NUCLEAR WASTE MANAGEMENT ORGANIZATION
SOCIÉTÉ DE GESTION DES DÉCHETS NUCLÉAIRES

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NWMO BACKGROUND PAPERS
6. TECHNICAL METHODS

6-12 LONG-TERM USED NUCLEAR FUEL WASTE MANAGEMENT - GEOSCIENTIFIC REVIEW OF THE SEDIMENTARY SEQUENCE IN SOUTHERN ONTARIO

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NWMO Background Papers

NWMO has commissioned a series of background papers which present concepts and contextual information about the state of our knowledge on important topics related to the management of radioactive waste. The intent of these background papers is to provide input to defining possible approaches for the long-term management of used nuclear fuel and to contribute to an informed dialogue with the public and other stakeholders. The papers currently available are posted on NWMO's web site. Additional papers may be commissioned.

The topics of the background papers can be classified under the following broad headings:

1. **Guiding Concepts** – describe key concepts which can help guide an informed dialogue with the public and other stakeholders on the topic of radioactive waste management. They include perspectives on risk, security, the precautionary approach, adaptive management, traditional knowledge and sustainable development.
2. **Social and Ethical Dimensions** - provide perspectives on the social and ethical dimensions of radioactive waste management. They include background papers prepared for roundtable discussions.
3. **Health and Safety** – provide information on the status of relevant research, technologies, standards and procedures to reduce radiation and security risk associated with radioactive waste management.
4. **Science and Environment** – provide information on the current status of relevant research on ecosystem processes and environmental management issues. They include descriptions of the current efforts, as well as the status of research into our understanding of the biosphere and geosphere.
5. **Economic Factors** - provide insight into the economic factors and financial requirements for the long-term management of used nuclear fuel.
6. **Technical Methods** - provide general descriptions of the three methods for the long-term management of used nuclear fuel as defined in the NFWA, as well as other possible methods and related system requirements.
7. **Institutions and Governance** - outline the current relevant legal, administrative and institutional requirements that may be applicable to the long-term management of spent nuclear fuel in Canada, including legislation, regulations, guidelines, protocols, directives, policies and procedures of various jurisdictions.

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LONG-TERM USED NUCLEAR FUEL WASTE MANAGEMENT - GEOSCIENTIFIC REVIEW OF THE SEDIMENTARY SEQUENCE IN SOUTHERN ONTARIO

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EXECUTIVE SUMMARY

A geoscientific assessment examining the suitability of the Paleozoic sedimentary rock occurring beneath southern Ontario to host a Deep Geologic Repository (DGR) for used nuclear fuel is described. The assessment involved a review of international radioactive waste management programmes in sedimentary media and a compilation of existing and publicly available geoscientific information for southern Ontario. A geosynthesis of this latter information was used to evaluate the suitability of the bedrock formations within this sedimentary sequence in the light of international experience. A structured approach consistent with international practice was undertaken to assess multiple and independent lines of reasoning regarding isolation properties, long-term stability of the flow system and geotechnical aspects. Middle to Upper Ordovician shales and limestones in southern Ontario were identified as potential host units.

Internationally, considerable experience with understanding the suitability of sedimentary media for radioactive waste management purposes has been gained over the last decade. Radioactive waste management programmes in Switzerland (Nagra), France (Andra), Belgium (Ondraf/Niras), Spain (Enresa) and Japan (JNC) have focussed on argillaceous media, which collectively refers to clay-rich sedimentary rock in various stages of induration (clays, shales). Safety Cases or comparable milestones targeted at deep geological disposal have recently been completed by Nagra, Andra and Ondraf/Niras. The development of these Safety Cases was supported by well established collaborative research programmes at the Mont Terri (Switzerland), Mol/Dessel (Belgium) and Bure (France) Underground Research Laboratories. The key safety related attributes of argillaceous media include:

- the horizontally bedded and weakly deformed units in sedimentary sequences are geometrically simple and straight-forward to conceptualise;
- the target formations are sufficiently homogeneous, which enhances predictability;
- the formations possess very low permeabilities, thus mass transport is likely diffusion dominated;
- transport through the pore space is very slow, and sorption on clay minerals retards the migration of many dissolved species;
- the formations possess an ability to self-seal fractures and faults;
- multiple lines of geoscientific evidence indicate the geosphere is robust to long-term perturbations on geologic time scales (*i.e.* erosion, glaciation, permafrost); and
- the formations provide sufficient geomechanical stability for safe repository construction and operation.

Salt formations also have favourable characteristics for long-term radioactive waste management as demonstrated at the Waste Isolation Pilot Plant in New Mexico, United States (licensed in 1999) and the German programmes at Gorleben and Morsleben. It is evident that sedimentary formations possess significant advantages for long-term waste management and Safety Case development and have become the preferred media where geologic settings permit.

Southern Ontario is underlain by a sedimentary 'layer cake' comprised of Paleozoic formations of Cambrian to Devonian (543 - 354 Ma) age. The near horizontally bedded and only weakly deformed sequence consists of shales, limestones, dolomites, sandstones and evaporites (salt, gypsum/anhydrite). These sedimentary rocks occur geologically within the Michigan and

Appalachian sedimentary basins and attain a maximum thickness of ca. 1500 m. Background geoscientific information with which to establish the geologic setting for the purpose of the assessment was assembled primarily through scientific literature and other public domain sources. A synthesis of this information permitted characterisation of the bedrock lithology, stratigraphy, structure, diagenesis/basin evolution, physical and chemical hydrogeology, stress regime, seismology, resource potential and geomechanical attributes.

Based on this synthesis, an initial assessment of formation suitability was completed using four simple criteria: i) existence of low hydraulic conductivity rock mass; ii) sufficient formation depth below ground surface (=200 m); iii) sufficient formation thickness (=100 m); iv) simple geometry (*i.e.* internal homogeneity, lateral continuity). In applying these criteria, suitable bedrock formations were identified as the Middle/Upper Ordovician age (ca. 470 - 443 Ma) shales (Blue Mountain, Georgian Bay and Queenston Formations) and underlying limestones (Simcoe Group, *i.e.* the Gull River, Bobcaygeon, Verulam and Lindsay Formations). These formations are laterally continuous throughout large regions of southern Ontario. A further more detailed assessment of these Ordovician sedimentary rocks was undertaken using an internationally accepted framework developed through the NEA Features, Events and Processes Catalogue for Argillaceous Rocks (FEPCAT). This assessment further supported the initial results.

Specific lines of geoscientific reasoning supporting the conclusions drawn in the report include:

- The thickness of the Ordovician shales and limestones well exceeds 100 m, a value internationally regarded as a siting preference;
- The degree of vertical and horizontal heterogeneity of geological and hydrogeological attributes in the potential host formations is limited and reasonably well known;
- Hydrochemical evidence indicates very long underground residence times of formation waters and no resolvable cross-formational flow at depth over geological periods of time;
- A surficial fresh-water flow system is underlain by a stagnant hydrogeological regime. Given the absence of exfiltration areas for deep ground waters, flow does not occur or is very limited. Solute transport is probably dominated by diffusion;
- Deep infiltration of surficial waters is unlikely due to the high density of brines occurring in the deep underground and due to the presence of several low-permeability formations, such as shales or evaporites, that confine the more permeable units; and
- Tunnelling in deeply buried shales and limestones appears to be feasible in spite of high horizontal stresses.

Based on current knowledge, there are a multitude of independent arguments suggesting that Ordovician shales and limestones occurring beneath southern Ontario provide a highly suitable environment to host a deep geological repository for spent fuel. There is no evidence that would *a priori* seriously question the feasibility and long-term safety functionality. From a geoscientific perspective, the chance of success to complete a convincing safety case is substantial. One very positive aspect is the potential for using multiple lines of evidence (*e.g.* predictive flow/transport modelling *vs*. hydrochemical evidence *vs*. understanding of the hydrogeological system) to strengthen the safety case.

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1. INTRODUCTION

1.1 FRAMEWORK AND SCOPE

Within the last decade, international geoscientific research of sedimentary rock formations has improved the technical basis with which to understand and evaluate the suitability of such settings for long-term nuclear used fuel management. This research has provided the rationale for continued study of argillaceous rocks (*i.e.* clays and shales) within the Belgian, French, Swiss, Spanish and Japanese radioactive waste management programmes. Within these programmes, particularly the former three, a significant reliance is placed on the geosphere for long-term confinement and isolation. Based on site-specific geologic settings such programmes have cited formation stability at geologic time scales (1 million years [Ma] and more), formation homogeneity and predictability, favourable confinement characteristics and insensitivity to geologic perturbations as strong evidence for pursuing national studies in argillaceous media.

The Canadian Nuclear Waste Management Organisation is investigating approaches for long-term management of nuclear fuel waste. One approach is the Deep Geologic Repository (DGR) concept where nuclear used fuel would be sealed within self-supporting, corrosion resistant canisters emplaced in an engineered repository excavated to depths of 500 to 1000 m in the plutonic rock of the Canadian Shield (CTECH, 2002). From a geologic perspective, the Canadian Shield sub-crops approximately 625,000 km^2 of Ontario and in its entirety forms one of the largest stable Archean cratons in the world. Another approach is a Deep Geological Repository in alternative geologic media, such as shales, carbonates or evaporites.

This peer-reviewed background document examines the geoscientific basis to assess the potential of Paleozoic sedimentary rocks in southern Ontario[1], specifically those within the Michigan and Appalachian Basins, as host media for a nuclear used fuel repository. The assessment considers geoscientific attributes, characteristics and/or properties in the context of potential suitability for long-term waste form isolation. The study area and regional tectonic framework for the investigation are shown in Figure 1-1. The assessment is founded on a thorough and rigorous review of geoscientific literature available in the public domain, as referenced within this document.

1.2 OBJECTIVES

The purpose of this study is to complete an initial assessment of the potential suitability of Paleozoic sedimentary rocks within southern Ontario as they pertain to the safe implementation of a Deep Geologic Repository, using readily available geoscientific information. The specific objectives of this study are as follows:

1. To complete a review of international geoscience radioactive waste management research and development activities and advances as they relate to implementation of the Deep

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[1] The term *southern Ontario* is used to describe the region shown in yellow in Figure 1-1. *Southwestern Ontario* is used to address the area southwest of Toronto, bound by Lakes Erie and Huron.

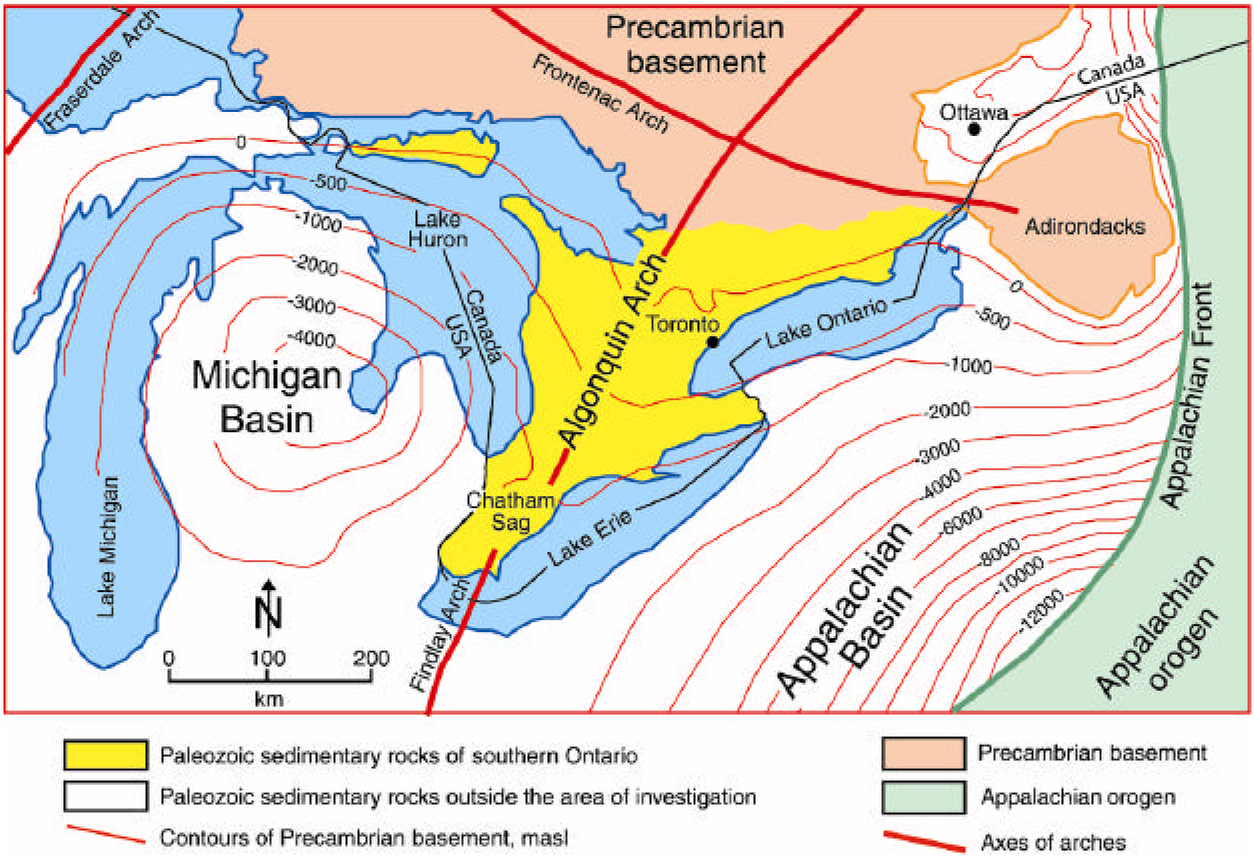

Figure 1-1: Large-scale tectonic elements in southern Ontario and definition of study area (adapted from Johnson *et al.* 1992).

Geologic Repository concept in sedimentary media. The intent is to develop an understanding of the advantages and disadvantages of sedimentary rock with respect to

i) site characterisation and geosphere conceptualisation; and

ii) alternative lines-of-reasoning as they influence/support the development of a safety case for a deep repository.

2. To summarise aspects of sedimentary rock environments relevant to long-term repository safety (*i.e.* predictability, homogeneity, stability and the like). The basis for this objective is found principally in existing safety cases for international radioactive waste management programmes in sedimentary (mostly argillaceous) rocks.

3. To complete and document a literature review of geoscientific information as it relates to the geologic evolution, structural/tectonic framework, mineralogy, seismicity, hydrogeologic and hydrogeochemical conditions and mass transport properties of the Paleozoic argillaceous and carbonate formations in southern Ontario.

4. To contrast evidence from international geoscience research against that available in southern Ontario with respect to long-term nuclear used fuel confinement and isolation. This assessment should consider the following elements;
   i) geosphere stability and predictability as relevant to confidence in site characterisation;
   ii) sedimentary host rock attributes/properties amenable to safe implementation of the Deep Geological Repository concept (*e.g.* extensive low permeability strata, variably saline flow system [fresh water - saline water - brine], formation thickness, possibility of pervasive reducing geochemical environment, geologic dissolution [absence], favourable hydraulic gradients [density/gravity], anomalously elevated hydraulic heads, evidence for erosion rates at geologic time scales);
   iii) geosphere predictability as relevant to assessing long-term ground water flow system evolution and repository performance; and
   iv) post-closure safety.

5. To assess and identify gaps in knowledge with respect to Paleozoic sedimentary rocks in southern Ontario in the context of the implementation of the Deep Geologic Repository concept.

2. SEDIMENTARY MEDIA FROM A WASTE DISPOSAL PERSPECTIVE - AN OVERVIEW

On an international level, crystalline basement and argillaceous rocks (clay, shale, marl) are target rock types for about two thirds of all ongoing and planned disposal programmes for various types of radioactive waste. The remaining programmes consider, in the order of decreasing importance, salt, gypsum/anhydrite, volcanic/volcanoclastic rock, sandstone and limestone (overview in Witherspoon & Bodvarsson 2001). Among the active and most mature programmes for the disposal of high-level radioactive waste, crystalline basement rocks (*e.g.* Canada, Finland, Sweden, Switzerland), clays/shales in various states of induration (*e.g.* Belgium, France, Spain, Switzerland) and salt (*e.g.* Germany) are most frequently considered. The main characteristics of these three rock types are summarised in Table 2-1.

Table 2-1: Comparison of relevant characteristics of different host-rock types for the disposal of high-level radioactive waste

Property	Crystalline basement	Clay and shale	Salt
Availability at suitable depth	**Available in very large volume over wide areas**	Variable	Variable
Geometry and heterogeneity	Possible occurrence of fault and fracture networks at all depths	**Well-defined, generally flat-lying strata, only limited heterogeneity in the vertical and horizontal dimensions**	Well defined (flat lying salt beds), well defined to very complex (salt domes)
Explorability, predictability	Exploration of faults from the surface may be difficult	**Excellent: laterally predictable, geometry easy to demonstrate and illustrate even to non-technical audiences**	Excellent (flat lying salt beds) to challenging (salt domes)
Permeability	Low to heterogeneous	**Generally very low and spatially homogeneous**	**Very low**
Self sealing of faults and of the excavation-disturbed zone	Limited	**Very efficient**	**Very efficient**
Retardation properties	Variable; efficiency of matrix diffusion still under discussion	**Excellent (high sorption, colloid filter)**	**Complete isolation**
Stability vis-à-vis repository-induced perturbations (thermal pulse, chemical environment, coupled processes, gas migration)	**High**	Requires site-specific evaluation; coupled processes are important	Requires site-specific evaluation; thermal pulse stronger than in other rock types; chemical environment is not an issue; problem areas: gas migration, salt solubility
Geomechanical stability and engineering properties	**Very favourable**	Demanding issue, requires site-specific evaluation	**Very favourable**

Bold red entries highlight the key positive properties for which the rock type is considered.

Given the substantially different properties of crystalline basement rocks, argillaceous rocks and salt, repository designs and safety functions of the geosphere are rock-specific. For example, the Swedish and Finnish repository designs for granitic rock rely heavily on the engineered barriers (copper canisters, bentonite buffer). The most important functions of the geosphere are to protect the repository from the human environment and to provide favourable hydrogeological, geochemical and geomechanical conditions for the engineered barrier system. On the other hand, much more emphasis is placed on the geosphere as a transport barrier in most sedimentary environments. The recent Belgian safety case for Boom Clay considers the barrier function of the geosphere to a much higher degree than that of the engineered barriers, which are treated in a simplified way.

Table 2-2 provides an overview of the leading disposal programmes targeted at sedimentary rocks. In addition to these programmes, methodological underground rock laboratories are in operation at Mont Terri (Opalinus Clay, Switzerland) and Tournemire (Toarcian - Domerian shales, France).

Table 2-2: Basic characteristics of the most advanced disposal programmes in sedimentary rocks

Country	Host formation, site	Rock type	Waste type	Status
Belgium	Boom Clay at Mol	Soft clay	SF, VHLW, LL-ILW	Ongoing work in a underground rock laboratory; recent synthesis available (SAFIR 2)
France	Callovo-Oxfordian at the Site Meuse-Haute Marne (Bure)	Shale	VHLW, (SF), LL-ILW	Siting process and surface-based investigations completed, underground rock laboratory under construction
Germany	Salt at Gorleben	Salt	SF, VHLW, ILW, LLW	Project suspended in 2000 for 3 to 10 years
Germany	Salt at Morsleben	Salt	LLW	Repository (legacy of the former German Democratic Republic) operating until 1998, finally stopped in 2001
Germany	Konrad Mine	Repository hosted by limestone, overlying shales function as confining units	ILW, LLW	Licensed in 2002
Spain	Spanish Reference Clay in the Duero Basin	Soft clay	SF, LL-ILW	First stage of the project completed in 1999. No site specific activities undertaken since then. Government decision on future strategy expected for 2010
Switzerland	Opalinus Clay in the Zürcher Weinland	Shale	SF, VHLW, LL-ILW	Siting process and surface-based investigations completed and synthesised
Switzerland	Palfris Formation at Wellenberg	Hard fractured marl	L/ILW	Siting process and surface-based investigations completed; project abandoned as consequence of a cantonal referendum
USA	Salt at WIPP (New Mexico)	Salt	LL-ILW	Operating

SF = spent nuclear fuel, VHLW = vitrified high-level waste, (LL-)ILW = (long-lived) intermediate-level waste, LLW = low-level waste

3. PRESENTATION OF KEY NATIONAL PROGRAMMES IN SEDIMENTARY ROCKS

Among the leading disposal programmes in sedimentary rocks, major milestones have recently been completed by the following organisations:

- Nagra, Switzerland: *Entsorgungsnachweis* (demonstration of disposal feasibility) for Opalinus Clay in the Zürcher Weinland
- Andra, France: *Référentiel géologique* (geoscientific characterisation) and *Dossier 2001 Argile* (safety assessment) for the Callovo-Oxfordian shales in the eastern Paris Basin
- Ondraf/Niras, Belgium: *SAFIR 2* progress report and safety assessment for Boom Clay.

All three programmes are targeted at argillaceous rocks in different states of induration.

3.1 DEMONSTRATION OF DISPOSAL FEASIBILITY IN OPALINUS CLAY, SWITZERLAND

3.1.1 Framework

Sediment-covered crystalline basement rocks in northern Switzerland have been investigated by Nagra (National Cooperative for the Disposal of Radioactive Waste) since 1980, and milestone reports include Nagra (1985, *Projekt Gewähr*), Thury *et al.* (1994, geological synthesis report) and Nagra (1994, safety report). In their evaluation of this project, the Swiss Federal Nuclear Safety Inspectorate (HSK) considered the demonstration of geotechnical feasibility and of nuclear safety as fulfilled. The third component needed for the *Entsorgungsnachweis* (demonstration of disposal feasibility), the identification of a specific site containing a rock body of sufficient size with the properties that were assumed in the safety assessment, was regarded as not satisfactorily fulfilled. By consequence, the Swiss government required that alternative options in sedimentary rocks be considered and brought to the same level of sophistication as the crystalline basement programme. After the consideration of different options, Nagra selected Opalinus Clay (a Middle Jurassic shale formation) as the primary target and initiated investigations in the Zürcher Weinland (northeastern Switzerland) in 1995. One deep borehole was drilled at Benken, and a 3D seismic campaign was performed. Several older boreholes and 2D seismic data were re-analysed. An international underground research laboratory in Opalinus Clay was established at Mont Terri (northwestern Switzerland). Even though this laboratory is outside the siting region and located in a different tectonic setting, it provided valuable information (data and concepts) that could be extrapolated to the Zürcher Weinland. Fields where the learning effect was particularly high include geochemistry, geomechanical behaviour and gas issues. On this basis, Nagra prepared reports on the geoscientific understanding (*"geosynthesis"*), on safety assessment and on construction and operation of a deep geological repository (Nagra 2002a,b,c). These reports are the basis for the full *Entsorgungsnachweis* and are currently being reviewed by the regulatory bodies.

3.1.2 Site characterisation

Opalinus Clay is a flat-lying, vertically and horizontally very homogeneous and thus geometrically simple shale formation. In the proposed siting area, major faults are absent. There is ample evidence from other sites that faults cross cutting the Opalinus Clay are hydraulically insignificant, indicating a high efficiency of self sealing processes. The Opalinus Clay is bound by a sequence of lithologically more heterogeneous units with generally low hydraulic conductivity. This additional barrier was conservatively ignored in safety assessment calculations and was treated as a "reserve FEP" that could be considered in future.

One of several innovative aspects of the investigations in Opalinus Clay is the development and application of a multitude of techniques for pore-water analysis (squeezing, leaching, direct sampling in boreholes, thermodynamic modelling) and interpretation. These techniques were developed and synthesised mainly at Mont Terri (Pearson *et al.* 2003), but they were also successfully applied in the siting area in the Zürcher Weinland. Among others, stable water isotopes (δ^{2}H, δ^{18}O), Cl and δ^{37}Cl in pore water were analysed in samples from the Benken borehole, and curved profiles were obtained. Modelling of these profiles (Gimmi & Waber 2004) yielded the following conclusions:

- The observed natural tracer distributions can be interpreted as diffusion profiles. The time scales over which the diffusion process took place lie in the order of 0.5 - 1 Ma. This value is consistent with independent evidence (onset of infiltration of fresh water into the underlying aquifer).
- Resulting diffusion coefficients are consistent with laboratory measurements on small samples, thus there is no resolvable scale dependence.
- The shape of the profiles cannot be properly reproduced by model runs in which even a small advective component (up or down) is included, thus Peclet numbers must be small, and transport has been diffusion-dominated over large scales in time and space.

The interpretation of the tracer profiles provides an independent line of evidence in support of a stagnant, diffusion-dominated system. This type of argument has been highly appreciated by various reviewers, including the regulatory authorities.

Measured hydraulic conductivity in Opalinus Clay at Benken is 2E-14 m/s (vertical) to 1E-13 m/s (horizontal), and slight overpressures were identified. While the process that generated the overpressures is not clearly established, their existence is yet another line of evidence indicating very low permeability.

A large number of geomechanical *in situ* and laboratory experiments were performed, and material constitutive laws for short- and long-term deformation were derived. Model calculations based on these laws demonstrate that, in spite of horizontal overpressures and a marked stress anisotropy, geomechanical stability of shafts and tunnels is sufficient at repository depth (650 metres below ground surface [mbgs]), and only minor support measures are required.

Transport of repository derived gas was studied extensively. It could be shown that classic two-phase flow and possibly pathway dilation are the relevant transport mechanisms, while the generation of gas induced fracturing can be excluded.

Short-term perturbations of Opalinus Clay, induced by the construction and presence of the repository, were shown to be limited and not safety-relevant. Long-term evolution was also studied, and the most important effects that could impact on repository safety are uplift and erosion. However, over the time scale of 1 Ma, the safety-relevant consequences are insignificant. The future geochemical system is characterised by slow out-diffusion of salinity, and it was shown that this process will remain quantitatively insignificant over the next 1 Ma. The geochemical environment and reducing redox conditions are and will remain buffered by the rock over the time scales of interest.

3.1.3 Post-closure safety assessment

In Nagra's approach to long-term safety assessment, there is an explicit link between the (highly simplified) conceptual models used for transport calculations and the (more complex) models derived from geoscientific investigations. Nagra (2002b) define the following *safety functions* for the barrier system:

1. Isolation from the human environment
2. Long-term confinement and radioactive decay within the disposal system
3. Attenuation of releases to the environment.

