ages and the Deicke K-bentonite (Figure 4.1).

4.1 Stratigraphic Correlation Across the Laurentian Platform

The Middle and Upper Ordovician stratigraphy of the Nashville Dome is to serve as a control section for correlation between the Appalachian Basin and the Algonquin arch of southern Ontario. The Nashville Dome is an analog of the Algonquin arch that both sat as structural highs along with the Cincinnati and Findley arches during the development of the Appalachian Mountains from Ordovician Taconic time onward through Devonian Acadian time. Because the Nashville Dome was less affected by the lithosphere loading of the Taconic Orogeny, its stratigraphy was not flooded by a clastic section. Carbonate deposition was relatively continuous during the Middle and Late Ordovician and this stratigraphy is much more sensitive to global eustatic sea level changes. The Middle and Upper Ordovician of the Nashville dome presents a record of 11 depositional sequences that, presumably can be traced into both the Appalachian Basin and across the Algonquin arch (Holland and Patzkowsky 1998). Each sequence of the Nashville Dome has a maximum flooding zone with aggradational stacking rather than discrete maximum flooding surfaces (Figure 4.1).

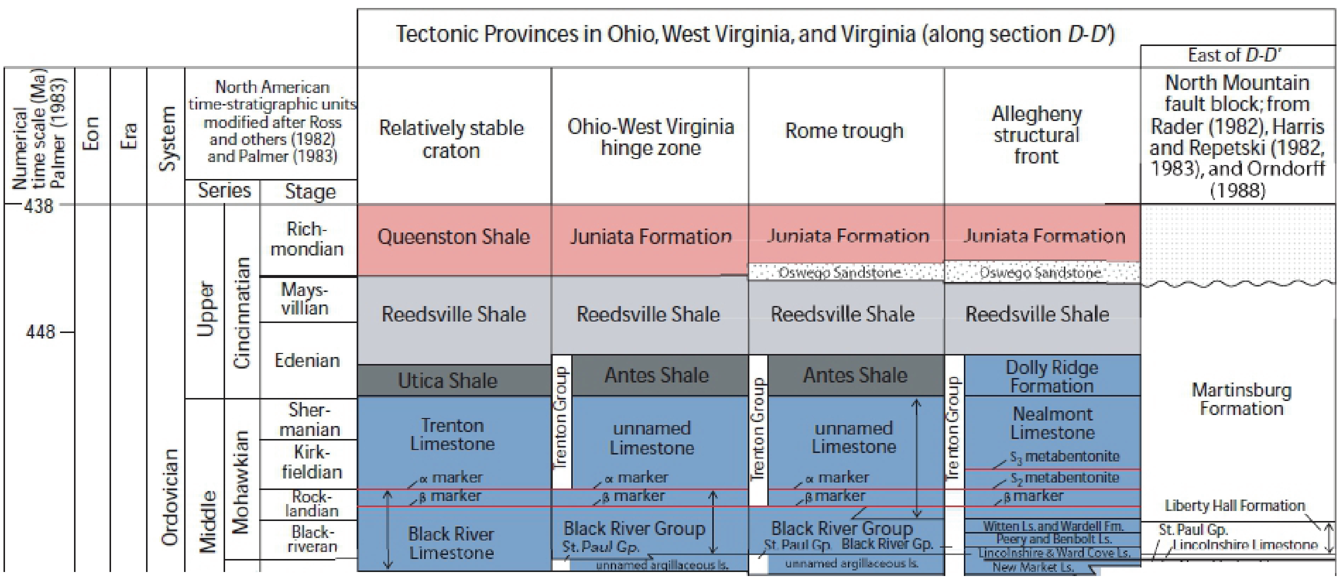
Condensation features are much more common at transgressive surfaces than within the maximum flooding zone. The expression of these parasequences and sequences changes with the onset of the Taconic orogeny at the M4 sequence (Figure 4.1). Although parasequences from equivalent depositional environments can be recognized before and after the onset of the orogeny, their facies composition changes completely. Sequences following the orogeny display fewer paleokarst features, more pyritized and ironstained hardgrounds at flooding surfaces and transgressive surfaces, and more phosphatic lags and mineralization at transgressive surfaces, than those preceding the orogeny. A relative sea-level curve for the Nashville Dome has a long-term (> 5 Ma) component presumably dominated by subsidence and a short-term (1–3 Ma) component consisting of 10–50 m fluctuations that is primarily the result of eustasy.



Notes: Summarized from Holland and Patzkowsky (1997). The Taconic orogeny is closely timed with most of these changes and is initiated late in the M4 sequence. CSS refers to Sweet's conodont-based graphic correlation (Sweet 1984). D and M in the sequences column indicate the positions of the Deicke and Millbrig K-bentonites. The durations of the unconformities are poorly constrained, and the missing lowstand systems tracts are each assumed to represent one-third of their respective sequences.

Figure 4.1: Depositional Sequences and Major Lithological Changes of the Middle and Upper Ordovician of the Nashville Dome

While the onset of the Taconic Orogeny is taken at the time of deposition of the Ordovician K-bentonites, the arrival of the starved section at the base of the Utica and Antes shales occurred during the Shermanian Stage (Figure 4.2). At the Bruce nuclear site, the onset of the Taconic Orogeny is missing due to the Knox unconformity separating Cambrian sandstones and Mid Ordovician shales of the Shadow Lake Formation, which were deposited some time after the beginning of regional tilting and flooding had begun. In the Michigan Basin, the onset of the Taconic Orogeny is observed as a bevelling of the upper portion of the Glenwood and the top of the St. Peter formations prior to deposition of the overlying Black River carbonates, coinciding with changes to local and regional tectonics (Nadon et al. 2000). In a 1998 revision, Ryder moves the base of the Utica and Antes well down into the Shermanian (Ryder et al. 1998). The base of the Shermanian is 453.5 Ma and less than a million years from the time of deposition of the Millbrig K-bentonite. This implies that the Utica-Antes correlates with the M5 parasequence of Holland (Holland and Patzkowsky. 1998). In the Appalachian Basin a thick shale sequence of Edenian-Maysvillian age, the Reedsville, follows the Utica-Antes. The Queenston-Juniata sequence is Richmondian in age.

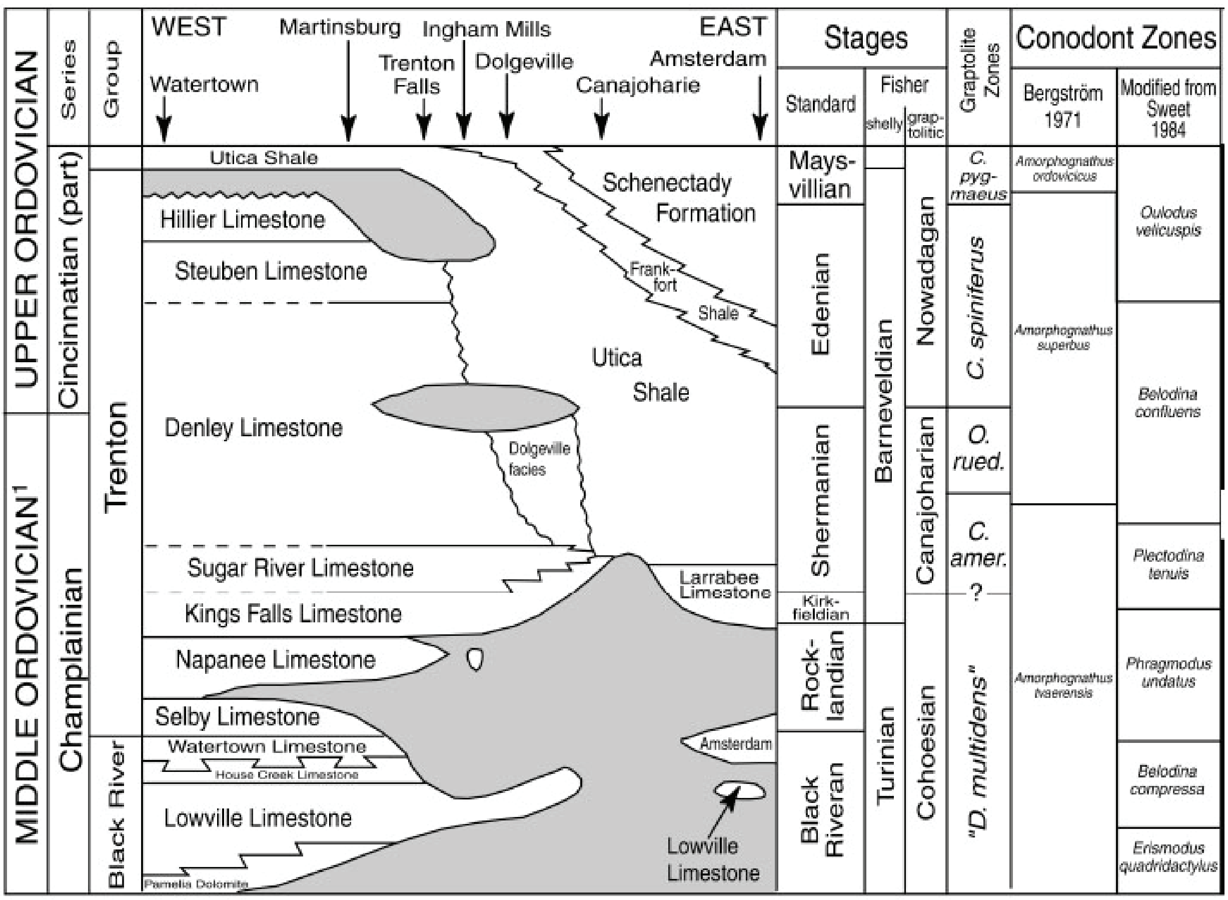


Note: Adapted from Ryder (1991). The Deicke K-bentonite is the β-marker in this chart.

Figure 4.2: Correlation Chart of the Middle and Upper Ordovician Stratigraphic Section through West Virginia and Ohio

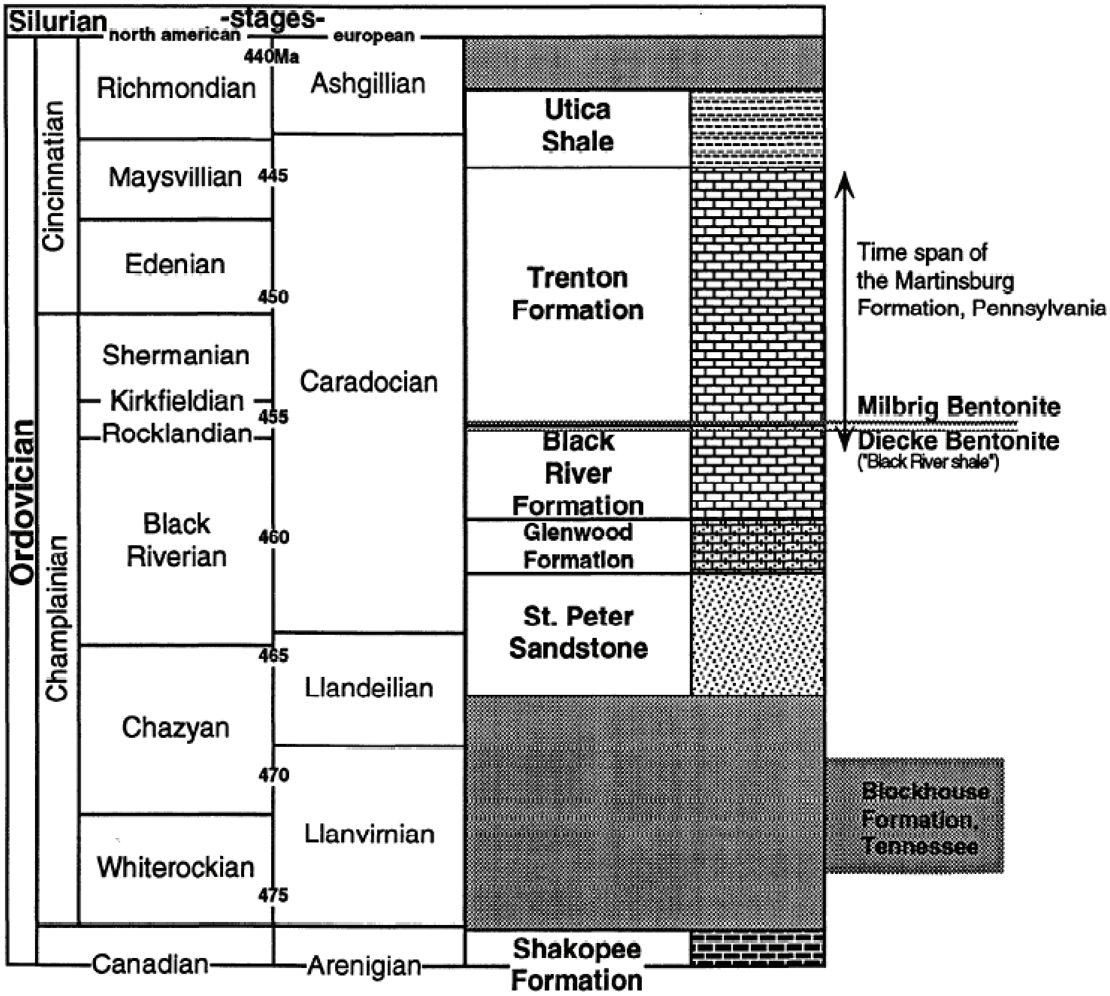
In a recent cross section of the Utica in New York State from east to west, the age of the Utica decreases from the base of the Shermanian in the east to the Maysvillian in the west (Weary et al. 2000). Using the time scale of Howard and Patzkowsky (i.e., Figure 4.1), the Utica shale progrades across Laurentia through a period of as much as 6 Ma and during several parasequences.

Carrying the detailed sequences of the Nashville Dome to the Algonquin arch is more difficult. The Trenton Group of the Appalachian Basin may or may not carry up into the Edenian (Ryder et al. 1998). Work in the Michigan Basin makes the same approximate correlations with the top of the Trenton Group placed in Maysvillian time which should include the C2 parasequence of the Nashville Dome. The Utica Shale carried into Richmondian time which may include parasequences C3 and C4 of the Nashville Dome (Coakley et al. 1994, 1995). This means that the total thickness of the Utica Shale in the Michigan Basin correlates with the top of the Reedsville-Utica package in the Appalachian Basin (Figure 4.4). Ryder shows the Utica getting younger as it progrades onto the Findley Arch (Drozd and Cole 1994, Ryder et al. 1998) and the same younging to the west is shown in New York State (Weary et al. 2000). The top of the Utica in the Michigan basin is as much as 8 Ma younger than the base of the Utica in New York State. Later in this report an analogy will be drawn between the Utica shale and the Marcellus Shale. The Utica shale is deposited under an area larger than the Marcellus. The Juniata Formation in the Appalachian Valley and Ridge is the same age as the top of the Utica black shale in the Michigan Basin.



Note: From Weary et al. (2000).

Figure 4.3: Stratigraphic Relationships of the Black River and Trenton Groups in New York State Showing the Range of Ages Based on Conodont Sampling



Note: From Coakley and Gurnis (1995).

Figure 4.4: Stratigraphic Column for the Ordovician of the Michigan Basin

In studies of southern Ontario, the Trenton Group is carried well up into the Maysvillian as is the case for the Michigan Basin (Figure 4.5). This suggests that a great deal of the Reedsville of the Appalachian Basin is chronologically equivalent to the Cobourg Formation and Collingwood Member of southern Ontario. On the Algonquin Arch the Blue Mountain-Georgian Bay sequence is roughly equivalent in age to the Utica black shale of the Michigan Basin but 4-6 Ma younger that the basal portion of the Utica in NY, for example.

4.2 Tecto-Stratigraphic Origin of the Bruce Nuclear Site Seal Rock

The post-Knox unconformity has been interpreted by some Appalachian geologists as the product of loading of the Ordovician Laurentian margin by obducted volcanic arcs and ophiolites (Jacobi 1981). The unconformity exists as far west as NV and CA and, hence, negates the possibility that the Knox unconformity has a solely regional origin related to tectonic loading affecting eastern Laurentia during the Early to early Middle Ordovician (Hatcher 2007). The withdrawal of the Early to early Middle Ordovician seas from much of Laurentia is assumed to be the origin of the unconformity.

Seq	Series	Stage	Stratigraphic Nomenclature					
			Michigan Basin			Appalachian Basin		
4	Lower Silurian	Llandoverian		St Edmund Fm				
				Dyer Bay Fm				
				Cabot Head Fm		Cataract Gp	Cabot Head Fm	Grimsby Fm
				Manitoulin Fm			Whirlpool Fm	
3	Upper Ordovician	Richmondian			Queenston Fm			
					Georgian Bay Fm			
		Maysvilian			Blue Mountain Fm			
2	Upper Ordovician	Maysvilian	Simcoe Gp	Lindsay Fm	Collingwood Fm	Trenton Gp	Cobourg Fm	
		Edenian						
	Middle Ordovician	Shermanian		Verulam Fm			Sherman Fall Fm	
		Kirkfieldian		Bobcaygeon Fm			Kirkfield Fm	
		Rocklandian				Black River Gp	Coboconk Fm	
		Blackriverian		Gull River Fm			Gull River Fm	
			Basal Gp	Shadow Lake Fm			Shadow Lake Fm	
1	Upper Cambrian	Croxian	Munising Fm	Trempealeau Fm			Little Falls Fm	
				Eau Claire Fm			Theresa Fm	
				Mt Simon Fm			Potsdam Fm	

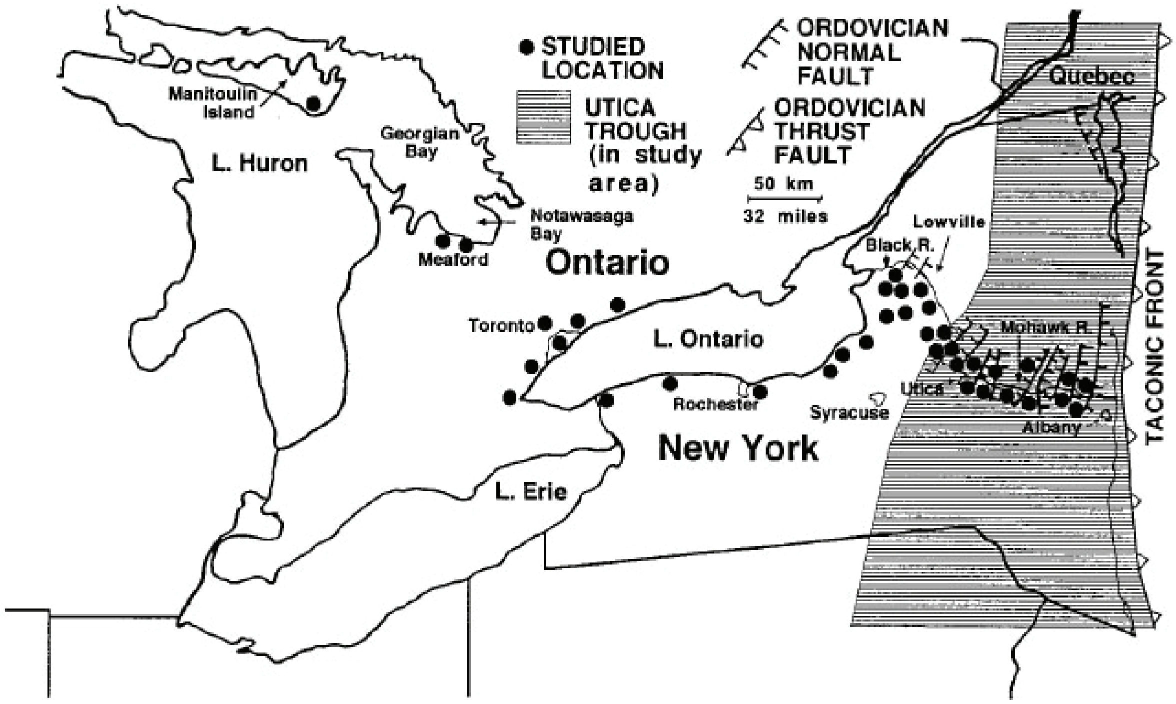
Shale	Sandstone	Sandstone / Dolomite
Shale / Sandstone	Limestone	Dolomite

Note: Adapted from Johnson et al. (1992).

Figure 4.5: Succession and Nomenclature of Paleozoic Formations in Southern Ontario, Michigan and Appalachian Basins

Presently, there is general agreement that the onset of the Taconic Orogeny is seen in the Rocklandian to Shermanian stages of the Middle Ordovician which included sequences M5 and M6 of previous workers (Holland and Patzkowsky 1998). These are interpreted to be composite sequences and are each subdivided into three smaller-scale sequences, which also have counterparts in the New York – Ontario strata (Brett et al. 2004). Depositional sequences, especially in the late Shermanian to Edenian, indicate that tectonically controlled patterns of basinal subsidence and uplift of crustal blocks (perhaps reflecting forebulge migration) accompanied the onset of the Taconic orogeny. The Taconic orogeny transformed the southeastern edge of Laurentia from a carbonate platform to a siliciclastic-dominated foreland basin into which the seal rock of the Utica black shale was deposited (Quinlan and Beaumont 1984, Tankard 1986).

The Orogeny extended across Laurentia as far as the present Michigan Basin (Lehmann et al. 1995) and is the consequence of the collision of Laurentia with a series of island arcs (Rowley and Kidd 1981). The collision caused lithospheric flexural downbuckling of Laurentia to create the foreland basin into which the seal rock of the Utica black shale was deposited (Quinlan and Beaumont 1984, Tankard 1986). Subsidence of the eastern portion of the foreland basin in New York, the Utica trough, was at least partly the result of movement along high-angle faults that formed grabens and half grabens that dropped to the east (Bradley and Kidd 1991) (Figure 4.6).



Notes: Outcrop locations used by Lehmann et al. (1995). The approximate position of the Utica trough parallels the strike of normal faults that were active during the Ordovician Bradley and Kidd (1991).

Figure 4.6: Map Showing Outcrops Locations

The onset of the Taconic orogeny was accompanied by a diachronous east to west progression of subsidence as indicated by a progressive westward change from carbonate platform to a siliciclastic basin (Lehmann et al. 1995). Earliest recorded clastic rocks indicative of the onset Taconic orogeny are the basal part of the Martinsburg Formation of latest Rocklandian age, found in Dauphine County, PA (MacLachlan 1967). This is the age of the M4 sequence on the Nashville Dome (Holland and Patzkowsky 1998). In other locations on the margin of Laurentia the onset of the Taconic orogeny is marked by an argillaceous limestone succession with deeper marine limestone interbedded with shale as is characteristic of the lower most Shermanian Coburn Formation in Central PA (Figure 4.7).