Based on these safety functions, a set of features of the barrier system was derived that are key to providing the safety functions. These features are termed *"pillars of safety"* because they are well understood and insensitive to perturbations, and they are the basis for the safety concept.

In addition to realistic and conservative calculation cases, a number of so-called "what if ?" cases were quantified, in order to explore and clearly illustrate the robustness of the repository system. "What if ?" cases simulate the influence of perturbations to key properties of the "pillars of safety" that are outside the range of possibilities supported by scientific evidence.

A synoptic summary of the results of dose calculations is shown in Figure 3-1. The scenarios that yield the highest doses are those related to human actions (namely borehole penetration) and some "what-if ?" calculations (namely transport along transmissive discontinuities or poor near field combined with pessimistic geochemical data set and increased water flow). Even in these cases, the resulting doses are well below the regulatory limit, and this illustrates the robustness of the barrier system.

A first international peer review of the safety aspects (*i.e.* of Nagra 2002b and parts of Nagra 2002a) was performed under the auspices of the OECD Nuclear Energy Agency (NEA). The overall feedback was very positive and encouraging (NEA 2004a).

3.2 FRENCH PROGRAMME IN THE EASTERN PARIS BASIN, FRANCE

3.2.1 Framework

Following the formulation of the Waste Act by the French government in 1991, Andra (French National Agency for Radioactive Waste Management) selected three sites as candidates for the disposal of high-level radioactive waste. These included shales in the eastern Paris Basin (specifically at the site called Site de l'Est or Site Meuse-Haute Marne or Bure), silty shales at

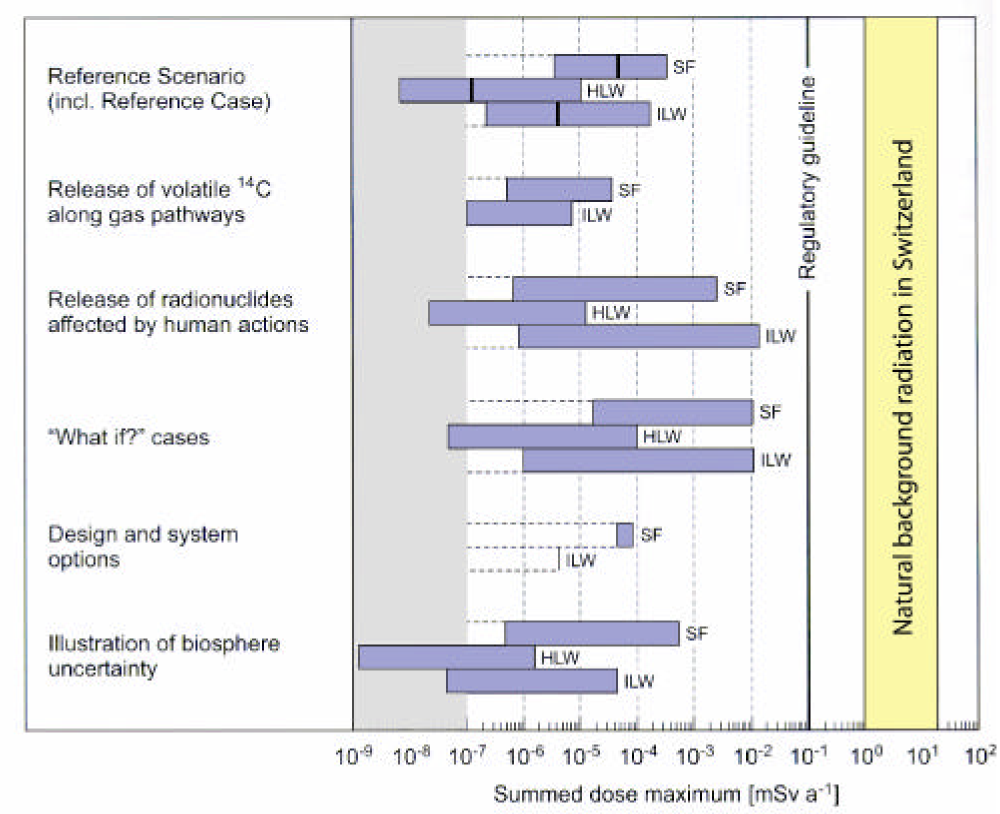

Figure 3-1: Maximum doses (sums of all nuclides) obtained from safety assessment calculations for a deep geological repository in Opalinus Clay of northeastern Switzerland, considering various scenarios and parameter variations. SF = spent fuel, HLW = vitrified high-level waste, ILW = long-lived intermediate-level waste. Taken from Nagra (2002b).

Marcoule (Gard) and a sediment-covered granite in western France. Andra undertook preliminary studies at all three sites (Andra 1999a,b,c) and applied for licences to construct underground research laboratories. In 1998, the government decided to authorise the construction of an underground research laboratory in Callovo-Oxfordian shales of the eastern Paris Basin and further asked for the identification of a new site with outcropping crystalline basement.

The target area in the eastern Paris Basin was first investigated on the basis of 9 boreholes and 2D and 3D seismic campaigns. The geological, hydrogeological, geochemical and geomechanical results and interpretations are summarised and synthesised in Andra (1999d, in French). Subsequently, a synthesis document dealing with the feasibility of a deep repository and a preliminary safety assessment was elaborated (Andra 2001, in English).

Shaft sinking for the underground research laboratory near Bure is currently under way. The next milestone will be the elaboration of a comprehensive document dealing with geoscientific, engineering and safety-related issues in 2005, followed by a strategic decision by the government in 2006. Should the results of research conducted in the underground laboratory be favourable, it could become a potential site for disposal.

3.2.2 Site characteristics and safety assessment

The Callovo-Oxfordian shales are flat-lying, 138 m thick and buried under 420 m of younger sedimentary rocks at the location of the rock laboratory. They are sandwiched between low-potential aquifers hosted by limestones. They show only limited heterogeneity in the vertical and horizontal dimensions. Andra (2001) conclude that the target formation

- has a simple geometry, is sufficiently homogeneous and predictable,
- has a very low permeability, thus transport is likely diffusion dominated,
- is robust against repository-induced disturbances
- has a geomechanical stability sufficient for safe construction and operation,
- is robust against long-term disturbances (erosion, permafrost etc.).

The preliminary safety assessment considered only two scenarios (normal evolution scenario and a scenario assuming seal leakage and upward flow) and a number of parameter variations. In the normal evolution scenario, resulting doses to man are well below the regulatory limit, the most important contributors being ^{129}I and ^{36}Cl. In the case of seal leakage, the confining formation is short circuited, which results in maximum doses in the order of 1 mSv/a. This value reflects the superposition of several conservative assumptions that underlie the calculations, and future efforts are planned to reduce the degree of conservatism.

The OECD Nuclear Energy Agency organised an international peer review of Andra (2001). The review team in general confirmed that the strategy pursued, the data and interpretations gained and the project-relevant conclusions made are sensible (NEA 2003a). Two points of criticism related to the fact that the possible effects of gas production were not considered, and that the documentation of hydrogeological modelling did not reflect all the work that had actually been performed. Suggestions for further geoscientific work included:

- Study of natural tracer profiles
- Clarifications regarding the hydraulic significance of faults
- Study of the origin of the observed overpressures.

3.3 SAFIR 2 INTERIM REPORT ON DISPOSAL IN BOOM CLAY, BELGIUM

3.3.1 Framework

The Belgian programme is managed by Ondraf/Niras (Belgian Agency for radioactive waste and enriched fissile materials). Weakly consolidated clays have been studied as potential host rocks for decades, mainly the Tertiary Boom Clay under the nuclear site of Mol/Dessel. Since 1975, three sampled deep drillings with extensive geophysical logging and two high resolution seismic campaigns have been carried out on site, moreover, a large amount of parameters of different natures have been determined in laboratory and/or *in situ*. An underground research laboratory hosted by Boom Clay at the depth of 220 m was built and progressively extended for numerous *in situ* experiments. Recently, the facility has been further extended (second shaft, connection gallery). The underground laboratory is not necessarily a disposal site (siting issues are yet to be addressed). A second-priority target is the underlying Yper Clay, which has received less attention to date.

One peculiarity in Belgium is the absence of a regulatory framework, thus Ondraf/Niras has adopted international principles for guidance. Every ten years, Ondraf/Niras has produced a progress report and synthesis of current knowledge for the Belgian government. The most recent such report is SAFIR 2 (Safety Assessment and Feasibility Interim Report 2) published in 2001 (Ondraf/Niras 2001). This report documents the first comprehensive safety assessment in Belgium, taking the Boom Clay at Mol as an example. The format of the document is a hybrid between progress report and safety case, therefore it is very voluminous (almost 1500 pages).

3.3.2 Site characteristics and safety assessment

Boom Clay is a flat-lying, weakly consolidated (porosity ca. 35 - 40 %) clay formation subcropping in northern Belgium. At the Mol site, formation thickness is ca. 100 m, and overburden thickness is slightly less than 200 m. Boom Clay is sandwiched between two exploited aquifers. Simplicity of the large-scale geometry and outstanding internal homogeneity are key characteristics.

Transport is most likely diffusion-dominated. However, some uncertainties exist on the upscaling of hydraulic conductivity. Depending on the choice of parameters, advection through the matrix may play a role, while fracture flow can be excluded due to the plastic nature of the clay. Diffusion coefficients are higher than in more heavily consolidated argillaceous rocks.

Given the low strength of Boom Clay, tunnels require massive concrete lining. Cement-based materials may also be used as backfill for waste types with negligible heat production. The geochemical disturbance to the geosphere is regarded as marginal.

Safety assessment calculations considered both engineered and natural barriers, but the degree of detail was higher for the geosphere than for the engineered barrier system, thus the safety case relies on the favourable properties of the geosphere to a high degree. In addition to the normal evolution scenario, a number of altered-evolution scenarios were analysed. These scenarios included water exploitation drilling, fault activation, glaciation, poor sealing of the repository, gas-driven transport and exploratory drilling penetrating the repository. Some calculation runs, in particular those assuming the drilling of a borehole close to the repository and subsequent water extraction from the underlying aquifer, resulted in maximum doses in excess of 1 mSv/a. Taking advantage of the full chain of barriers in future calculations and setting the calculated doses in perspective against the (low) probability of occurrence may attenuate these doses and associated risks.

The SAFIR 2 report was subjected to an international peer review by the Nuclear Energy Agency (NEA 2003b). While the overall judgement of the review team was very positive (mature and promising programme covering all relevant aspects), several critical points were addressed, among which the following ones are of general interest:

- In order to increase transparency, the objectives of status reporting and safety assessment should in future be separated into separate, less voluminous documents.

- The degree of sophistication to which safety-relevant aspects were addressed varies, some of the older work requires updating. Recent developments in safety analysis (such as use of safety functions, alternative safety indicators, and qualitative arguments) should be considered consistently.

- The presented safety case takes full advantage of the barrier function of the Boom Clay, which is not the case for the engineered barriers. Future assessments should consider all parts of the multi-barrier system to a comparable degree of detail.

4. R & D RELATED TO ARGILLACEOUS SYSTEMS CO-ORDINATED BY THE OECD NUCLEAR ENERGY AGENCY (NEA)

The Nuclear Energy Agency (NEA) co-ordinates various international initiatives related to the disposal of radioactive waste, mainly through working groups such as the IGSC (Integration Group for the Safety Case) and the Clay Club (Working Group on the Characterisation, the Understanding and the Performance of Argillaceous Rocks as Repository Host Formations). Recently completed or ongoing projects with direct relevance to argillaceous media are presented below.

4.1 CATALOGUE OF CHARACTERISTICS OF ARGILLACEOUS ROCKS

The objective of this project is to compile, in a consistent format, a numeric data base of relevant parameters (including statements on variability and reliability) of argillaceous media currently considered in the framework of radioactive waste disposal. Parameters considered relate to geometric aspects, regional geology, mineralogy, rock and pore water chemistry, petrophysics, hydraulics, flow, solute transport and geomechanics. In addition to numeric values, each site is documented in a short introduction, augmented by a set of key illustrations. Currently, a draft document is available (NEA in prep.), accessible to Clay Club Members. A revision (completion and quality assurance of the data base), followed by publication as an open document, is envisaged at a later stage.

4.2 FEPCAT PROJECT

The objectives of FEPCAT (Features, events and processes catalogue for argillaceous rocks) included the identification of FEPs that are relevant for the characterisation of argillaceous host rocks in the framework of radioactive waste disposal, a compilation of available information on these FEPs, an overview of the relevance of the FEPs for performance assessment and the way they are considered in the safety case, and a synthesis documenting the state of knowledge vis-à-vis what is needed for the safety case. In total, 59 FEPs were defined, addressing 1) the undisturbed geosphere, 2) short-term perturbations related to the presence of the repository, and 3) long-term geological evolution. The project has been recently completed and is available as an open document (Mazurek *et al.* 2003).

4.3 SELF SEALING IN ARGILLACEOUS ROCKS

Self sealing is a naturally occurring process, with a number of underlying contributory mechanisms, that leads to a reduction of fracture transmissivity. Many of these mechanisms are time dependent. Self sealing is an important buffering process by which the hydraulic significance of (re)activated natural fractures and faults or induced structures in the excavation-disturbed zone along tunnels and shafts is diminished.

The NEA Clay Club organised a topical session on self sealing in argillaceous rocks (NEA 2001a) and launched an initiative targeted at the compilation of empiric observations and experiments related to self sealing and the understanding of underlying mechanisms. The project is currently in preparation by the British Geological Survey (see interim reports by Horseman 2001 and Horseman *et al.* 2004) and is expected to be finalised in 2005.

4.4 INTERPRETATION OF TRACER PROFILES

At several sites, data sets on the spatial distribution of natural tracer concentrations and isotopic ratios in pore waters of argillaceous rocks are available (anions, water isotopes, noble gases). Regular, curved profiles were observed for some tracers in several formations but are absent in others (Mazurek *et al.* 2004). In the former, the tracer distributions were interpreted as natural diffusion profiles (see, *e.g.*, Gimmi & Waber 2004 for Opalinus Clay in Switzerland). Tracer profiles can be considered as large-scale and long-term experiments by which the transport properties can be estimated and further constrained. They provide complementary information to that obtained from experiments in laboratories or underground facilities, where typical spatial scales are 1 cm to 1 m and temporal scales rarely exceed 1 year. Natural tracer profiles can bridge the gap between these scales and those required for performance assessment (typically tens to hundreds of m and 0.1 to 1 Ma). They further provide an independent line of evidence for system understanding, as well as for safety considerations in qualitative and quantitative terms. A project proposal to investigate the nature of natural tracer profiles and the mechanisms that control them has been submitted to the NEA Clay Club and, if accepted, would run from 2005 to 2006.

4.5 METHODS OF SAMPLING AND INTERPRETATION OF PORE WATERS IN ARGILLACEOUS FORMATIONS

Due to the generally very low hydraulic conductivity, pore waters of argillaceous rocks cannot be sampled by standard *in situ* techniques. A number of purpose-designed *in situ* and laboratory methods, such as squeezing, leaching or *in situ* vacuum extraction, have been developed in order to constrain certain aspects of pore water chemistry. A project initiated by the NEA, documented in Sacchi *et al.* (2000, 2001), gives an overview. Very recent advances in sampling technology and strategies for interpretation, namely at the Mont Terri Underground Rock Laboratory (Opalinus Clay, Switzerland), have been undertaken and are reported in Pearson *et al.* (2003).

4.6 WATER, GAS AND SOLUTE MOVEMENT THROUGH ARGILLACEOUS MEDIA

Based on an initiative of the NEA Clay Club, Horseman *et al.* (1996) wrote a textbook that provides the theoretical foundations for the understanding of clay-water-solute interactions, transport processes and the various couplings that are important in argillaceous formations. The book addresses both macroscopic and microscopic scales and also documents the relevant investigation methods for all scales.

4.7 NEA WORKSHOPS DEALING WITH PROPERTIES OF ARGILLACEOUS MEDIA

- A recent workshop was dedicated to the long-term stability and buffering capacity of argillaceous host formations. It is documented in a proceedings volume (NEA 2004b).

- The first workshop of the AMIGO (Approaches and Methods for Integrating Geological Information in the Safety Case) series dealt with the use of multiple lines of evidence to support the safety case (NEA 2003c). One session was dedicated to the safety case for Opalinus Clay in NE Switzerland.

- A topical session of the NEA Clay Club dealt with structural and sedimentary heterogeneities in argillaceous rocks and the methods with which such heterogeneities can be identified and characterised. Documentation is provided in NEA (1998a).

- Fluid flow through fractures and faults in argillaceous media was addressed in a joint NEA/EC workshop (NEA 1998b).

4.8 OTHER RELEVANT NEA INITIATIVES

The following NEA projects, while not specifically targeted at argillaceous rocks, are worth mentioning:

- NEA (2001b) makes a step towards the mechanistic understanding of sorption (ion exchange, surface complexation) on mineral surfaces, in order to complement the empiric distribution coefficient (K_d) approach currently used in performance assessment models. The second phase of this project is currently ongoing, and first results are documented in Payne *et al.* (2003) and Davis *et al.* (2003).

- A workshop organised by the NEA and documented in NEA (1999) addressed the use of hydrochemical information for evaluating confidence in ground water flow model simulations. This was one of the early initiatives to promote the use of multiple lines of evidence in making the safety case.

- Gas generation and migration through the engineered barriers and the geosphere have been studied on an international level. Key documents include Rodwell *et al.* (1999), Rodwell (2000) and NEA (2001c).

5. LONG-TERM STABILITY OF ARGILLACEOUS FORMATIONS

The regulatory time scale over which safety has to be demonstrated varies among different countries. According to a recent document of the NEA, *"there is an increasing consensus among both implementers and regulators that, in carrying out safety assessments, calculations of dose or risk should not be extended to times beyond those for which the assumptions underlying the models and data used can be justified"* (NEA 2004c). In practice, rigorous, quantitative models are required over time scales of at least 10 thousand years (ka). Over longer periods of time, typically up to 1 Ma, less rigorous and qualitative arguments become important, *e.g.* predictions based on palaeo-hydrogeology, natural analogues and safety indicators (collectively termed "multiple lines of evidence"). Over a period of some hundreds of thousands of years, most fission and activation products will have decayed to insignificant levels, and the remaining activity is comparable to that of the natural uranium ore from which the nuclear fuel was originally produced (see, *e.g.*, Marivoet *et al.* 2004).

The main fields in which long-term structural, hydrogeological and geochemical geosphere stability needs to be addressed include

- Seismic activity, tectonic regime
- Geochemical evolution
- Erosion and loading.

The understanding of past features, events and processes (stratigraphic sequence, structure, hydrochemical, mineralogical and hydraulic evolution) is a key element to constrain future evolution and potential changes. In the case of events (such as earthquakes), the study of the probability of occurrence is important. For slow processes (such as erosion), the expected rates of change need to be addressed.

One favourable aspect for which argillaceous formations are considered in the framework of waste isolation is their efficiency to attenuate the consequences of external perturbations, often referred to as buffering capacity (*e.g.* pore water composition and redox state, self sealing of faults).

5.1 SEISMIC ACTIVITY, TECTONIC REGIME

The possible consequences of seismic events include displacement (rupture), shaking (vibration) and changes in the local stress and therefore hydrologeological regime.

5.1.1 Displacement

The layered structure of (originally horizontally bedded) sedimentary formations provides excellent markers for the identification of tectonic movements that occurred since deposition. Fault displacements with vertical components can be mapped by seismic tools, and they document the integrated tectonic history of the formation. For example, a 3D seismic campaign was conducted in the target region for a deep geological repository in Opalinus Clay

(Switzerland) (Birkhäuser *et al.* 2001). Faults with vertical displacements of =4 m could be identified by the analysis of seismic attributes. The absence of such faults in the potential siting area is taken as evidence for long-term structural stability as no major faults were created since the deposition of the shale 180 Ma before present[2]. Given the fact that the present-day stress field in northern Switzerland is considered to be stable, there is good reason to extrapolate the findings over the next 1 Ma.

In areas of more northerly latitude, mechanical load changes related to the cyclic advance and retreat of glacial sheets has resulted in Quaternary faulting and seismicity. There is some consensus that seismicity occurs mainly during and immediately after deglaciation, while much less activity is related to the (generally slower) stages of glacial advance (Muir-Wood 1989, 2000, Firth & Stewart 2000, Stewart *et al.* 2000). The best known example is the 150 km long Parve fault with up to 13 m vertical displacement in northern Scandinavia. Musson (2004) points out that the extrapolation of present-day seismicity to the far future may be misleading due to the transient effects of glacial cycles.

It is generally acknowledged that, given the existence of fault patterns in most shale formations and the underlying sedimentary and crystalline units, fault reactivation may take place while the creation of new faults is highly unlikely (see, e.g, Firth & Stewart 2000).

5.1.2 Shaking

Shaking is important over the time when the repository contains voids, *i.e.* before backfilling. It is a well known fact that seismic acceleration decreases with depth due to the decreased effects of surface waves (see, *e.g.*, Sykora & Bastani 1998). Examples are known where tunnels and mines remained intact, whereas surface damage was substantial (see the recent, comprehensive review by Bäckblom & Munier 2002). If a repository is located in a seismically quiet region, the risk of post-closure damage due to shaking is generally regarded as irrelevant.

5.1.3 Effects on ground water flow

Earthquakes result in a rapid redistribution of stress conditions, especially in the vicinity of the active faults. Resulting pore pressure changes may lead to transient flow events (changed discharges of springs and rivers over hours to months to years). Such features have been observed in connection with strong earthquakes in shallow, high-permeability systems. Whether upwelling of deep ground waters may occur in connection to strong earthquakes is under debate (Muir-Wood & King 1993, Rojstaczer *et al.* 1995). Given the generally layered nature of sedimentary basins, short-term transient flow would be expected to occur within higher-permeability units, *i.e.* horizontally. The hydro-mechanical response of shales to stress changes can be quantified, provided sufficient experimental data are available.

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[2] The existence of major pure strike-slip faults without any vertical displacement is unlikely.

5.1.4 Self sealing

The effects of swelling, softening and homogenisation (re-arrangement of clay particles) in faults and fractures in clay-rich formations lead to a gradual decrease of transmissivity, a feature called self sealing (Horseman *et al.* 2004). There is a substantial experimental and empiric data base supporting the existence of self sealing in soft to strongly indurated and over-consolidated argillaceous media (NEA 2001a). Self sealing is one of the primary factors favouring the choice of argillaceous media as potential host formations for the isolation of radioactive waste. Self sealing reduces the permeability of natural faults to levels comparable with the matrix, and it also reduces the hydraulic significance of the excavation-disturbed zone of tunnels after backfilling and resaturation.

5.1.5 Conclusions

If a repository is located in an area of low seismic activity, the consequences of earthquakes are most likely negligible, with the possible exception of areas where massive ice sheets may be expected during future glaciations. The existence of structural marker horizons in sedimentary sequences facilitates the identification of even small faults, and the quantification of the integrated displacement that occurred along them over geological time scales. The hydraulic consequences of fault movements are attenuated by self sealing, which is considered to be an efficient buffering mechanism in clays and shales.

5.2 GEOCHEMICAL EVOLUTION

5.2.1 Identification of transport processes and rates of exchange

Argillaceous formations considered as potential hosts for radioactive waste are typically parts of layered sedimentary sequences containing aquifers (*e.g.* carbonates, sandstones) and aquicludes (*e.g.* shales, evaporites). In many situations, the latter formations are sandwiched between aquifers that contain glacial or post-glacial waters with chemical and isotopic compositions different from those in the aquicludes. This chemical contrast initiates a slow solute exchange and frequently gives rise to curved tracer profiles on the scale of the formation (*i.e.* 100 m and more). Typically, anions (Cl, I, Br) and water isotopes (δ^2H, δ^{18}O) are studied and, in many cases, the profiles are interpreted as natural diffusion profiles (*e.g.* Opalinus Clay at Benken and Mont Terri, Switzerland, Couche Silteuse at Marcoule, France, Toarcian-Domerian at Tournemire, France; see Mazurek *et al.* 2004). For Opalinus Clay, the following conclusions could be drawn (Gimmi & Waber 2004):

- Diffusion has been the dominating mass transport process over large scales in time and space.
- Laboratory-derived diffusion coefficients are applicable on the formation scale.
- The formation can be considered as a homogeneous medium.

The good system understanding derived from such studies also allows predictions concerning the future evolution of pore water composition. As shown in Figure 5-1, the out-diffusion process will continue but has negligible consequences over the time scale of 1 Ma. If needed, alternative scenarios with changed boundary conditions in response to climatic or environmental changes (such as a marine transgression) could be quantified. Thus, a good understanding of the hydrogeochemical regime in the past can be used for predictions into the future.

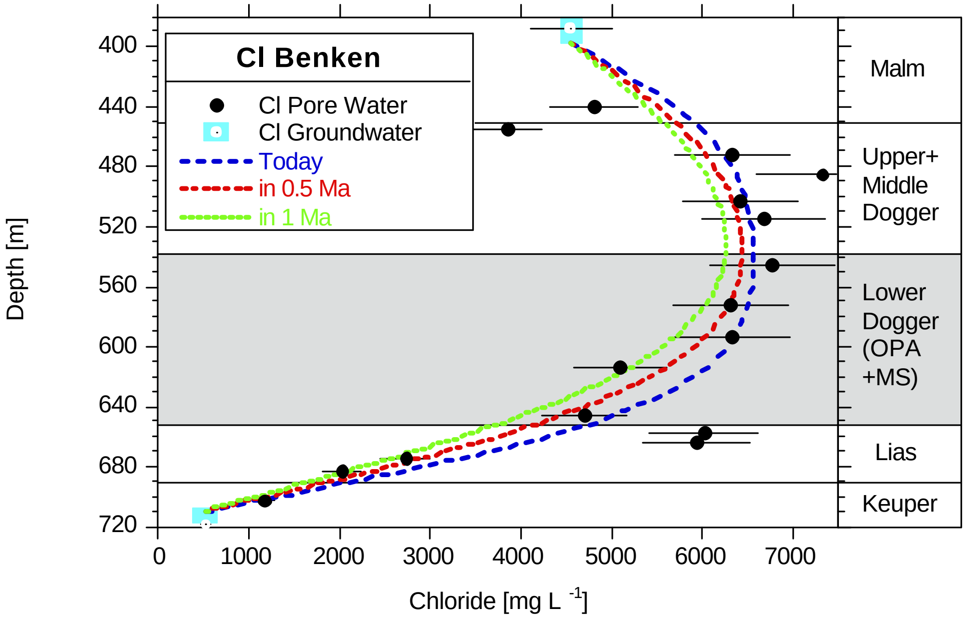

Figure 5-1: Predicted diffusion dominated evolution of chloride contents in pore waters of the Benken borehole (NE Switzerland) 0.5 and 1 Ma after today. Grey: Potential host formations (Opalinus Clay [OPA] and Murchisonae Beds [MS]). Taken from Gimmi & Waber (2004). Cl Ground water: Cl contents in aquifers that constitute the boundary conditions for the diffusion profile. Cl Pore water: Cl contents in free water of low-permeability rocks (predominantly shales), determined by aqueous leaching.

5.2.2 Chemical and redox buffering

The chemical characteristics of clay minerals result in a high sorption capacity, which is one of the main reasons why clays and shales are considered as potential host formations for radioactive waste repositories. In contrast to anions, most other dissolved species in clays and shales are controlled by equilibria with minerals by mechanisms such as ion exchange and dissolution / precipitation equilibria with carbonate and silicate minerals. Likewise, reducing conditions are buffered by sulphides, organic matter and/or siderite and chlorite. The buffering capacity for chemical composition and redox state is substantial in argillaceous media and can be quantified using geochemical models (Beaucaire *et al.* 2004, Pearson *et al.* 2003). The large geochemical buffering capacity is one of the major advantages of argillaceous media when compared to crystalline rocks.

5.2.3 Conclusions

Pore water composition and redox state of argillaceous media are controlled by the solid phases, and the buffering capacity is substantial. Short-term (geologically speaking) perturbations in the surrounding aquifers due to glacial periods do not significantly affect the geochemical character of the argillaceous unit itself. Conservative species that are not controlled by the rock (essentially anions and water) move by diffusion, and this process presents an independent line of evidence in the interpretation of the long-term evolution of the hydrogeochemical system.

5.3 EROSION AND LOADING

Provided that a repository site is located in a geologically stable area, the rates of sediment deposition and fluvial erosion are slow and can be ignored over a timescale of 1 Ma. However, the load changes related to the possible advance and retreat of ice sheets during future glacial periods, together with possible localised deep glacial erosion, as well as transient vertical isostatic movements and lithospheric flexuring, require consideration.

5.3.1 Loading

Glacial loading may cause overpressures and pore water squeezing out of argillaceous formations (see Marschall *et al.* 2004 for Opalinus Clay in Switzerland). As long as the total load does not exceed the maximum stress experienced by the formation in the geological past (pre-consolidation stress), the formation will deform elastically, with limited effects on the pore space. Once pre-consolidation stress is exceeded, irreversible compaction is expected. However, such a situation is not realistic for most over-consolidated formations.

5.3.2 Erosion

Erosion of overlying strata and/or the removal of a glacial load mainly reduces the vertical stress component and thus may affect the stress regime. Overall stress release may lead to underpressures and a hydraulic gradient directed into the argillaceous formation. Depending on the geomechanical properties, fractures may be created. However, such inelastic responses are expected only at very shallow levels (<200 m overburden) for the clay and shale formations considered in the framework for waste disposal, if at all. In Opalinus Clay in Switzerland, water inflows into tunnels were only observed at depths <200 m (Gautschi 2001), compared to the planned repository depth at 650 mbgs.

5.3.3 Vertical movements

Differential vertical isostatic movements may lead to transient fault activity (see Chapter 5.1.1), and such effects need to be studied on a site-specific basis. The hydrogeological implications in sedimentary basins are not well characterised but are probably limited to shallow depths (ca. <200 m), given their layered nature. Moreover, palaeo-hydrogeological methods (*e.g.*

identification of glacial waters infiltrated along reactivated faults) could be used to constrain the effects of past glacial periods.

5.3.4 Conclusions

Available evidence suggests that the hydro-mechanical effects of glacial overburden and glacial deep erosion on deeply buried argillaceous formations in sedimentary basins are small. However, the data base is limited, and the situation should be evaluated on a site-specific basis.

6. OVERVIEW: SEDIMENTARY ROCK CHARACTERISTICS IN SOUTHERN ONTARIO

6.1 LITHOSTRATIGRAPHY OF PALEOZOIC SEDIMENTARY ROCKS

Sedimentation throughout the Paleozoic (Cambrian - Devonian, 543 - 354 Ma b.p.)[3] occurred predominately in shallow inland seas. Carboniferous sediments were probably present but were later eroded (with the exception of a small occurrence along the St. Clair River). Synsedimentary epeirogenic movements (uplift, subsidence, tilting) and movements along faults are recorded by variable sediment thickness and erosional gaps.

An overview of the nomenclature and lithologic content of all sedimentary formations in southern Ontario is depicted in Figure 6-1 (after Johnson *et al.* 1992). This Paleozoic record is subdivided into 8 sedimentary sequences, all separated by major erosional gaps that correlate with orogenic events occurring at the plate margin[4]. As a generalisation, the combined thickness of the sub-horizontally bedded sedimentary formations is least on the crest of the Algonquin Arch (due to more limited sedimentation and/or later erosion) and increases towards the Michigan and Appalachian Basins (see Figure 1-1).

The sedimentological interpretation of the Paleozoic rocks is detailed in Johnson *et al.* (1992). The dominant rock types are clastic sediments (sandstones, shales, mostly derived from the uprising Appalachian Orogen), platform carbonates (limestones, dolomites) and evaporites (in the Silurian Salina Formation). Composite stratigraphic columns of the Michigan Basin and Appalachian Basin of southern Ontario are shown in Figure 6-2. Very generally, the proportion of clastic sediments is higher in the Appalachian Basin (due to the proximity of the orogen), whereas carbonates and evaporites are somewhat more frequent in the Michigan Basin.

6.2 STRUCTURAL FEATURES

6.2.1 Regional tectonics and structure

Algonquin Arch, Chatham Sag, Findlay Arch

Southern Ontario is located along the southeastern rim of the North American Craton. The crystalline basement rocks in this area are overlain by the Paleozoic sedimentary rocks of the Western St. Lawrence Platform (Johnson *et al.* 1992). Within the central part of the study area, a SW-NE trending feature known as the *Algonquin Arch* occurs in the crystalline basement (Figure 1-1, Figure 6-3). The position of the axis of this structure varied somewhat over geologic time. Looking along the axis of this Arch, the crystalline basement unconformity is exposed in the northeast at 200 - 300 metres above sea level (masl) and then progressively plunges towards the southwest, reaching an elevation of ca. -1000 masl in the *Chatham Sag*. From

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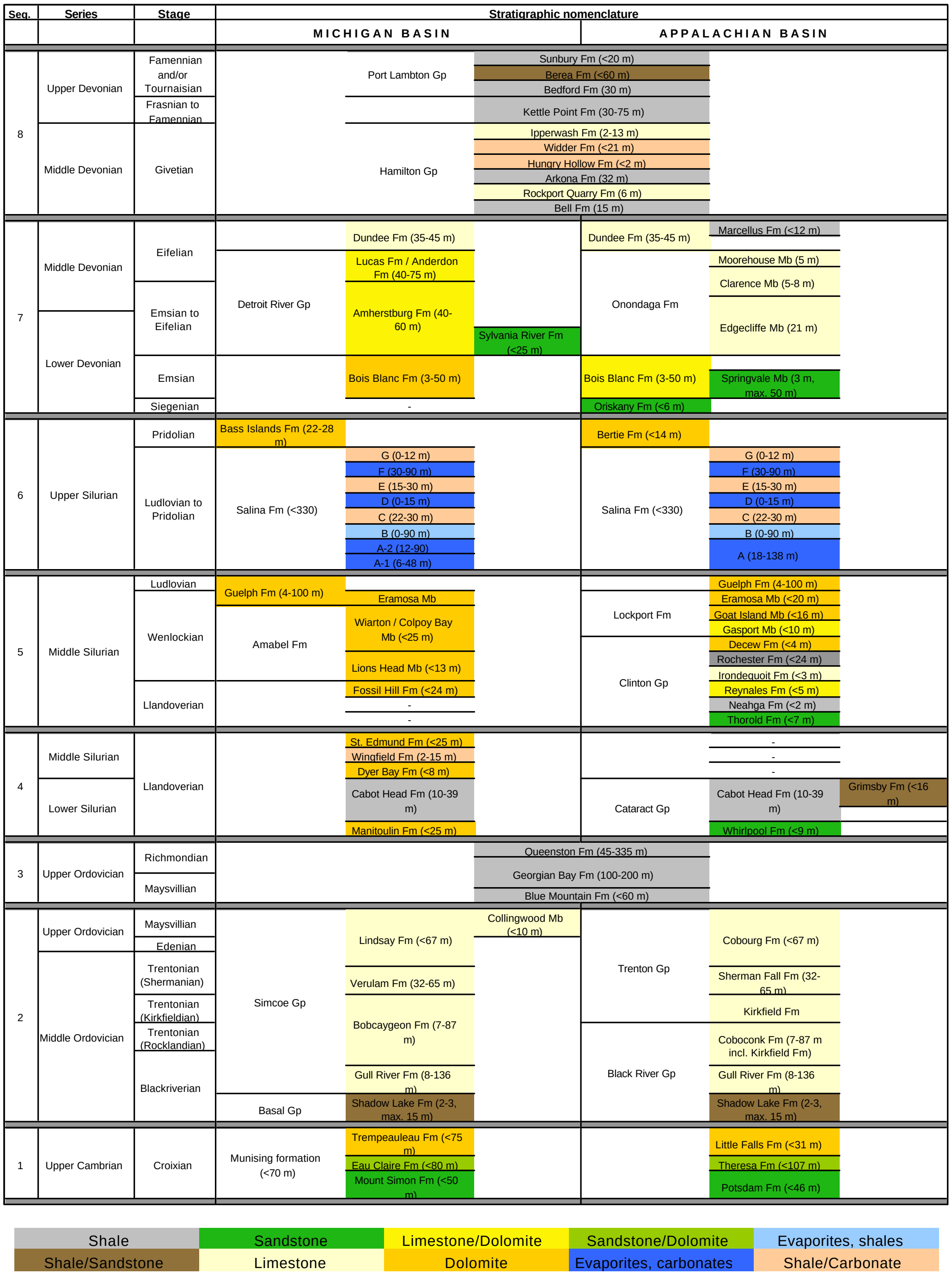
[3] This report uses the geological time scale published by Geological Society of America (1999).

[4] One reviewer pointed out that the stratigraphic nomenclature and interpretation as presented in Figure 6-1 has been partially revised in more recent publications. The same is also true for the definition of the eight sedimentary sequences. For example, Brett *et al.* (1995) revised Silurian stratigraphy of the Niagara region. Because Johnson *et al.* (1992) remains the most recent comprehensive reference documenting the full stratigraphic column of southern Ontario, this report stays with their version. Future studies should consider the more recent updates for specific formations and regions.



Seq.	Series	Stage	Stratigraphic nomenclature					
			MICHIGAN BASIN			APPALACHIAN BASIN		
8	Upper Devonian	Famennian and/or Tournaisian		Port Lambton Gp	Sunbury Fm (<20 m)			
					Berea Fm (<60 m)			
					Bedford Fm (30 m)			
		Frasnian to Famennian			Kettle Point Fm (30-75 m)			
	Middle Devonian	Givetian		Hamilton Gp	Ipperwash Fm (2-13 m)			
					Widder Fm (<21 m)			
					Hungry Hollow Fm (<2 m)			
					Arkona Fm (32 m)			
					Rockport Quarry Fm (6 m)			
					Bell Fm (15 m)			
7	Middle Devonian	Eifelian		Dundee Fm (35-45 m)		Dundee Fm (35-45 m)	Marcellus Fm (<12 m)	
			Detroit River Gp	Lucas Fm / Anderdon Fm (40-75 m)		Onondaga Fm	Moorehouse Mb (5 m)	
							Clarence Mb (5-8 m)	
	Lower Devonian	Emsian to Eifelian		Amherstburg Fm (40-60 m)	Sylvania River Fm (<25 m)		Edgecliffe Mb (21 m)	
		Emsian		Bois Blanc Fm (3-50 m)		Bois Blanc Fm (3-50 m)	Springvale Mb (3 m, max. 50 m)	
		Siegenian		-		Oriskany Fm (<6 m)		
6	Upper Silurian	Pridolian	Bass Islands Fm (22-28 m)			Bertie Fm (<14 m)		
		Ludlovian to Pridolian	Salina Fm (<330)	G (0-12 m)		Salina Fm (<330)	G (0-12 m)	
				F (30-90 m)			F (30-90 m)	
				E (15-30 m)			E (15-30 m)	
				D (0-15 m)			D (0-15 m)	
				C (22-30 m)			C (22-30 m)	
				B (0-90 m)			B (0-90 m)	
				A-2 (12-90)			A (18-138 m)	
				A-1 (6-48 m)				
5	Middle Silurian	Ludlovian	Guelph Fm (4-100 m)				Guelph Fm (4-100 m)	
		Wenlockian		Eramosa Mb		Lockport Fm	Eramosa Mb (<20 m)	
			Amabel Fm	Wiarton / Colpoy Bay Mb (<25 m)			Goat Island Mb (<16 m)	
							Gasport Mb (<10 m)	
				Lions Head Mb (<13 m)		Clinton Gp	Decew Fm (<4 m)	
							Rochester Fm (<24 m)	
							Irondequoit Fm (<3 m)	
		Llandoverian		Fossil Hill Fm (<24 m)			Reynales Fm (<5 m)	
				-			Neahga Fm (<2 m)	
				-			Thorold Fm (<7 m)	
4	Middle Silurian	Llandoverian		St. Edmund Fm (<25 m)			-	
				Wingfield Fm (2-15 m)			-	
				Dyer Bay Fm (<8 m)			-	
	Lower Silurian			Cabot Head Fm (10-39 m)		Cataract Gp	Cabot Head Fm (10-39 m)	Grimsby Fm (<16 m)
				Manitoulin Fm (<25 m)			Whirlpool Fm (<9 m)	
3	Upper Ordovician	Richmondian			Queenston Fm (45-335 m)			
					Georgian Bay Fm (100-200 m)			
		Maysvillian			Blue Mountain Fm (<60 m)			
2	Upper Ordovician	Maysvillian	Simcoe Gp	Lindsay Fm (<67 m)	Collingwood Mb (<10 m)	Trenton Gp	Cobourg Fm (<67 m)	
		Edenian						
	Middle Ordovician	Trentonian (Shermanian)		Verulam Fm (32-65 m)			Sherman Fall Fm (32-65 m)	
		Trentonian (Kirkfieldian)		Bobcaygeon Fm (7-87 m)			Kirkfield Fm	
		Trentonian (Rocklandian)				Black River Gp	Coboconk Fm (7-87 m incl. Kirkfield Fm)	
		Blackriverian		Gull River Fm (8-136 m)			Gull River Fm (8-136 m)	
			Basal Gp	Shadow Lake Fm (2-3, max. 15 m)			Shadow Lake Fm (2-3, max. 15 m)	
1	Upper Cambrian	Croixian	Munising formation (<70 m)	Trempeauleau Fm (<75 m)			Little Falls Fm (<31 m)	
				Eau Claire Fm (<80 m)			Theresa Fm (<107 m)	
				Mount Simon Fm (<50 m)			Potsdam Fm (<46 m)	

Shale	Sandstone	Limestone/Dolomite	Sandstone/Dolomite	Evaporites, shales
Shale/Sandstone	Limestone	Dolomite	Evaporites, carbonates	Shale/Carbonate

Figure 6-1: Succession and nomenclature of Paleozoic formations in southern Ontario (Michigan and Appalachian Basins, Ottawa Embayment excluded). Compiled from Johnson *et al.* (1992). Grey horizontal bars indicate major unconformities. "Seq" = sedimentary sequence as defined in Johnson *et al.* (1992). Colour codes define the dominating lithologies of each formation in a simplified way. At least the Salina Formation is lithologically more complex, both in the vertical and the horizontal dimension. The Figure shows only the relative age relationships, and the vertical axis is not to scale, neither to time nor to thickness).

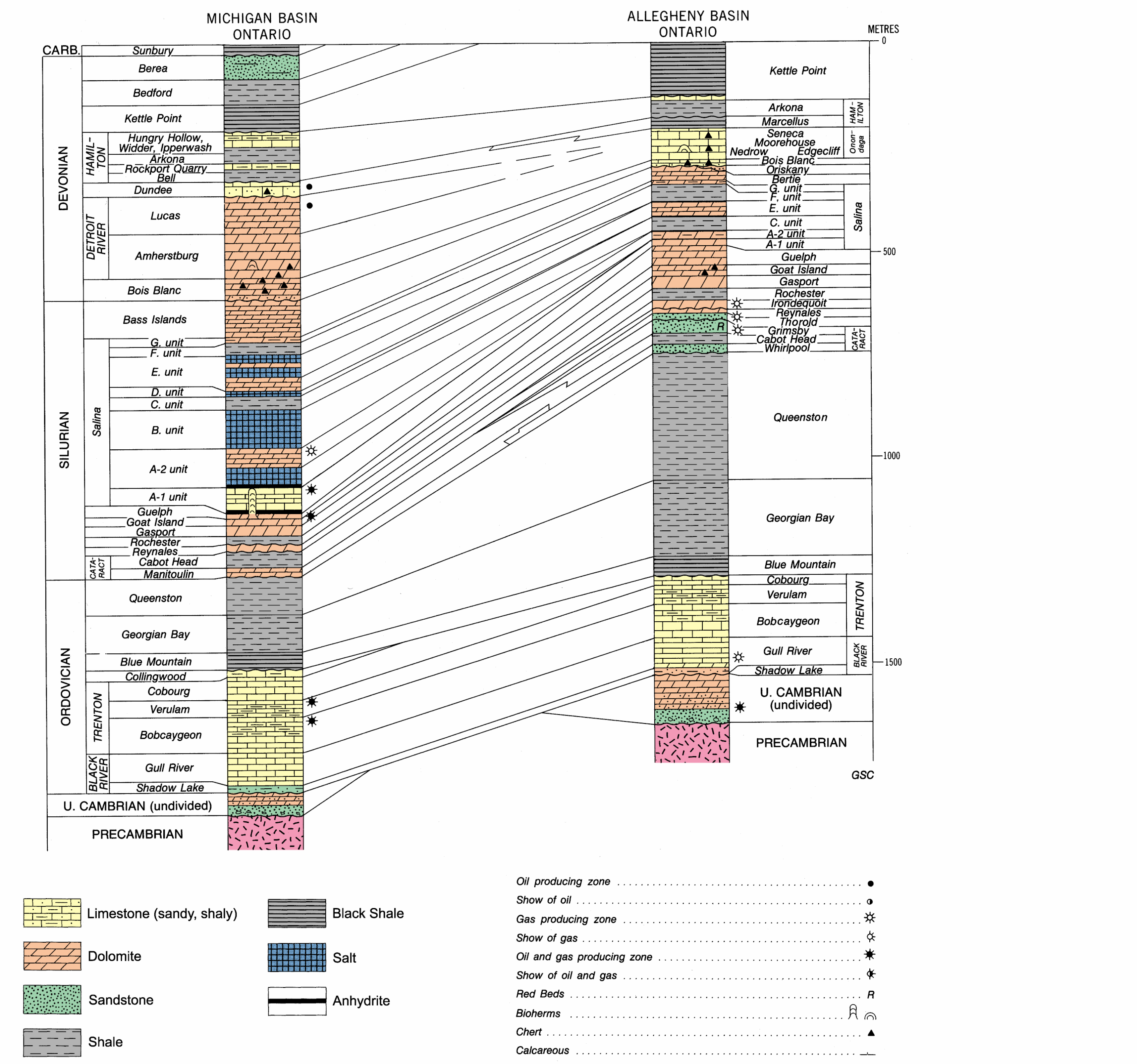


Figure 6-2: Composite stratigraphic columns of southern Ontario. Adapted from Sanford (1993a).

this axial depression, the basement rises to the southwest along the *Findlay Arch*, the southwest continuation of the Algonquin Arch. The general dip of the strata towards southwest to south means that the oldest (Ordovician) rocks are exposed in the northeastern part of southern Ontario, and the youngest (Devonian) units crop out in the Chatham Sag in the southwest (Figure 6-3).

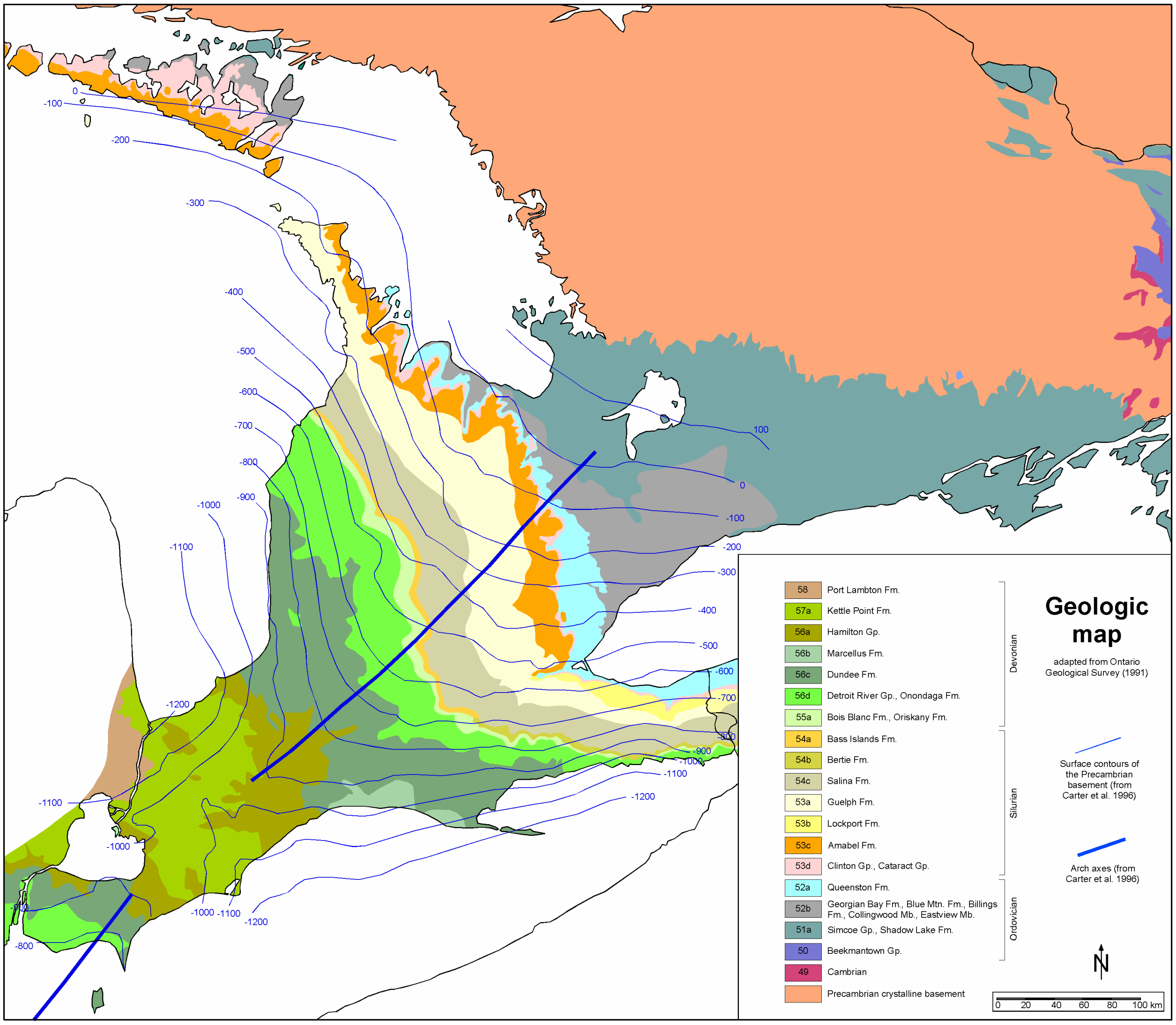


Figure 6-3: Geologic map of southern Ontario (redrawn from Ontario Geological Survey 1991) and surface contours of the Precambrian basement (from Carter *et al.* 1996).

Michigan and Appalachian Basins

The Algonquin Arch separates two major basins, namely the *Michigan Basin* to the northwest and the *Appalachian Basin* (or *Allegheny Trough*) to the southeast (Figure 1-1). Thus, in a NW-SE profile across southern Ontario, the Algonquin Arch is recognised as a basement high with thinner or missing sediments, while the thickness of the sedimentary cover increases towards the flanks. The Michigan Basin is a circular-shaped intracratonic basin with a diameter of 500 - 600 km, centred in Michigan, with a maximum depth of over 4 km. The Appalachian Basin is a foreland basin of the Appalachian orogen, and therefore elongated along the Appalachian front. The maximum thickness of Paleozoic sediments of more than 12 km is observed along the Appalachian front, with decreasing thickness towards the northwest. Given the different geotectonic situations of both basins, their architecture is markedly different. Southern Ontario includes only the distal parts of both basins, with a maximum thickness of Paleozoic sedimentary rocks slightly less than 1500 m.