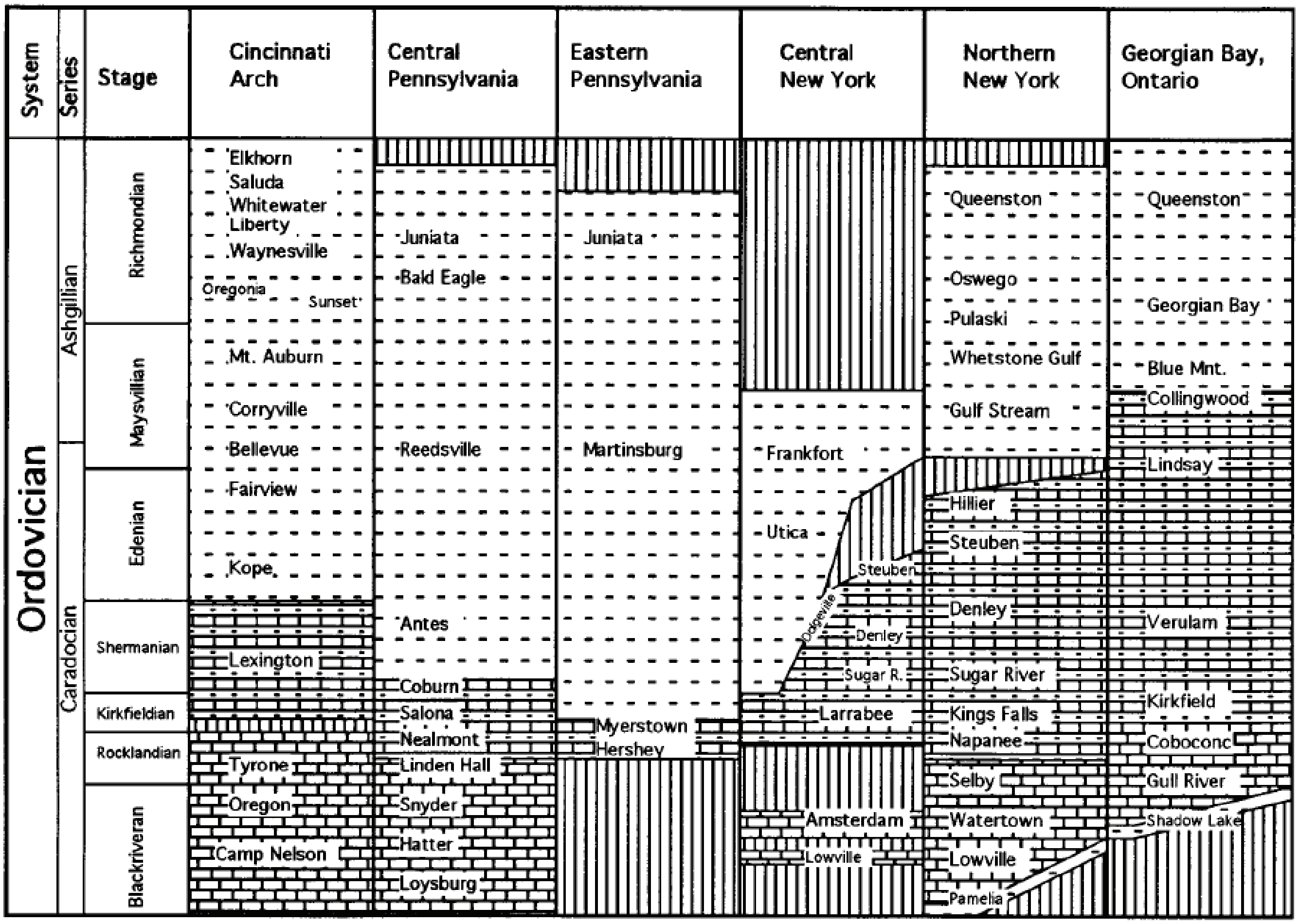
Lithospheric loading and tectonic down flexing is accompanied by a transgressive systems tract (TST). One characteristic of a TST are sediment-starved, stratigraphically condensed intervals between underlying argillaceous limestones and the overlying siliciclastic rocks. This is true for both the Ordovician Taconic orogeny and the Devonian Acadian orogeny (Ettensohn 1991). Limestone below a condensed interval is typically part of a deepening upward succession of strata. Condensed intervals are characterized by early diagenetic cementation of limestones, abundant organic material, oil shales, and phosphatic pebbles and moulds of fossils (Russell and Telford 1983). The condensed interval in Ontario, represented by the Collingwood Member of the Cobourg Formation, is 10 m thick along Georgian Bay; approximately 8m thick at the Bruce nuclear site and thins progressively toward the southeast (Armstrong and Carter 2010, INTERA 2011, Lehmann et al. 1995). Armstrong and Carter (2010) note that where the Collingwood is absent, a phosphatic lag is observed in the form of a thin phosphate horizon, unconformably separating the Cobourg and Blue Mountain Formations. At the Bruce nuclear site, both the Collingwood Member and a thin ~10 cm phosphatic lag are observed. Since both features are observed at the Bruce nuclear site it is presumed that several metres of the organic - rich upper portion of the Collingwood Member have been eroded and the phosphates deposited unconformably on top. In the Utica trough, centimetre- to decimetre-thick condensed intervals rest unconformably on Trenton strata. At least 7 Ma passes from the deposition of the lower Martinsburg in PA and the deposition of the starved sequence of the Collingwood Member at the Bruce nuclear site. This encompasses 5 major sequences on the Nashville Dome (Holland and Patzkowsky 1998).

In New York and Ontario, the black-shale magnafacies is made up of at least five units (from oldest to youngest, with corresponding graptolite zonation) (Figure 4.8). This stratigraphy indicates that the 7 Ma between the Martinsburg and Collingwood is not one continuous transgressive systems tract (TST). Rather, the base of each unit is defined by a centimetre to decimetre-thick bed containing phosphatic shell debris and clasts of underlying limestone that typically have phosphatic or pyritic crusts around them. The upper surfaces of underlying limestones typically display solution pitting and corroded, mineralized firm grounds to hardgrounds, indicating a period of nondeposition, erosion, and authigenic mineralization. These phosphatic/ pyritic beds at the bases of black shale units are interpreted as being the products of stratigraphic condensation. Each unit represents a westward pulse of foreland-basin fill, which in turn records an episode of tectonic subsidence in the Taconic foreland basin (Lehmann et al. 1995). If this interpretation is correct the Taconic orogeny is much like the Acadian orogeny with its four episodes of tectonic subsidence (Ettensohn 1985b). A lithostratigraphic cross section from the Utica trough to the Algonquin axis reflects the westward thinning of the Taconic section (Figure 4.9).

4.2.1 The Appalachian vs. Michigan Basin

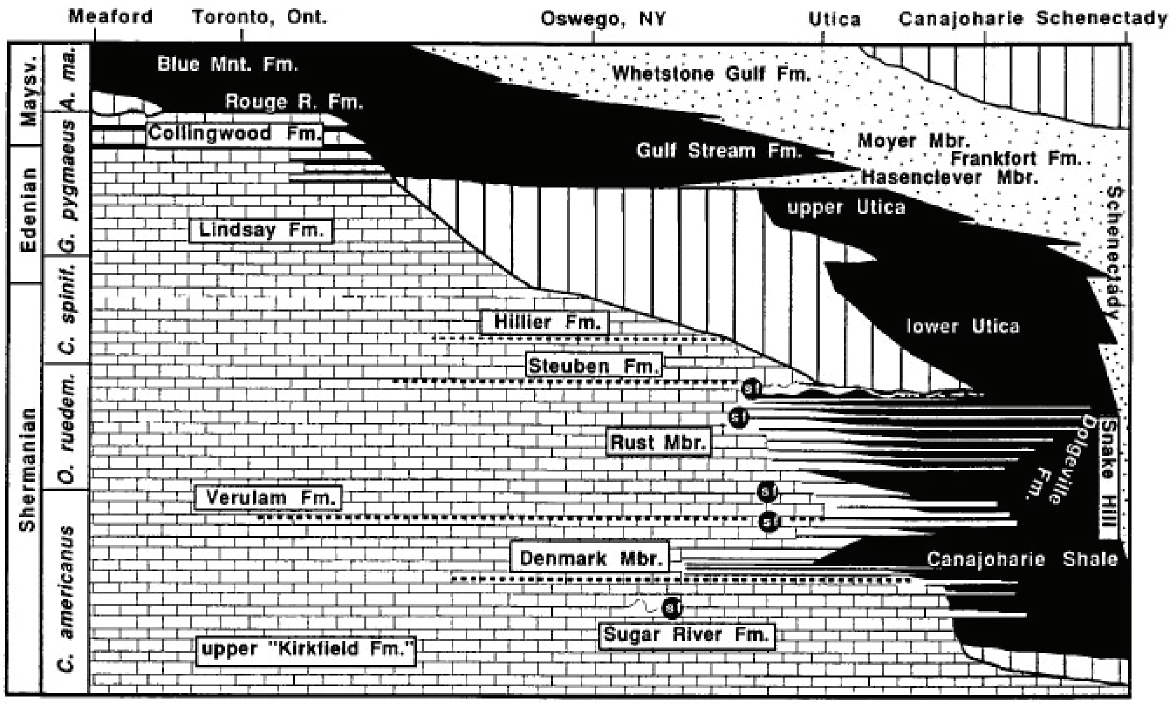
The onset of the Taconic orogeny in the Michigan Basin is seen in a shift from basin-centered deposition to a depositional pattern that tilts toward the east with the deposition of the Black River carbonates (Coakley et al. 1994). The Black River thickening is taken to occur between 1-2 Ma before the deposition of the Deike K-bentonite (Coakley and Gurnis 1995). This tilting is recorded in the form of isopach for the Trenton which become progressively thicker toward the east (Figure 4.10). It is known that the Trenton is not a chrono-stratigraphic unit but rather becomes younger toward the Algonquin Arch and the Michigan Basin (Figure 4.8). The Trenton Group at the Bruce nuclear site is as young as the Maysvillian Cobourg Formation on the west site of the Algonquin Arch.

The effect of the loading of the southeastern margin of Laurentia is seen in the stratigraphic columns from either side of the Algonquin Arch in southern Ontario (Figure 4.11). While the difference in thickness of the Black River and Trenton carbonates is minimal, the eastward thickening of the Taconic clastic wedge of the Queenston Delta is significant. This is largely a consequence of the tectonic loading and subsequent relaxation at the edge of Laurentia.



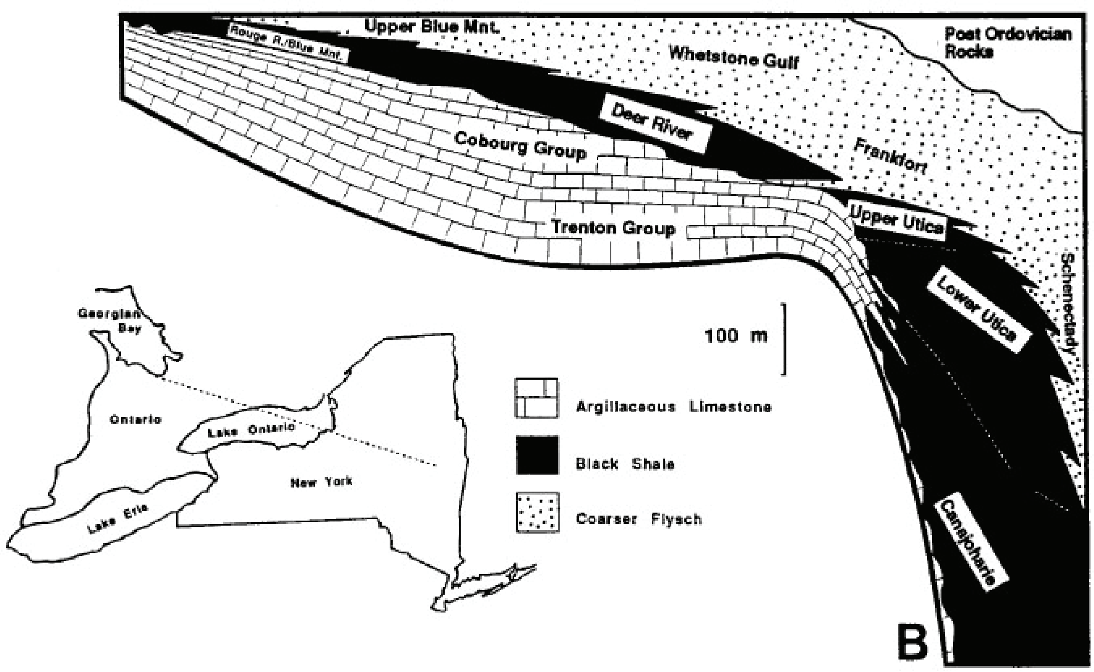
Notes: Adapted from Lehmann et al's Figure 2 (Lehmann et al. 1995). Only formational names are included on this diagram. Note the three very generalized packages of strata: the siliciclastic-free carbonate rocks (shown in a brick pattern), the argillaceous carbonate rocks (shown as alternating bricks and dashed lines), and the clastic wedge (shown as dashed lines). Hiatuses are shown as vertical lines. The Blackriveran clastic rocks in New York and Ontario are basal arkoses and related siliciclastics that are present between underlying Precambrian basement strata and overlying carbonates of the Black River Group. The clastic wedge strata contain a moderately large amount of limestone distal of the Taconic orogen (Georgian Bay Formation in Ontario and Edenian through Richmondian units near the Cincinnati Arch).

Figure 4.7: Caradocian and Ashgillian Strata of Northeastern and North-Central North America



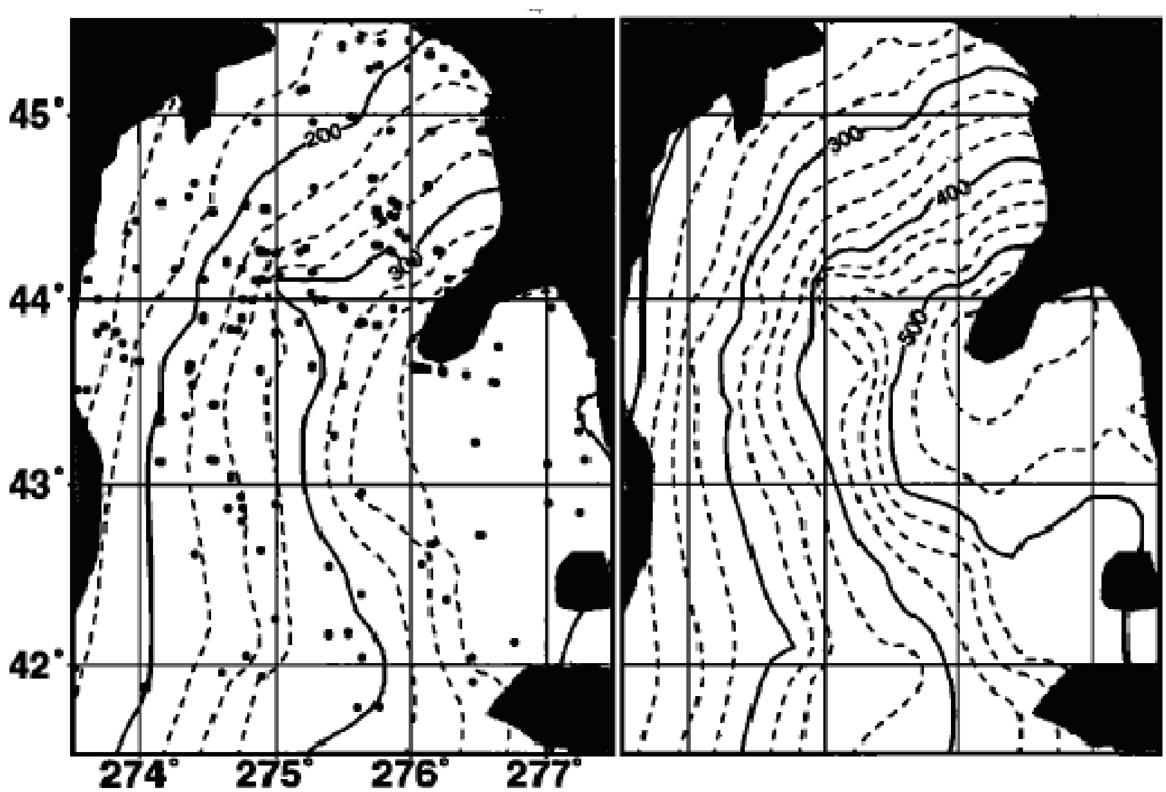
Note: From Lehmann et al. (1995).

Figure 4.8: Biostratigraphy and Associated North American Stages (Maysv. 5 Maysvillian) of Middle to Upper Ordovician Black Shale



Note: From Lehmann et al. (1995).

Figure 4.9: A Lithostratigraphic Cross-Section from the Utica Trough to the Algonquin Axis



Notes: The time period includes the Blackriveran through the Maysvillian Stages and the rocks include the Black River and Trenton Groups and the shales of the Utica-Queenston clastic wedge Coakley et al. (1994).

Figure 4.10: Isopach and Decompacted Isopach Maps for the Period of Eastward Regional Tilting of the Michigan Basin during the Taconic Orogeny

4.2.2 Taconic vs. Alleghanian Orogenies

The seal rock at the Bruce nuclear site is the basal portion of a clastic wedge, the Queenston Delta, which owes its accommodation space to the tectonic loading at the southeastern edge of Laurentia. This seal rock, mainly the Utica black shale, changes character depending on its location relative to the tectonic load. In the Appalachian and Michigan Basins there are Devonian analogs to the basal portion of the Queenston Delta. These may be seen in the composite stratigraphic columns of southern Ontario. Tectonic loading of the southeastern edge of Laurentia during the Devonian Acadian Orogeny is also responsible for a clastic wedge, the Catskill Delta. Within the Catskill Delta are several black shales (Marcellus and Geneseo) that are similar to the Utica (Blue Mountain) black shale in many respects. Both are the consequence of tectonic loading and this report will make use of these black shales as analogs. (Ettensohn 1991, Ettensohn 1985a, 1985b, 1994).

4.3 Facies Description and Paleodepositional Setting

The base of seal rock of the Bruce nuclear site is considered the black shales (Collingwood Member of the Cobourg Formation) first deposited in uppermost Trenton time. In the Appalachian Basin the equivalent to the Bruce nuclear site seal rocks include the Antes and

Utica black shales (Ryder et al. 1998). In southern Ontario these units include the Rogue River black shales and the younger Blue Mountain Formation. The 150- to 300-ft-thick Utica and Antes shale are the thickest most wide spread of the Lower Paleozoic black shale intervals.

The base of these seal rocks is characterized by a starved sequence. This means that sea level has increased rapidly enough that deposition is near the source area and that distal portions of the sedimentary basin receive very little clastic material. Starved sequences are usually high in organic content and very fine grained. Preservation of organic material requires that waters contain less than 1 ml/L of dissolved oxygen (Rhoads and Morse 1971). Often this occurs within an oxygen minimum layer which is found in many coastal areas at a depth between 100 and 500 m where oxygen might be less than 0.5 ml/L (Demaison and Moore 1980). These are the conditions that reached across the Algonquin Arch in Maysvillian time and lead to the deposition of the basal portion of the Bruce nuclear site seal rock, including the Collingwood Member and lower Blue Mountain Formations.

Core samples and outcrop exposures suggest that a discontinuous erosion surface above the Collingwood is present only in the westernmost portion of the outcrop belt (along Georgian Bay) (Lehmann et al. 1995). Where the disconformity occurs, the uppermost shale of the Collingwood Formation is slightly pyritic and the lowermost shale of the overlying Blue Mountain Formation contains phosphatic, limestone, and oil shale intraclasts.

A thin phosphate horizon approximately 10 cm thick has been observed in all Bruce nuclear site cores at the contact between the Collingwood Member and Blue Mountain formations (INTERA 2011). The significance of the phosphate nodules at the base of the Blue Mountain is seen by looking elsewhere. Phosphate nodules in gray and black shale of the Devonian Appalachian Basin range from isolated features nearly spherical to ellipsoidal in shape. In other places the nodules are interconnected to appear as trains of ellipsoidal nodules. For all practical purposes, these are the geometries of carbonate concretions in these sample dark gray to black shale formations. The nodules rarely show an internal structure. Other studies have found that nodules consist or peloids, cements, and microfossils, usually radiolarians (Kidder 1985). The peloids, interpreted as fecal pellets, are subspherical and composed of finely crystalline apatite with a long dimension of approximately 100 μm. These nodules can average as much as 30% P_2O_5 (Runnels et al. 1953). Shale normalized enrichments in middle rare earth elements (REE) developed as the phosphatic concretions lithified under reducing conditions in pore waters of organic-rich muds (Kidder et al. 2003)

There appears to be a connection between phosphate and the oxygen-minimum zone because phosphate nodules are most abundant near the upper and sometime the lower contact between black shale and more oxic facies. In the Appalachian Basin phosphate nodules are found at the top of the black Chattanooga Shale where they often straddle the contact between the black shale and the overlying gray shale of the Maury Formation (Conant and Swanson 1961). Their position relative to black shale indicates that slow regression favors the development of phosphate whereas rapid transgression suppresses phosphogenesis within the starved sequence at the base of black shale. Shale compaction around the nodules suggests that the nodules formed within the sediments rather than at the surface. One interpretation is that upwelling is an important component of phosphogenic system because it supplies the source of phosphorus (Kidder 1985).

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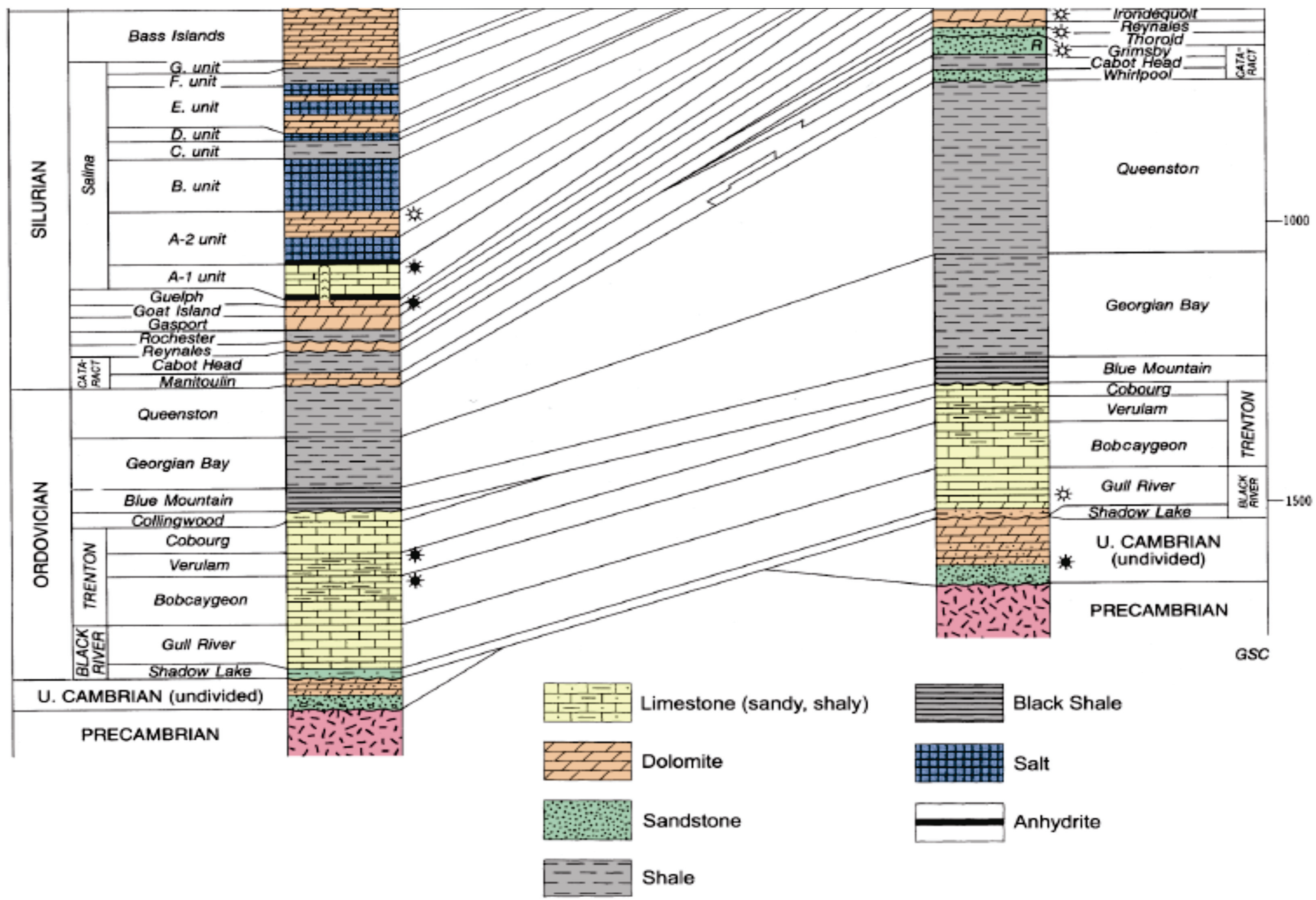

Note: From Mazurek (2004) after Sanford (1993).

Figure 4.11: Composite Stratigraphic Columns of Southern Ontario

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4.3.1 Total Organic Content (Utica Trough)

Samples of the Utica and Antes from the Appalachian Basin have Total Organic Carbon (TOC). TOC source rocks in the range from 0.28% to 4.26% (Ryder et al. 1998). These are values consistent with the Blue Mountain Formation near the Bruce nuclear site (Obermajer et al. 1999b). This is not nearly the richness of the Devonian Marcellus shale which is known to range above 12% TOC.

Regionally, the Collingwood Member contains organic matter with up to 11% TOC (Armstrong and Carter 2010) and has likely sourced oils which are reservoired in Cambrian and Ordovician traps. Barker (1984) found that this unit contains 1-10% TOC with the upper 2-10 m hosting the richest yields, this is the portion thought to have been eroded from the Bruce nuclear site. TOC is thought to generally increase northward based on samples from the Georgian Bay region consistently yielding higher values than those from the Toronto area (e.g., Obermajer et al. 1999). The overlying lower part of the Blue Mountain yields a TOC content of 1-5% (Barker 1984).

4.3.2 Total Organic Content of the Utica Shale (A-OSS)

When sampling TOC for the Utica shale throughout the basin, contours close around a high of TOC < 4% (Figure 4.12). This maximum is located in central PA and into eastern Ohio. Organic content significantly decreases toward the Algonquin Arch and the Bruce nuclear site.

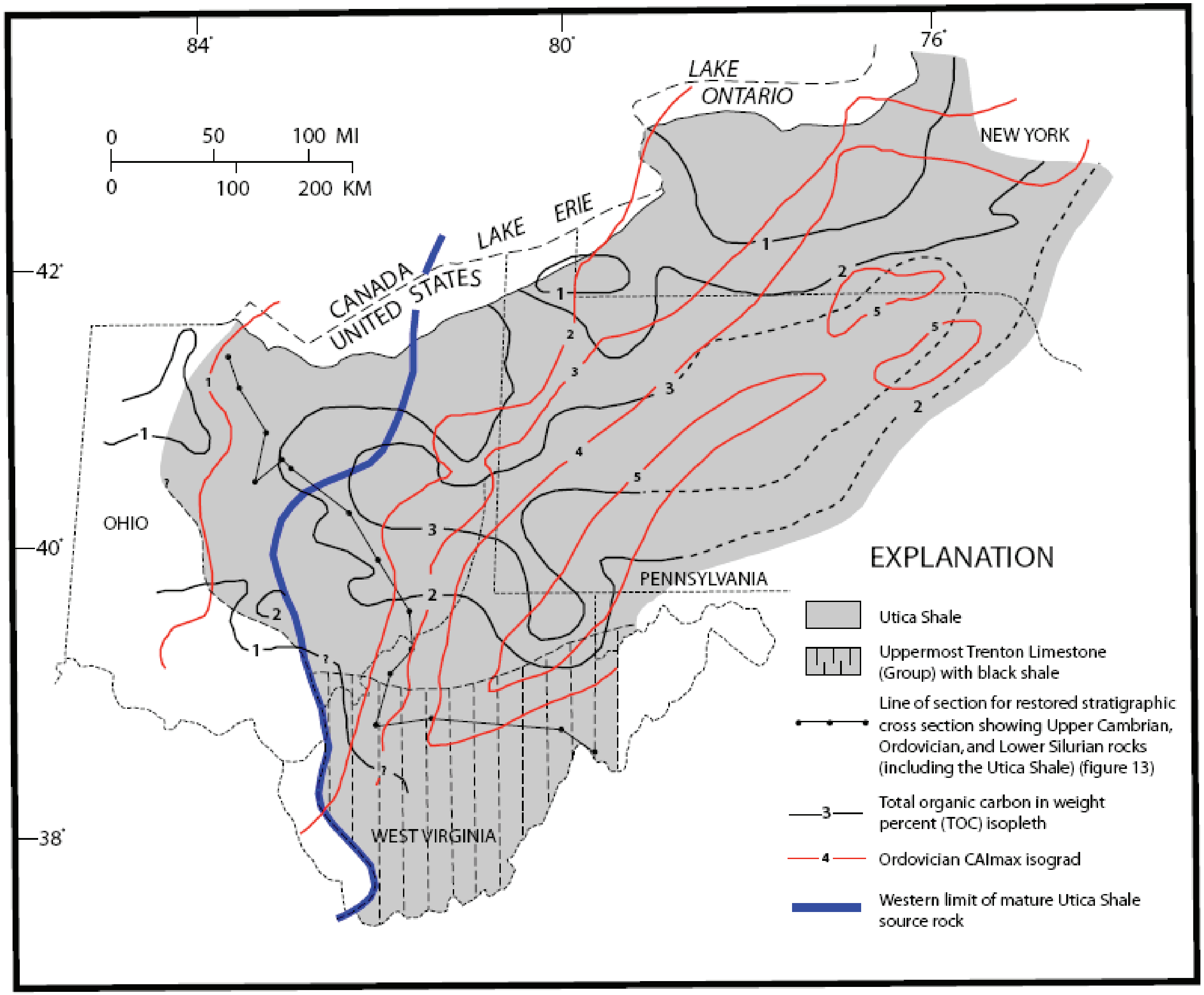
4.3.3 Total Organic Content at the Bruce Nuclear Site

The Blue Mountain Formation of the Algonquin Arch correlates with the Utica Shale in the Appalachian Basin. The distinction is that that TOC in the Blue Mountain Formation is less than that found in the Utica Tough of New York State (Figure 4.13). Although the TOC increases as the Blue Mountain Formation is approached from the north, it does not increase to the level required of a black shale. TOC peaks at 2.5% close to the top of the Collingwood formation, before decreasing to 1.5% at the base of the Blue Mountain (INTERA 2011). TOC then rapidly decreases from the base upwards with an average of <0.5% recorded at the top of the Blue Mountain. Lower values ~0.3% are recorded in the overlying Georgian Bay and Queenston shales. As a general rule, black shale has a TOC > 1.5%, so only the thin upper portion of the Collingwood formation at the Bruce nuclear site may be classified as a black shale.

4.3.4 Mineralogy of the Georgian Bay-Blue Mountain Section at the Bruce Nuclear Site

Within the seal rocks the amount and thickness of limestone, siltstone and sandstone interbeds decreases downward (Armstrong and Carter 2010). The sandstones and siltstones are commonly calcareous and contain both calcite cement and calcareous bioclastc material. Limestone ‘hard beds’ are typically fossiliferous while the shales tend to be noncalcareous.

Core logging from DGR-2 suggests that the Blue Mountain Formation is 42.7 m thick and can be divided into an Upper and Lower Member (INTERA 2011). The Upper Member is 38.1 m thick and the Lower Member is a 4.6 m thick unit of hard, dark grey calcareous shale. Sulphurous and petroliferous odors are present throughout the Blue Mountain Formation at the Bruce nuclear site. The core mineralogy of the Upper Member using petrographic techniques is estimated as illite and other clays (83-85%), carbonate (10%), quartz (5%), and pyrite (0-2%). This result is consistent with XRD analyses showing the clay content from whole rock mineralogy to be on the order of 70% for the Ordovician shales INTERA (2011).



Note: Adapted from Ryder (2008).

Figure 4.12: Distribution of Weight Percent of Total Organic Carbon in the Utica Shale

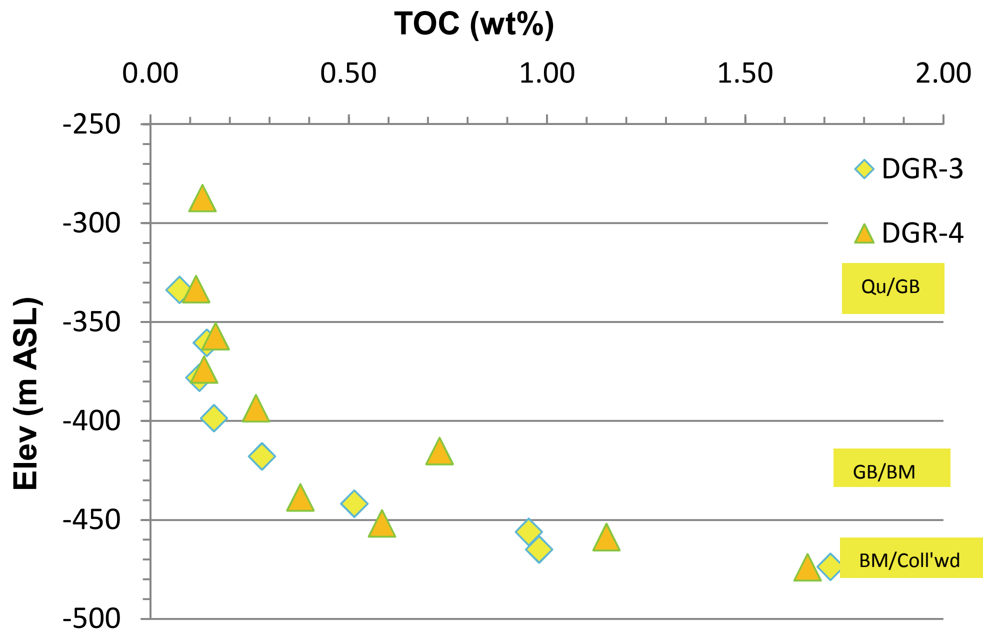


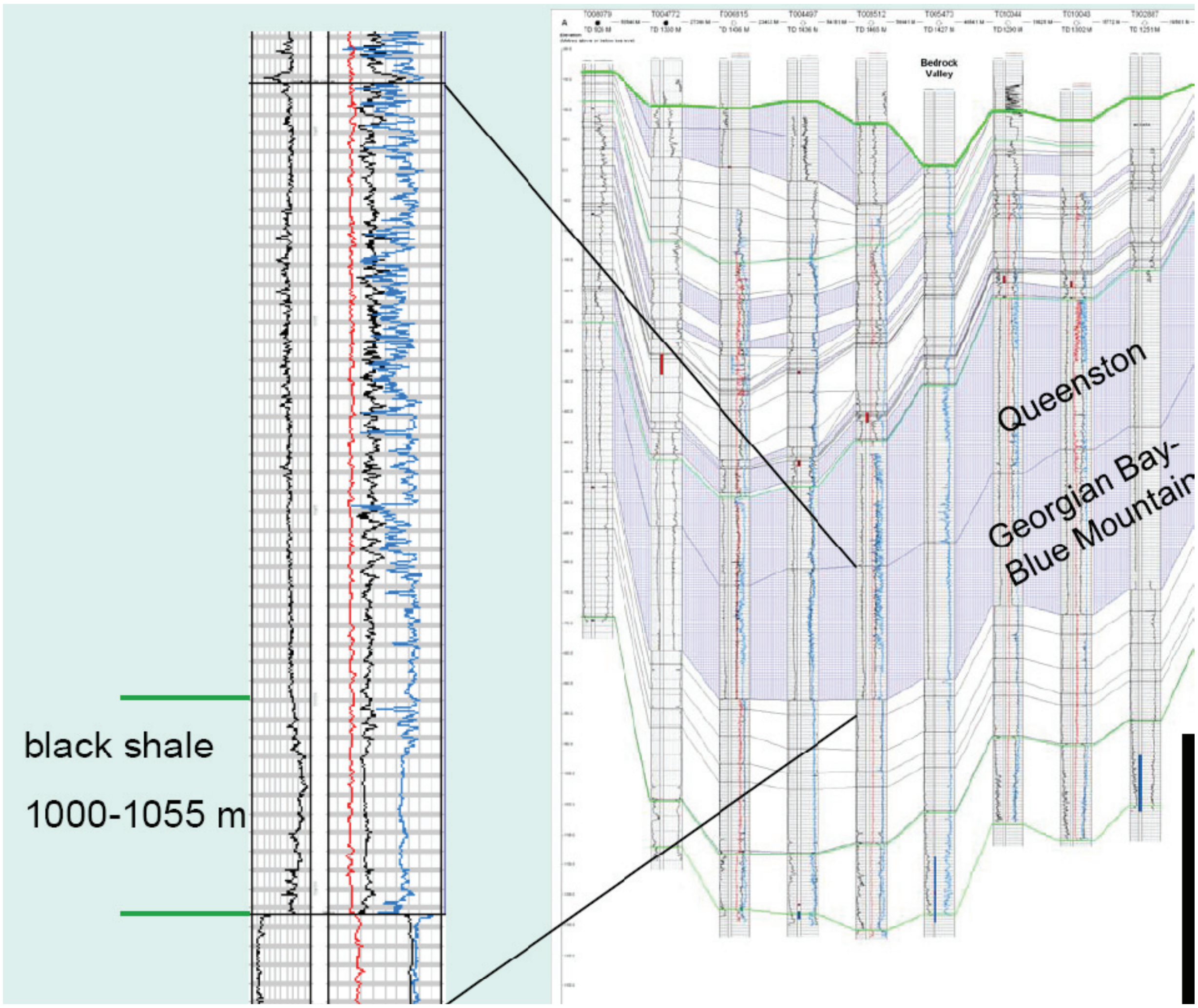
Figure 4.13: TR-08-29, Laboratory Organic Geochemistry Testing of DGR-3 and DGR-4 Core

The clay content of the seal rock at the Bruce nuclear site is unusual relative to equivalent units of the Utica deposited closer to the edge of Laurentia. In New York State the Utica shale consists of more than 50% detrital quartz and feldspar which reflects its proximal position relative to the Utica trough (Paktinat et al. 2007). Here the mineralogy is quartz (25%), calcite (26%), Fe dolomite (8%), plagioclase (8%), pyrite (4%), smectite (8%), illite (13%), chlorite (6%), and organic material (2%). Less than 25% of the mineral grains in the proximal Utica are clay compared with more than 70% of the grains in the Blue Mountain Formation at the Bruce nuclear site.

The high clay content of the Blue Mountain Formation at Bruce nuclear site is not only high relative to more proximal equivalents in the Utica shale but it is also high for economically productive gas shale in general including the Marcellus, Barnett, Haynesville, and Fayetteville. High clay contents can lead to more effective sealing of minor-displacement faults or fractures in the vicinity of Bruce nuclear site.

4.4 Electric Log-based Facies Description

To build a natural analog case for the Ordovician cap rock integrity at the Bruce nuclear site, the structure of Ordovician hydrocarbon reservoirs and sealing mechanisms throughout Michigan and Appalachian basins must be examined. An analog is only as good as the similarity of properties including the characteristics of electric log-based facies. The Blue Mountain Formation consists of black shale with sufficient organic carbon to drive a gamma ray log above 180 API units which is generally regarded in industry as the cut-off for prospective gas shales (Figure 4.14). The search for Blue Mountain equivalent rocks starts in the proximal portion of the Taconic Basin in New York State.

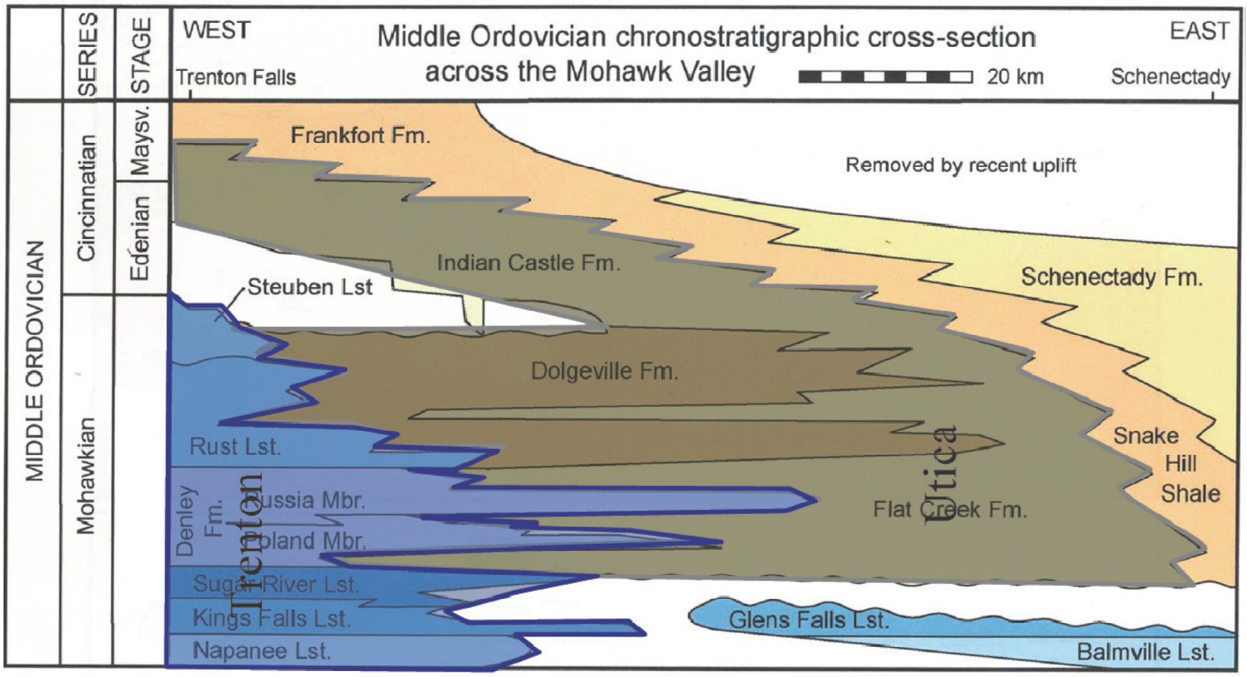


Note: Adapted from Carter (2009).

Figure 4.14: Blue Mountain Formation Electric Logs from Ontario

The stratigraphy of the Utica shale in the Utica trough of the Mohawk Valley is complex. Whereas Lehmann et al (1995) recognize the Canajoharie Shale below the Dogleville and Utica proper (Figure 4.8), Weary et al (2000) identify the Utica shale with the Dogleville facies (Figure 4.3). Recently Nyahay et al (2007) have further subdivided the Utica Group into three formations within the Mohawk Valley: The Flat Creek, Dolgeville, and Indian Castle (Figure 4.15). The range of TOC varies within the three Utica shale units (Figure 4.16).

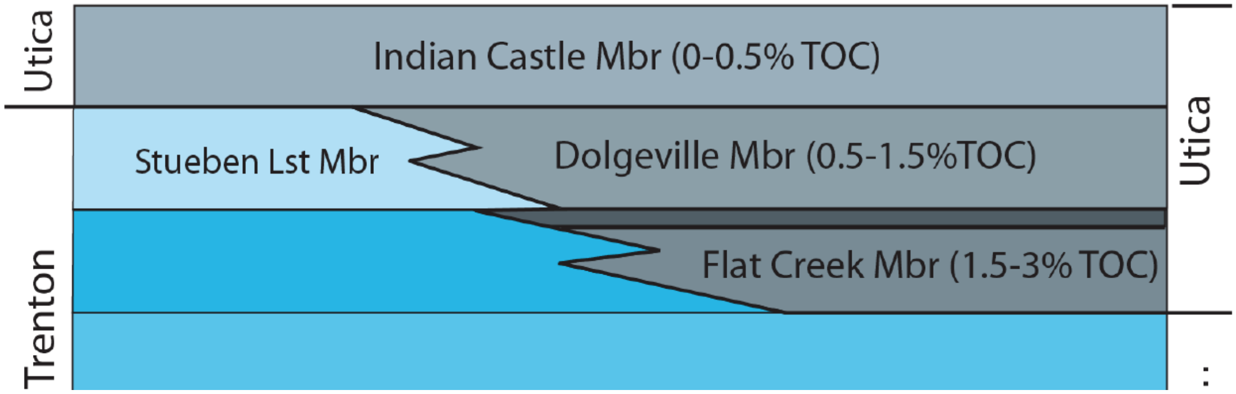
Organic rich shale is apparent in electric logs by its high gamma ray signature and concomitant density (Schmoker 1979, 1980, 1981). Several studies in the Appalachian Basin have shown that density might be more sensitive as a quantative measure of TOC than the gamma ray log (Schmoker 1979). In New York State the electric logs through the Utica shale reflect its organic content and are visible on gamma ray logs (Figure 4.17).



Notes: Adapted from Nyahay et al. (2007). Trenton Limestone units are shown in blue and Utica shale units shown in dark brown. The Mohawkian Series is equivalent the Shermanian Stage.