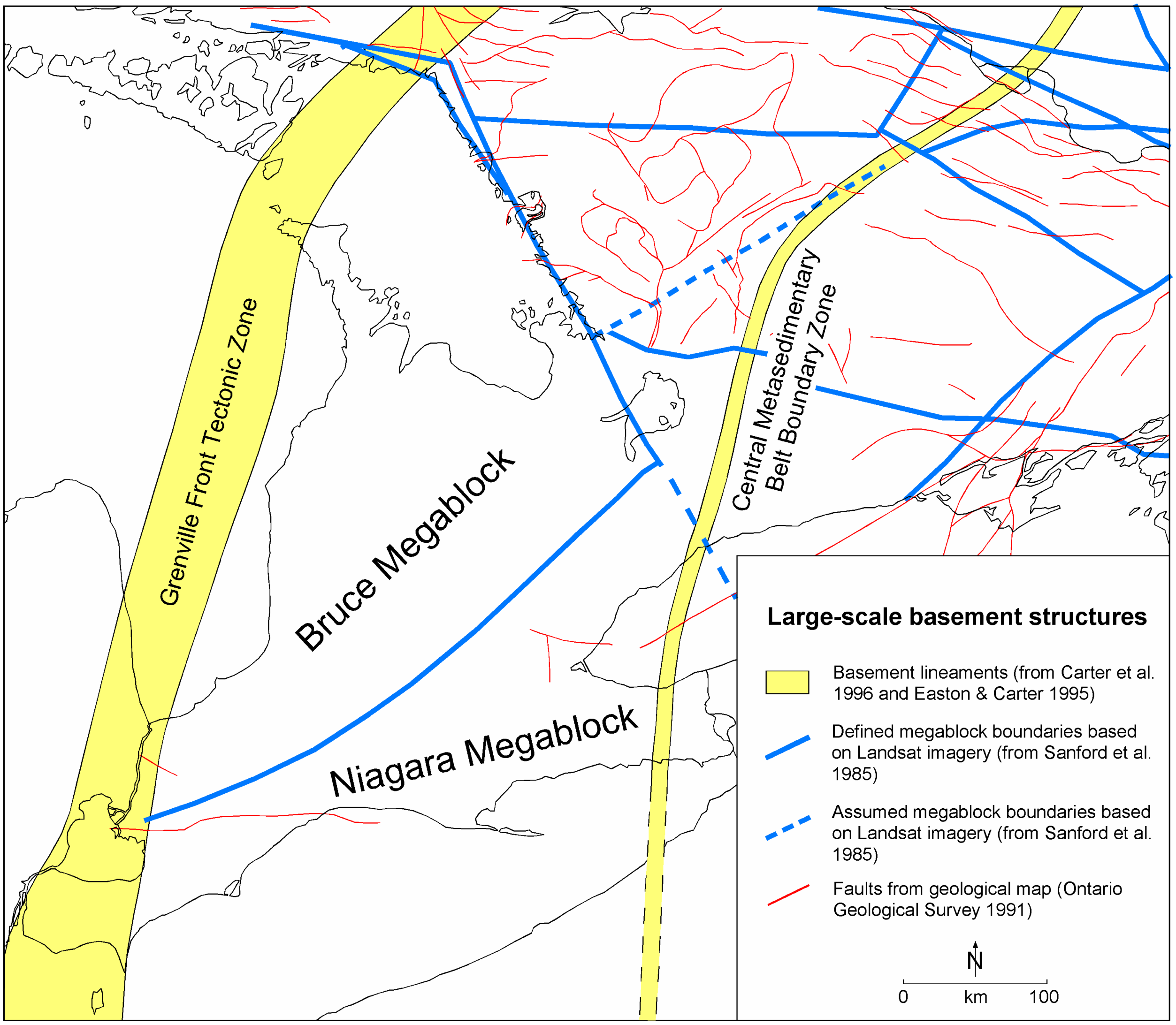


Figure 6-4: Large-scale tectonic elements in southern Ontario. Compiled from Sanford *et al.* (1985), Easton & Carter (1995) and Ontario Geological Survey (1991).

Lineaments and megablocks

Sanford *et al.* (1985) defined major lineaments in southeast Canada on the basis of Landsat imagery and interpreted these in terms of structures separating crustal blocks. Two lineaments are of interest here (Figure 6-4): One lineament runs from the Georgian Bay coast line southeast toward the Toronto area. The other lineament runs SW-NE beneath southern Ontario (and thus roughly coincides with the Algonquin Arch) and terminates at the intersection point with the first lineament. On the basis of these lineaments, Sanford *et al.* (1985) defined the *Bruce Megablock* in the northwestern part of southern Ontario and the *Niagara Megablock* in the southeastern part. They regard these blocks as units with a partly independent tectonic evolution dominated by periodic basement reactivation. They noted that the fracture pattern in the Bruce Megablock is relatively simple when compared to the Niagara Megablock. Historic earthquakes are known from the latter block but are rare in the former, even though the causal relationships are not clear.

Major structures in the Precambrian basement are the Grenville Front Tectonic Zone and the Central Metasedimentary Belt Boundary Zone (Figure 6-4, Easton & Carter 1995). These NNE-SSW trending zones in the crystalline basement do not have a clear expression in the overlying sedimentary rocks.

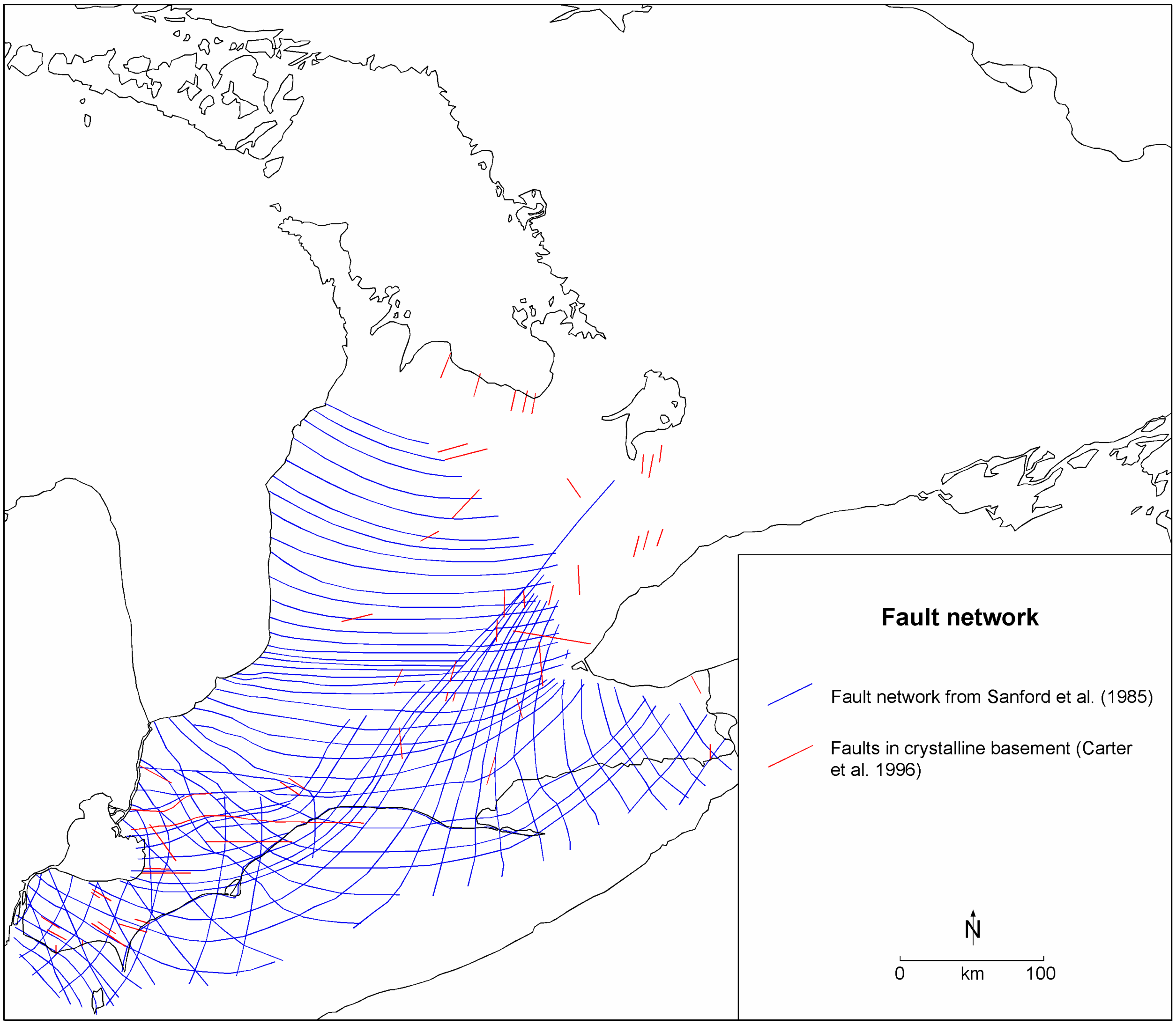


Figure 6-5: Faulting and fracturing in southern Ontario (compiled from Sanford *et al.* 1985 and Carter *et al.* 1996).

Conceptual fracture framework, basement control

On a more detailed scale, Sanford *et al.* (1985) used isopach maps of selected marker formations to derive a conceptual framework of 3 fracture systems for southwestern Ontario (Figure 6-5). Synsedimentary faulting is attributed mainly to relative movements along basement faults between the Algonquin Arch and the two basins on either side. The length of the fractures lies in the range of tens to hundreds of km, and their spacing is 10 - 30 km. They are not observed on the surface and the probability of seismic movement along them is most likely very low. Their apparent density is higher in the Niagara Megablock when compared to the Bruce Megablock. The important role of the basement is at least partially corroborated by Carter *et al.* (1996), who compiled regionally mapped basement faults (also shown in Figure 6-5). While their deterministic fault pattern is less continuous than Sanford *et al.*'s (1985) conceptual view (presumably due to data limitations permitting the identification of individual faults), some degree of consistency is observed in terms of fault orientations. Carter *et al.* (1996) identified basement faults mainly in the southern part of the region (Chatham Sag, Findlay Arch), as well as along the southwestern rim of the Algonquin Arch. Only a small density of faults was identified in the Bruce Megablock. However, this could be due to the fact that only a limited number of boreholes are available from this region, and, as a consequence, it is possible that more regional scale faults exist (T. Carter, pers. comm. 2004).

The crystalline basement surface contours illustrated in Figure 6-3 reveal a smooth regular pattern, and no correlation to faults in the overlying sedimentary cover is evident. This is in apparent conflict with profiles shown in Sanford *et al.* (1985) where vertical offsets of up to 100 m are shown in the sedimentary cover. However, the density of boreholes penetrating the Precambrian basement (>880 over the entire area of interest; cf. Figure 6-16) often does not permit detailed mapping of basement contours with a resolution better than 100 m. Seismic data indicate that most major faults identified in the sedimentary cover also displace the Precambrian basement surface and thus imply basement tectonics (T. Carter, pers. comm. 2004).

Salt dissolution and collapse structures

In the western part of the region (Michigan Basin), several salt beds were deposited in the Upper Silurian Salina Formation (members A2, B, D, F). Towards the east, the salt grades into anhydrite. Extensive salt dissolution took place recurrently, leading to salt collapse structures in the overlying uppermost Silurian and Devonian strata. The original occurrence of salt and the areas where it was dissolved are shown in Figure 6-6. This Figure is based on very detailed maps for all salt horizons published by Sanford (1976). Figure 6-7 illustrates the structures related to salt dissolution.

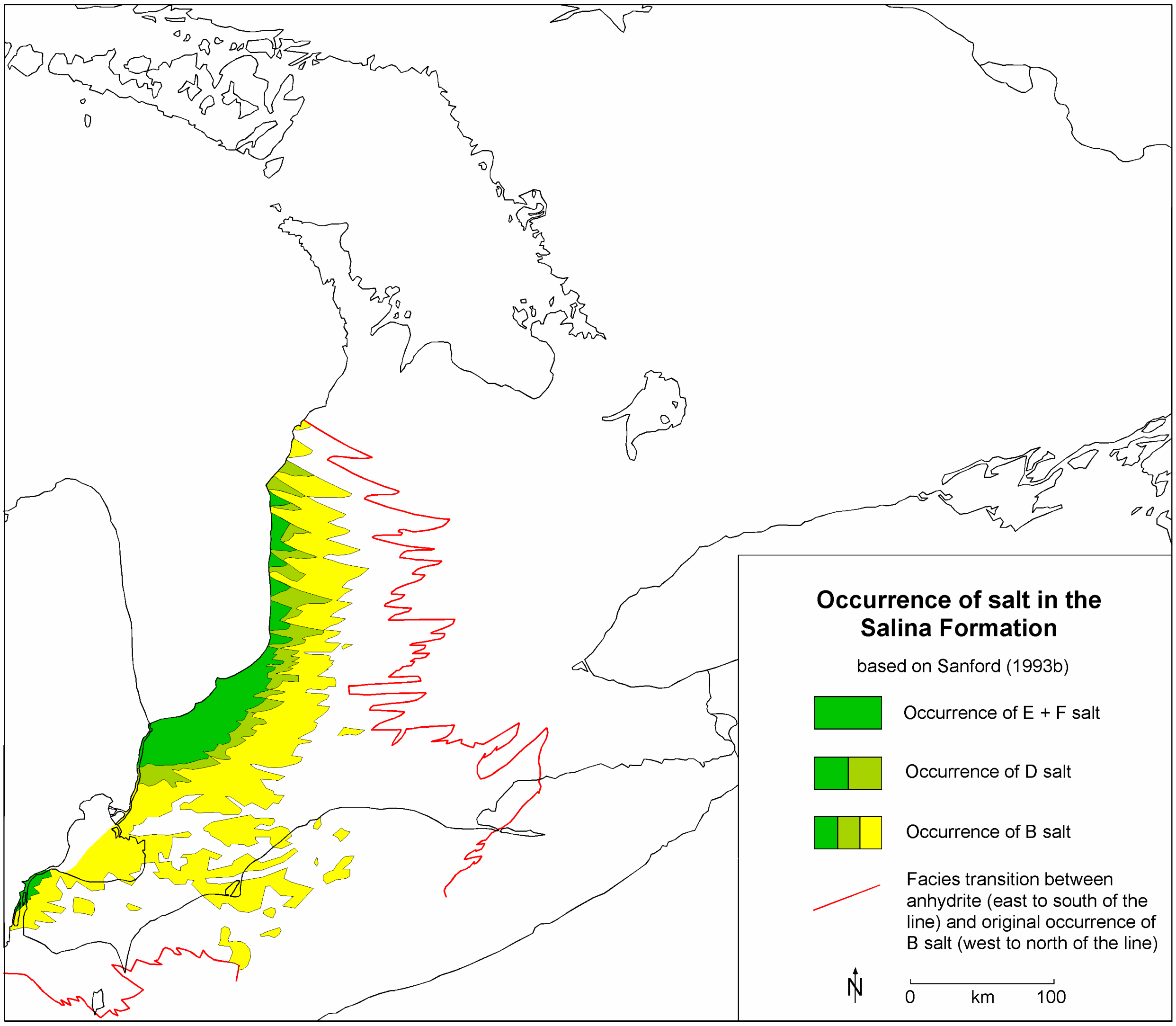


Figure 6-6: Distribution of salt in the Salina Formation in southern Ontario (from Sanford *et al.* 1985).

Geological profiles

In spite of the substantial number of boreholes, seismic investigations and surface information, only few quantitative geological profiles across and along the Algonquin Arch are available in the literature. One useful profile given by Russell & Gale (1982; redrawn from Geological Survey of Canada 1969) is shown in Figure 6-8. It runs obliquely to the Algonquin Arch from Toronto to Windsor/Detroit. Sanford (1976) provided a series of profiles across the Algonquin Arch for Silurian and Devonian strata, and a limited number of profiles are given by Brigham (1971). However, none of these profiles account for the fracture framework that was later proposed by Sanford *et al.* (1985).

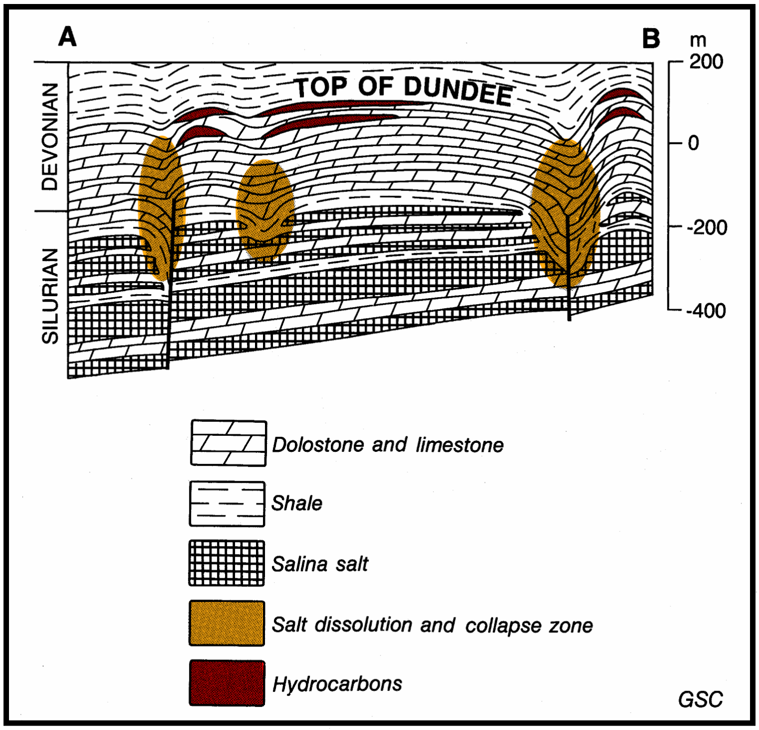


Figure 6-7: Illustration of fault-related salt dissolution in the Salina Formation. NNW-SSE profile across the Petrolia oil field near Sarnia, taken from Sanford (1993b).

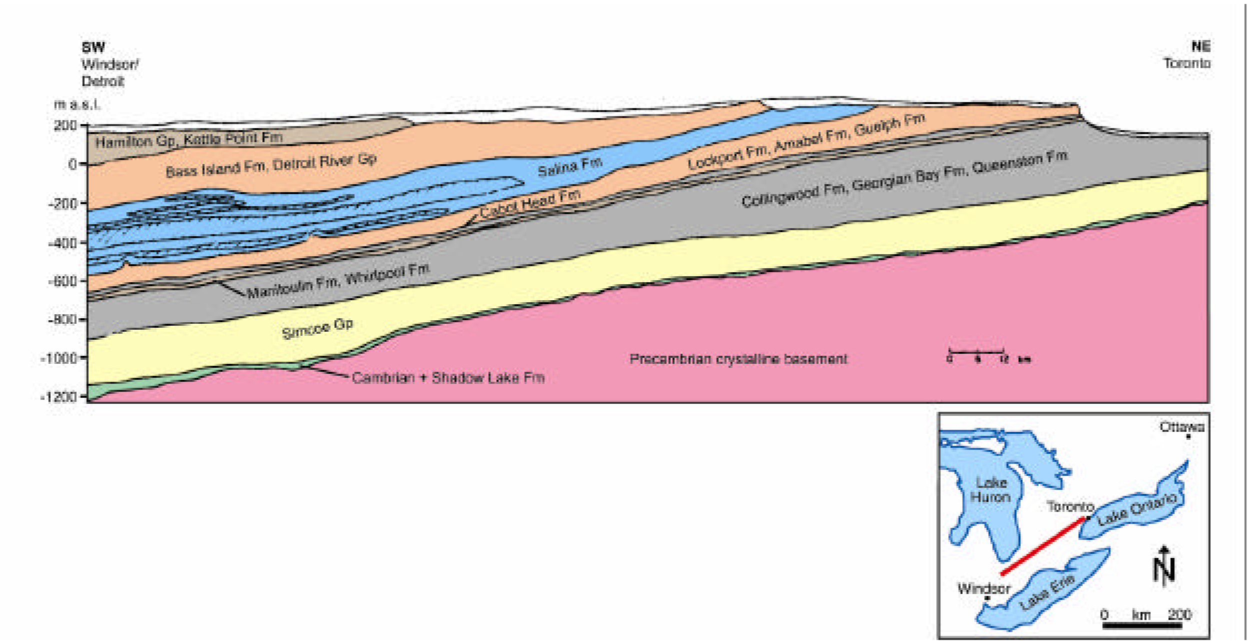


Figure 6-8: Geological profile across southwestern Ontario. The profile runs obliquely to the Algonquin Arch (profile line shown in red in the inset). Adapted from Russell & Gale (1982), who based the profile on Geological Survey of Canada (1969).

Overall, it appears that sufficient data are available for the construction of quantitative geological profiles, but full use of existing data has not been made or at least is not documented in the literature. A detailed 3D geological model of southern Ontario would be a valuable tool for visualisation. Such a model could be based on the extensive petroleum well data base of the Ministry of Natural Resources (available from the Ontario Oil, Gas and Salt Resources Library, www.ogsrlibrary.com).

6.2.2 Tectonic history

During the Phanerozoic, southern Ontario was affected by plate-tectonic processes at the margin of the craton (Sanford *et al.* 1985):

- Throughout the Cambrian to the base of the Ordovician, the tectonic regime was characterised by rifting and sea-floor spreading due to the opening of the Iapetus ocean (Proto-Atlantic). In this period, processes at the plate margin affected the craton to a very limited degree and included some faulting, uplift and plutonism.

- In Ordovician to Permian times, the geotectonic style changed substantially from spreading to contraction of the Iapetus ocean. The southeast margin of the North American plate became active, *i.e.* was characterised by contraction and finally continent-continent collision, witnessed in the Appalachian Mountain Belt. A number of extended orogenic stages can be distinguished, the most prominent being the Taconian (Upper Ordovician), Salinic (Middle Silurian), Caledonian (Lower Devonian), Acadian (base Carboniferous) and Alleghenian (Upper Carboniferous). In detail, the sequence of orogenic events is more complex and involves a larger number of unconformities in the sedimentary record (Ettensohn 1994). The processes along the plate margin led to the formation of the Appalachian Foreland Basin, which was fed by detritus of the Appalachian belt. The craton itself was also affected, mainly by epeirogenic movements of arches (such as the Algonquin Arch) and subsidence of intra-cratonic basins (such as the Michigan Basin). Sanford *et al.* (1985) pointed out the close relationship between plate tectonics and epeirogeny within the craton.

- Throughout the Mesozoic and Cenozoic, the plate margin (now further east, beyond the Appalachians) was again passive. Evidence for post-Devonian faulting (mostly related to the opening of the Atlantic Ocean) comes from the St. Lawrence Rift, *e.g.* at Charlevoix, and from the Ottawa Graben. Earthquakes in these regions indicate continued activity (mostly thrust faulting on reactivated normal faults; J. Adams, pers. comm. 2004). The degree to which the opening of the Atlantic Ocean affected southern Ontario is not clearly established.

6.3 HYDROGEOLOGICAL PROPERTIES

Hydrogeological information on sedimentary formations of southern Ontario is summarised in Novakowski & Lapcevic (1988), Raven *et al.* (1992) and Golder Associates (2003). These authors report hydraulic conductivities and heads from a number of deep boreholes in southern Ontario. In addition, Intera (1988) provide qualitative and semi-quantitative data from mines and geotechnical openings in the region, in most cases at shallow levels (even though not always fully documented). These data are regarded as secondary background information only. Singer *et al.* (1995) compiled information on transmissivity and ground water quality in the surficial flow system but did not provide information on deeper levels.

Hydraulic data are available for most formations of the layered sedimentary sequence. An apparent exception is the vertically and laterally heterogeneous Salina Formation, which has not been characterised in detail. Also, the geographic distribution of the data is not regular (Table 6-1), and so care must be taken when using formation-specific data in a region distant from the measurement point.

Table 6-1: Sources and geographic distribution of hydrogeological data

Stratigraphic age	Main data sources	Additional data sources
Devonian	Deep boreholes in Sarnia region	Tunnels (Bruce, Nanticoke), deep mines (Hagersville, Goderich, Ojibway)
Upper Ordovician (Queenston Formation) and Silurian	Boreholes in Niagara region	Tunnels (Niagara), deep mines (Drumbo, Goderich, Ojibway)
Middle and Upper Ordovician (Georgian Bay Formation - Shadow Lake Formation)	Boreholes on N shore of Lake Ontario (Missisauga/Lakeview GS, Bowmanville/Darlington NGS)	Tunnels at Darlington (N shore of Lake Ontario), boreholes at Wesleyville, shallow geotechnical excavations

6.3.1 Hydraulic conductivity

Available data for hydraulic conductivity (K) are summarised in Appendix 1 and shown graphically in Figure 6-9[5]. They all represent *in situ* experimental data based on packer tests in vertical or steeply inclined boreholes. Regarding the interpretation and application of these data, the following points should be borne in mind:

- The minimum values for K are in many cases defined by the detection limit of the test method, so actual minimum and geometric mean formation values could be lower.
- Individual packer intervals may intersect more than one formation. If a high hydraulic conductivity value is measured, it is not clear in such cases to which of the formations the value should be attributed. In the present document, no attempt was undertaken to deconvolute such packer tests, and the measured value was conservatively assigned to both formations.
- The majority of the measurements were made at depths <200 mbgs. At least for clay-rich formations, possibly also for other lithologies, increasing overburden leads to decreasing

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[5] Data from Wesleyville (Port Hope, north shore of Lake Ontario) are not considered in Figures 6-9 and 6-10. Intera (1988) report hydraulic conductivities of up to 4E-6 m/s for the Lindsay and Verulam limestones at this site. However, the data appear to be from very shallow levels (only tens of m overburden, even though not fully documented), and values given by different authors quoted in Intera (1988) are not fully consistent for this site.

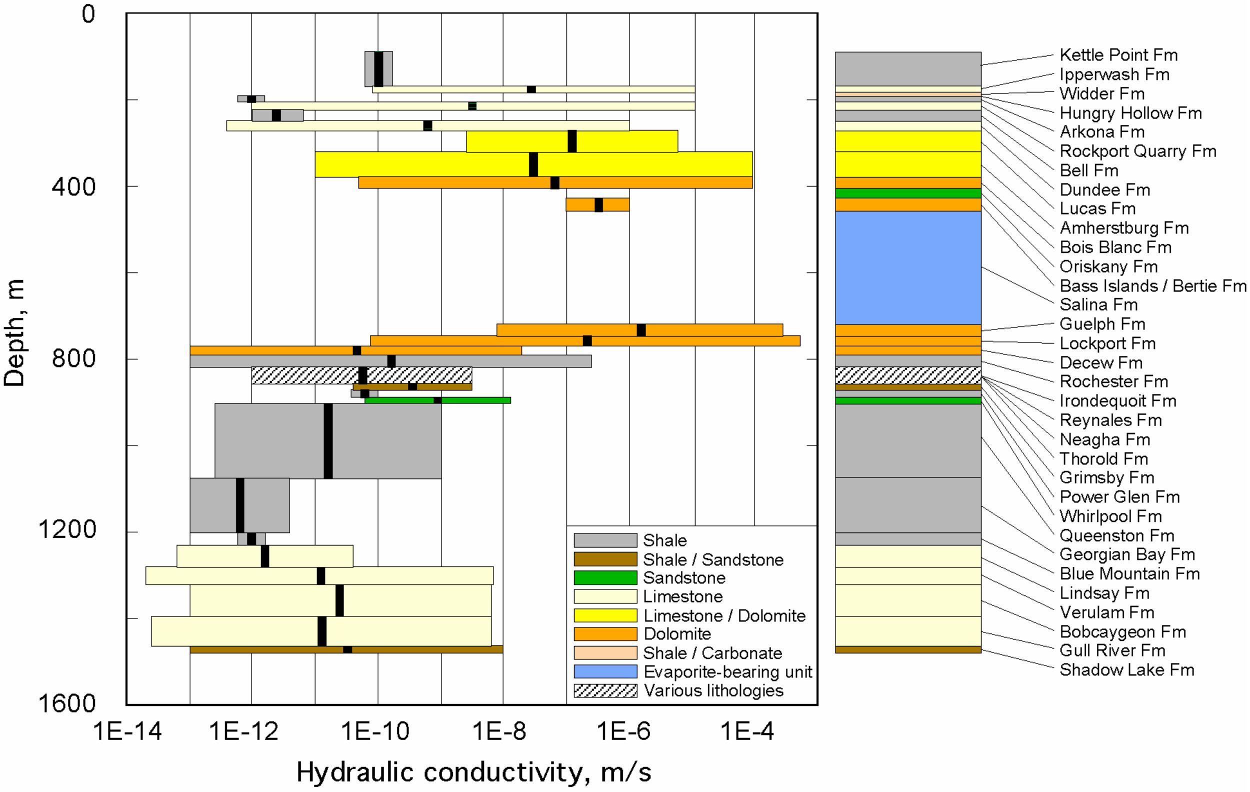


Figure 6-9: Formation-specific hydraulic conductivity values of Paleozoic formations in southern Ontario, based on *in situ* packer tests in boreholes. The stratigraphic succession is based on Sanford *et al.* (1985). Formation thicknesses and names may differ as a function of location. Hydraulic data are based on Appendix 1 where original data by Novakowski & Lapcevic (1988), Intera (1988), Raven *et al.* (1992) and Golder Associates (2003) are compiled. Lithologic data are based on Figure 6-1 and Johnson *et al.* (1992). Black bars are geometric means, coloured bars show the full range of individual measurements. No ranges are available for the Kettle Point, Arkona and Blue Mountain shales.

hydraulic conductivity (*e.g.* Hekel 1994, Gautschi 2001, Nagra 2002a). Thus the hydraulic conductivities shown in Figure 6-9 may overestimate the values at potential repository depths.

- Given the subhorizontal bedding of many formations, some degree of anisotropy of hydraulic conductivity can be expected. Conductivity values that relate to the vertical direction may be lower than the ones measured in (mostly vertical) boreholes.

In spite of these limitations, recognisable correlation between rock type and hydraulic conductivity is evident. Based on the data in Appendix 1, rock type-specific ranges are given in Figure 6-10. It is obvious that dolomites and dolomitic limestones have the highest hydraulic conductivities and so presumably represent potential regional aquifers. On the lower end, shales and dolomite-free (often argillaceous) limestones have the lowest hydraulic

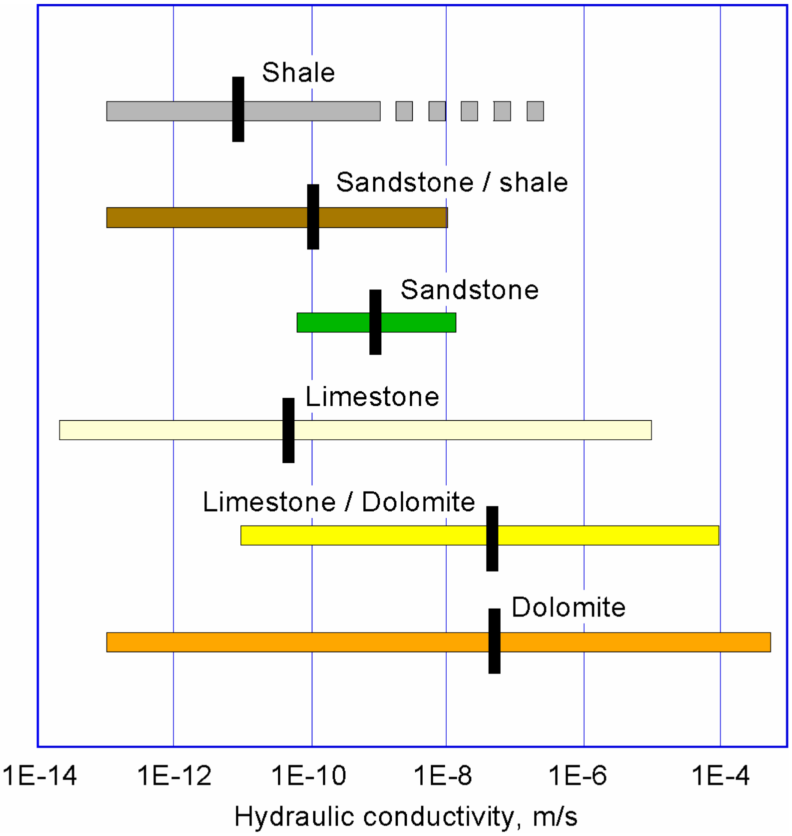


Figure 6-10: Hydraulic conductivity of Paleozoic formations in southern Ontario as a function of rock type, based on *in situ* packer tests in boreholes. Hydraulic data are based on Appendix 1 where original data by Novakowski & Lapcevic (1988), Intera (1988), Raven *et al.* (1992) and Golder Associates (2003) are compiled. Lithologic data are based on Figure 6-1 and Johnson *et al.* (1992). Black bars are geometric means, coloured bars show the full range of individual measurements. For shale, all data indicate K <1E-9 m/s, with the exception of one outlier in Rochester Shale (52 m overburden). The outlier is shown by stippling and was also included in the calculation of the geometric mean.

conductivities. The good correlation between rock type and hydraulic behaviour facilitates the extrapolation of the data to formations and regions for which hydraulic data are not available. If at least the lithologies are known, the expected range of formation specific hydraulic conductivity can be estimated. This feature also facilitates the extrapolation of measured values in the horizontal dimension, provided the lithology is laterally homogeneous. Thus, this approach at least partially reduces uncertainties arising from the scarcity of existing data in certain geographic regions.

The vertical distribution of hydraulic conductivity in the sedimentary sequence of southern Ontario, as illustrated in Figure 6-9, can be subdivided into 8 hydrogeologic units as shown in Table 6-2. The only criteria used for this subdivision include 1) hydraulic conductivity and 2) lithology. Note that the hydrogeologic units do not always correspond to the sedimentary sequences shown in Figure 6-1 because the latter are defined by major unconformities in the sedimentary record. For example, limestones and dolomites would, from a sedimentological

Table 6-2: Hydrogeological units in Paleozoic sedimentary rocks of southern Ontario

Hydrogeol. unit no.	Age	Formations from	Formations to	Thickness in Michigan Basin, m	Thickness in Appalachian Basin, m	Dominant lithologies	Hydrogeological characteristics
8	Middle to Upper Devonian	Dundee Fm	Kettle Point Fm	200	160	Shale, limestone	Generally very low (shales) to moderate hydraulic conductivities, with some high values in limestones (mainly Dundee Fm). The shales most likely act as barriers for vertical flow
7	Upper Silurian to Middle Devonian	Bass Islands / Bertie Fm	Lucas Fm	340	125	Dolomite, (limestone)	High hydraulic conductivity, potential aquifer
6	Upper Silurian	Salina Fm		400	160	Heterogeneous, containing evaporites: salt, dolomite, (shale, anhydrite)	No hydraulic data are available. Evaporitic beds most likely act as barriers for vertical flow, but horizontal flow may take place *e.g.* in dolomitic beds
5	Middle Silurian	Decew Fm	Guelph Fm	55	150	Dolomite	High hydraulic conductivity, potential aquifer
4	Lower to Middle Silurian	Whirlpool / Manitoulin Fm	Rochester Fm	40	160	Heterogeneous: shale, (limestone, sandstone) in Appalachian Basin; dolomite, shale in Michigan Basin	Generally low hydraulic conductivity. However, existing data relate exclusively to the Niagara region. Due to westward facies change towards dolomitic rocks, higher conductivities can be hypothetically inferred for the Michigan Basin. The Rochester Fm is missing N of a line connecting Goderich and Hamilton
3	Upper Ordovician	Blue Mountain Fm	Queens-ton Fm	220	500	Shale	Very low hydraulic conductivity, all geometric means <1E-10 m/s, all reported values <1E-9 m/s
2	Middle to Upper Ordovician	Gull River	Cobourg / Lindsay Fm	250	220	Limestone	Very low hydraulic conductivity, all geometric means <1E-10 m/s, all reported values <1E-8 m/s. Qualitative and semiquantitative arguments indicate some higher values and/or spatial heterogeneity
1	Cambrian - Lower Ordovician	Mount Simon / Potsdam Fm	Shadow Lake Fm	50	100	Sandstone, dolomite	Lower part not tested; presumably contains horizons with higher hydraulic conductivity

Note: Thicknesses represent only approximate guidelines due to lateral variability.

point of view, typically be attributed to the same sequence because they are both carbonates. On the other hand, due to their contrasting hydraulic properties, they are distinguished in a hydrogeological classification.

The thickness of each bedrock formation is known to vary regionally. The thicknesses of the hydrogeologic units listed in Table 6-2 provide an average estimate determined from inspection of Figure 6-2 and a review of petroleum well records by T. Carter (pers. comm. 2004).

The following points can be made on the hydrostratigraphic conditions:

- Hydrogeological units 5 and 7 are dominated by dolomites and have high hydraulic conductivities. These units are the main potential regional aquifers, particularly where they occur near surface.
- On the other end of the spectrum, units 2 and 3 have very low hydraulic conductivities and so represent aquicludes. It is remarkable that not only the shales but also the underlying limestones have such low values.
- In the framework of hydrochemical investigations, McNutt *et al.* (1987) sampled formation waters from a substantial number of boreholes in southwestern Ontario and southeastern Michigan (see also Chapter 6.4). The fact that they were able to retrieve waters from the Trenton Group limestones (hydrogeological unit 2) at several locations means that this unit may have an appreciable hydraulic conductivity, even though no quantitative measurements were reported. The enhancement of hydraulic conductivity is probably due to local dolomitisation along faults. Thus, for this unit, the site-specific representativity of the data given in Figure 6-9 requires further investigations.
- The Salina Formation (unit 6) is sandwiched between the dolomite aquifers of units 5 and 7. Due to the presence of evaporites and some shales, lithologies of presumably very low hydraulic conductivity limit vertical advection, while horizontal flow is possible. Salt dissolution resulted in collapse structures, which are possible pathways for fluid flow.
- A similar anisotropy of large-scale hydraulic conductivity is expected in the lithologically heterogeneous units 1, 4 and 8.

6.3.2 Hydraulic head

Information regarding formation pressures is documented in Novakowski & Lapcevic (1988) and Raven *et al.* (1992). Further data, *e.g.* from hydrocarbon wells throughout southwestern Ontario, may exist but were not obtained for this study. The calculation of environmental heads on the basis of pressure measurements requires the consideration of fluid density, given the presence of brines even at relatively shallow levels (see below).

Novakowski & Lapcevic (1988) studied hydraulic conductivity and hydraulic head in boreholes penetrating Upper Ordovician to Middle Silurian strata (Queenston to Guelph Formations) of the Niagara region. Hydrostatic pressures were found in the Guelph Formation, which occurs at shallow levels (less than 60 mbgs) and is in hydraulic communication with the upper Niagara River. All underlying units (Lockport, Clinton and Cataract Groups, Queenston Formation, max. 150 mbgs) show substantial (often 20 - 50 m) over- or underpressures. Underpressures are likely due to the proximity of the Niagara Gorge (hydraulic connection of dolomite aquifers to exfiltration areas at lower elevation). Overpressures are at least partially related to low-permeability units such as the Rochester Shale. They were not evaluated quantitatively by

Novakowski & Lapcevic (1988). The largest vertical hydraulic gradients often occur along lithological contacts to shales (Rochester, Neagha and Queenston Formations), and this can be taken as evidence of very low hydraulic conductivity in these units at least in the vertical direction.

Raven *et al.* (1992) studied hydraulic heads in a number of boreholes throughout southern Ontario. They identified overpressures at remarkably shallow levels of 50 - 310 mbgs (up to 1.7 times hydrostatic). The highest overpressures correlate with gas shows (in fractures or in limestone beds) in otherwise low-permeability shales, shaly limestones or shaly sandstones. In specific, major overpressures were identified in the Ordovician Simcoe Group (Gull River, Bobcaygeon, Verulam and Lindsay limestones), in the Silurian Clinton Group (mainly Rochester shale) and in the Devonian Hamilton Group (Bell and Arkona shales, Rockport Quarry limestone). The overpressures are explained by up-dip gas migration in permeable strata, with subsequent accumulation in low-permeability caprocks. A vertical migration distance of 50 - 100 m (corresponds to 6 - 18 km in the horizontal direction) is sufficient to explain the observations. The role of the shaly formations as capping units indicates that these rocks have a very low large-scale permeability and so efficiently retain gas.

6.4 HYDROCHEMICAL PROPERTIES

6.4.1 Hydrogeochemistry

Ground-water samples were taken from oil- and gas-producing wells and so are restricted to southwestern Ontario and to the deeper parts of the Michigan Basin in Michigan. No data are available from the northern part of the study area, or from very low-permeability formations (such as shales) anywhere in the study area. McNutt *et al.* (1987) and Frape *et al.* (1989) reported and interpreted a data base consisting of major-ion concentrations, stable isotope data of water and $^{87}Sr/^{86}Sr$ ratios from 14 boreholes. Radioactive isotopes that could provide age information were not analysed. Sampling depths were not indicated but are >300 m in most cases. The main findings reported were:

- Most waters are Na-Ca-Cl or Ca-Na-Cl brines (Total Dissolved Solids typically 200 - 300 g/L). Representative chemical compositions are given in Table 6-3.

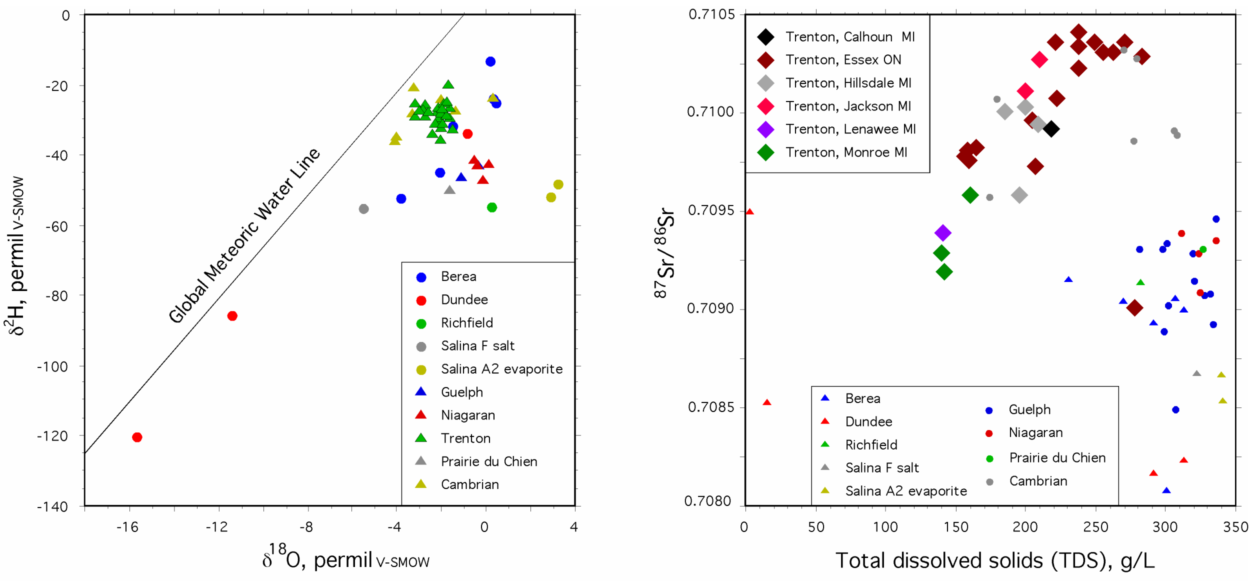
- In a $\delta^{18}O$ *vs.* $\delta^{2}H$ plot (see Figure 6-11), the values for all formations (except some shallow samples from the Dundee Formation and the Upper Detroit River Group, see below) lie on the right side of the Global Meteoric Water Line. This is a typical feature in many sedimentary basins (see, for example, Kharaka & Carothers 1986) and is taken as an indication of very long residence times and *in situ* water/rock interaction. The evolutionary or mixing trends (slopes in the plot) defined by the samples are consistent with previous data from the Michigan and Appalachian Basins.

- $^{87}Sr/^{86}Sr$ of most samples is higher than the sea-water value at the time of deposition of the hosting formation. This trend is clearest in the Ordovician units and is taken as evidence of water/rock interaction and, thus, of long residence times.

Table 6-3: Representative compositions of formation waters from southwestern Ontario and from southeastern Michigan

	Precambrian	Cambrian	Trenton Gp	Guelph Fm	Salina Fm	Dundee Fm
Ca	65.0	48.0	32.5	31.3	8.2	31.5
Na	16.9	43.8	49.7	65.5	100.0	70.6
Mg	0.01	6.09	5.96	7.77	2.85	5.41
K	0.12	1.39	2.07	1.88	2.60	3.03
Sr	1.39	1.21	0.62	0.435	0.215	0.75
Cl	156.0	179.8	150.3	189.0	207.0	179.0
Br	1.09	1.53	1.19	1.39	0.59	1.05
SO_4	1.14	0.26	0.335	0.25	0.75	0.165
TDS	241.0	282.0	242.7	297.6	322.2	291.6

Data are in g/L. Source: McNutt *et al.* (1987).



a. b.

Figure 6-11: Chemical characteristics of formation waters from southwestern Ontario and Michigan (data from McNutt *et al.* 1987).
a. Stable water isotopes.
b. Total dissolved solids *vs.* $^{87}Sr/^{86}Sr$. Sampling areas are indicated for the Trenton Group.

- In diagrams of $\delta^{18}O$ *vs.* $\delta^{2}H$ (Figure 6-11), Sr *vs.* $^{87}Sr/^{86}Sr$ (Fig. 5 in McNutt *et al.* 1987), K/Na *vs.* Br/Cl (Dollar *et al.* 1986) and other isotope plots (S. Frape, pers. comm. 2004), each formation has a distinct field, with only limited overlap. This can be taken as evidence of separate ground water evolution in each of the sampled formations and, thus, as an argument against hydraulic connections between them. Some overlap is observed between the data of the Trenton Group limestones and the underlying Cambrian units.

- Three different ground water mixing trends are recognised on the basis of Na and Ca contents. 1) The dominating trend is a mixing line of Na-rich, Ca-poor waters originating from salt dissolution with Ca-rich, Na-poor waters typical of the deep Michigan Basin. This trend is best seen in Silurian carbonates. 2) A secondary trend indicates dilution of the brines by less saline waters and is mainly recorded in Silurian sandstones. 3) A third trend indicates dilution by Ca-poor but relatively Na-rich water. It is best seen in Ordovician carbonates and in Silurian sandstones. The origin of this fluid is speculative but could represent northward migration of dilute Na-Cl basin fluids from the Findlay Arch region (Frape *et al.* 1989). There is no information regarding the time when the three mixing processes occurred.

- McNutt *et al.* (1987) report hydrogeochemical data from the Trenton Group limestones (Middle to Upper Ordovician) from six different locations. Some locations lie on the axis of the Algonquin/Findlay Arches (*e.g.* Essex, Monroe), others are located in the deeper part of the Michigan Basin (*e.g.* Jackson and Hillsdale, some 150 km west of Essex). Two observations can be made: 1) Irrespective of the location, water isotopes show near-identical ratios over the entire area (see Figure 6-11), 2) TDS and $^{87}Sr/^{86}Sr$ show some variation and correlate positively (Figure 6-11), which is consistent with mixing trend 3 above.

- From a geochemical point of view, there is no relationship between the sedimentary brines and those in the underlying Precambrian basement.

In the Chatham Sag and in Lakes Ontario and Erie, water samples with distinct properties were taken at shallow levels:

- McNutt *et al.* (1987) report waters from the Middle Devonian Dundee Formation (limestone) in Elgin County with 3 - 15 g/L TDS. The sample depth is estimated at ca. 150 mbgs based on available geological maps and profiles. The $\delta^{18}O$ and $\delta^{2}H$ values of these samples lie close to the Global Meteoric Water Line and indicate recharge under cold (*i.e.* glacial) climatic conditions. It appears that the overlying Hamilton Group shales locally have a permeability high enough to allow infiltration of meteoric water. The enhanced permeability of shales at depths less than 200 m is a well-known observation elsewhere (*e.g.* Gautschi 2001).

- In a region southeast of Sarnia, saline waters were sampled at shallow levels (<150 mbgs) in the Dundee Formation (16 - 25 g/L) and in the underlying Detroit River Group (13 - 53 g/L) (Weaver *et al.* 1995). Most of these waters can be explained as mixtures of formation waters and meteoric waters that infiltrated before and during oil production. At one locality, a deeper component (interpreted as a mixture of 1) brines from the underlying Silurian Salina Formation or the Lower Detroit River Group and 2) glacial water) is evident. Weaver *et al.* (1995) concluded that this situation reflects cross-formational upward flow. The locality is in an area where several mappable faults occur (Brigham 1971). Given the fact that oil migrated into post-glacial till in this area, upward hydraulic gradients have existed in geologically recent times and may also have affected the upward movement of the deeper fluids. While such a model would be consistent with the available data, it is not unique (incomplete chemical characterisation of the system volume) and could be strengthened or disqualified if water ages based on radioactive isotopes were available.

- S. Frape (pers. comm. 2004) identified waters with a salinity of up to 5 g/L in lake-bottom sediments of Lakes Ontario and Erie and attributes them to recent exfiltration from the bedrock. The locations where this situation occurs can be correlated with known, major tectonic features in the crystalline basement (see Figure 6-4). The observed salinity, whether due to advection or diffusion, relates to hydrogeologic features that occur at shallow levels, and more investigations would be needed to clarify the relevance for depths of several hundreds of metres.

6.4.2 Interpretation

The implications related to flow system evolution based on hydrogeochemical evidence are:

- Except for very shallow levels, there is ample evidence for very long underground residence times of the brines (salinity, water and Sr isotopes).

- Admixtures of a dilute Na-Cl brine and of a low-salinity glacial water can be recognised in some formations. The time at which the first mixing occurred is unknown.

- Some chemical and isotopic characteristics can be used to discriminate among formations. The existence of such formation-specific characteristics argues against cross-formational connectivity and flow since burial diagenesis (at which time major flow events did occur, see Chapter 6.6.3). Similarities exist between brines in Middle Ordovician and in Cambrian formations.

- One case of geologically young cross-formational flow in the Chatham Sag is described in the literature (Weaver *et al.* 1995). While the interpretation of the data is not unique, in principle, such flow could occur at a local scale via well-known faults shown in Figure 6-3 or along faults related to the dissolution of salt in the Salina Formation. The study relates to possible vertical flow in Devonian and Silurian formations but not in the underlying Ordovician.

- Based on unpublished data, S. Frape (pers. comm. 2004) concluded that overlaps in the chemical and isotopic characteristics of different formations, documenting cross-formational flow events, do occur but are restricted to the major tectonic boundaries in the crystalline basement (Grenville Front Zone and Central Metasedimentary Belt Boundary Zone, see Figure 6-4).

- No data on radioactive isotopes are available, thus only indirect evidence exists on the age structure of the brines. In principle, the present-day brine composition could represent a mixture of an even more saline fluid and a young, meteoric component with a proportion of up to several tens of percent. Such an interpretation is highly speculative and unlikely because it contradicts other lines of evidence. It could be further disqualified in future by absolute dating methods.

- The Trenton Group limestones are the only unit for which good spatial information is available (6 sites, see Figure 6-11). The similarity of water isotope data over the whole region suggests that mixing with meteoric water that could have descended along faults did not occur. In such a case, some degree of spatial heterogeneity in the water isotope data would be expected.

6.5 REGIONAL FLOW SYSTEM

Literature dealing with the large-scale flow conditions within southern Ontario is not currently available, and so only some general observations can be made based upon the data previously described.

1. *Boundary conditions*

- Lateral boundary conditions: The elevations of Lake Huron/Georgian Bay and Lake Erie are almost identical (177 and 174 masl). Lake Ontario is lower, with an elevation of 75 masl The basement unconformity (outcropping along an E-W line connecting Georgian Bay and Kingston) has an elevation of ca. 200 - 300 m in the western and central parts and then drops to the level of Lake Ontario in the east.

- Topographic relief: Southern Ontario is a flat region in the areas where Devonian (in the southwest part) and the Ordovician (in the northeast part) rocks crop out (Figure 6-3). Relief is more pronounced in the central part where Silurian carbonates crop out, especially at the Niagara Escarpment along the Ordovician/Silurian boundary. The highest elevation of 546 m is located some 20 km south of the southern end of Georgian Bay.

2. *Geometric aspects of potential aquifers, in- and exfiltration areas*

- Based on Table 6-2, the main potential aquifers are the dolomites of hydrogeological units 7 (Upper Silurian to Middle Devonian) and 5 (Middle Silurian). Unit 1 (Cambrian to Lower Ordovician) possibly represents a small and relatively thin aquifer. The bands along which these aquifers crop out can be seen in Figure 6-3 and represent the most relevant potential in- or exfiltration areas.

- Anisotropy of hydraulic conductivity and of the regional flow system: The aquifers are separated by hydrogeological units of low to very low hydraulic conductivity. Large-scale water flow in the aquifers is expected to be confined by the low-permeability shale, limestone and evaporite beds above and below the aquifers. Thus flow could occur within individual aquifer formations but would be limited across the horizontally layered sedimentary sequence, unless major sub-vertical faults exist that provide connected hydraulic pathways.

- The hydrogeochemical characteristics of formation waters indicate a separate geochemical evolution in each potential aquifer. Except for a possible hydraulic connection between hydrogeological units 1 and 2, there are no indications for migration pathways across low-permeability shale and limestone formations (however, the evidence base is limited and should be confirmed).

- Geometry of hydrogeological units and flow directions: Strata generally dip gently to W-SW-S (see Figure 6-8). Should deep infiltration into the potential aquifers occur[6], the flow directions would have to be down-dip into the deeper parts of the Michigan and Appalachian Basins.

- All formation waters (except at very shallow levels) are brines that have not been noticeably diluted by young meteoric waters. The high density of the brines renders the deep penetration of fresh water physically difficult.