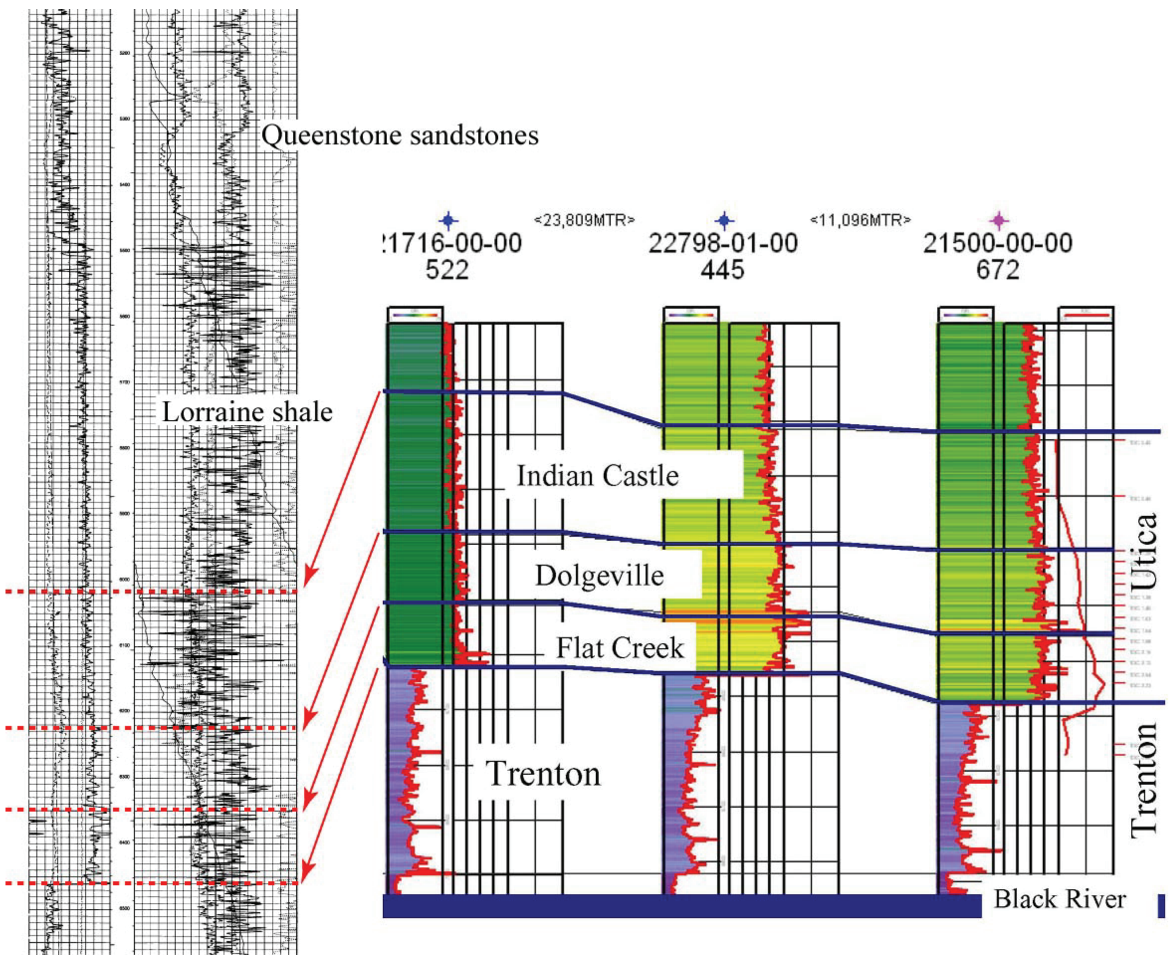
Figure 4.15: Middle Ordovician Chronostratigraphic Cross Section Across the Mohawk Valley

Black shales are identified by noting the API value for gray shales. For the Lorraine shale this API value is 140, typical of gray shales. The gamma ray API of the Indian Castle Member of the Utica is barely above that for the gray shale with some peaks at API = 160. This unit would be considered a gray shale and it has a TOC ≤ 0.5% which is also consistent with a gray shale. The Flat Creek Member has a couple of gamma ray spikes at API = 240 which is consistent with a TOC ≈ 5% (Figure 4.17). The Dolgeville Member has gamma ray API between the extremes, consistent with its TOC content. The density log of 22798-01-00 is not particularly revealing (Figure 4.17).



Note: From Nyahay et al. (2007)

Figure 4.16: Variation in Total Organic Carbon in the Utica Shale of the Mohawk Valley



Notes: Adapted from Nyahay et al. (2007). Three color logs on the right are gamma ray logs. The log on the left is the raster log for 22798-01-00 showing both a gamma ray (left) and density track (solid line on right).

Figure 4.17: Logs Through the Utica Shale of New York

4.4.1 The Utica Black Shale

The seal rock at the Bruce nuclear site may be understood by viewing its counterpart, the Utica black shale where it outcrops in the Central Appalachian Valley and Ridge (Figure 4.18). Rocks of the Trenton-Black River are exposed below the Utica black shale which is several million years older than its counterpart, the Cobourg Formation of the Bruce Peninsula. The transition through the Trenton-Black River involves a series of carbonates that become more thinly bedded and argillaceous (Figure 4.19). This transition shows up on the gamma ray log was a gradual increase in API number. The base of the seal rock (the Antes in Central PA) is a pyritic rich rock (Figure 4.20 and 4.21) The highest API gamma ray signature and lowest density (undercompaction) are found at the base of the Utica shale where density probably correlates better with TOC than gamma ray count (Schmoker 1977, 1979, 1980, 1981) (Figure 4.22). In the next section it will be shown that the TOC of the Utica black shale is considerably lower than the Devonian Marcellus Formation.

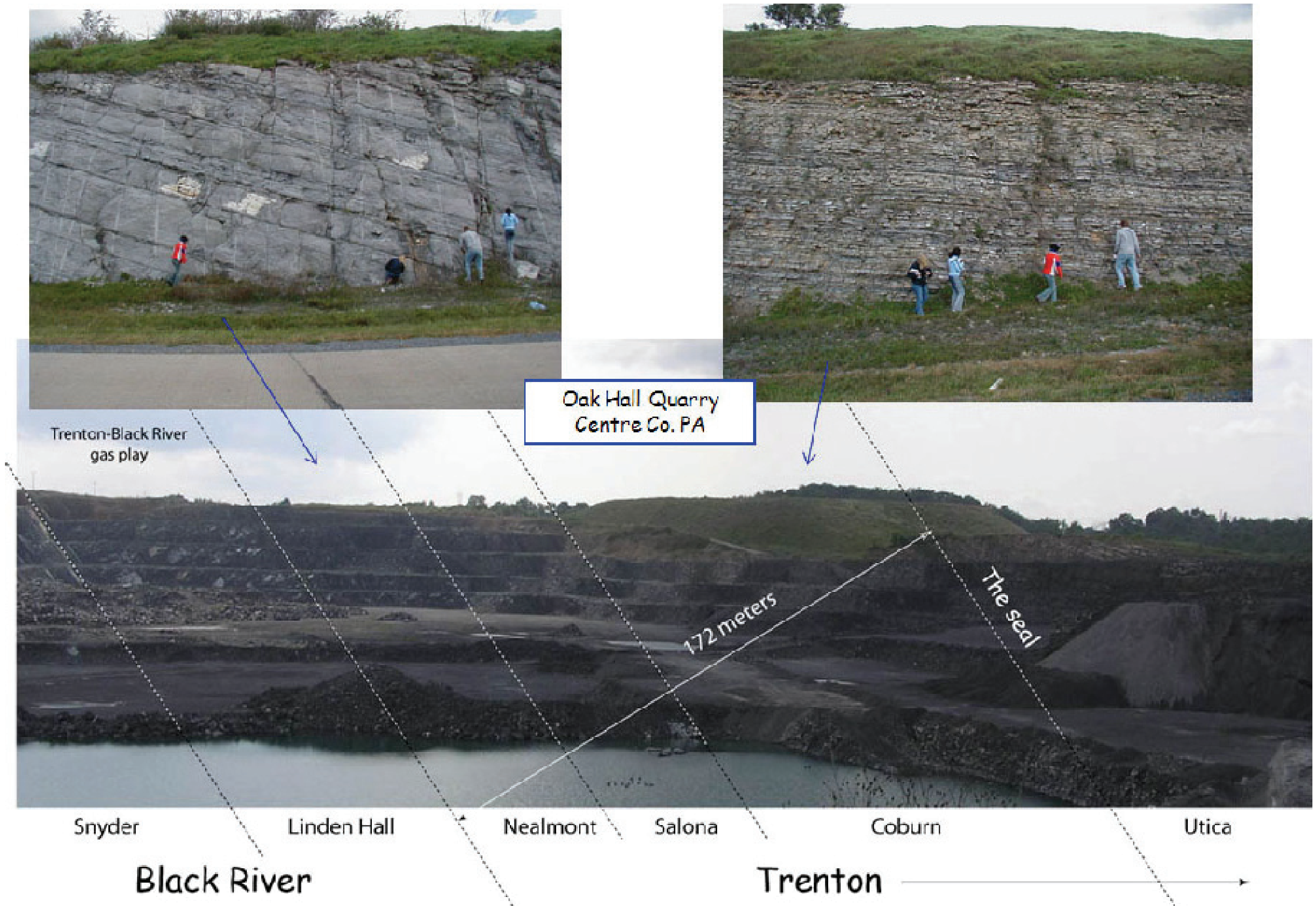
4.4.2 The Marcellus and Geneseo Black Shales

The Marcellus has a TOC of as much as 12% Nyahay et al. (2007) and shows a decrease in density towards the base of the formations. Density of the Utica (Blue Mountain Formation) is also observed to decrease with depth, at the base of the unit (Figure 4.22). From this exercise, we conclude that the Blue Mountain and Marcellus are not perfect analogs because of the difference in TOC. It is, however, important to note that both shales have the highest TOC at the bottom of the section, which is the location of the most rapid sea level rise for both black shales. Electric logs of the Blue Mountain shale reflect the variation in TOC (Figure 4.14).

A second black shale in the northern (NY) part of the Appalachian Basin, the Geneseo/Burket, is more akin to the Blue Mountain and Utica than the Marcellus. Both the Geneseo/Burket and Utica show relatively modest gamma ray anomalies while carrying the signature of a low density black shale which approaches 150 feet in thickness. This is the seminal characteristic of the gamma ray logs from the Blue Mountain (Figure 4.14). These black shales are consistent with Schmoker's model for the behaviour of Appalachian Basin black shale in which the organic content of the shale is better represented by the rock's density, rather than its gamma-ray signature (Schmoker 1979). Later we shall make the case that all three shales are a consequence of a starved clastic environment immediately following the loading of the edge of Laurentia. The reason that the Utica, Marcellus and Geneseo/Burket make appropriate analogues is that all three owe their origin to crustal flexure rather than eustatic sea level change as the mechanism driving the transgression and concomitant starved sequence in these three black shales. Other Devonian black shale of the Frasnian and Famennian stages are a consequence of eustatic sea level fluctuations.

4.5 Thermal Maturity

Thermal maturity is measured using a number of techniques including Rock/Eval, vitrinite reflectance (%R_o), conodont color alteration index (CAI), and thermal alteration index (TAI). Vitrinite reflectance is most effective when the source consist has an abundance of humic material (Type III kerogen). Woody plants were not abundant on earth before the Upper Devonian so another indicator of thermal maturity must be employed for Ordovician rocks. Because conodonts are abundant in Ordovician marine rocks, CAI is an effective indicator of thermal maturity. Of course, Rock/Eval is an effective indicator of thermal maturity in both Ordovician and Devonian rocks.



Note: The Repository will be excavated from the Cobourg Formation which is equivalent in stratigraphic position and time to the Coburn formation in Central PA.

Figure 4.18: Exposures of the Trenton-Black River in the Valley and Ridge of Pennsylvania

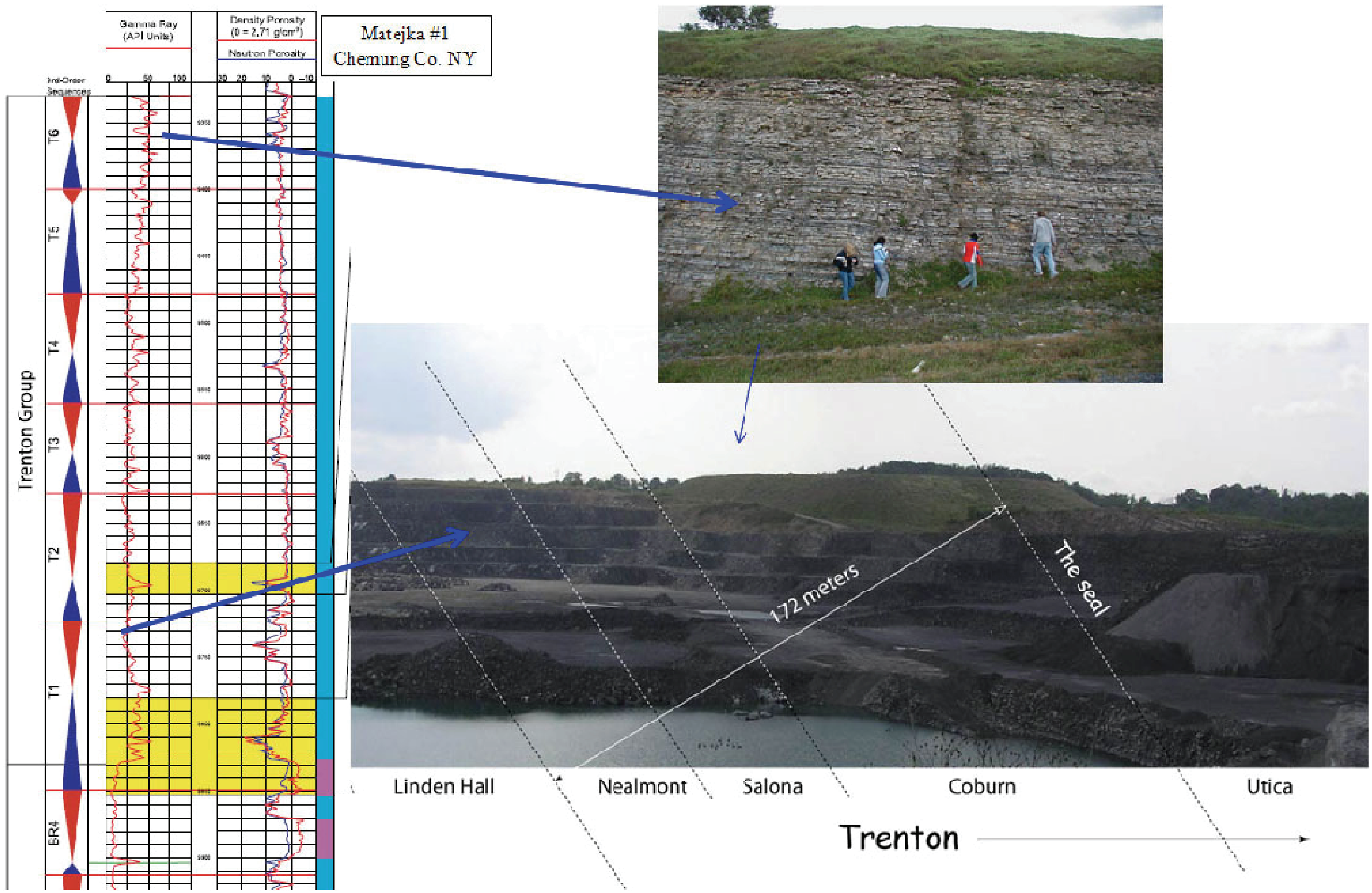


Figure 4.19: Transition Through the Trenton-Black River Group with Increasing Clay Content Upward

Figure 4.20: The Pyritic Base of the Utica Black Shale in Central PA

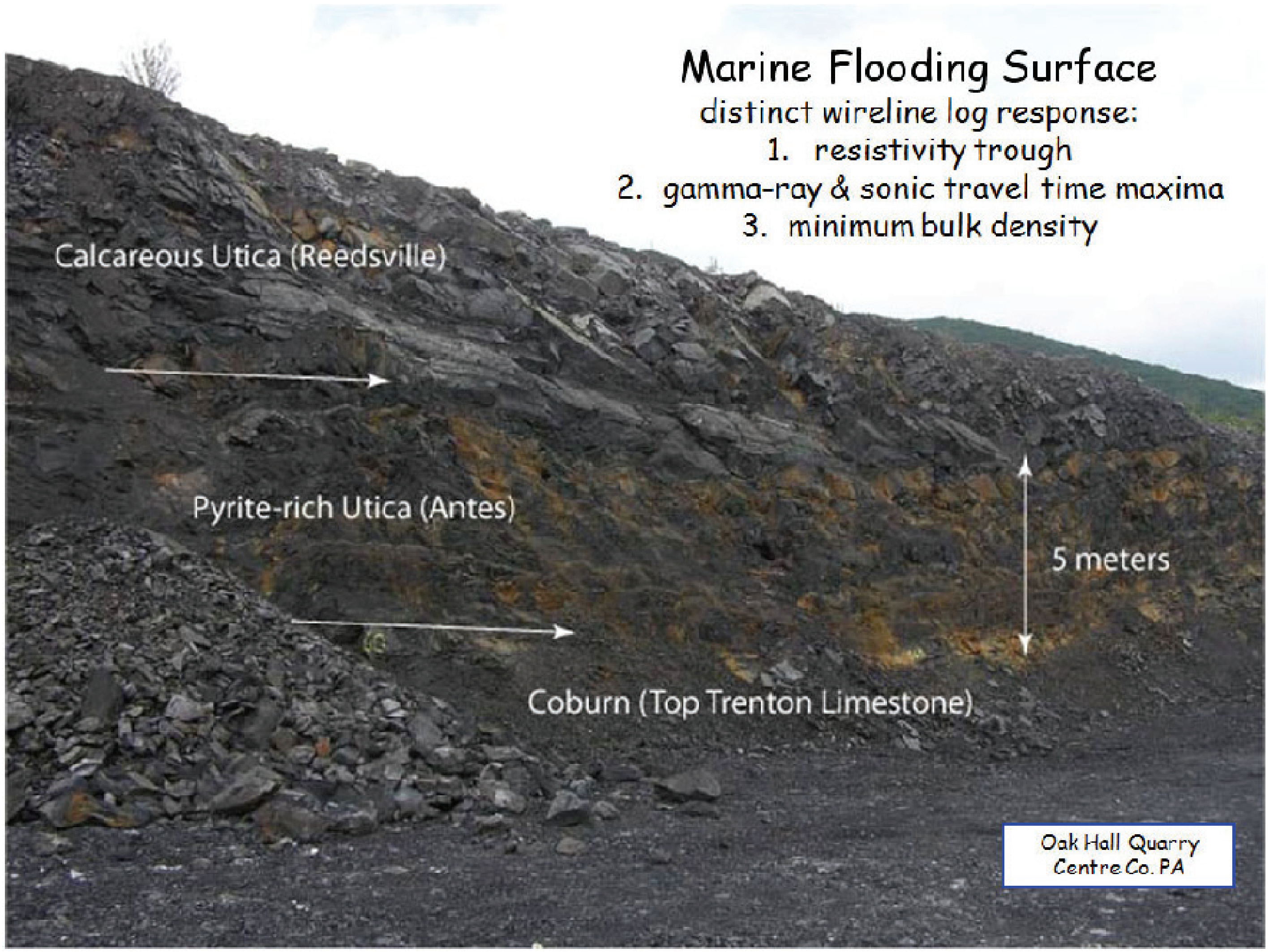


Figure 4.21: Base of the Utica Black Shale in Central PA

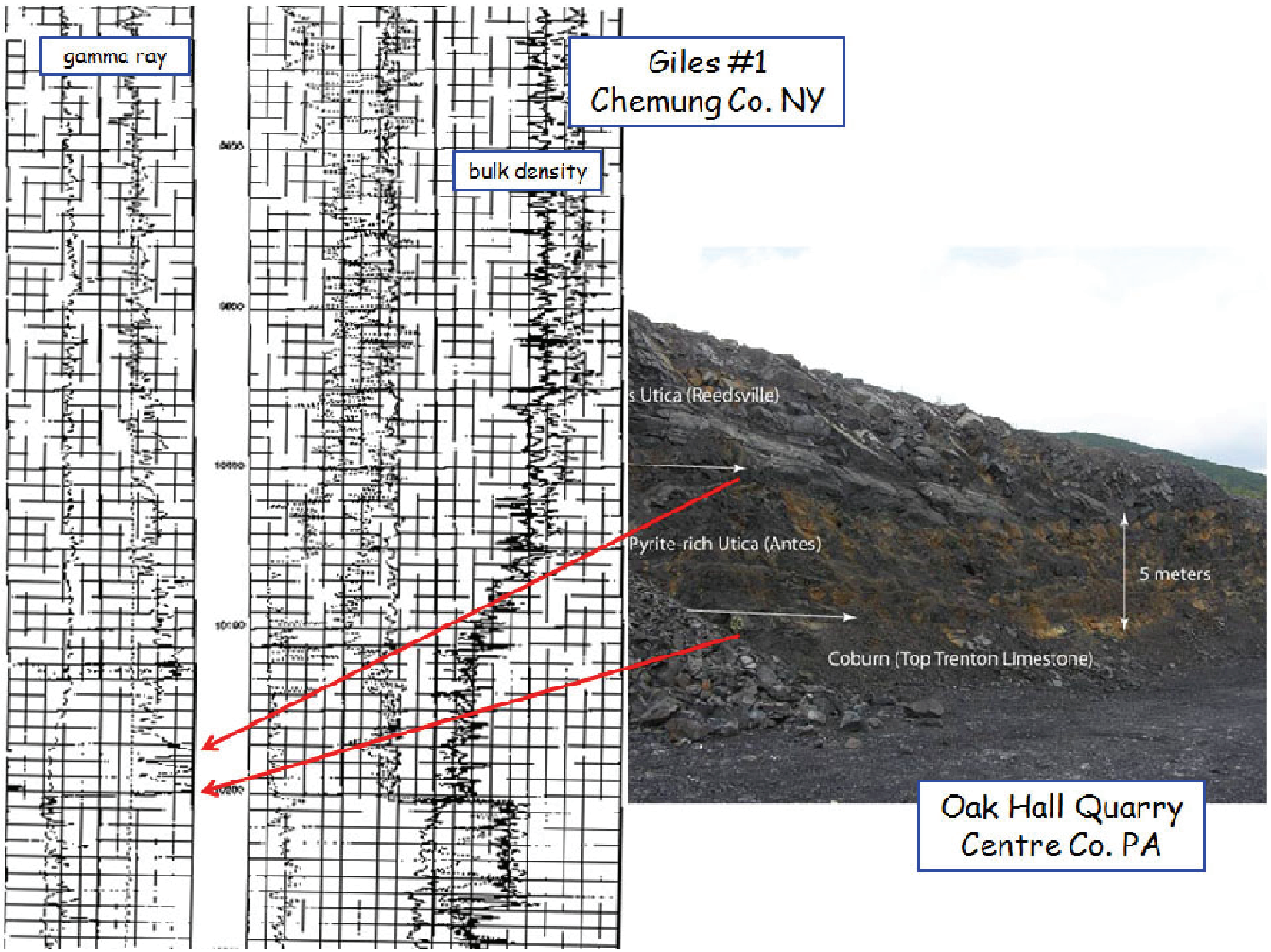


Figure 4.22: Gamma Ray and Density Logs for the Utica Formation in New York State

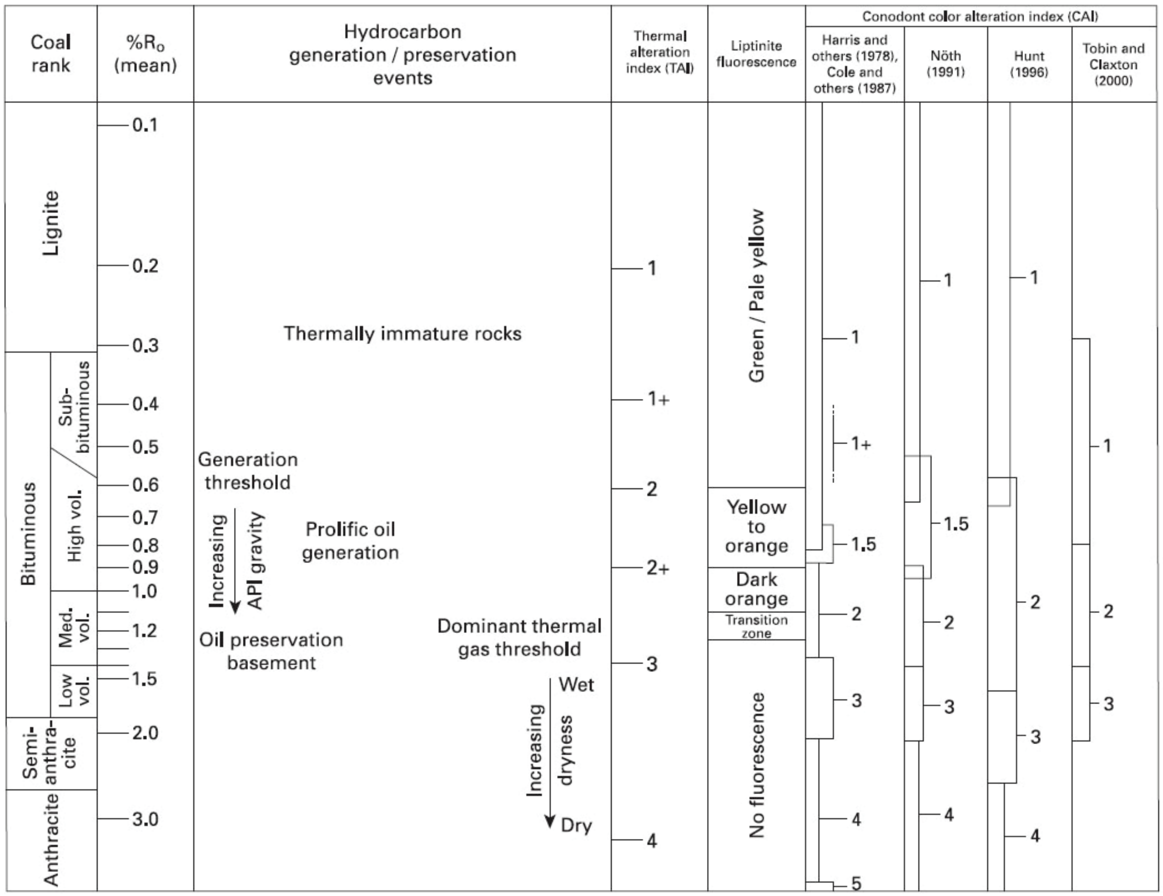
Thermal maturity of organic matter is estimated from Rock/Eval using T_{max} (temperature maximum of S_2) and PI (productivity index) Details of Rock/Eval Pyrolysis are given in (Hunt 1996). The zone of oil generation ranges between T_{max} temperatures between 435°C and 460°C and PI values between 0.1 and 0.4. Oil generation starts at an $R_o \approx 0.6\%$ which is at the top of the range for CAI = 1 (Figure 4.23). Oil is preserved in rocks through an $R_o \approx 1.5\%$ which corresponds to the top of the range of CAI = 2. Above these values gas is generated through the cracking of oil. The thermal maturity of Ordovician source rocks at the Bruce nuclear site shall be compared with those from the Appalachian Basin.

In the Appalachian Basin the CAI decreases from CAI = 5 at the Allegheny Front of Pennsylvania to CAI < 1.5 near the Findley Arch (Figure 4.24). Based on the contours of the USGS SIM Map 3006, none of the Ordovician source rocks in southern Ontario reached a CAI =2. Given this range of thermal maturity and the large volume of Utica/Antes black shale, abundant oil and natural gas must have been generated from this package of Ordovician rocks.

Several studies in the southern Ontario region conclude that the Utica shale equivalents in the Algonquin Arch region are mature with respect to petroleum production (Powell et al. 1984). The trend toward decreasing thermal maturity northward along the Algonquin Arch was confirmed by Rock-Eval measurements showing immature ($T_{max} < 435$°C) Collingwood shale on St. Joseph and Drummond Islands north of the Bruce nuclear site (Snowdon, 1984). Just to the east of the Bruce nuclear site on Georgian Bay, the Collingwood shales have an $R_o = 0.5\%$ which is consistent with the results from the St. Joseph and Drummond Islands (Obermajer et al. 1999b). The thermal maturity for the Collingwood and Blue Mountain shales increases to $R_o = 0.7\%$ in the Toronto area which is consistent with the USGS CAI contours (Figure 4.24). This thermal maturation trend suggests that the organic rich portion of the Blue Mountain shale at the Bruce nuclear site may be marginally mature (i.e., $T_{max} \approx 435$°C), backed up with the observation of minor oil seeps observed in logged core (INTERA 2011).

4.6 Subsidence and Thermal History

Thermal maturity (history) of a rock is a calculation of the degree to which organic metamorphism has progressed giving an approximate measurement of the maximum temperature the rock has been subjected to. Burial curves for the Michigan and Appalachian Basins show considerable variation in maximum depth depending on distance from the central portion of the basin. Because the Bruce nuclear site is located on the Michigan side of the Algonquin Arch, the burial history of the Michigan Basin better represents the Bruce nuclear site. The Michigan basin has a multistage subsidence history reflecting both the Taconic and Acadian orogenies much like the Appalachian Basin (Cercone 1984, Reszka 1991, Howell and van der Pluijm, 1990 1999). At the onset of the Taconic orogeny, the Michigan basin tilted to the east during Trenton-Utica time (Coakley et al. 1994, Coakley and Gurnis 1995, Howell and van der Pluijm 1990, 1999, Nadon et al 2000). The central portion of the Michigan Basin reached maximum depth during the early Permian about 280 Ma with the Utica shale buried to about 4 km. The northern part of the basin saw the Utica reach in excess of 3 km in early Permian. On the NE corner of the basin in the Manitoulin Island region, the Utica reached about 1.5 km (Coniglio et al. 1994). To understand the thermal history of the Bruce nuclear site in more detail an Appalachian Basin to Findlay Arch analysis is employed (Rowan 2006).



Note: From Repetski et al. (2008).

Figure 4.23: Table for Thermal Maturity Based on Various Indicators

Thermal history models for the Appalachian Basin are restricted to the relatively undeformed part of the basin and extend from the Rome trough in West Virginia and Pennsylvania northwestward to the Findlay arch in Ohio (See Figure 2.1 for cross section transects). Present understanding of the timing of maximum depth of burial plus the uplift and erosion history of the Appalachian Plateau of West Virginia is based on (U-Th)/He and apatite fission track dating methods with paleotemperatures from fluid inclusions and vitrinite reflectance (Reed et al. 2005). In models for Lines #1 and #2 presented here, maximum burial occurs during the Mid-Permian (270 Ma) and is followed by steady erosion until present day (Rowan 2006).

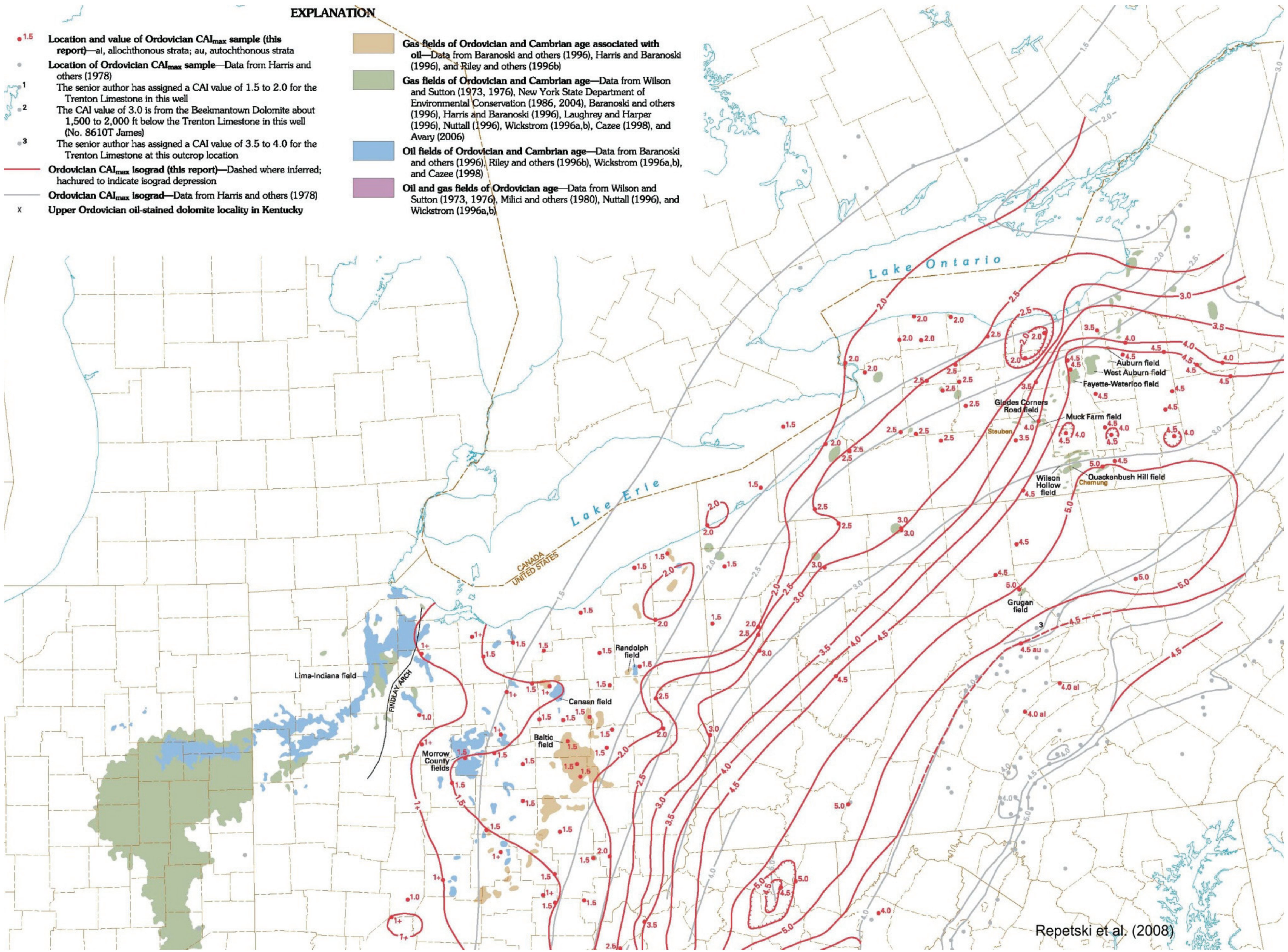


Figure 4.24: Contour Map for CAI in Ordovician Rocks of the Appalachian Basin

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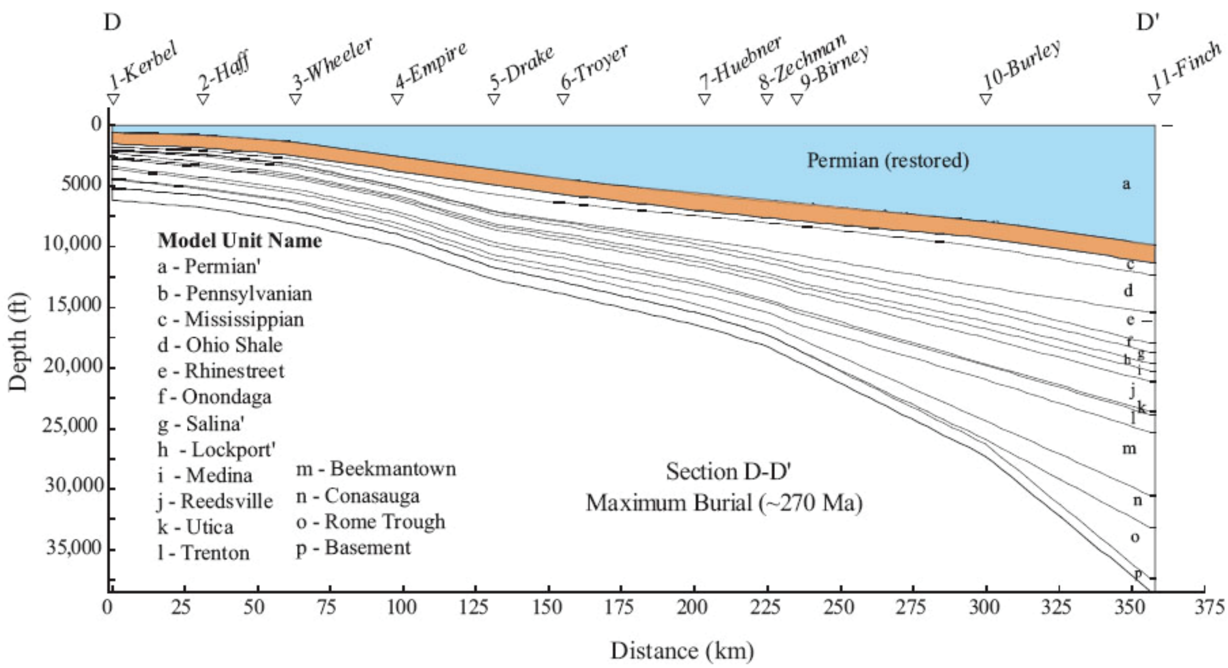
The burial/thermal history models provide calculated thermal maturity (R_o%) values for the entire stratigraphic sequence, including hydrocarbon source rocks, along cross sections. In contrast, the R_o and conodont CAI data available in the literature are sparse and limited to specific stratigraphic intervals. The cross section for Line #1 shows the Utica at a depth of 9.8 km under the Finch well in the deeper part of the West Virginia Appalachian Plateau (Figure 4.25). The Utica equivalent under the Bruce nuclear site (i.e., base of the Blue Mountain shale) has a burial history represented by the Wheeler well with the Kerbel well on the Findlay Arch. The maximum depth of Bruce nuclear site Utica is taken as 1.98 km based on the Wheeler well.



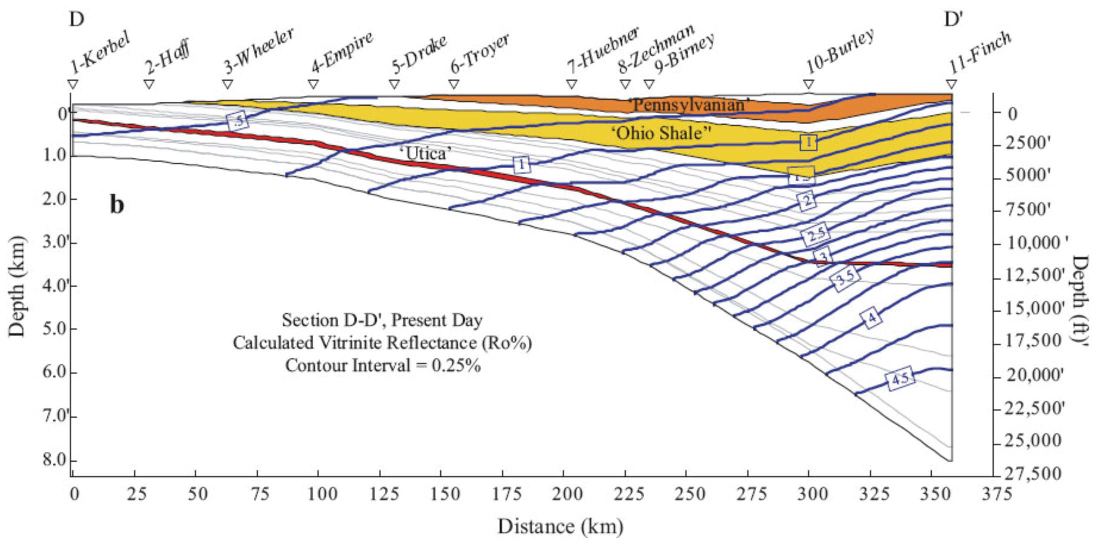
Note: Adapted from Rowan (2006).

Figure 4.25: Cross Section for Line #1 in Figure 4.15 Showing the Maximum Depth of Burial in the Early Permian (270 Ma)

The thicknesses of restored Permian strata were adjusted to match the following thermal maturity data: 1) vitrinite reflectance (R_o%) measurements on Pennsylvanian coals, 2) reflectance (R_o%) measurements of dispersed vitrinite in the Devonian Marcellus Shale, and 3) conodont alteration index (CAI) values measured in conodonts in the Devonian Onondaga and Ordovician Trenton-Black River limestones (Figure 4.25). The model-calculated %R_o-depth profiles are in fair to good overall agreement with the thermal maturity measurements (Rowan 2006). The results of the burial history models are presented over the entire 2D model domain at present day (Figure 4.26). Figure 4.27 shows profiles of thermal maturity (shown as vitrinite reflectance, Ro%) for the Ordovician 'Utica' model unit (comprised almost entirely of Utica Shale) along the cross sections of Line #1 at present day and at selected earlier times (Rowan 2006). In this figure, the Utica Shale reached thermal maturity (i.e., entered the oil window) as early as Middle to Late Devonian time (360 – 390 Ma) in wells located in the deepest portion of the basin in Pennsylvania and West Virginia. Thus, from Middle – Late

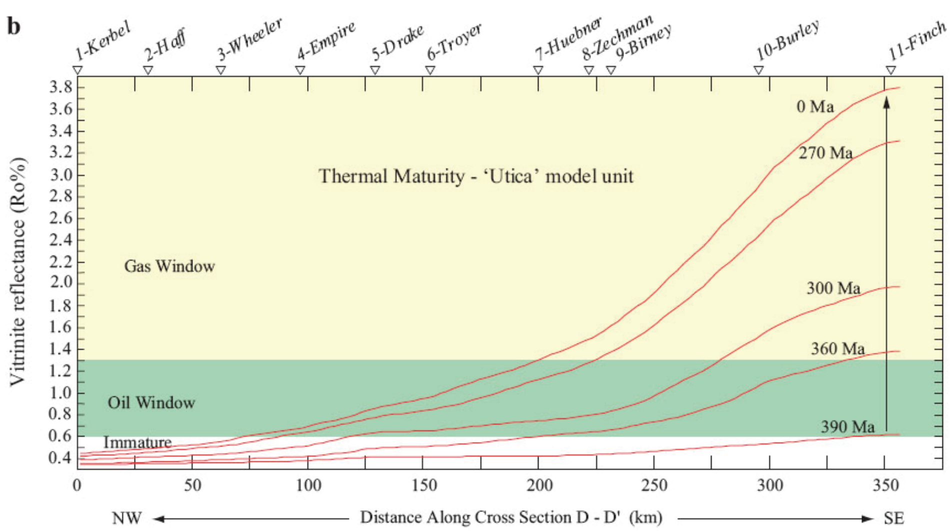
Devonian onward there was the potential for Utica-sourced hydrocarbons to migrate through the basin. The Utica Shale reached thermal maturity at progressively younger ages from southeast to northwest due to the decreasing overburden thickness away from the basin depocenter.

At wells located near the crest of the Findlay arch the model predicts a thermal maturity for the Utica Shale below that of the oil window. This model predicts that the Bruce nuclear site based on the Wheeler well just about reaches the oil window sometime between 270 Ma and the present.



Note: Adapted from Rowan (2006).

Figure 4.26: Model for Ro for Present Day Cross Section for Line #1



Note: Adapted from Rowan (2006).

Figure 4.27: Calculated Thermal Maturity Profiles for the Utica Shale Along Line #1

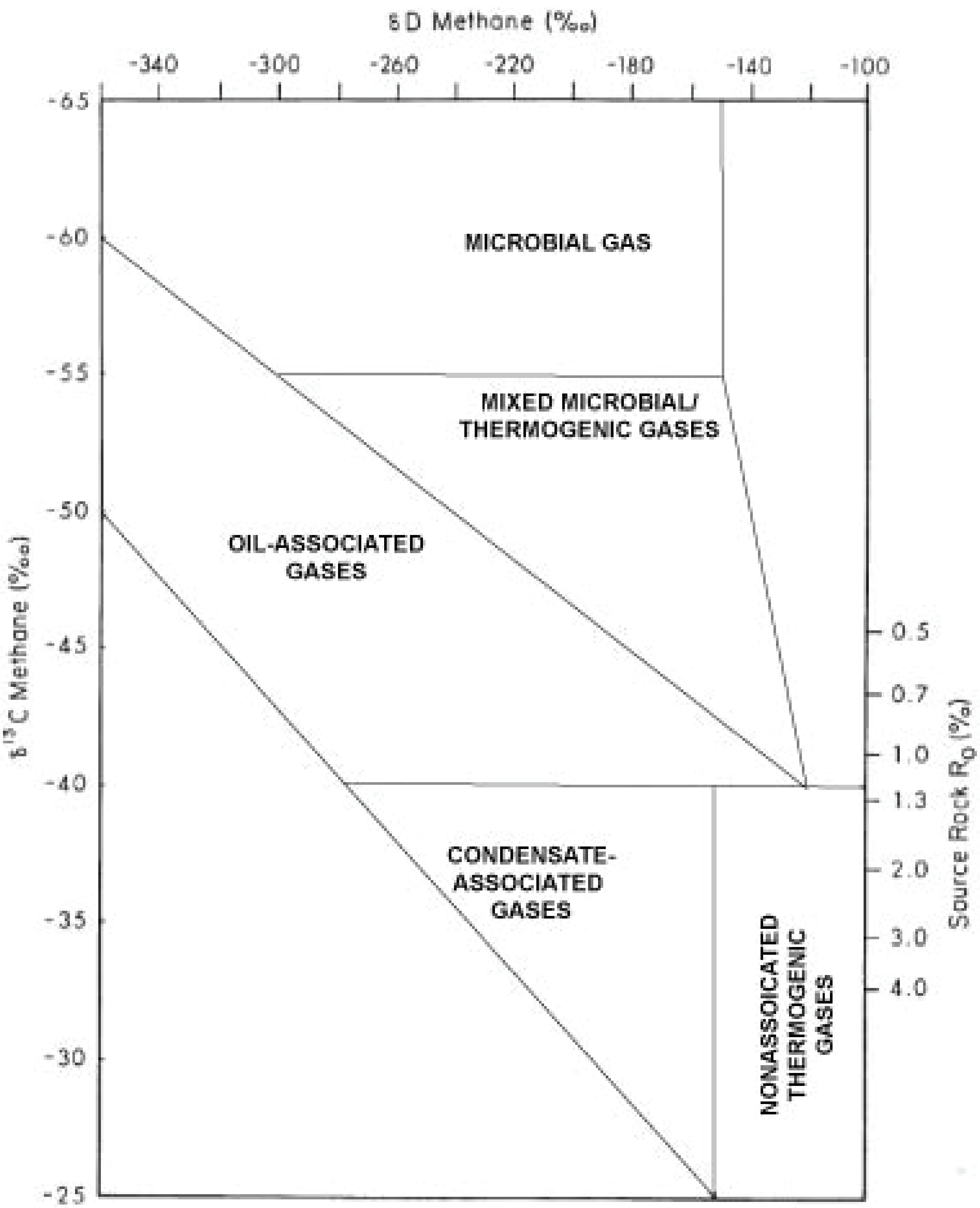
4.7 Gas Isotopes

Natural gases can be characterized genetically using four properties: ethane (C_{2+}) concentration, carbon and hydrogen isotope variations in methane, and carbon isotope variation in ethane (Schoell 1983). Primary gases originate by two processes – bacterial respiration (biogenic methane) and thermal alternation of liquid or solid precursors (thermogenic methane). Bacterial gases are devoid of most C_{2+} hydrocarbons and the methane is depleted in ^{13}C. Methane of thermogenic origin is associated with increased petroleum and ^{13}C content, which reflects the thermal maturity of the source rock. It is common practice to use a plot of the methane carbon isotope ($\delta^{13}C$) versus the methane deuterium isotope ($\delta^{2}H$) to define the evolution of natural methane gas during burial (i.e., to distinguish gases of biogenic origin from those of thermogenic origin) (Figure 4.28). The ^{13}C and D isotopes can be used to examine methane generation and transport; however, the isotopes cannot be used to determine the age of the methane.