3. Regional flow pattern

- Fresh water infiltrating into the potential aquifers is most likely expected to have a major strike-parallel component of flow for reasons of buoyancy (the density of the brines is substantially higher than that of fresh water) and due to the absence of exfiltration areas (and therefore of hydraulic gradients) for waters flowing into the deep basins. Thus shallow-level flow would occur from the spine of the Algonquin Arch towards the Basins to the northwest and southeast.

- If topographic relief is considered as the main driving force for flow, waters infiltrating into the Silurian sedimentary rocks at the point of highest elevation would be driven by hydraulic gradients of ca. 0.005 towards southeast (Hamilton) or ca. 0.004 towards northwest (Bruce Peninsula). Large-scale, shallow-level hydraulic gradients elsewhere in southern Ontario are presumably smaller.

- Given the very long underground residence times of the brines underlying the shallow-level flow system, it is likely that these formation waters have been stagnant or moving very slowly over geological periods of time.

- Major faults are known in the Chatham Sag (Electric, Dawn, Kimball-Colinville) and were documented by Brigham (1971) and Carter *et al.* (1996). Whether cross-formational flow occurred in these structures is not currently clear.

- The depth and nature (shape and sharpness) of the interface between the shallow-level flow system and the underlying brines is not well documented and, in order to be properly addressed, would require additional investigations. Some data may exist from hydrocarbon wells but were not available for this study.

- Overpressures identified in low-permeability formations are possibly due to gas migration from greater depth. In principle, it is possible that gas migration provides a mechanism for basin-scale water flow towards the basin edges. Such a slow upwelling of water would not be easily recognised on the basis of the available data set. However, this scenario is no more than a speculation that should be considered when describing the full spectrum of plausible alternatives.

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[6] NB: This is an extreme, very unlikely hypothesis that is contradicted by several independent data sets. It is mentioned here in the sense of a conservative "what if ?" scenario.

- Indications of shallow-level hydraulic gradients directed upward exist in the Chatham Sag (oil in postglacial till) and in Lakes Ontario and Erie (enhanced salinity in lake-bottom sediments). All these occurrences correlate with known tectonic structures. Hydraulic gradients at depth are not well characterised and require further studies.

- The present-day geothermal gradient in southern Ontario is low (14 - 23 °C/km, depending on rock type; see Speece *et al.* 1985), and no regional variation is documented. It appears unlikely that thermal effects could act as driving forces for regional flow.

To summarise: the flat-lying sedimentary rocks form a sequence of layers with highly contrasting hydrogeological properties, *i.e.* a succession containing both potential aquifers and aquicludes. In spite of the presence of potential aquifers, flow is very limited below a shallow-level flow system[7]. More site-specific data would be required to support this hypothesis.

6.6 DIAGENESIS AND BASIN EVOLUTION

6.6.1 Maximum burial depth

The Paleozoic sedimentary sequence contains numerous erosional gaps (Figure 6-1), but the individual unconformities are considered to represent <100 m erosion each and therefore are of little relevance for the overall evolution of the basin (Cercone & Pollack 1991). The most complete sedimentary record (up to Upper Devonian) is found in the Chatham Sag, where the crystalline basement unconformity is at ca. -1000 masl (Figure 6-3). The amount of post-Devonian erosion increases when moving northeast along the Algonquin Arch, and progressively older strata are exposed on the surface. In the Lake Simcoe area, where the crystalline basement unconformity is located at ca. 100 masl, the amount of erosion is more than 1000 m greater than that occurring in the region of the Chatham Sag.

The youngest rocks cropping out in southern Ontario (Upper Devonian, very small occurrences of Mississippian) were probably buried under Permo-Carboniferous and/or Mesozoic sediments now eroded. For the deep Michigan Basin, Cercone (1984) and Cercone & Pollack (1991) argue for a missing Carboniferous section of 1000 m, which may also have been present (in reduced thickness) in southern Ontario. Very immature Upper Jurassic sediments in Michigan indicate that the Michigan Basin was stable since that time and no further sedimentation occurred.

Coniglio & Williams-Jones (1992) extrapolated Cercone's (1984) data to the northeast Michigan Basin (outcropping today on Manitoulin Island) and concluded that the maximum depth of burial of the Middle Ordovician Trenton Group limestones was >1500 m. However, this value is uncertain, if not speculative, due to the absence of site-specific information.

It is concluded that all sedimentary rocks of southern Ontario are over-consolidated, with higher over-consolidation ratios in the northeast and lower values in the southwest. However, the absolute values are not well constrained.

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[7] The depth of the interface between the shallow flow system and the underlying stagnant brines is not well characterised but probably varies between a few tens of m to a maximum of ca. 200 m.

6.6.2 Maximum temperature and palaeo-geothermal gradient

The thermal history of southern Ontario is not well characterised, one of the reasons being the scarcity or absence of vitrinite in the organic matter. On the basis of conodont and acritarch alteration parameters, Legall *et al.* (1981) estimated burial temperatures of <60 °C for the Upper Ordovician to Devonian, and 60 - 90 °C for the Cambrian to Middle Ordovician. Powell *et al.* (1984) concluded that the Cambrian to Silurian formations are mature with respect to petroleum generation, whereas the Devonian is marginally mature or immature. Macauley & Snowdon (1984) and Baird & Brett (1989) identified an increase in maturity from northwest (Manitoulin Island) to southeast (Toronto, New York State).

Obermajer *et al.* (1996) used a multitude of maturity indicators and calculated equivalent vitrinite reflectance values. The results are summarised in Table 6-4, together with temperatures derived from these data using the EasyR_0 approach of Sweeney & Burnham (1990) for different times of burial. While these times are not well known, they are most likely within the range 50 - 200 Ma as shown in Table 6-4. The resulting temperatures are slightly higher than those given by Legall *et al.* (1981). They also show a higher maturity in the southeast (Toronto) when compared to the northwest (Georgian Bay).

Table 6-4: Vitrinite reflectance (VR) data derived by Obermajer *et al.* (1996) and calculated burial temperatures using the EasyR_0 approach of Sweeney & Burnham (1990)

Formation	Age	Area	calculated VR, %R_0	T_{max}, °C for a burial lasting 50 Ma	100 Ma	200 Ma
Marcellus Formation	Middle Devonian	Southern part of southern Ontario	0.52	77	73	70
Blue Mountain Formation	Upper Ordovician	Southern part of southern Ontario	0.71	103	99	95
Collingwood Member	Upper Ordovician	Toronto area	0.69	100	96	93
Collingwood Member	Upper Ordovician	Georgian Bay area	0.48	70	67	63

In the deep parts of the Michigan Basin (in Michigan), Cercone & Pollack (1991) modelled the maturity of organic material. The observed maturity cannot be explained by the present-day thermal regime, and so deeper burial and/or higher heat fluxes must be invoked. The latter alone cannot explain the data because they do not account for the observed degree of maturity at shallow levels. The most plausible solution is the assumption of an "insulating blanket" consisting of 1000 m thick shaly, coal-bearing Carboniferous sediments (now eroded) with low thermal conductivity. Such a blanket, together with an average geothermal gradient of 40 - 60 °C/km(8), could explain the observed maturity level of all Paleozoic strata and implies maximum

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[8] These values are results of the model calculations and have no independent basis. They are substantially higher than present-day gradients. Assuming a Carboniferous blanket thicker than 1000 m would yield lower gradients, and vice versa.

temperatures of 40 - 60 °C for the Upper Devonian. The transferability of these findings to southern Ontario is not clear. However, a similar, even though less strongly pronounced, blanketing effect can be envisaged.

6.6.3 Rock/water interaction and fluid migration

The most important diagenetic processes that involved major fluid migration include

- dolomitisation of limestones
- partial dissolution of Silurian salt
- generation and migration of hydrocarbons.

Dolomitisation

By extent, dolomitisation of limestones is the most relevant diagenetic feature. Several Cambrian, Silurian and Devonian formations are heavily dolomitised, while the effects are less pervasive in the Ordovician (see Figure 6-1). Shale diagenesis is not addressed in detail in the literature.

The dolomitisation of the Middle and Upper Ordovician carbonates is bound to fractures, even though it may be locally pervasive (Coniglio & Williams-Jones 1992, Middleton *et al.* 1993 and Coniglio *et al.* 1994). Dolomitisation also occurred in the Upper Ordovician shales, suggesting that at some time these units were open to diagenetic fluids. The dolomitising fluids originate either in the deeper parts of the Michigan or Appalachian Basins or in the overlying Silurian evaporites. The timing of deep burial diagenesis is not well constrained but most likely Late Paleozoic - Early Mesozoic. Coniglio & Williams-Jones (1992) attributed dolomitisation of Ordovician limestones to burial diagenesis, most likely triggered by compaction-derived brines that travelled up dip from the deeper parts of the Michigan Basin. Dolomitisation of the overlying Silurian sequence was probably due to the ingress of sea water, possibly triggered by hydrothermal fluid circulation. According to fluid-inclusion data, the diagenetic fluid was a Ca-Cl ± Mg-Cl brine. The same fractures along which dolomitisation occurred acted as conduits for hydrocarbon migration.

Middleton *et al.* (1993) and Coniglio *et al.* (1994) identified fluid inclusions in diagenetic dolomite with homogenisation temperatures of up to 220 °C in Ordovician carbonates of Manitoulin Island and of southwestern Ontario. They attribute these high temperatures to hydrothermal fluids that migrated along fractures, even though the heat source (presumably in the crystalline basement) is not known. Hydrothermal convection cells could provide a mechanism for dolomitisation as well as for the occurrence of small Mississippi-Valley Type (MVT) Pb-Zn deposits in dolomites. According to S. Frape (pers. comm. 2004), small MVT deposits occur mainly along the main basement structures shown in Figure 6-4 (Grenville Front Zone and Central Metasedimentary Belt Boundary Zone) and trend towards the big MVT deposits of Illinois and Indiana.

Salt dissolution

At least a substantial part of salt dissolution that is observed along the spine of the Algonquin Arch occurred soon after deposition. This is witnessed by anomalous thicknesses of the overlying uppermost Silurian Bertie and Bass Islands Formations and of rapid lateral facies changes in the Lower to Middle Devonian depositional sequence 7 (Johnson *et al.* 1992). Surface-derived waters that caused salt dissolution descended along faults, such as the network proposed by Sanford *et al.* (1985). There are no clear indications that salt dissolution occurred at post-Devonian times.

Hydrocarbon generation and migration

The generation of oil and gas is related to burial diagenesis that occurred in the late Paleozoic. The main migration pathways are fractures and faults (such as the fracture framework of Sanford *et al.* 1985) or zones affected by dolomitisation. The time at which hydrocarbon migration occurred is not well constrained. Middleton *et al.* (1993) and Coniglio *et al.* (1994) conclude on the basis of textural evidence and on fluid-inclusion data that migration was coeval with mineral formation during the late stages of burial diagenesis.

According to S. Frape (pers. comm. 2004), many hydrocarbons were generated at temperatures related to burial diagenesis (*i.e.* well below 100 °C), while other oil and gas fields are related to higher temperatures best explained by the hydrothermal effects discussed above. Mixtures of both hydrocarbon types are observed in some fields.

Other effects

Ziegler & Longstaffe (2000a,b) studied alteration minerals along the Precambrian unconformity of southern Ontario. They identified authigenic K-feldspar, chlorite and illite in the uppermost Precambrian, Cambrian and lowermost Ordovician strata. K/Ar dating of K-feldspar yielded 412 - 453 Ma (Upper Ordovician - Lower Devonian). Chlorite formed at temperatures of 100 - 260 °C from basinal brines evolved from sea water. This event is attributed to the large-scale migration of deep basinal fluids from the Appalachian (and possibly the Michigan Basin) in response to compression related to the Ordovician Taconic orogeny. Illite in the same units crystallised 299 - 365 Ma b.p. (Upper Devonian - Upper Carboniferous), but the conditions of crystallisation are not well constrained. It is concluded that the basement unconformity was a large-scale conduit for fluids at least during the Paleozoic.

Conclusions

The hydrogeological system in the sedimentary sequence of southern Ontario was active during deposition and burial diagenesis, which extended throughout the Paleozoic, possibly into the early Mesozoic. Cross-formational flow may have occurred during this stage, specifically at times when the sediments where weakly consolidated. Since that time, there are few (if any) indications of basin-wide or cross-formational flow events.

6.6.4 Karst formation in carbonates

A substantial number of erosional unconformities have been identified in the Paleozoic sedimentary sequence, indicating that the rocks were recurrently exposed to meteoric waters (Johnson *et al.* 1992). Carlson (1992) described palaeo-karstic collapse breccias, pipes and dolines in the Upper Silurian Bass Islands dolomite. Kobluk et al. (1977) identified dissolution features in tne Bertie Formation of the Hagersville - Niagara region. These features document karstic dissolution related to the Silurian/Devonian disconformity, with penetration depths of at least 10 m. Smith *et al.* (1988) noted that the bioherms of the Middle Silurian Guelph Formation were recurrently subjected to synsedimentary karstic dissolution, which led to zones of enhanced laterally extensive porosity and permeability. Kobluk (1984) identified minor (cm to dm scale) palaeo-karst features in limestone beds along the Ordovician/Silurian boundary on Manitoulin Island. Apart from this, there are no records of palaeo-karst in any other Ordovician formation (such as the Middle to Upper Ordovician limestones of the Trenton / Black River Groups). Quaternary karst has been identified in Silurian dolomites and Devonian carbonates (D. Armstrong, pers. comm. 2004).

6.7 STRESS STATE AND NEOTECTONICS

6.7.1 Stress state

Stress conditions in Canada were compiled in a data base by Adams (1987), updated by Adams (1995). The data are based on the analysis of earthquake focal mechanisms, borehole breakouts and hydraulic fracturing and overcoring tests in boreholes. Southeast Canada is one of the best studied regions. An up-to-date version of the regional stress map can be found in the 2004 release of the World Stress Map (Reinecker *et al.* 2004), which shows data from the periodically updated data base originally initiated by Zoback *et al.* (1989). Further data come from a breakout study in oil and gas boreholes of southern Ontario (Yassir *et al.* 1992). The main results are as follows (mainly taken from Adams & Bell 1991 and Reinecker *et al.* 2004):

Relative magnitudes and orientations of stress axes

- The area east of the Canadian Cordillera is part of the Mid-Plate Stress Province. The maximum horizontal stress σ_H is larger than the vertical stress σ_v. Figure 6-12 shows the trajectories of σ_H in southeastern Canada and in the northeastern U.S. σ_H strikes ENE to NE, essentially parallel to the St. Lawrence Rift.

- Overcoring tests in the uppermost 2 km of the Precambrian basement of Canada show that σ_h often exceeds σ_v, even though not consistently. Thus both horizontal stresses dominate over the overburden pressure, and stress conditions most frequently correspond to those of a thrust regime. The difference (σ_H - σ_h) increases with depth. The predominance of thrust faulting (often with some strike-slip component) is also consistent with evidence based on focal mechanisms of recent earthquakes, which typically characterise stress conditions at deeper crustal levels. Normal-fault focal mechanisms are subordinate and mostly occur only in specific regions far from the area of interest (Queen Charlotte Transform, Arctic Archipelago). At shallow crustal levels, different stress regimes

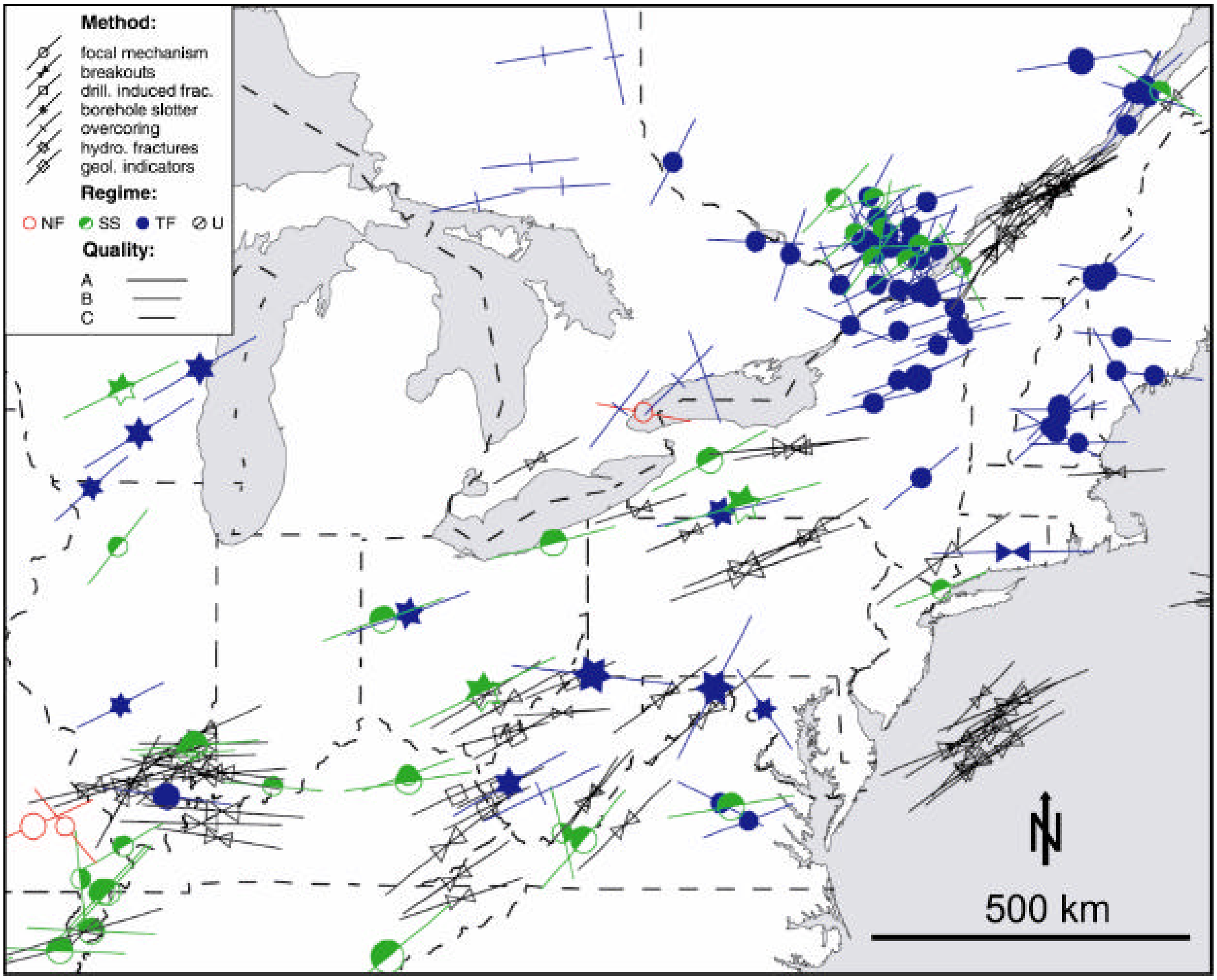

Figure 6-12: Stress map of southeastern Canada and of the northeastern U.S. (from Reinecker *et al.* 2004). Lines indicate the direction of σ_{H}, and length of lines is a measure of data quality. NF = normal-fault regime, SS = strike-slip regime, TF = thrust fault regime, U = regime unknown. Note that different data points refer to different depths below surface.

with $\sigma_v > \sigma_H$ were identified in sedimentary rocks in the Western Canadian Sedimentary Basin and to the east offshore on the Scotian Shelf.

- Strike-slip dominates in the central U.S. as far north as the southern shores of Lakes Erie and Ontario. Evidence for normal (extensional) focal mechanisms in Lake Ontario exists (Adams *et al.* 1989, Bent *et al.* 2003) but is very tenuous (J. Adams, pers. comm. 2004).

- Only few data are available that are specific to southern Ontario. Adams & Bell (1991, Fig. 5) show data from the Niagara Megablock indicating that the direction of σ_H is ENE. According to Figure 6-12, a thrust regime or a strike-slip regime (or a combination of both) appear most likely and so, in both cases, $\sigma_1 \sim \sigma_H$. Yassir *et al.* (1992) compiled data on borehole breakouts in southern Ontario and compared the resulting directions of horizontal stress axes with data based on other indicators. All methods indicate that the direction of σ_H is in the NE quadrant. The fact that focal mechanisms yield results consistent with those based on surface features (pop-ups, quarry floor buckes) suggests that the orientation of σ_H does not change substantially with depth.

- Deglaciation 10 ka b.p. resulted in radial flexural stresses. These are probably compressional at the moment but could have been extensional during migration of the forebulge. Postglacial thrust faults indicate different σ_H directions than those observed today. Glaciation-induced stresses are thought to make only a small contribution to the contemporary stress field in southeast Canada.

Absolute stress magnitudes

The sedimentary rocks of the St. Lawrence Platform show stress conditions that are very similar to those of the crystalline basement, and stress decoupling between basement and cover rocks appears not to occur. Figure 6-13 shows that hydraulic fracturing data indicate stress magnitudes for σ_H = 18 MPa, σ_h = 12 MPa and σ_v = 8 MPa (calculated from overburden) at 300 m depth. Further extrapolation to depths of 400/500 m would result in approximate values of σ_H = 21/23 MPa and σ_h = 14/16 MPa. Assuming an average density of 2650 kg/m^3 results in overburden stresses σ_v = 11/13 MPa. In any case, σ_H ˜ σ_1, σ_h ˜ σ_2 and σ_v ˜ σ_3.

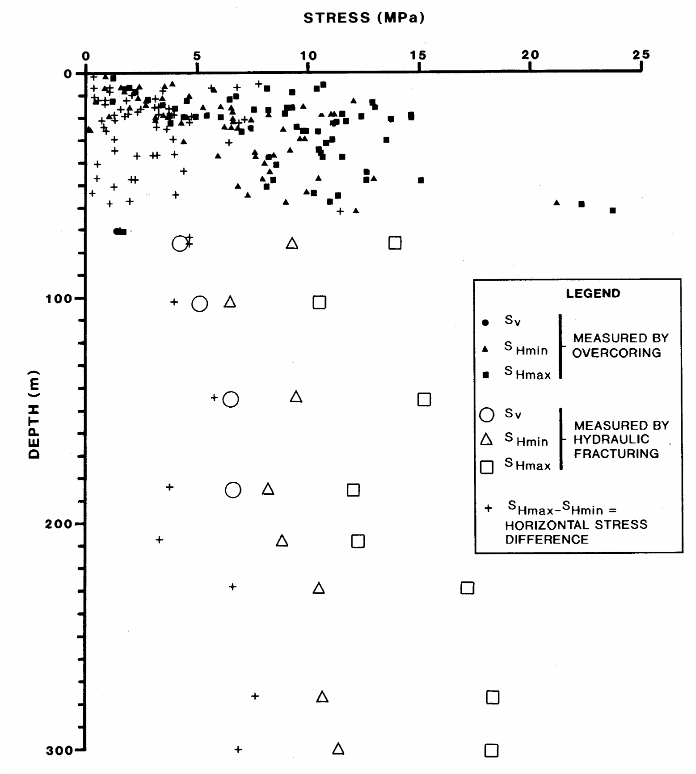

Figure 6-13: Stress magnitudes in sedimentary rocks of the St Lawrence Platform (southeastern Canada) to a depth of 300 m. Taken from Adams & Bell (1991).

6.7.2 Seismicity

Much of Canada east of the Cordillera is largely aseismic but contains several discrete zones with enhanced seismicity. An overview is given in Adams & Halchuk (2003) and Adams & Atkinson (2003), and a discussion is provided by Adams & Basham (1991). In southeast Canada, seismic regions include the lower St. Lawrence and Charlevoix zones (both reactivating the Paleozoic St. Lawrence Rift), the Ottawa River zone (reactivating the Paleozoic Ottawa-Bonnechère Rift) and the North Appalachians Zone. Another active zone is the Atlantic shelf offshore east Canada. A band of earthquakes north of the Ottawa River is tentatively related to fractures induced by the passage of a mantle hot spot in the Cretaceous.

The largest known earthquake in the Paleozoic Ottawa-Bonnechère Graben system had a magnitude of 6.2. Focal depths in this graben are typically 5 to 20 km, and focal mechanisms are invariably thrusts with horizontal σ_1, which confirms the existence of a compressive regional stress regime.

In southern Ontario, seismicity is weak and largely limited to the Niagara Megablock, while the Bruce Megablock is virtually aseismic. As shown in Figure 6-14, one earthquake of magnitude 5.0 occurred along the southern shore of Lake Erie. Some earthquakes of magnitude 4 - 5 were identified along the Ottawa River (Ottawa-Bonnechère Graben), in the southern part of Lake Erie and in the Niagara region. Adams & Basham (1991) put forward the speculative idea that earthquakes in the latter two regions are related to a possible extension of the St. Lawrence Rift beneath Lakes Ontario and Erie.

On the basis of historic earthquake records and ground motion relations, Adams & Halchuk (2003) provided probabilistic maps of spectral seismic acceleration in Canada. As shown in Figure 6-14 for 5% damped spectral acceleration for 0.2 s period, southern Ontario lies in a region where the seismic acceleration that will occur within 50 years with a probability of 2% is <0.4 g. In the Bruce Megablock, the expected acceleration is <0.2 g, which is a very low value. For seismically active areas, such as around Charlevoix in the St. Lawrence Rift, values >1 g are indicated. The contours in Figure 6-14 are directly applicable for the assessment of seismic hazard during the operational phase of a deep geological repository (tunnels remain open for years to decades). However, seismic events with longer recurrence times need to be considered when addressing post-closure behaviour.