Stable isotope geochemistry of methane was used to understand the origin of natural gas in the Appalachian Basin (Laughrey and Baldassare 1998). The gases were correlated to local Ordovician source rocks equivalent to the Utica of the Appalachian Basin. Lower Silurian Medina Group gases in northwestern Pennsylvania are late-mature and probably originated in Utica source rocks. Lower Silurian Tuscarora Formation gases produced from fractured sandstones near the Allegheny structural front in central Pennsylvania are post-mature hydrocarbons that correlate with local source rocks (i.e., the Utica).

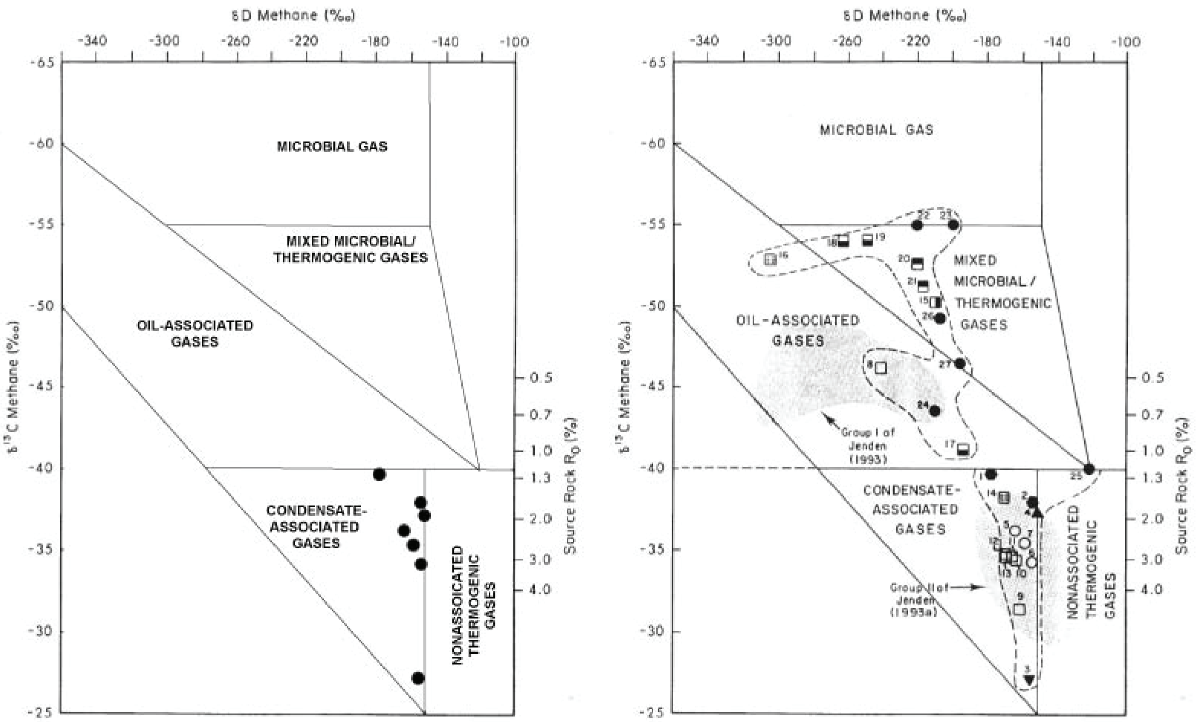
Gases produced from structural traps in the Devonian Ridgeley Sandstone and Huntersville Chert of western Pennsylvania are isotopically diverse and reflect both the entrapment of mature oil-associated gases (Figure 4.29). Autogenic gases produced from Devonian black shales are post-mature along the Allegheny Front and early-mature along the northwest basin flank. The early-mature gas is autochthonous and thermogenic. Most Upper Devonian gases produced across the Plateau are oil-associated gases that were emplaced in reservoirs prior to maximum burial of the Paleozoic section during the Alleghanian Orogeny. Some Upper Devonian gases, however, could be residues of diffusive gas leakage or possible mixtures of thermogenic gases that migrated into or from reservoirs located along regional fractures.

Gases produced from bituminous Pennsylvanian coals of the Appalachian Plateau have varied methane $\delta^{13}C$ and methane δD contents and may be mixtures of thermogenic gas and microbial gas (data #22-27). The data from the Bruce nuclear site on the Bruce Peninsula indicate two distinct zones of methane – one biogenic and one thermogenic (INTERA 2011). Biogenic methane typically has δD values < -300 ‰ whereas thermogenic processes generate δD > -250 ‰. When the $\delta^{13}C$ and δD data are plotted independently as a function of depth, two independent sources of methane seem plausible (Figure 4.30). It should be noted that a preliminary microbiological investigation did not find evidence of active methanogens within the Ordovician sediments, which may indicate that both the biogenic methane and the thermogenic methane are ancient. Only two samples were analyzed for the microbiological study - one from the Queenston Formation above the methanogenic zone, and one from the Cobourg Formation below the methanogenic zone (INTERA 2011).



Note: Figure from Schoell (1983).

Figure 4.28: The Processes of Methane Genesis Based on the Variations in Deuterium and ^{13}C in Natural Gases



Notes: From Laughrey and Baldassare (1998). Left: Data from gases produced from Cambrian and Ordovician rocks of Pennsylvania and Ohio (two samples). Right: The entire data suite of Laughrey and Baldassare with sample numbers indicating: 1-7 = Cambrian to Silurian gases, 6-21 = Devonian gases, 22-27 = Pennsylvanian gases. Maturation trends increase down and to the right on the deuterium-13C diagram.

Figure 4.29: The Processes of Methane Genesis Based as Indicated by the Variation of Deuterium and ^{13}C in Natural Gases

In the Appalachian Basin gases in porous rocks above and below the Utica Shale have an isotopic signature consistent with either condensate or dry (non-associated) gases. The thermal maturity of the Cambrian-Ordovician carbonate gases (HS Unit #7 of INTERA 2011) of the Bruce Peninsula is significantly less than their counterparts in the Appalachian Basin (Figure 4.31). These data suggest that the process of gas generation in the regional study area (RSA) is different from that observed in the Utica shales of the Appalachian Basin.

The prospect for long-term seals in the A-OSS will depend on the veracity of a number of concepts. These concepts will draw on a number of sources starting with an analysis of pressure-depth relations in the Appalachian region (Russell 1972). Russell made a number of observations and assumptions that will apply to questions about the long-term effectiveness of the Upper Ordovician Georgian Bay-Blue Mountain-Collingwood shales as a seal.

Russell (1972) assumed that reservoirs are effectively sealed. For Russell this means that fluid volumes that enter or leave the reservoir are too small to control fluid pressure in the reservoir. This statement is misleading if it is interpreted to mean that little, if any, fluid passes out of the reservoir after charging if the reservoir is sandstone. For black shale, this assumption may imply that fluid neither enters nor leaves. The density of joints and veins in the Devonian section of the Appalachian Basin suggest that fluid migration was significant. Clearly fluid leaves source rocks following maturation and because Devonian sandstone reservoirs have been charged. The present overpressure within the Marcellus gas shale suggests that Russell's assumption should be modified to account for overpressured gas despite the migration that must have taken place and the presence of joints and veins within the shale. It is a fact that black shales are effectively sealed at present even with joints and veins.

An effective seal rock containing joints and veins is possible under two circumstances. First, joints and veins can remain isolated within the seal rock without transporting fluid from within. This may have been the case for the early J_1 joint set hosted within black shale of the basin (Engelder et al. 2009). However, the J_2 joint pattern in the Devonian shale section of the Appalachian Basin strongly suggests that fractures are interconnected between the black shales including the Marcellus and the overlying gray shales and distal turbidites. By the time of propagation of J_2 joints, the network joints tied source and reservoir with high permeability channels, the joints. The presence of overpressure to this day suggests that joints within the black shales are not presently transporting gas at rates not allowing dissipation over geologic time. Evidence points to joints becoming self-sealing without filling like veins. This is a paradox although we know that hydraulic fracture stimulation of gas shales is not effective without a proppant. It may be that the properties of shales are such that under normal stresses at depths of a km or more, normal stress across these joints causes them to close and self seal.

Regarding Russell's view that fluid flow is not the critical factor in controlling pressure, evidence still supports this conclusion in the Appalachian Basin. The only modifications that might be made to Russell's assumption is that fluid flow was probably significant but that self-sealing, despite long-term out flow from the source rock, is more likely the answer to maintaining long term seals in overpressured gas shales of the Appalachian Basin.

The Bruce nuclear site pressure regime suggests a different picture for the role of fluid flow in generating overpressure by hydrodynamic flow. While the shales of the Blue Mountain are underpressured relative to hydrostatic, the underlying carbonates are slightly overpressured. One interpretation is that hydrodynamic flow originating in the Michigan Basin is responsible for the subseal pressure below Bruce nuclear site.

4.8 Poroelasticity

Generation of joints in black shale by natural hydraulic fracturing requires an increase in pore pressure to overcome the least stress in the shale (Engelder and Lacazette 1990, Miller 1995). Pore pressure causes a poroelastic increase in rock stress. Exhumation and concomitant draining of excess pore pressure causes a relaxation of rock stress which in the Appalachian Basin is manifested in the stress profile through Devonian shales (Evans et al. 1989a). Ryder et al. (1998) proposed that poroelastic deformation was probable in the Utica and Antes shale of the Appalachian Basin during generation of oil and gas.

The underpressures in the seal rock at the Bruce nuclear site have several explanations. One is that it is a manifestation of the poroelastic response to Cenozoic erosional unburdening (INTERA 2011). The Marcellus and other Devonian shale are underpressured in the southern portion of the Appalachian Basin in WVA and KY (Russell 1972). One of the explanations for the Appalachian Basin underpressuring is also exhumation-related.

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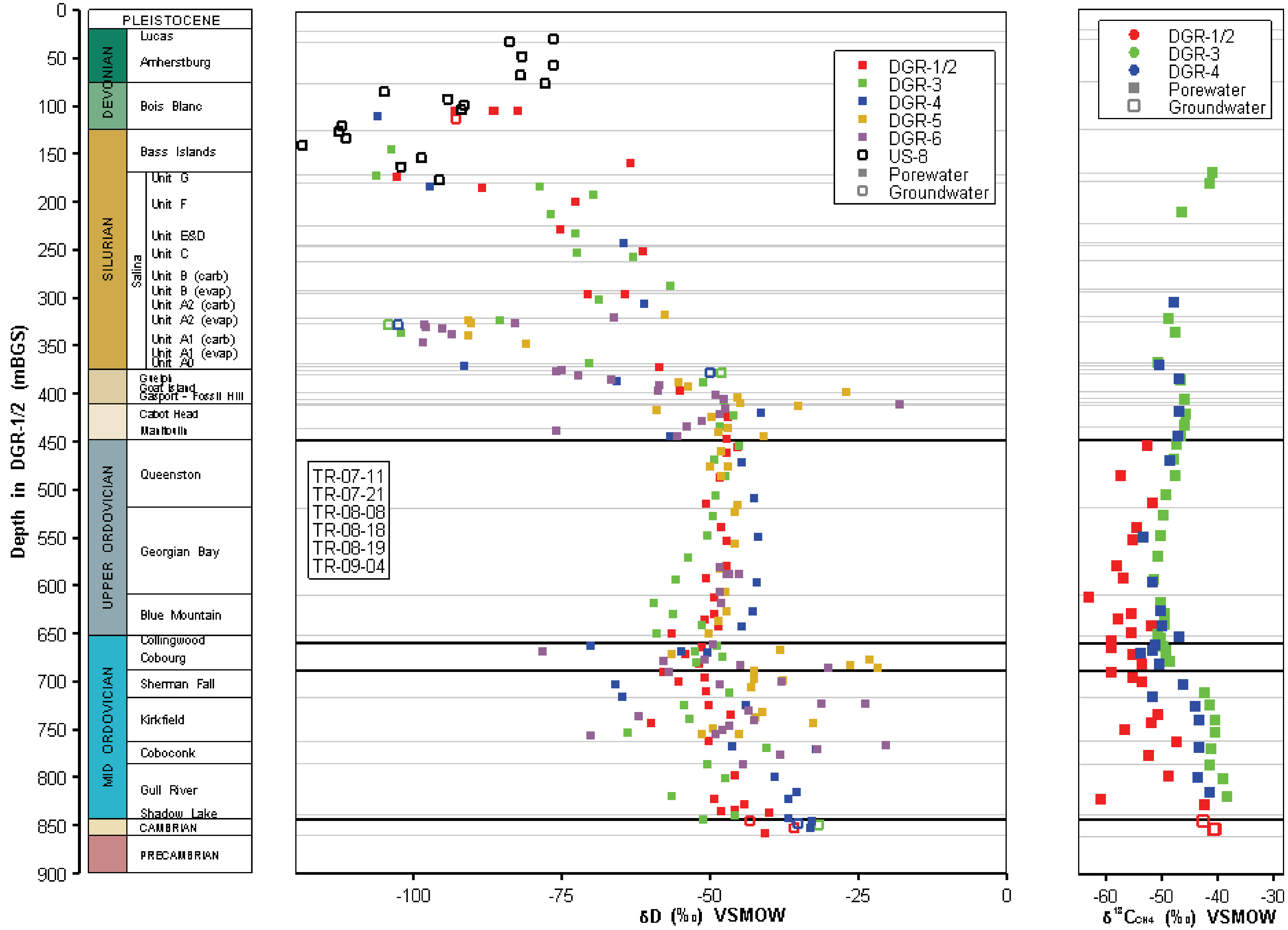

Note: From INTERA (2011).

Figure 4.30: Deuterium and ^{13}C Isotopes of Methane in Pore Water and Groundwater for Bruce Nuclear Site Boreholes

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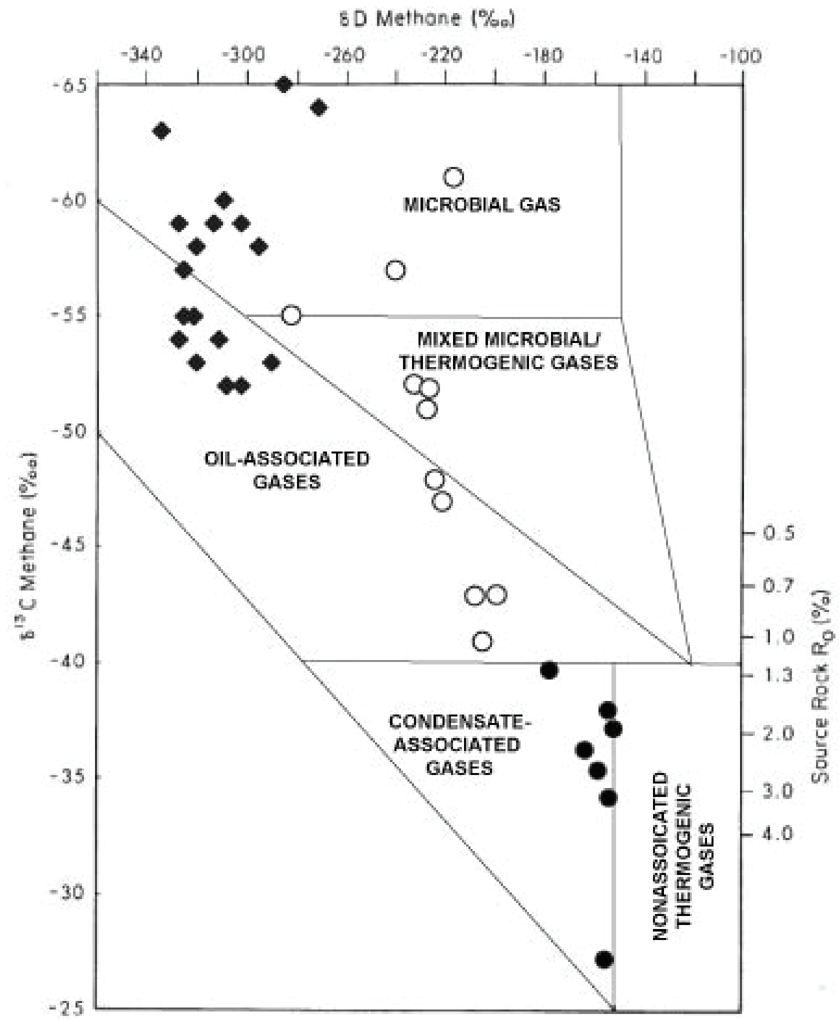
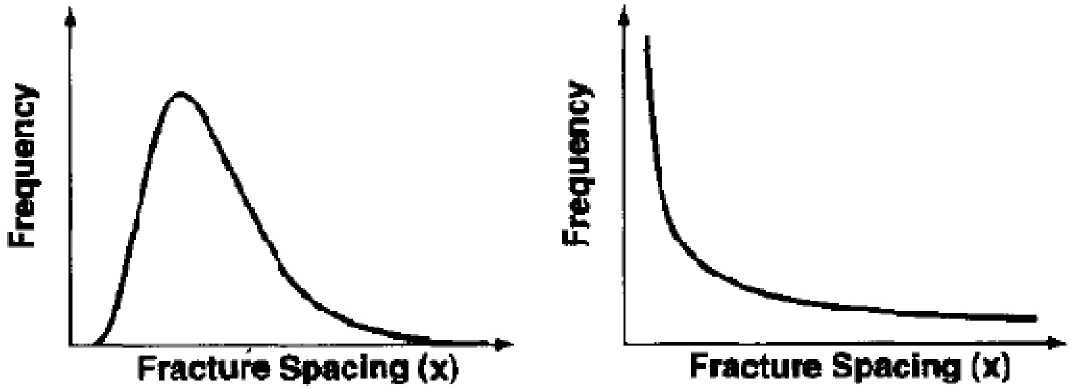


Notes: Adapted from Schoell (1983). Solid circles – Isotope data from the Cambrian-Silurian rocks of the Appalachian Basin (Laughrey and Baldassare 1998). Open circles – Isotope data from the regional aquitard including carbonates below the Cobourg. Solid diamonds – Isotope data from the seal rocks for the DGR site including the Blue Mountain and Georgian Bay Formations.

Figure 4.31: The Processes of Methane Genesis Based as Indicated by the Variation of Deuterium and ^{13}C in Natural Gases

4.8.1 Fractures in the Bruce Nuclear Site Boreholes

76 mm core was recovered from DGR boreholes INTERA (2011). Natural fracture frequency was calculated as the total number of identified natural fractures divided by the length of recoverable core. RQD (Rock quality designation) was also reported for the Bruce nuclear site core (International Society of Rock Mechanics 1977). As a general rule, RQD generally decreases as fracture frequency increases. When assessing the mechanism for the formation of natural fractures from core, the RQD is not very useful.



Notes: From Gross and Engelder (1995). Left: Log-normal distribution of vertical joints that may be characteristic of the seal rocks at the DGR site. Right: Power-law distribution of fractures with a variety of orientations that may be characteristic of the upper 200 m of rock at the Bruce nuclear site.

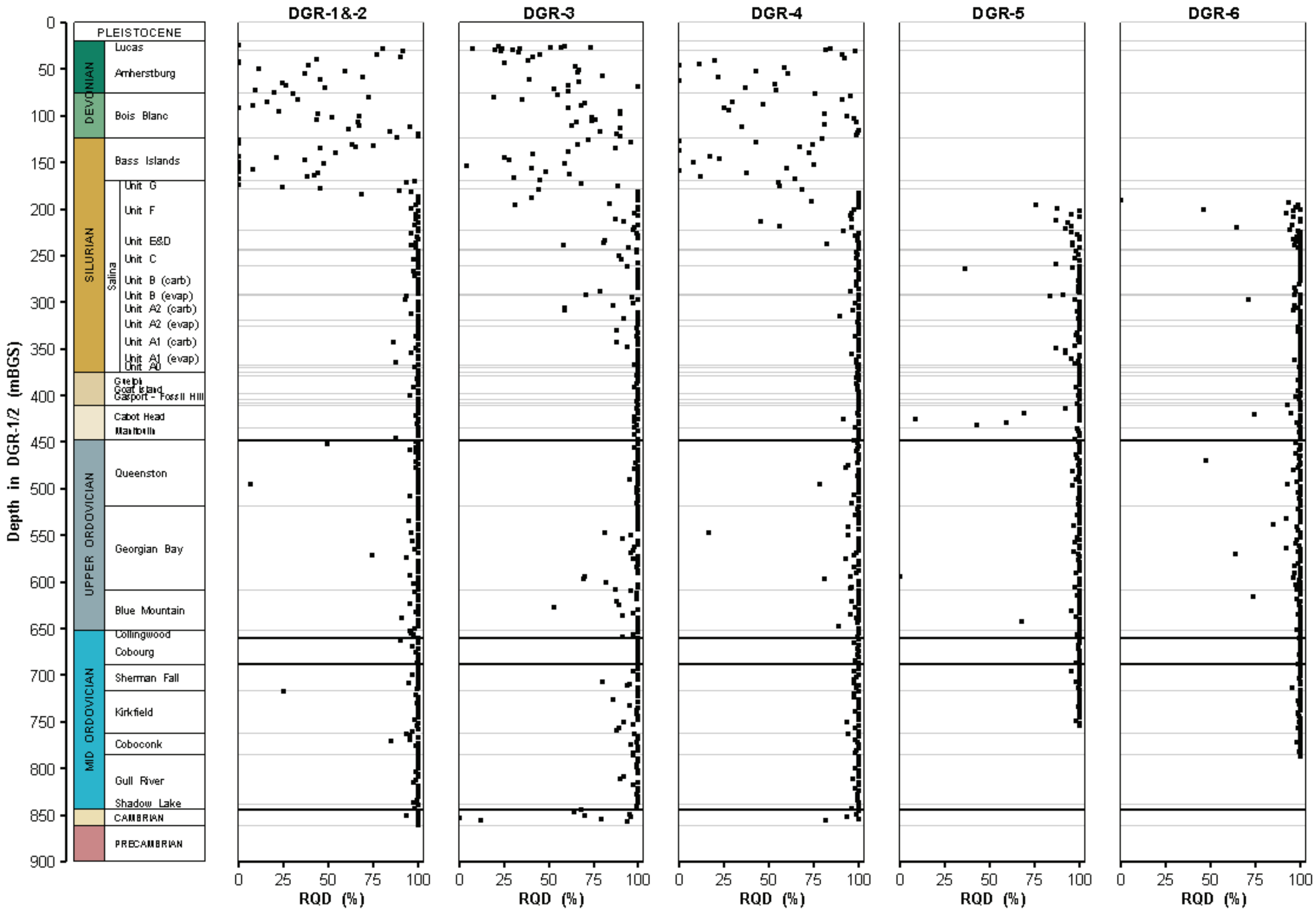
Figure 4.32: Examples of Hypothetical Fracture Distributions at the Bruce Nuclear Site

If the fractures in the seal rocks of the Bruce nuclear site are vertical joints, spacing may follow log-normal distribution typical of well developed, bedding-confined (i.e., mechanically layered) joints (Figure 4.32) (Gross 1993, Huang and Angelier 1989). The Devonian and Upper Silurian dolostones at the Bruce nuclear site are moderately to highly fractured and may follow a negative exponential or power-law trend similar to joints found in crystalline (i.e. massive, non-layered) rocks (Segall and Pollard 1983).

Bias can enter joint frequency data for a number of reasons. A vertical core is a scanline that does not return a true measure of fracture frequency unless the data are normalized for the orientation of the scanline relative to the plane of the fractures (Narr and Suppe 1991, Priest and Hudson 1976). The true spacing (s_t) is always less than the apparent spacing (s_a) according to the relationship $s_t = s_a (\cos \alpha)$ where α is the angle between the scanline and the normal to the planar discontinuities (Brady and Brown 2006). Only when $\alpha = 0$, $s_t = s_a$. In the extreme case where the scanline and the fractures are parallel, there will be no intersection and apparent joint frequency will become zero. The significance of this bias is that the seal rocks at the Bruce nuclear site may be cut by vertical joints (i.e., the log-normal distribution in Figure 4.32) that are under sampled because the core holes are subparallel to these hypothetical joints. This potential under-sampling problem was removed with the drilling of inclined boreholes (DGR-5 and DGR-6) that demonstrated that there is no significant increase in the occurrence of fractures or a decrease in RQD with depth (Figures 4.33 and 4.34).

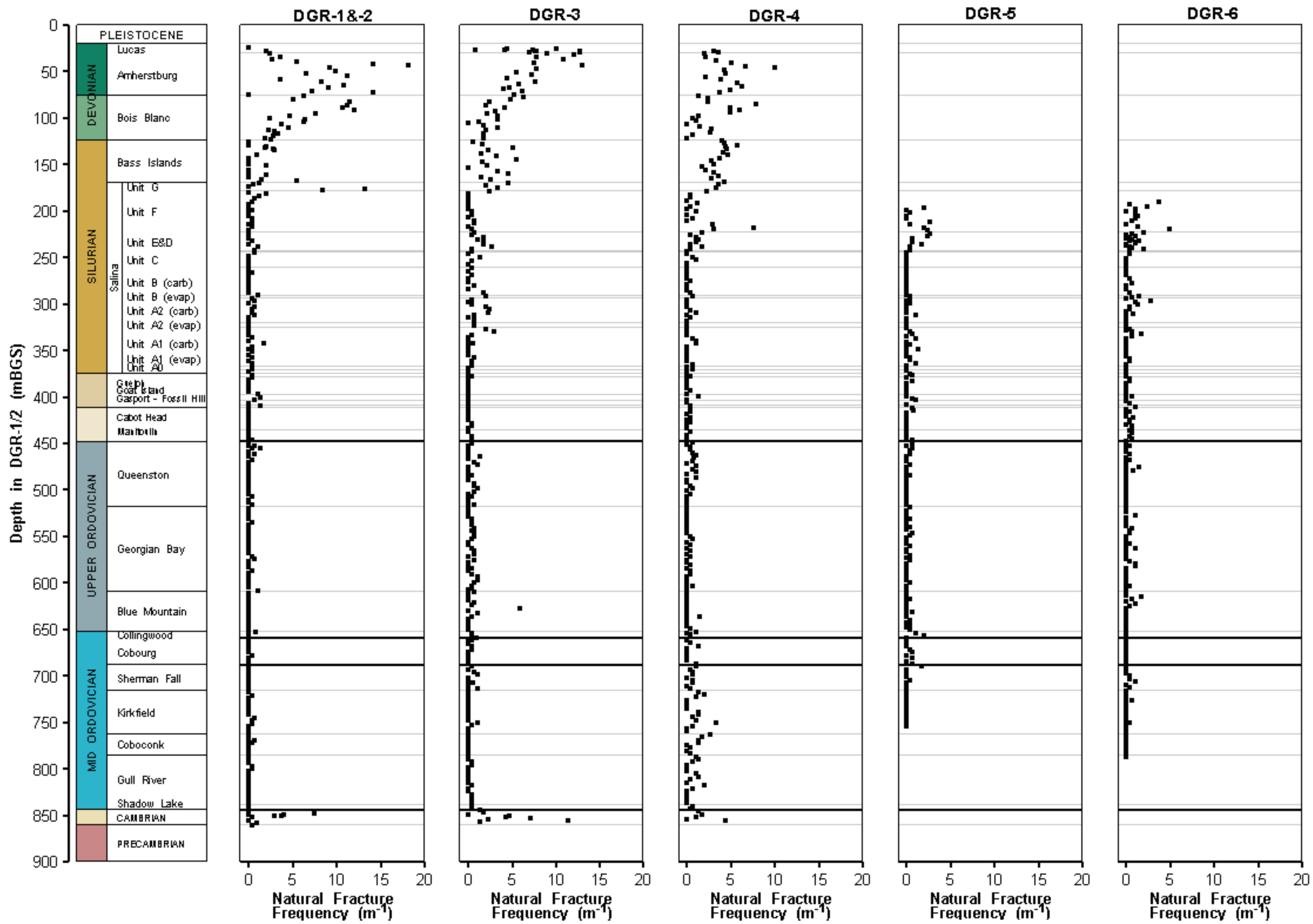
4.8.2 Maturation-related Fracture Systems

The joints of the Appalachian Plateau seal rocks are largely maturation-related (Engelder et al. 2009). Thermal maturation at Bruce nuclear site was insufficient to generate the volume of gas necessary to drive natural hydraulic fractures. Therefore, the sampling shown in Figure 4.34 may accurately represent the joint population through the Bruce nuclear site seal rocks.



Note: From INTERA (2011).

Figure 4.33: Profile of Core RQD at the Bruce Nuclear Site



Note: From Intera (2011).

Figure 4.34: Profiles of Natural Fracture Frequency for all DGR Boreholes

4.8.3 Basement-controlled Fracture Systems

Basement fracture systems consist of a regional pattern of basement discontinuities that have slipped. If the slip post-dates deposition of cover rock, the cover rock may fracture either by jointing or faulting depending on amount of fault slip. Fractures related to Laramide-type drape fold are one of example of such a fracture system where jointing may appear systematic over an area, yet are not regional (Engelder et al. 1997). Other fractures of this nature are the basement-rooted wrench faults that host gas fields in the discontinuous dolomites of the Upper Ordovician Black River Group in south-central New York (Coniglio et al. 1994, Smith 2006). In New York most Black River gas fields occur in and around elongate fault bounded lows interpreted to be negative flower structures. In many instances these wrench faults die out in the Trenton and Utica Formations suggesting that they were ceased to be active as the Taconic orogeny came to an end. This relationship has been observed in southern Ontario in the vicinity of the RSA where the youngest mapped faults are Ordovician in age (Armstrong and Carter 2010).

There are two schools on this question. One school argues that cover rock is pervasively fractured with some regions being more intensely fractured than other regions (Jacobi 2002, Sanford et al. 1985). The other school holds that, like the model of Smith (2006) for the basement-rooted wrench faults, basement faults die in the Lower Paleozoic section without affecting rocks further upsection. This is particularly likely where thick sections of Silurian evaporites separate Devonian sections from basement faulting. The pervasive fracture patterns in Devonian shales are so beautifully regular principally because post-Devonian basement-related fault slip has not overprinted these rocks for form less regular fracture patterns.

Seismic Reflection Survey Results from the Bruce nuclear site (INTERA 2011) indicated the possibility of minor faulting originating from the Precambrian basement. These appeared to be high angle faults that cut through the Cambrian-Ordovician section and disappeared in the Ordovician clastic section above the Blue Mountain Formation in the shales of the Georgian Bay Formation (Figure 4.35). The orientations of the inclined boreholes DGR-5 and DGR-6 were drilled to order to intersect the interpreted fault zones that cross seismic lines, including that shown in Figure 4.36. Results of this drilling did not indicate the presence of faults (Watts et al. 2009). Borehole triangulation of marker beds through the Ordovician section across the Bruce nuclear site footprint does not support any significant (metre scale or greater) offset in the stratigraphy (Watts et al. 2009).

Seismic line #7 (Watts et al. 2009) indicated a pair of faults that resemble a Trenton-Black River (TBR) hydrothermal structure. While the possibility exists that may be a minor transform fault, several of the characteristics of a major hydrothermal gas reservoir are missing. The most important characteristic of a TBR gas reservoir is the sag in the seismic profile such as that shown in Figure 4.37. This sag is not seen in seismic line #7 at the Bruce nuclear site. Regardless, the integrity of the seal rocks at the Bruce nuclear site will only be disrupted if faults are high permeability pathways. There is no evidence from hydraulic testing (abnormal pressures, strong hydraulic gradients) that permeable structures and conduits exist in the vicinity of the Bruce nuclear site.

4.8.4 Shallow Joints at the Bruce Nuclear Site

Neotectonic joints are exhumation-related (Hancock and Engelder 1989). As such neotectonic joints should be more common in near-surface rocks. Our understanding of exhumation-related stress is based on the following. The least compressive principal stress, σ_3, is horizontal in the lower portion of the brittle, intercontinental crust but commonly becomes vertical in the upper kilometre or two. This characteristic of the brittle crust is reflected in earthquake focal mechanism data from the eastern United States where strike-slip and normal fault mechanisms are indicative of horizontal σ_3 and thrust mechanisms are indicate vertical σ_3. Using the 58 focal mechanisms in the World Stress Map data base from the USA east of longitude 104°W, strike-slip faulting is the most prominent mechanism at depths greater than 8 km whereas thrust faulting is most the prominent mechanism at depths less than 8 km (Figure 4.38). In particular, thrust and thrust-strike-slip mechanisms constitute 90% of all data in the top 2 km east of the Rocky Mountain Front. These focal mechanism data come from a region of North America where the maximum horizontal compressive stress, S_H, is uniformly ENE.

The vertical pattern of focal mechanisms is akin to an interchange of the orientation of principal stress axes, σ_3 and σ_2, rather than a stress rotation. The least compressive principal stress, σ_3, is horizontal in the lower portion of the brittle, intracontinental crust but commonly becomes vertical in the upper kilometre or two.

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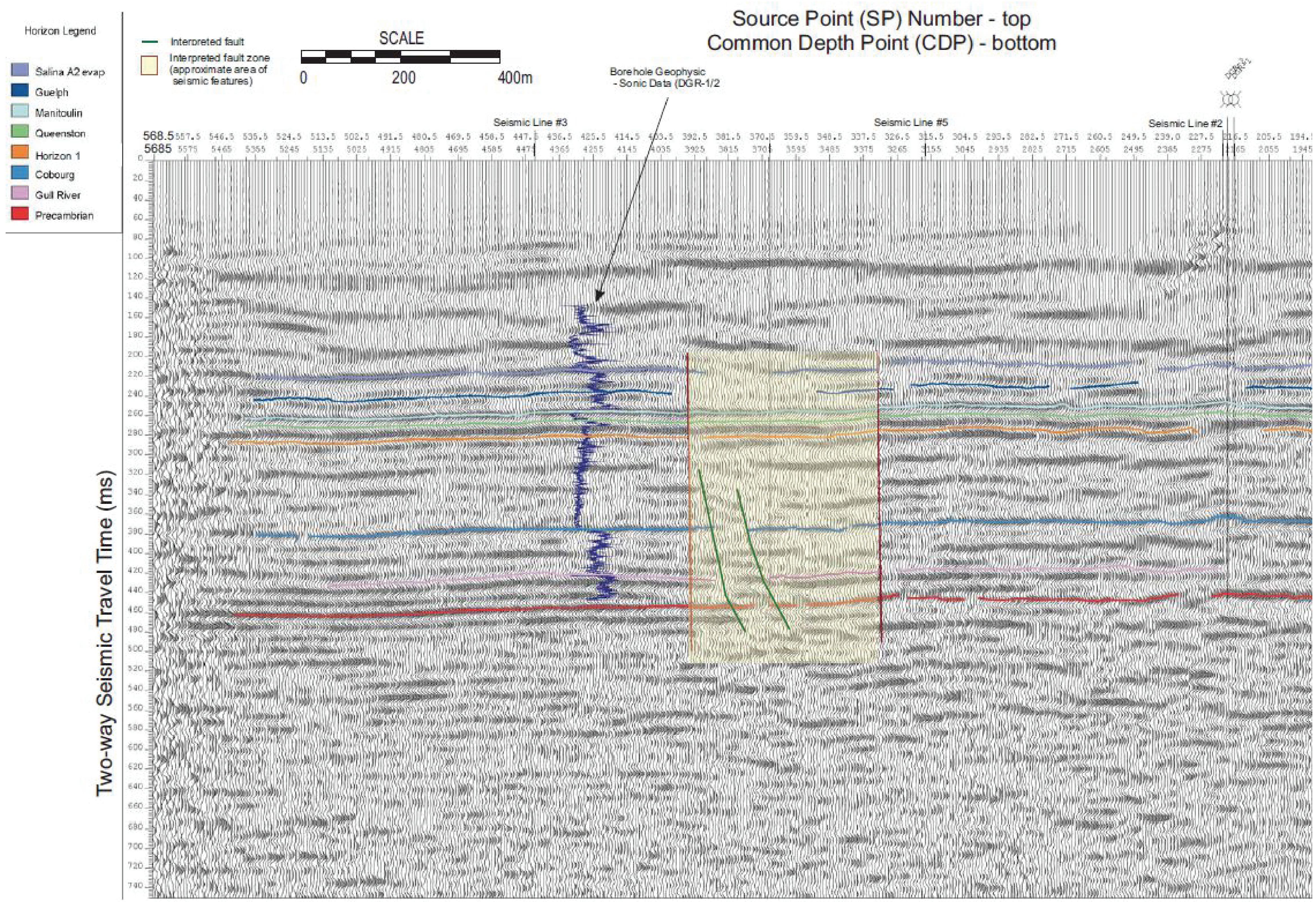
The pattern of stress reflected in earthquakes within the stable North American platform is even clearer in global compilations of stress measurements showing an upwardly increasing ratio, R, of least horizontal to vertical stress ($R = S_h/S_v$ with compressive stress positive) through the top 2 km of the crust (Brown and Hoek 1978). R continues to increase upward and becomes extreme within the zone of thermally and topographically induced compressive stress in the top few meters of the crust (Martel 2006, Sbar et al. 1984). An upwardly increasing R is characteristic of sedimentary basins including regions of normal faulting (Plumb 1994). At the western end of the Bohemian massif, Germany, the interchange of the orientation of principal stresses (i.e., σ_2 and σ_3) takes place in crystalline basement, thus indicating that the causal mechanism for the interchange is not an artefact of sedimentary rocks (Brudy et al. 1997). Looking downward into the crust, the trend of $R < 1$ continues into crystalline basement to depths of at least 8.6 km, the deepest in situ stress measurement to date (Brudy et al. 1997, Lund and Zoback 1999). The same trend carries downward through a combination of sedimentary cover over crystalline basement as seen in the Great Lakes region of North America (Haimson and Doe 1983). A stress profile showing R as a function of depth is referred to as the *Brown-Hoek stress profile* (BHSP), (Figure 4.38).



Note: From INTERA (2011).

Figure 4.35: Processed and Interpreted Bedrock Stratigraphy and Structure for Seismic Line #1 at the Bruce Nuclear Site

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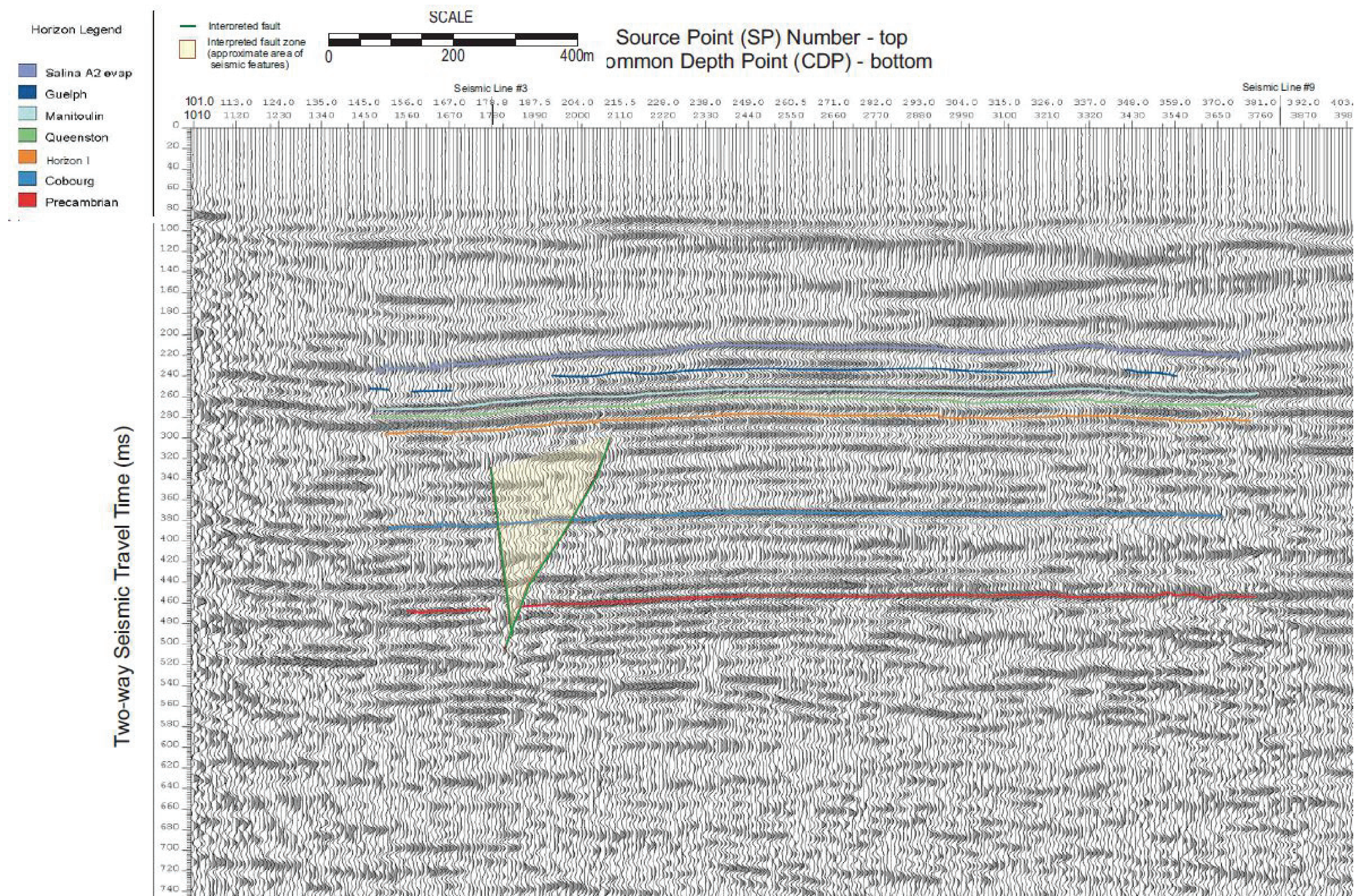

Note: From Watts et al. (2009).