Mohajer *et al.* (1992) studied faulting in Quaternary and underlying Paleozoic sediments of the Toronto area and observed normal faults with up to 1.25 m displacement. While they did not draw definite conclusions on the genetic aspects of faulting, they pointed out that the faults could in principle be of seismotectonic origin. Such an interpretation is in conflict with the contention of previous authors (*e.g.* Adams & Basham 1991) that the region is tectonically quiet. Mohajer *et al.* (1992) also pointed out that the consideration of palaeo-seismic evidence may have an impact on earthquake hazard predictions. In a comment to this paper, Adams *et al.* (1993) found the evidence for seismotectonic faulting unconvincing and favoured a glaciotectonic origin. In such a case, deformation would be related to changes in the glacial load

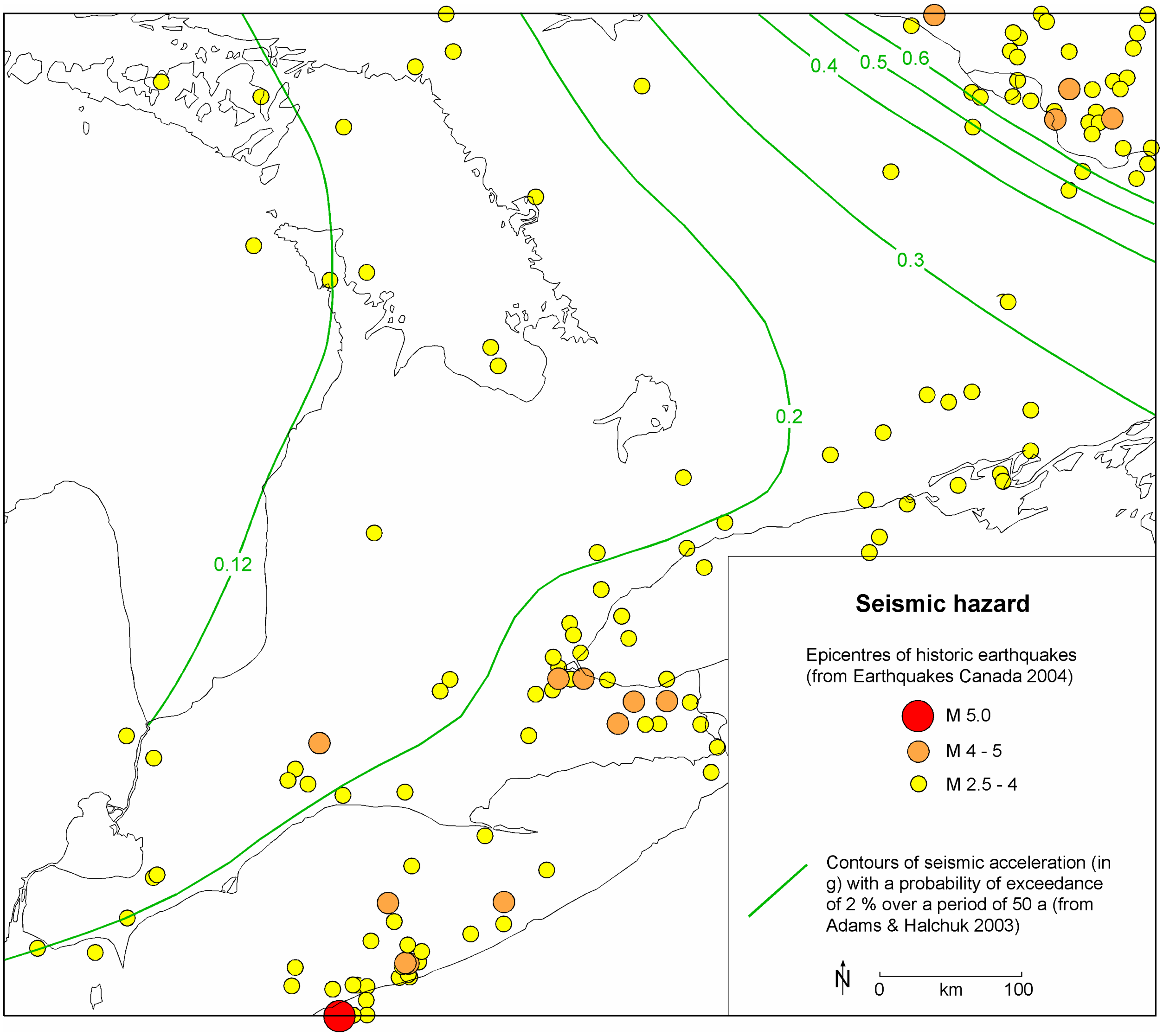

Figure 6-14: Earthquake epicentres and contours of seismic surface acceleration in southern Ontario. Epicentres are from Earthquakes Canada (2004). Acceleration contours are from Adams & Halchuk (2003) and refer to a period of 0.2 s (shape of contours on maps for other periods is similar). Contours show ground accelerations that are expected to occur with a probability of 2% within a time period of 50 years.

and/or ice push and so would have no significance for earthquake hazard prediction (unless the Laurentide ice sheet advances again into the region). The controversy has not been fully resolved (Mohajer *et al.* 1993). More recently, Godin *et al.* (2002) revisited the same outcrops in the Rouge River Valley and also integrated evidence from a number of new boreholes. They concluded that 1) surficial faults cannot be connected geographically from one site to the other, 2) fault offset rapidly decreases with depth, and 3) most studied faults are kinematically compatible with ice flow directions. Thus, their study indicates a glaciotectonic origin for most if not all of the deformation features observed. Eyles & Mohajer (2003) disagree with some of the conclusions and see seismotectonic faulting as a possible mechanism for the observed faulting. A consensus is yet to be found (see reply by Godin *et al.* 2003).

6.7.3 Vertical movements and erosion

Clark *et al.* (1990) set up a physical and numeric model to calculate the isostatic response (vertical movement) to the retreat of the Laurentide ice sheet in the Great Lakes region (6 - 12 ka b.p.) on a crustal scale. The resulting uplift/subsidence rates are absolute, *i.e.* they refer to the geoid and not to a relative reference point, and are shown in Figure 6-15. In the region of interest, the zero contour is predicted to run from Windsor across the Niagara Megablock and then along the south shore of Lake Ontario. Regions north of this contour are currently uplifting (up to 3 mm/a in the northern part of southern Ontario), while subsidence occurs further south. Clark *et al.* (1990) pointed out that, according to their model, the zero contour has been migrating northward, and will continue to do so, in response to the gradual decay of the isostatic adjustment due to the melt-off of the ice sheet. Vertical uplift also induces radial horizontal strain (see Chapter 6.7.1).

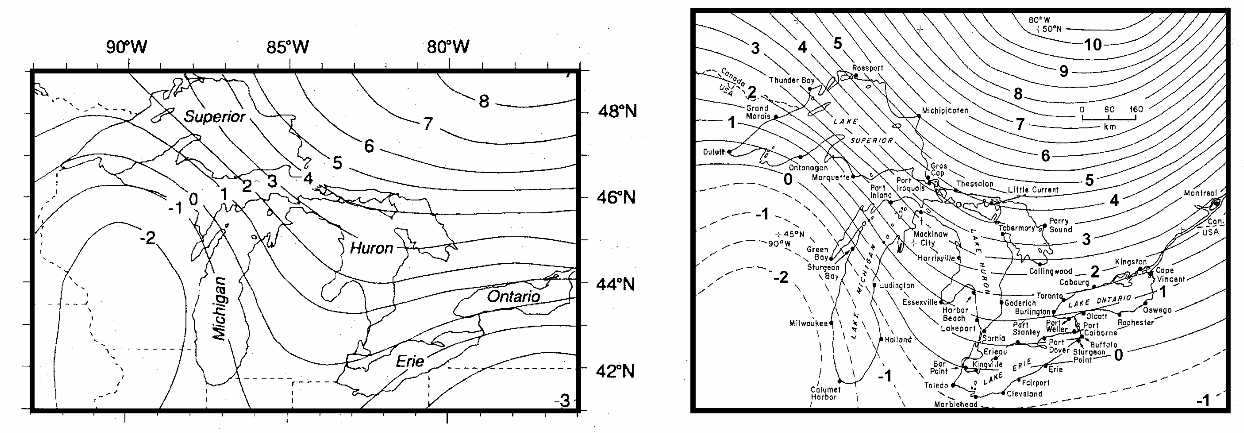

Figure 6-15: Vertical crustal movements in southeastern Canada relative to the geoid, based on model calculations of Clark *et al.* (1990; left) and Tushingham (1992; right). Contours are in mm/a, positive values mean uplift.

A similar model was developed by Tushingham & Peltier (1991), and the resulting pattern of vertical movements is also shown in Figure 6-15. Both models yield comparable results with relatively minor differences. Tushingham (1992) compared the predictions of both models to actual measurements of relative vertical movements from lake level gauges in the Great Lakes area. He concluded that the model by Tushingham & Peltier (1991) fits the direct observations slightly better than the one of Clark *et al.* (1990).

Based on shoreline investigations, the northern part of the Great Lakes area has been tilted upward toward the north by 0.5 m/km over the last 14 ka. Differential vertical movements had a great effect on the shape and drainage pattern of the Great Lakes, whose outlet location changed several times since deglaciation. Based on their model calculations, Clark *et al.* (1990)

propose that the present-day outlet of Lakes Michigan and Huron at Sarnia will switch to Chicago within 2 ka because Chicago is subsiding, while Port Huron is uplifting.

In summary, southern Ontario is currently uplifting in its central and northern parts, while the southern part is stable or even subsiding. The present-day situation cannot be extrapolated far into the future because the current vertical movements are strongly affected by the transient caused by the last glacial retreat. Isostatic lithospheric rebound decays exponentially and has typical relaxation times[9] of 2 - 4 ka, which largely depend on the viscosity of the underlying mantle (W. R. Peltier, pers. comm. 2004). Peltier (1998) derived relaxation times of 3.4 ka for the Canadian Shield (southeastern Hudson Bay and James Bay areas, Quebec) and 4.4 ka for Scandinavia (Angerman River, Sweden). Once isostatic equilibrium is attained, vertical movements are expected to be negligible. Predictions into the far future depend critically on whether another ice sheet advances south.

The possible erosion related to uplift is not quantified in the literature. In the crystalline basement outcropping north of southern Ontario, such erosion would be very limited given the nature of the rocks and the moderate relief. Erosion rates in the sedimentary cover will be higher and could be targeted in future studies. A potential method to constrain erosion rates would be the study of volumes and ages of sediments deposited in the Gulf of St. Lawrence, even though these represent erosion from a catchment area much larger than the region of interest.

6.7.4 Postglacial faulting

A recent generic review of glacio-seismotectonics, *i.e.* the crustal response to glacial loads that change in time and space, is provided by Stewart *et al.* (2000).

Observations

Postglacial faults displacing glacial striations are common features in southeastern Canada and occur along an arc from western Ontario to Newfoundland (Adams 1989). Throws are mostly small (<10-100 mm) and indicate steep thrust movement. The strike direction is generally tangential to the former ice-sheet margin, *i.e.* E-W in Ontario to SW-NE in Newfoundland. The depth extent is not known, but the range of 10 to max. 500 m appears plausible (Adams 1989). Large faults with throws >1 m as known from Scandinavia have not been found to date in southeastern Canada.

Pop-ups (superficial folds) are a feature that occurs in sedimentary rocks of southern Ontario. They are open anticlines containing some broken rock, typically with amplitudes of a few m, lengths of 50 - 1000 m and widths of 5 - 10 m. While it is suspected that pop-ups affect only the uppermost metres to dekametres below ground, no direct observations are available on their depth extent.

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[9] Relaxation time reflects the time after which uplift decays to a fraction of 1/e ˜ 0.37 of the initial value.

Fenton (1994) compiled literature pertaining to postglacial faulting in eastern Canada (annotated bibliography). A number of case studies from southern Ontario included in that compilation report postglacial faults with displacements of metres to dekametres. J. Adams (pers. comm. 2004) is of the opinion that shoreline and lake-bottom features that were used to identify the faults do not provide sufficient proof and that alternative interpretations potentially better explain the observations. While he points out that postglacial faults with large displacements cannot be currently excluded, their existence is yet to be demonstrated.

Interpretation

The position and orientation of the thrust faults along the former ice-sheet margin indicates that they formed during or shortly after deglaciation. Their tangential alignment suggests that σ_1 was horizontal and N-S in Ontario at that time, *i.e.* at a high angle to its current orientation (Figure 6-12). Adams (1989) suggests that such a transient change of the stress field at shallow crustal levels is due to lithospheric bending in response to the changing glacial overburden. In this conceptual model, an excess compressive stress is expected along the ice margin during glacial retreat. This excess stress is horizontal, normal to the ice margin and in the order of 20 MPa. This value exceeds that of the contemporary stress (Figure 6-13) and thus becomes dominant. Along the forebulge outside the ice sheet (presumably tens to hundreds of km away), lithospheric flexuring may lead to an excess tensile stress of ca. 20 MPa at shallow levels, which may result in an overall tensile stress regime. While the faults and pop-ups can be interpreted as compressive structures formed along the ice margin, field evidence of tensile structures formed on the forebulge is lacking.

Conclusions

At very shallow crustal levels, the stress field is heterogeneous both in time and space in response to glaciation/deglaciation cycles. High excess stresses, possibly linked with seismic activity, may be expected along the margin of rapidly retreating glacial sheets. However, the small strains actually observed along the postglacial faults in southeast Canada indicate that the overall effects are limited and have a short lifetime.

6.8 ECONOMIC RESOURCES

Economic deposits that are exploited in the subsurface of southern Ontario include oil, gas, salt and gypsum (Sanford 1993b). There is also some limited potential for metal deposits in carbonates, but no mining activities have been undertaken to date. Several rock types are quarried on the surface, including limestone, dolomite, shale and sandstone.

6.8.1 Hydrocarbons

Oil and gas occur mainly south of the line connecting Sarnia and Toronto. A summary of the main features is given in Table 6-5.

Table 6-5: Overview of hydrocarbon occurrences in southern Ontario

Age	Reservoir rocks	Trapping mechanism	Geographic distribution
Devonian	Carbonates of Dundee Formation and Detroit River Group	Structural traps generated by dissolution of underlying salt (see Figure 6-7)	Southwestern Ontario (Chatham Sag)
Upper Silurian	Reef limestones of the Guelph Formation, carbonates of the Salina Formation (A1, A2)	Related to patch and pinnacle reefs in Guelph Formation	Along the edge of the Michigan Basin (from Lake St. Clair north along the the shore of Lake Huron)
Lower to Middle Silurian	Sandstones (Whirlpool, Grimsby, Thorold Formations) and dolomites (Irondequoit Formation)	Permeability pinchout due to internal heteregeneity of the host formations (spatially variable cementation)	Occurrence of the sandstones and pools mainly along the north shore of Lake Erie (Appalachian Basin, Niagara Megablock)
Middle Ordovician	Limestones of the Black River and Trenton Groups	Pools in porous and permeable zones in the vicinity of rejuvenated faults along which spatially limited dolomitisation took place (permeability pinchout). Upper Ordovician shales may act as caprocks	Southwest end of southern Ontario (London - Windsor area). Limited potential (not exploited) in the whole Niagara Megablock, low potential in the Bruce Megablock (3 small gas pools known; low density of reservoirs expected because of less dense faulting and/or more limited dolomitisation)
Cambrian	Sandstones, dolomites	Pools generated by faulting and tilting (juxtaposition against low-permeability limestones of the Black River Group)	Mainly along the erosional boundary of the Cambrian along a line connecting Windsor and Hamilton. No reservoirs known on the Michigan Basin side

Summarised from Sanford (1993b) and T. Carter (pers. comm. 2004).

Given the fact that hydrocarbon occurrences are a living record of palaeo-fluid flow, some relevant conclusions can be drawn:

- The Cambrian reservoirs are capped by Middle Ordovician Black River / Trenton Group limestones. The function of the latter as caprocks is an independent confirmation of their very low permeability.

- The occurrence of Ordovician reservoirs along dolomitised faults in limestones indicates that, at least locally, the Black River / Trenton Group limestones are porous and permeable. It is concluded that there is some spatial heterogeneity in the degree of dolomitisation and, thus, of hydraulic properties in these units. According to Sanford (1993b), the potential for fluid entrapment is low in the Bruce Megablock north of Sarnia due to the limited extent of fault reactivation and dolomitisation. Some workers proposed that dolomitising fluids are sourced in the deep Appalachian Basin, thus do not penetrate beyond the crest of the Algonquin Arch (however, there is no general consensus on this; T. Carter, pers. comm. 2004).

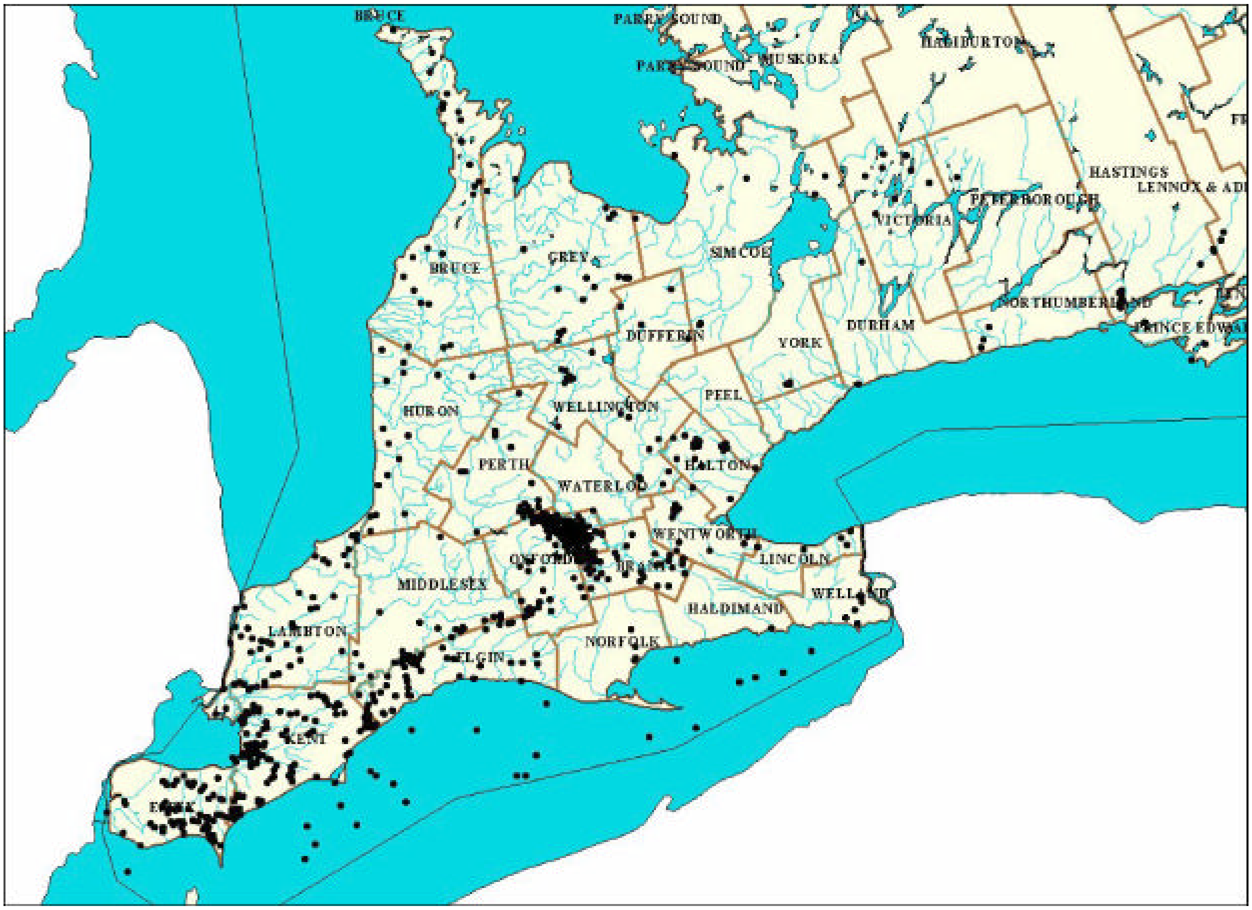

Figure 6-16: Map showing the locations of boreholes that penetrated the crystalline basement in southern Ontario. Based on data from the Ontario Petroleum Data System, courtesy of T. Carter, 2004.

- Hydrocarbons of all ages occur mainly in the southwest edge of southern Ontario and in the Niagara Megablock north of Lake Erie. Only small occurrences in the Silurian are found in the Bruce Megablock.

To date, some 50'000 gas and petroleum exploration and exploitation boreholes have been drilled in southern Ontario. The Ontario Ministry of Natural Resources has records for more than 20'000 of these boreholes (available at www.ogsrlibrary.com; T. Carter, pers. comm. 2004). Figure 6-16 shows the distribution of boreholes that penetrated the whole sedimentary pile down to the crystalline basement. The drilling activities bear the following implications:

- There are a substantial number of boreholes that are not recorded in the database of the Ministry, thus additional sources of information should be considered for a comprehensive overview of drilling activities, particularly for site-specific investigations.

- Many boreholes are unplugged, or the plugging does not meet present-day standards.

It is concluded that a future assessment of potential regions for a deep geological repository should consider 1) presently exploited hydrocarbon resources, 2) resources that are not economic today but may become so in the future, and 3) drilling activities related to hydrocarbons.

6.8.2 Salt

Halite occurs in different horizons of the Salina Formation in the Michigan Basin (see Figure 6-6). It is currenty being exploited in Goderich and south of Windsor. In addition, salt is being used as a host rock for the storage of natural gas and refined petroleum in the Sarnia - Windsor area.

6.9 ASSESSMENT OF FORMATIONS AND REGIONS REGARDING THEIR SUITABILITY TO HOST A DEEP GEOLOGICAL REPOSITORY

The sedimentary column of southern Ontario is a sequence of clastic, calcareous and evaporitic units. The geometric arrangement of these units is relatively simple, and the lateral predictability of most units is good. This represents a good basis for the identification of units that appear suitable to host a deep geological repository for radioactive waste.

In the last few years, there has been a development internationally towards the clear and transparent demonstration of the logic of reasoning that leads to the identification of potential disposal sites (see *e.g.* AkEnd 2002 for Germany). The definition of criteria as a basis for the evaluation process has become very important. In this document, a set of geoscientific criteria are defined and applied consistently to southern Ontario. It is meant to provide a reasoned scoping level geoscientific assessment that could be beneficial to a more rigorous future assessment in which more detailed geoscientific and non-geoscientific criteria were evaluated.

The assessment is subdivided into two steps, the first one addressing the potential formation(s) (vertical dimension), the second one dealing with the regional or areal aspects of formation location (horizontal dimensions).

6.9.1 Assessment of formations

Among the most important criteria for assessing the suitability of a sedimentary rock formation to host a repository are:

- Low hydraulic conductivity
- Low hydraulic gradient
- Sufficient depth below surface
- Sufficient thickness
- Simple geometry (internal homogeneity, lateral continuity)
- Favourable retardation properties.

The assessment procedure, illustrated in Figure 6-17, uses the sedimentary column of the Michigan Basin part of southern Ontario. However, very similar conclusions would be reached when using the column of the Appalachian Basin. Through consideration of these criteria the

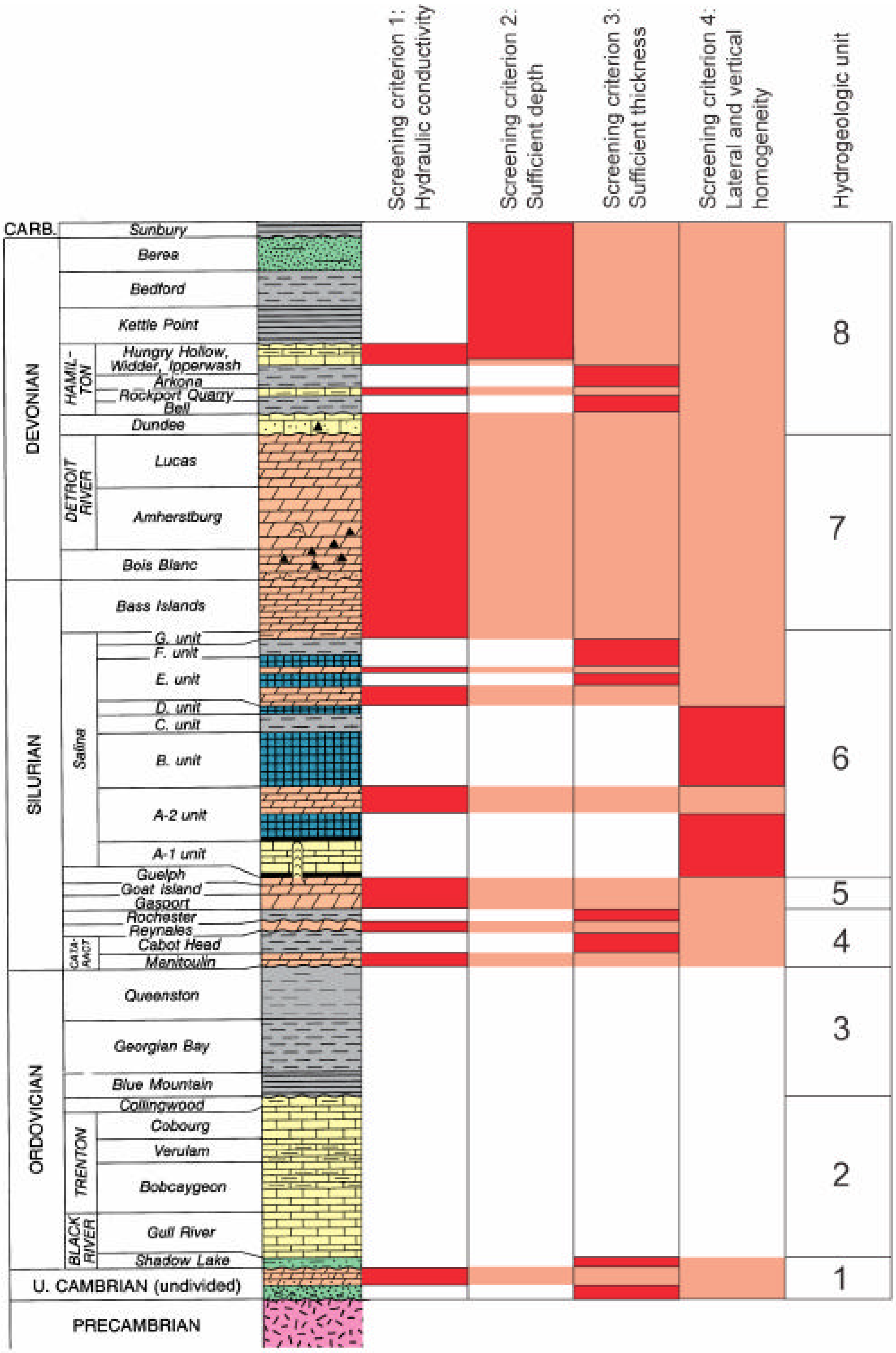

Figure 6-17: Assessment of formations in southern Ontario with regard to their suitability to host a deep geological repository for radioactive waste. The procedure is exemplified using the Michigan Basin profile from Figure 6-2. Dark red: Formations excluded in the respective assessment step; light red: excluded in previous steps.

purpose is to identify those formations with properties suited for further consideration. Only those criteria are applied for which sufficient information is currently available.