Figure 4.36: Processed and Interpreted Bedrock Stratigraphy and Structure for Seismic Line #7 at the Bruce Nuclear Site

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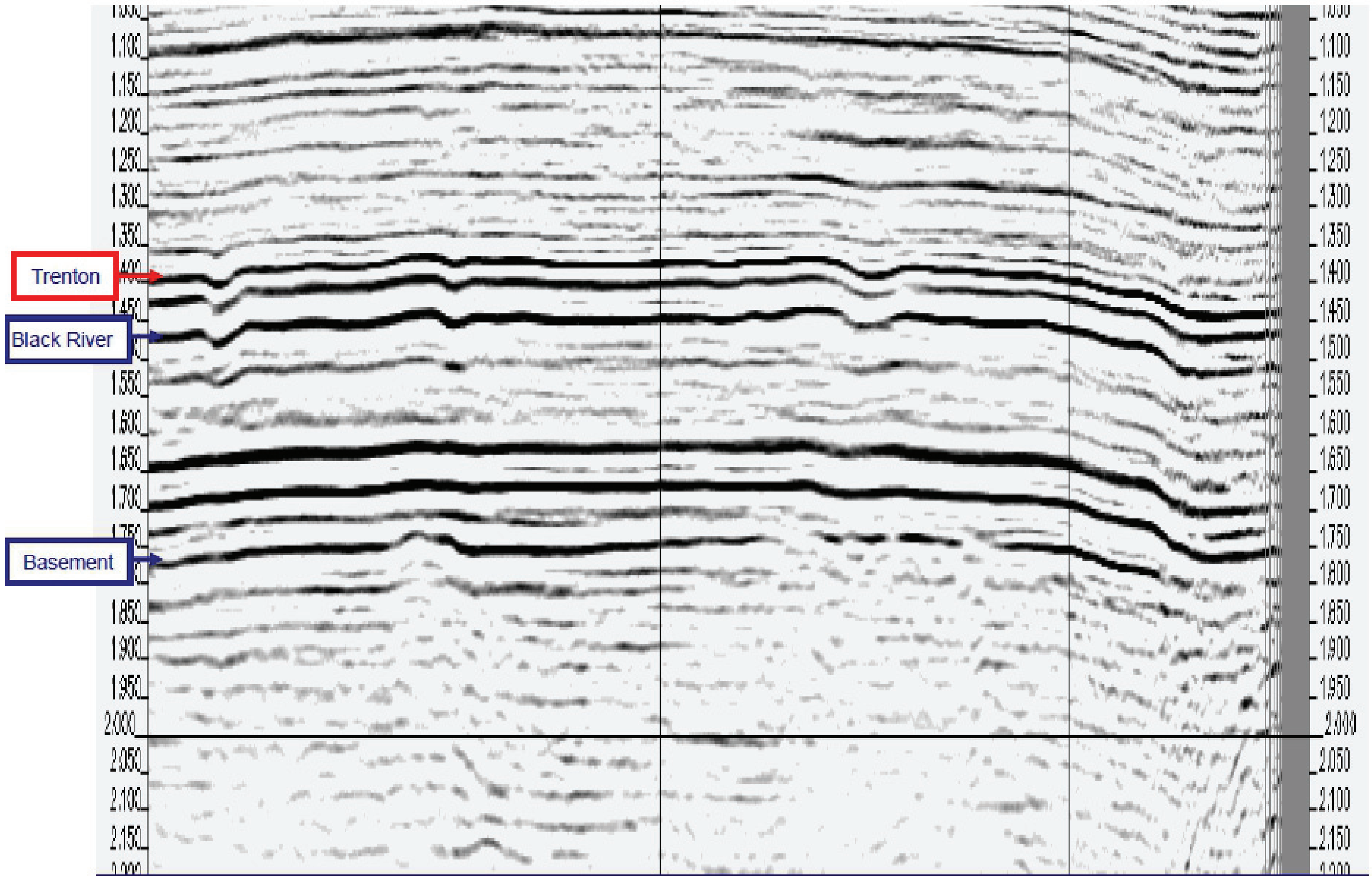
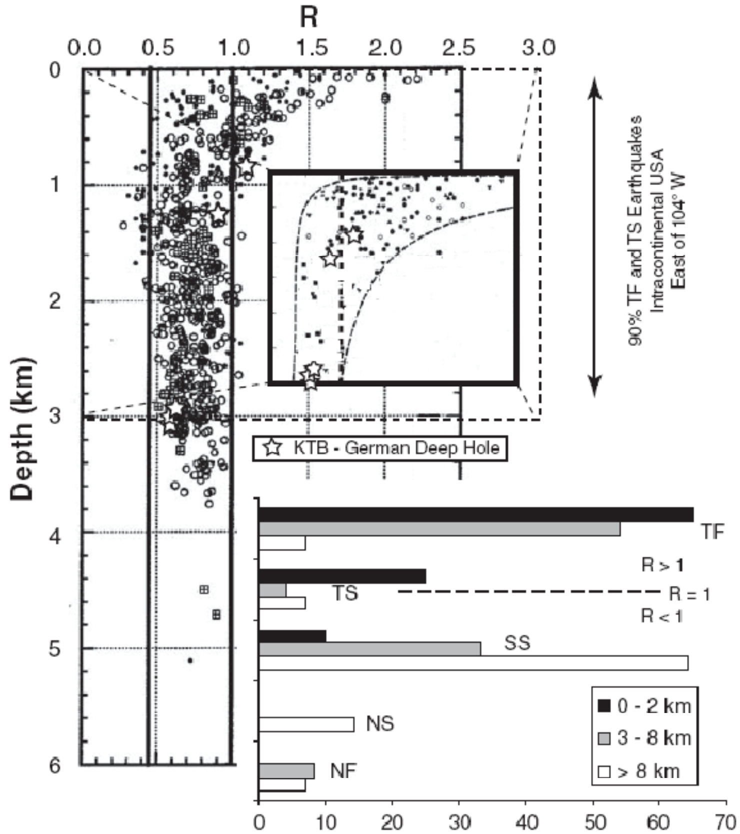


Notes: Gas play showing sags in Ordovician carbonates that are stratigraphically equivalent to the host carbonates of the Bruce nuclear site. After Smith and Nyahay (2005).

Figure 4.37: Seismic Line From New York State Displaying Trenton-Black River Stratigraphy



Notes: Adapted from Plumb (1994). Upper inset is an earlier BHSP including data from both crystalline and sedimentary rocks to a depth of 3 km where dashed line indicates R = 1 (adapted from Brown and Hoek 1978). Lower inset shows a compilation of all 58 focal mechanisms from the United States east of longitude 104° (taken from the World Stress Map data base). Data divided into three tiers as indicated. TF – thrust fault mechanisms (R > 1), TS – thrust-strike slip mechanisms (R ≈ 1), SS – strike slip mechanisms (R < 1), NS – normal-strike slip mechanisms (R < 1), NF – normal fault mechanisms (R < 1).

Figure 4.38: A Brown-Hoek Stress Profile to a Depth of 6 km in Sedimentary Basins

Total stress in the crust reflects a superposition of components, some of which may be eliminated in searching for the mechanism responsible for the BHSP. First, vertical stress ($S_v = g\rho_{ob}z$), a function of integrated overburden density, ρ_{ob}, gravity, g, and depth, z, is nearly linear with depth in the upper crust except in the near surface in regions of topographic relief where horizontal compressive stress is high (Martel 2006, Miller and Dunne 1996). Because the upward increase in R starts below depths affected by topographic relief, the BHSP must reflect a mechanism that carries horizontal compressive stress, S_h, into the top 2 km of the crust. The limits of horizontal stress in the upper crust are governed by frictional strength along fault zones (Byerlee 1978). Such strength along normal and thrust faults provides lower and upper bounds for the BHSP in an actively deforming Earth (Zoback and Townend 2001). However, frictional strength is overburden dependent and linear with depth and thus does not offer a mechanism for the interchange of the orientation of σ_2 and σ_3 in the outer crust (Brace and Kohlstedt 1980).

While stress measurements within some Plio-Pleistocene sedimentary basins come from rocks that are being buried for the first time and, hence, still subject to consolidation

(Karig and Hou 1992), the majority of stress measurements come from either crystalline rocks (Herget 1993) or sedimentary rocks where lithification terminates consolidation (Plumb 1994). Many of these older rocks are partially unloaded as a consequence of exhumation as is the case for the western end of the Bohemian massif and the larger North America platform. Unloading takes place with the removal of overburden and its concomitant decrease in vertical stress. The BHSP tells us that partial or complete exhumation modifies S_h in such a way that it is a condition necessary for an interchange of the orientation of σ_2 and σ_3 when rocks have passed to within 2 km of the surface. The guiding axiom of this report is that such an interchange of σ_2 and σ_3 is the manifestation of thermoelastic relaxation as rocks are gradually exhumed (Haxby and Turcotte 1976, Price 1966; Voight and St. Pierre 1974).

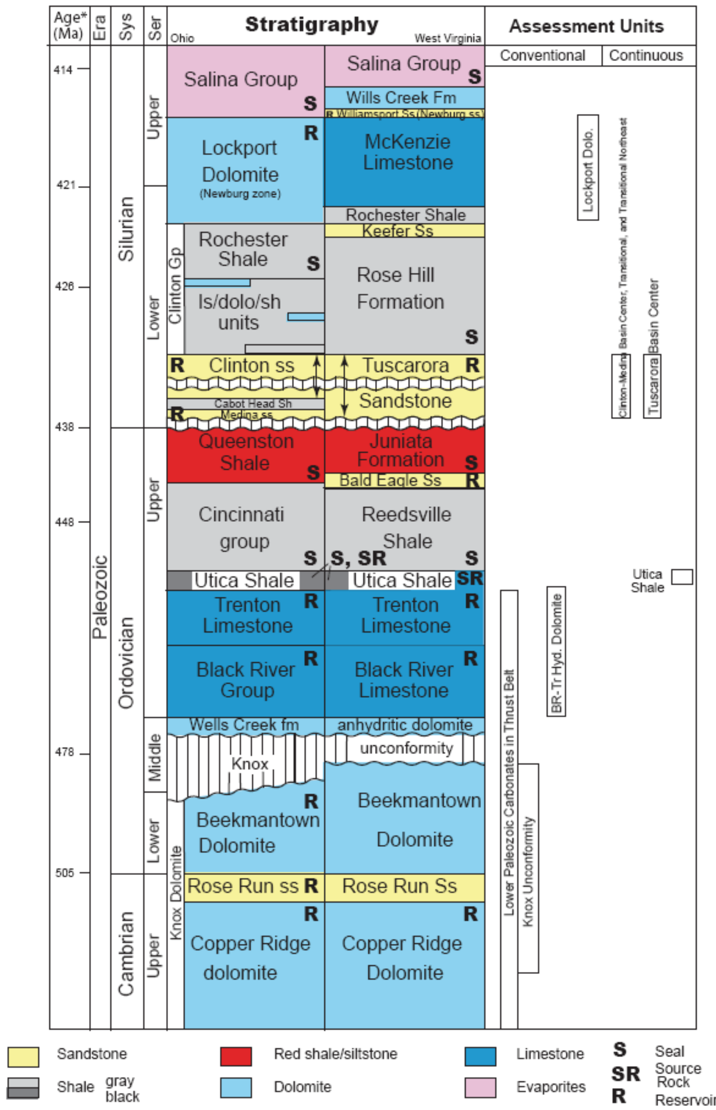
According to the BHSP, joint frequency should decrease with depth. This is seen the Bruce nuclear site core holes. Joint frequency is highest within 100 m of the surface at the Bruce nuclear site (Figure 4.33). It is reasonable to presume that these are exhumation-related neotectonic joints. In a stress field controlled by the BHSP, stress favours the propagation of joints that are subhorizontal or horizontal. These are going to be sampled with greater frequency in vertical core holes which is consistent with the in situ data. Sampling at the depth of the Bruce nuclear site confirms that neotectonic joints are less likely (INTERA 2011).

Detailed fracture mapping and neotectonic studies from the Bruce nuclear site indicate that the Bruce nuclear site is located in a tectonically stable zone with no active fault zones (Slattery 2011, Cruden 2011).

4.9 The Seal at the Bruce Nuclear Site

Within the greater A-OSS, the major seal rocks of the Utica-Lower Paleozoic TPS include the Utica Shale which acts as the source rock, seal and reservoir rock for unconventional gas (Figure 4.39). At the Bruce nuclear site, the equivalent rocks are the shales of the Blue Mountain-Georgian Bay sequence of HS#5 (Figure 1.1). Ideally, a repository should consist of a pressure compartment with seals on all sides (Figure 2.3). At the Bruce nuclear site the repository rocks of the Cobourg Formation are situated within a pressure compartment as indicated by freshwater head tests showing underpressuring. In fact, if the pressure gradient of the Bruce nuclear site is compared with that expected for an underpressured compartment, the interior of the compartment might extend from the Kirkfield Formation up through to the top of the Queenston Formation as indicated by a hydrostatic fresh water gradient (Figure 1.2). It may be said with some certainty that the Blue Mountain-Georgian Bay sequence has a low enough permeability to serve as a seal to whatever mechanism served to cause underpressuring in this interval.

The mechanism by which the seal rocks at the Bruce nuclear site became underpressured is uncertain at present. It is known that underpressuring occurs in relatively shallow (0.3-0.6 km) permeable rocks that are frequently isolated within, or interbedded with, low-permeability mudrock sections (Dickey and Cox 1977). Devonian gas fields of the southern half of the Central Appalachian Plateau are known to be underpressured (Russell 1972). There is clear evidence that underpressured rocks are partially exhumed (Bachu and Underschultz 1995). One of the popular explanations for underpressuring is dilation of mudrock with concomitant increase in pore volume during partial exhumation (Luo and Vasseur 1992, Neuzil and Pollack 1983). At least to a first approximation, underpressuring in the seal rocks at the Bruce nuclear site bodes well for the performance of the repository over a long time.



Notes: Adapted from Ryder (2008). This time scale does not follow the new time scale of (Gradstein et al. 2004).

Figure 4.39: A Correlation Chart for the Utica-Lower Paleozoic Total Petroleum System within the A-OSS

4.10 Self-Sealing Of Joints

There are two general mechanisms for self-sealing of joints: mineral filling and clay swelling, softening and re-arrangements. The former is common to veins (Engelder 1987, Fisher and Brantley 1992). The latter is common to fault zones (Knipe 1997). Often when faults seal, it is a consequence of clay or shale being dragged along the fault plane although faults cutting argillaceous rocks may immediately return to the permeability of the host material (Horseman 2001).

The presence of joints in overpressured gas shales could mean two things. First, it is fair to suggest that gas generation exceeds the shale's ability to expel the gas through the matrix of the rock. If leakage is along joints, the joints posses a permeability that is still relatively low although probably not that of the matrix. There remains the possibility the joints in shale, particularly organic-rich black shales seal to the extent that the rock behaves much like a stratigraphic seal without joints. Based on the site investigations, the Georgian Bay/Blue Mountain and perhaps Queenston formations at the Bruce nuclear site possess this property.

4.10.1 Fault-seal in Argillaceous Rocks

The literature contains many examples of fault-seal that are largely based on a shale-gouge ratio and the juxtaposition of shale against reservoir rocks (Knipe 1997). Minor faults and fractures that may exist in the vicinity of the Bruce nuclear site, and are cut up into seal rock of the Blue Mountain-Georgian Bay sequence, are presumably effectively sealed by the clay content found within the shale.

5. SUMMARY OF THE FOUR TASKS

Task I: Examine the structure of Ordovician hydrocarbon reservoirs and sealing mechanisms throughout Michigan and Appalachian basins in order to build a natural analog case for the Ordovician cap rock integrity at the Bruce nuclear site.

The Ordovician hydrocarbon reservoirs in the Appalachian and Michigan Basin are either unconventional black shales of the Utica Formation or confined hydrothermally-altered dolomite reservoirs within the Trenton-Black River sequence. The presence of gas in the Trenton-Black River fields of both the Michigan Basin and in New York area of the Appalachian Basin suggests that Ordovician shales including the Utica black shale were of sufficient seal quality to trap gas for long-term exploitation. While the overlying shale section at the Bruce nuclear site (the Blue Mountain-Georgian Bay sequence) is thinner than in the Appalachian Basin, there is little reason to doubt that the same ‘Utica’ seal at the Bruce nuclear site is viable. In fact, black shales in the northern Appalachian Basin are known to be overpressured, a characteristic of long-term integrity. The seal rock at the Bruce nuclear site is underpressured, while this means that a one-for-one analog between the seal rocks at the Bruce nuclear site and the overpressured gas shales of the Appalachian Basin is not possible to build, they share similar lithological characteristics. The principal characteristic is that in both cases, the shale section is reasonably thick and of sufficiently low permeability to allow an extrapolation between the shale of the Appalachian Basin and that of the Bruce nuclear site.

Task II: Analyze of structural styles of reservoir faulting and the mechanisms and nature of fault propagation into overlying Ordovician Shales.

Joints are considered the most likely brittle structure to disrupt seal integrity of a shale seal largely because of the extent to which they pervade black shale source rocks. Joints in black shales are natural hydraulic fractures driven by overpressured natural gas. This mechanism requires a degree of thermal maturation that is not found at the Bruce nuclear site. Hence, it comes as no surprise that joints in the seal rock are uncommon since the seal rock is situated below the depth at which neotectonic joints form.

Task III: Investigate the occurrence of shale gas within the Michigan and Appalachian basins to constrain the potential for commercial shale gas within the Ordovician Shales in the Bruce area of Ontario.

The likelihood of commercial shale gas at the Bruce nuclear site is low for two reasons. First, the TOC peaks in the darkest shale at ~2.5% and in general is <1% at the Bruce nuclear site. When this observation is combined with the low thermal maturity around the Bruce Peninsula, there is little chance of encountering petroleum or natural gas that is generated in situ. There is, however, some small chance that migration has allowed small accumulations in the vicinity of the Bruce Peninsula. Industry-related drilling and the Bruce nuclear site boreholes have shown there is no evidence for commercial occurrences of gas at the Bruce nuclear site.

Task IV: Utilize data from the DGR drilling program, which includes porosity and permeability data, TOC measurements, pore pressure data and pore fluid compositions for assessment of Ordovician shales in the RSA as a potential commercial source of unconventional hydrocarbons.

Each of these source rock characteristics (porosity data, TOC measurements, pore pressure data and pore fluid compositions) were examined in detail in this report. The combination of these source rock characteristics will not yield a rich unconventional gas play in the seal rocks of the Bruce nuclear site. The major reason is not a failure of one of these characteristics so much as it is the lack of thermal maturation that leads to low prospects for commercial gas in the seal rocks of the Bruce nuclear site.

6. CONCLUSIONS

The assignment in this report was to answer the question, “Do gas shales from known petroleum systems in the Appalachian and Michigan Basins provide a natural analogue for the long-term behaviour of the seal at the Bruce nuclear site”.

An analog to the seal rock at the Bruce nuclear site is made possible because the rocks correlate with Upper Ordovician sequences across the Appalachian and Michigan Basins. The seal rock at the Bruce nuclear site is the Blue Mountain and Georgian Bay Formations, which correlate with a number of formations that include the Utica (MI, NY, PA), Antes (PA), Pleasant Point (OH), Reedsville (PA), and Martinsburg (PA) Formations.

The tecto-stratigraphic event leading to the deposition of the seal rock at the Bruce nuclear site was the Taconic orogeny. This continental collision and associated subduction zone loaded the southeastern margin of Laurentia, starting in Blackriverian time (455 Ma) in the Michigan Basin and continuing for much of the rest of the Middle and Upper Ordovician. Lithospheric bending through subduction of the edge of Laurentia depressed the Laurentian lithosphere to create the accommodation space, which was subsequently filled by a clastic section that regionally comprises the Utica (Blue Mountain) to Queenston Formations. The Collingwood-Blue Mountain contact in Ontario is Maysvillian (447 Ma) and thus the deposition of the seal rock at the Bruce nuclear site trailed the formation of the Utica Trough by as much as 6 Ma. The seal rock at the Bruce nuclear site contains a much higher proportion of clay than its counterpart in the Utica Trough to the east. The higher clay content of the seal rock at the Bruce nuclear site may increase the ability of the rock to promote the self-sealing of joints and fractures. Starting in Kirkfieldian (Mohawkian) time, the downflexing was rapid enough that a starved section was created in which significant volumes of organic carbon were preserved. A starved section is characteristic of a transgressive systems tract (TST) indicating a rapid eustatic sea level rise that can be amplified by a tectonically induced (i.e., non-eustatic) sea level rise.

The Devonian section of the Appalachian Basin contains two black shales (Marcellus and Geneseo), which like the Ordovician sequence at the Bruce nuclear site were the product of a tectonically-induced sea level rise and therefore share the same mechanism for the generation of accommodation space. The basal portion of the Marcellus contains total organic content (TOC) > 12% making it much richer than the seal rock at the Bruce nuclear site. However, to the east of the Bruce nuclear site the underlying formation, the Collingwood, does have TOC > 10%, while the Collingwood at the Bruce nuclear site displays a maximum TOC of 2.5%, in a thin horizon close to the top of the formation. The basal portion of the Blue Mountain formation displays a peak TOC of <1.5%. By comparison, the Utica formation in the Appalachian Basin displays TOC in the range of 3% to 5% with a peak TOC of 5-6% in the starved section of the Utica Trough. The Blue Mountain Formation at the Bruce nuclear site contains on average less than 1.5% TOC and is not rich enough in organic matter to be considered a black shale. Thermal maturity of the Utica black shale in the Utica Trough reached a thermal maturity comparable to the dry gas window (CAI = 5 or $\%R_o = 3$) if not above. The seal rock at the Bruce nuclear site barely reached the oil window ($0.4 > \%R_o > 0.6$). This difference has strong implications for the presence of maturation-related jointing, with the Utica Trough pervaded by such joints and the Bruce nuclear site seal rock unlikely to be affected by such joints. This lack of maturation at the Bruce nuclear site is a consequence of subsidence (burial) that reached a total depth of approximately 1.5 km and likely no more than 2 km.

Lithologically, both the Marcellus and Blue Mountain shales display elevated TOC at their bases and both overly a phosphatic lag, indicating the onset of a starved clastic sequence and influx of organic material. The Geneseo and Utica shales both display electric log properties showing relatively modest gamma ray anomalies, while carrying signatures characteristic of low density black shales. These same electric log properties are also shared by the Blue Mountain Formation in Ontario.

A good seal rock is capable of maintaining a gas-pressure differential against hydrostatic (pressure in a free column of water) for significant lengths of time. The Appalachian Basin has gas traps below the Marcellus that reach more than 70% of the overburden stress. The Marcellus black shale is also overpressured throughout the northern Appalachian Basin, leaving no doubt about its effectiveness as a seal. In the southern portion of the Appalachian Basin gas shales are underpressured, as is the seal rock at the Bruce nuclear site. Gas generation leads to extensive and pervasive natural hydraulic fracturing (NHF).

The lack of hydrocarbons, maturation related fracturing, high clay content and the existence of underpressured compartments at the Bruce nuclear site demonstrate that when compared to a series of lithologically and stratigraphically similar analogues from the Appalachian and Michigan Basins, the Upper Ordovician cap rock at the Bruce nuclear site has maintained long-term integrity over geological time periods.

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8. ABBREVIATIONS AND ACRONYMS

A-OSS	Appalachian-Ouachita Stratigraphic System (includes rocks of the Michigan and Illinois Basins on the cratonward side of the Nashville Dome to Cincinnati to Findlay Arch to Algonquin Arch crustal upfold)
CAI	Conodont (color) Alteration Index
Cap rock	The 241 m of Upper Ordovician to Lower Silurian aquitards and aquicludes at the DGR site
DGR	Deep Geologic Repository
HS Unit	Hydrostratigraphic Unit
K_h	Horizontal hydraulic conductivity
NHF	Natural Hydraulic Fractures
OPG	Ontario Power Generation
$\%R_o$	A measure of vitrinite reflectance
RQD	Rock Quality Designation, as specified by the ISRM (International Society of Rock Mechanics, 1977)
S_2	mg HC/g generated by cracking kerogen between 350°C and 550°C
Seal rocks	The Georgian Bay-Blue Mountain-Collingwood stratigraphic package at DGR
σ_3	Tensile effective least principal stress where compressive stress is positive and $\sigma_1 > \sigma_2 > \sigma_3$
TAI	Thermal Alteration Index
T_{max}	Temperature maximum of S_2
TOC	Total Organic Carbon
TPS	Total Petroleum System
TST	Transgressive Systems Tract