Criterion 1: Low hydraulic conductivity

As shown in Figure 6-9 and Figure 6-10, there is a good correlation betweeen lithology and hydraulic properties. Dolomites and dolomitic limestones typically have hydraulic conductivities >1E-8 m/s, and often they have aquifer properties and thus appear unsuitable for waste isolation. In Figure 6-17, all massive dolomites and dolomitic limestones were excluded, not only those for which hydraulic data are available. While the hydraulic properties of the Salina Formation have not been measured, there is no reason why the dolomites in this formation should be hydraulically distinct from other dolomites in the sedimentary column. This assessment criterion excludes substantial parts of the Silurian to Middle Devonian from further consideration.

Unlike other limestones in southern Ontario, those of the Middle Devonian have mean hydraulic conductivities of 1E-9 - 1E-8 m/s, with a substantial spread of individual values. Moreover, geochemical evidence indicates the possible infiltration of meteoric waters into these formations (Chapter 6.4; Weaver *et al.* 1995). The Dundee Formation contains producing hydrocarbon reservoirs. The enhanced conductivities of the Middle Devonian limestones are likely due to their occurrence at shallow levels only (0 - ca. 350 m in the Chatham Sag), and thus they are also excluded from further consideration.

Criterion 2: Sufficient depth below surface

In the international context of geological disposal of high-level waste and spent fuel in sedimentary formations, there is a consensus that the isolating units should be buried under =200 m overburden (see Table 6-6). Depending on the local situation (uplift and erosion rates, risk of permafrost and deep glacial erosion, etc.), even much deeper levels are considered. Using a minimum overburden of 200 m as a criterion in southern Ontario excludes the Upper Devonian completely. Depending on geographic location, this criterion affects progressively older strata when moving northeast along the Algonquin Arch.

Table 6-6: Basic geometric features of sedimentary host formations considered as potential hosts for a high-level and/or spent fuel repository

Formation, locality, country	Thickness, m	Overburden, m
Boom Clay at Mol, Belgium	100	188
Opalinus Clay at Benken, Switzerland	113	539
Callovo-Oxfordian at Bure, France	138	420
Couche Silteuse at Marcoule, France	300	900

Criterion 3: Sufficient thickness

Internationally, there is a consensus that the minimum thickness of the host formation should be =100 m (see Table 6-6). While this value is not formally defined in regulations, it is considered appropriate because it warrants a minimum migration path for radionuclides from the repository to an aquifer of ca. 40 m, if the repository is located in the centre of the formation. Applying this criterion excludes, among others, several of the thin shale beds in southern Ontario (Figure 6-17).

Criterion 4: Lateral continuity and internal homogeneity

Lateral variations of sedimentary facies and formation thickness occur in southern Ontario but are generally well known, gradual and, thus, predictable. One exception to this rule is the extensive salt dissolution that occurred in the Salina Formation and resulted in a somewhat patchy distribution of the salt horizons that occur in the western and southwestern part of southern Ontario (see Figure 6-6). Dissolution occurred mainly along steeply dipping faults and resulted in a reduction of salt thickness, if not complete removal (Figure 6-7), and related collapse structures in the overlying formations. The B salt of the Salina Formation has a maximum thickness of ca. 90 m, and, with the overlying shale-rich C unit and the D salt, would fulfil the criterion of a minimum thickness of 100 m in a region along the coast of Lake Huron. However, the lateral heteogeneity of salt thickness, together with the lithological heterogeneity of units B to D of the Salina Formation (salt, shale, minor dolomite), makes exploration difficult and expensive. Therefore, this option is regarded as a second priority and is excluded for the time being.

At the base of the Salina Formation, salt, anhydrite, shale and limestone occur. In addition to the effects of salt dissolution, this sequence (units A1 and lower part of A2) is lithologically very heterogeneous (*e.g.* pinnacle reefs rising from the Guelph Formation). Exploration, site characterisation and safety assessment would have to deal with a complex system in which very different rocks would have to be addressed. Therefore, this sequence is excluded.

Results

The simple assessment criteria that were applied lead to the conclusion that hydrogeological units 2 and 3, *i.e.* the Middle to Upper Ordovician limestones and overlying shales, are the first-priority targets from the waste disposal perspective. The evaluation process is straight-forward, and most likely an assessment using alternative approaches would lead to the same result. Given the fact that there are many other requirements on formations to host radioactive waste than those few that were applied above, the characteristics of the chosen units will be discussed in more detail below.

6.9.2 Assessment of regions

The Upper Ordovician shales crop out in a wide area to the northeast-east side of the Niagara Escarpment (Figure 6-3). Towards the west-southwest, they are covered by a sequence of progressively thicker, younger sediments (Figure 6-8). The top of the Queenston Formation reaches an overburden of 200 m approximately within the band where the Salina Formation crops out on the surface (see Figure 6-3), thus the requirement of an overburden of 200 m is met to the southwest of this band. If the limestones of hydrogeologic unit 2 are considered as a host rock unit on their own, then the 200 m depth contour is located further to the northeast.

With a few exceptions, hydrocarbon occurrence and exploitation is limited to a region south of the line connecting Toronto and Sarnia (Chapter 6.8). If a repository should be located outside the region with extensive hydrocarbon resources, it should be placed north of this line. The issue of undetected resources and those that may become economic only in the future should be considered in the assessment.

Restrictions based on minimum overburden and the avoidance of regions used for hydrocarbon exploitation leaves a substantial part of the Bruce Megablock as the first-priority area for further evaluation. The onshore part of the Bruce Megablock is devoid of large-scale lineaments (Figure 6-4), and the fault pattern as suggested by Sanford *et al.* (1985) is simpler when compared to the Niagara Megablock (Figure 6-5). Only few faults were mapped in the underlying crystalline basement in this region (Figure 6-5; Carter *et al.* 1996). Few earthquakes are known from this region, and seismic hazard is considered very low (Figure 6-14). Current uplift rates are ca. 1 - 3 mm/a (Figure 6-15), but they are expected to dissipate within the next thousands of years (Peltier 1998) as the line of zero vertical movement progressively moves to the north.

6.10 BASIC CHARACTERISTICS OF UPPER ORDOVICIAN SHALES

The Blue Mountain, Georgian Bay and Queenston shales represent sediments derived from the Appalachian orogen. Their thickness generally decreases with increasing distance from the source. The combined thickness of all formations is 370 m in a borehole in Peel County (Appalachian Basin, west of Toronto) and 200 m / 174 m in boreholes near Goderich / Kincardine (both Michigan Basin).

6.10.1 Thickness, lithology and mineralogy

The Blue Mountain Formation is a fissile, noncalcareous, fairly homogeneous shale with organic-rich horizons (Johnson *et al.* 1992, Hamblin 1999). Deposition took place in a shallow marine environment below the storm wave base (*i.e.* > ca. 30 m). Thickness varies between 35 and 75 m, thinning to the north.

The Georgian Bay Formation is a shale with minor interbeds of siltstone, limestone and dolomite (more predominant upward and northward). These interbeds account for ca. 20 % of the formation and are laterally continuous (Hamblin 1999), with the highest proportion in the northwest (Michigan Basin). The depositional environment represents a shallowing upward storm-dominated shelf sequence. Thickness varies between 100 (in the northwest) and 250 m (in the southeast).

The Queenston Formation is a calcareous to noncalcareous, gypsiferous red and grey shale unit with interbeds of limestone and silt/sandstone (Johnson *et al.* 1992, Brogly *et al.* 1998). Deposition took place in deltaic, marine to non-marine flood plains. Extended sandstone channels are reported not to exist in southern Ontario. Thickness decreases from Lake Erie (240 m) to the northwest (45 - 60 m on Bruce Peninsula). Limestones are prominent in the middle of the Queenston Formation at Bruce Peninsula, but it is not clear how far south this heterogeneity extends (D. Armstrong, pers. comm. 2004). S. Frape (pers. comm. 2004) mentioned the occurrence of dissolved H_2S and methane in the Queenston Formation.

Quantitative mineralogical data for all shale formations are scarce. Russell & Gale (1982) report the data shown in Table 6-7. Lee & Lo (1993) report small amounts of vermiculite in all 3 shale formations, in addition to interlayered phases. The small measured free swelling strains suggest that the proportion of swelling clay minerals is limited.

Table 6-7: Mineralogical composition of Upper Ordovician shales

Data in wt%	Quartz	Feld-spars	Calcite	Dolom-ite	Clay minerals
Queenston Formation	12 - 34	0 - 9	2 - 30	0 - 8	60 (illite > chlorite > swelling clays)
Georgian Bay Formation	23 - 35	0 - 11	3 - 17	0 - 4	60 (illite > chlorite)
Blue Mountain Formation	21 - 28	1 - 2	0 - 3	0 - 3	70 (illite > chlorite)

Taken from Russell & Gale (1982).

6.10.2 Basic transport properties

Hydraulic conductivity data are given in Chapter 6.3, where very low values are reported. For the undisturbed matrix of Queenston Shale, Barone *et al.* (1990) report porosities of 0.102 - 0.114 and an effective diffusion coefficient[10] for Cl of 1.5E-11 m^2/s. Both values are similar to those reported for Opalinus Clay in Switzerland and the Callovo-Oxfordian in France (see Nagra 2002a, Fig. 5.10-1). No data are available on the possible dependence of porosity and diffusion coefficient on lithology/mineralogical composition, as well as, on geographic position. Barone *et al.* (1990) indicate a cation exchange capacity for Queenston Shale of 12.5 meq/100 g. Formation-specific investigations of sorption properties are not available. Given the limited, but demonstrable presence of swelling clays, sorption is expected to be an important retardation process in these rocks but cannot be currently quantified.

6.10.3 Geomechanical stability

The geotechnical feasibility of underground openings (boreholes, shafts, tunnels) in argillaceous rocks is more challenging when compared to limestones or crystalline rocks. Experience made

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[10] Barone *et al.*'s (1990) value of 1.5E-10 m^2/s represents the "pore-diffusion coefficient" as defined by Horseman *et al.* (1996, eq. 4.34) and Mazurek *et al.* (2003, p. 119). The definitions are as follows: $D_e = n\,\chi/\tau^2\,D_0 = n\,D_p$, with D_e = effective diffusion coefficient, D_p = pore diffusion coefficient, D_0 = free water diffusion coefficient, n = porosity, χ = constrictivity, τ = tortuosity; χ/τ^2 = geometry factor G. It follows that, in order to obtain an effective diffusion coefficient according to these definitions, the value reported by Barone *et al.* (1990) must be multiplied by porosity, yielding 1.5E-11m^2/s.

by the oil industry indicates that at least at great depth (2500 - 5000 mbgs), major borehole instability and collapse may occur if drilling parallel to bedding (Økland & Cook 1998, Willson *et al.* 1999). Laboratory experiments and model calculations showed that the development of instabilities depends on the relative orientations of

- bedding,
- drilling direction, and
- principal axes of the *in situ* stress field.

Instabilities are minimised if 1) the direction of drilling or tunnelling has an angle >20° to bedding, and 2) the anisotropy of the *in situ* stress field is minimised in the plane normal to the drilling / tunnelling direction.

In the Toronto area, numerous shallow-level tunnels (<30 m overburden) were successfully constructed in the Georgian Bay Formation. An adit in the Queenston Formation at Niagara Falls with up to 13.5 m diameter was constructed using meshes, bolts and shotcrete as support measures (Golder Associates 2003). The local stress field was markedly anisotropic (σ_H/σ_V = 2.5 - 5, Rigbey *et al.* 1992). However, there is no experience with deeper drilling and tunnelling in the Upper Ordovician shales.

Experience from Canadian mines in highly stressed crystalline rocks indicates that rockbursts with magnitudes in excess of M3, and triggered slip on faults may occur (J. Adams, pers. comm.). Such effects can be minimised by careful design. Major instabilities were observed in closed, flooded mines. To what extent these findings can be extrapolated to deep openings in the Ordovician shales is not clear. However, instability might not be a problem if the excavations are small and dry.

Table 6-8 compares some basic geomechanical parameters of the Upper Ordovician shales with those of other shale formations studied in the framework of waste disposal. The spectrum reaches from soft clays (*e.g.* Boom Clay) that require massive support (steel liner, concrete) to highly indurated units (*e.g.* Palfris Formation) that are self-supporting. The geomechanical properties of the Upper Ordovician shales indicate that these formations are slightly "harder" but still similar to those of Opalinus Clay in Benken, Switzerland. This finding is consistent with the similar maximum burial depth and compaction (1700 m for Opalinus Clay at Benken, Switzerland and 1500 - 2000 m for the Upper Ordovician shales in southern Ontario). Moreover, there is another analogy in that there are high horizontal stresses in both areas. Table 6-9 compares the stress conditions at 650 m depth in northern Switzerland (from Nagra 2002a) with those estimated for southern Ontario (rough extrapolation of the data in Figure 6-13). In both cases, σ_h is similar to σ_V, and $\sigma_H = \sigma_{max}$ with values 30 - 60% higher than the other stress components. The maximum stress anisotropy is slightly higher in southern Ontario (1.6) when compared to Opalinus Clay (1.4).

Given the analogy of geomechanical parameters and *in situ* stress regime, some of the experience and conclusions pertaining to Opalinus Clay can be tentatively extrapolated to the situation in southern Ontario. For Opalinus Clay, material constitutive laws were derived both for short- and long-term deformation (Nagra 2002a), and coupled hydro-mechanical model calculations were performed in order to predict the stability of underground openings (Nagra 2002c). The data base used for the calculations included a large body of experiments in the

Table 6-8: Summary of some basic geomechanical parameters of Ordovician shales and limestones in southern Ontario and of other argillaceous formations

	Reference	Moisture content, wt%	Uniaxial compressive strength, MPa	Uniaxial tensile strength, MPa	Dynamic modulus, GPa	Young's modulus, GPa	Poisson ratio, -
Queenston Formation (shale)	1	2.7	24[1]	2.6	20	10	0.38
	2		40	3		12	0.3
Georgian Bay Formation (shale)	2		36			20	0.2
Lindsay Formation (limestone)	2		60			40	0.3
Boom Clay at Mol, Belgium	3	17	2			0.3	0.43
Spanish Reference Clay, Spain	3	16	4.2		0.4	0.5	
Callovo-Oxfordian at Bure, France	3	6.4	25			5	0.30
Opalinus Clay at Benken, Switzerland	4	4.4	29	2	26	8.5	0.27
Couche Silteuse at Marcoule, France	3	3	70			17	0.15
Toarcian/Domerian at Tournemire, France	3	3	32				
Palfris Formation at Wellenberg, Switzerl.	3	0.4	50	4	40	17	0.21

References: 1 = Rigbey *et al.* (1992); 2 = Golder Associates (2003); 3 = NEA (in prep.); 4 = Nagra (2002a)

[1] General increase with depth

Table 6-9: Stress regime at a depth of 650 m in southern Ontario and in Benken, northern Switzerland

data in MPa	Southern Ontario	Benken, northeastern Switzerland
σ_H	27	22.6
σ_h	21	15.1
σ_V	17	15.9

Southern Ontario: based on a rough extrapolation of data from Figure 6-13. Benken: Taken from Nagra 2002a. σ_V in southern Ontario is calculated using a bulk dry density of 2.65 Mg/m^3.

laboratory, as well as, *in situ* experiments in the Mont Terri Underground Rock Laboratory. The main conclusions are as follows:

- TBM (tunnel boring machine) drilling of the emplacement tunnels (cross-section area 4.9 m^2) parallel to bedding is feasible, and only meshes and bolts are required as support. The maximum convergence of the tunnel using conservative assumptions is 24 mm. Emplacement tunnels will be aligned parallel to σ_H, which minimises stability problems.

- The excavation of caverns for long-lived intermediate level waste (cross-section area 77.7 m^2) and operation tunnels (26.5 m^2), again parallel to bedding, is also feasible but requires shotcrete lining.

These conclusions are tentative for the following reasons:

- Only very few geomechanical data (strengths, moduli) are available for the Upper Ordovician shales in southern Ontario.

- Stress data are available only to 300 m depth, and the extrapolation to deeper levels is subject to uncertainty. The stress anisotropy at 650 m appears to be slightly more substantial in southern Ontario than in the Swiss situation.

- There are no records on the rock types in which the stress data in Figure 6-13 were measured. In northern Switzerland, the observation was made that the stress distribution with depth is not smooth but subject to variations that exceed the measurement error (P. Blümling, pers. comm. 2004). In the currently preferred conceptual model for northern Switzerland, the horizontal loads are essentially carried by "hard" lithologies (such as limestones), which results in substantial stress anisotropy in these rocks. In "weaker" lithologies (such as shales), stress anisotropy is reduced by time-dependent deformation (viscous behaviour, "creep"). This model is supported by the observation that induced tensile fractures parallel to σ_H (which occur in situations of large stress anisotropy) only occur where the borehole penetrates "hard" lithologies, but not in "weak" units, such as shales. The contention that time-dependent deformation may reduce stress anisotropy in shales sandwiched between more competent, load-bearing formations is a positive effect regarding geomechanical stability of the shales[11].

Further in depth investigations would require an improved formation-specific data base of rock strength and of *in situ* stress measurements in the target formation at target depth.

6.11 BASIC CHARACTERISTICS OF MIDDLE TO UPPER ORDOVICIAN LIMESTONES

Different terminology was used for these formations in outcrop-based investigations in Ontario and in subsurface investigations by the hydrocarbon industry, mainly in the U.S. (Figure 6-1). In the Michigan Basin and on the crest of the Algonquin Arch, the limestones correspond to the Simcoe Group and include the Gull River, Bobcaygeon, Verulam and Lindsay Formations. In the Appalachian Basin, they correspond to the upper part of the Black River Group (Gull River and Cocobonk Formations) and the Trenton Group (Kirkfield, Sherman Fall and Cobourg Formations). The combined thickness of all formations is 200 m in a borehole in Peel County (Appalachian Basin, west of Toronto) and 220 m / 190 m in boreholes near Goderich / Kincardine (both Michigan Basin).

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[11] Consider the situation where $\sigma_H = \sigma_1$, $\sigma_h = \sigma_2$, $\sigma_V = \sigma_3$. According to the Kirsch equations, the maximum tangential compressive stress along a tunnel aligned parallel to σ_H is calculated as $\sigma_\Theta = 3\,\sigma_h - \sigma_V - \Delta P$, with ΔP = pressure in the tunnel - pore pressure in the formation. Thus increasing anisotropy in the far-field stress increases the tangential stress along the tunnel surface, and this may lead to shear failure, once the strength of the rock is exceeded. In contrast, minimising the stress anisotropy in the tunnel cross section minimises rock failure.

The sequence from the Gull River Formation (supratidal to lagoon facies) to the Lindsay Formation (open shelf) records an evolution from a restricted coastal facies to a shelf carbonate facies. Limestone, generally argillaceous, is the dominating lithology. Other lithologies include subordinate shale and dolomite. Specifically, the lower part of the Gull River Formation contains dolomitic limestones and dolomites. Quantitative mineralogical data are not available. Golder Associates (2003) give matrix porosities of 0.005 - 0.03 and an effective diffusion coefficient for Cl[12] of 5E-13 to 3E-12 m^2/s. Given the fact that transport in the limestones is most likely fracture controlled, the lower diffusion coefficients, together with lower clay contents, result in markedly less favourable retardation properties when compared to the overlying shales.

Several authors describe local, fracture-controlled dolomitisation (Sanford 1993b, Coniglio & Williams-Jones 1992, Middleton *et al.* 1993, Coniglio *et al.* 1994) which most likely results in enhanced porosity and permeability. The Trenton Group limestones contain hydrocarbon reservoirs in dolomites adjacent to faults. On the other hand, some situations indicate that the limestones act as tight caprocks for Cambrian hydrocarbon reservoirs. It is concluded that the limestones generally have very low permeability but contain fault-related lithological heterogeneities that have higher porosity and permeability than the rocks unaffected by dolomitisation.

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[12] Effective diffusion coefficients were calculated by multiplying the pore-diffusion coefficient of 1E-10 m^2/s (as indicated by Golder Associates 2003) by the porosity range.

7. SUITABILITY OF MIDDLE AND UPPER ORDOVICIAN FORMATIONS IN SOUTHERN ONTARIO AS HOST FORMATIONS FOR RADIOACTIVE WASTE

Based on international experience, shale formations are very efficient barriers to transport through the geosphere. On the other hand, tunnelling may be easier in limestones (even though feasible in shales, see Chapter 6.10). Based on these arguments, the following alternative safety strategies can be envisaged:

1. The repository is located within the Upper Ordovician shales, which also represent the formations that act as transport barriers

2. The repository is located within the Middle to Upper Ordovician limestones, but the safety case relies on the overlying Upper Ordovician shales as transport barriers (a strategy also pursued in the recently licensed German Konrad Mine, which is located in limestones that are overlain by thick shales)

3. The repository is located within the Middle to Upper Ordovician limestones, which also represent the formations that act as transport barriers.

In the following sections, the state of knowledge and a qualification of the Middle to Upper Ordovician shales and limestones in terms of suitability to host a spent fuel repository will be summarised. The framework chosen for this summary is based on NEA's FEPCAT project (Mazurek *et al.* 2003). This project identifies and describes geosphere-related FEPs (Features, Events and Processes) that are relevant for deep geological disposal in argillaceous media. Focussing on FEPs that were regarded very relevant was a higher priority than completeness, and, thus, a set of only 59 FEPs were dealt with. On the basis of a compilation of existing information on these FEPs (mostly derived from a number of national disposal programmes), FEPCAT provided a state-of-the-art overview of the understanding of relevant FEPs related to argillaceous media. The FEP list is reproduced in Appendix 2.

The top-level classification of the FEPs distinguishes 3 categories:

A Undisturbed system (*i.e.* the far field as it can be characterised at present)
B Repository-induced perturbations (*i.e.* short-term effects)
C Long-tem evolution (*i.e.* changes in the geosphere over geological time).

The following sections are organised according to these top-level categories. On a more detailed level, the structure follows the logic of the preceding Chapters (organised by technical disciplines) rather than the process-oriented top-down approach chosen in FEPCAT. Irrespective of the order, those FEPs are addressed that have a site-specific component, while other FEPs that are typically treated in a more generic way are not included.

7.1 FEP CATEGORY A: UNDISTURBED SYSTEM

- The large-scale geometry of the Paleozoic formations in southern Ontario is simple and reasonably well known. According to the current state of knowledge, the degree of lateral heterogeneity is limited and/or known. The combined thickness of the shales varies regionally but always well exceeds 100 m, a value considered internationally as a design criterion. (FEP 2)

- Internal heterogeneity in the Upper Ordovician shales is mainly due to lithological variability in the vertical dimension (limestone and siltstone beds). In the Middle to Upper Ordovician limestones, shale interbeds occur. More importantly, some degree of lateral heterogeneity is expected in the limestones due to dolomitisation along faults. (FEP 3, 14)

- The occurrence of a network of steeply dipping faults has been proposed in the sedimentary rocks of southern Ontario. Vertical displacements are limited (order of dekametres) and thus faults do not breach the lateral continuity of possible host formations. In an evaluation process, the faults can be explored by seismic methods. (FEPs 3, 4)

- The presence of clay minerals, including swelling species, in the Upper Ordovician shales suggests favourable sorption properties. Less favourable conditions are expected in the underlying limestones. However, no specific measurements are available for southern Ontario, leaving substantial uncertainty. (FEPs 20 - 21)

- The Upper Ordovician shales have a substantial matrix porosity (order of 0.1). In contrast to crystalline rocks, the accessibility of the pore space in shales to diffusing species is undisputed. In the case that transport occurs (or is assumed to occur) along faults, the surrounding matrix represents a large water reservoir accessible to matrix diffusion. In the underlying limestones, matrix porosity is much smaller, and matrix diffusion is expected to be a less efficient retardation mechanism. (FEP 8, 9)

- Hydraulic conductivities measured in the Middle to Upper Ordovician shales and limestones are generally very low, and thus advective transport is expected not to be significant. However, only a limited number of data from specific locations are available, thus representativity is yet to be established. The limestones act as caprocks for hydrocarbons in some settings (which indicates very low conductivity) but may also be reservoir rocks (which indicates higher conductivity along dolomitised faults). The fact that ground water samples could be obtained from the limestones in boreholes points in the same direction. Palaeo-karst phenomena were not observed in the limestones. (FEPs 1, 6)

- Anomalous hydraulic heads in various units are more the rule than the exception, which is an independent confirmation of the low relevance of advection. (FEPs 1, 5)

- Ground waters in the Middle to Upper Ordovician limestones are brines, and stable isotopes of water show a major oxygen shift. Both features are indicative of very long underground residence times (millions of years). However, the admixture of a small proportion of young, meteoric water would not necessarily be recognised because isotopic dating techniques have not been applied to date. Pore waters of the overlying shales were not investigated to date, but most likely they are brines as well. The corrosive action of brines on repository components (*e.g.* steel canisters) will require special attention in the planning of repository construction and operation. (FEPs 17, 24, 25)

- Redox conditions in all target formations are most likely reducing, given the presence of organic matter, pyrite and chlorite. The redox buffering capacity is expected to be substantial, with the possible exception of the deltaic redbeds in parts of the Queenston Formation. However, no redox measurements are explicitly documented in the literature. (FEPs 17, 27)

- Given the formation-specific chemical characteristics of ground waters, there are no indications of cross-formation flow in geologically recent times, with the possible exception of shallow levels. (FEPs 7, 23, 24, 25)

- Advective infiltration of meteoric waters into formations at deeper levels appears physically unlikely due to the high density of the brines. Slow mixing may occur but is expected to be dominated by diffusion. (FEP 7)

- There are no obvious exfiltration areas for the deep ground waters, and thus regional hydraulic gradients are expected to be small. Southern Ontario is located between deep sedimentary basins in which all formations occur at progressively deeper levels. (FEP 5, 7)

- The possible presence of hydrocarbons needs to be considered for repository construction and operation.

7.2 FEP CATEGORY B: REPOSITORY-INDUCED PERTURBATIONS

Many of the repository-induced effects that may occur are common to most disposal programmes which consider sedimentary rocks as the host formation. At the present stage, no site-specific information is available for southern Ontario, but data and experience from other programmes can be extrapolated. What follows is a list of those characteristics that are specific to southern Ontario.

- The geomechanical stability of limestones is generally undisputed. Tunnelling in the Upper Ordovician shales at depths of several hundreds of meters is probably feasible as well, given the over-consolidated nature of these rocks. However, a site-specific investigation programme is needed to further substantiate this conclusion. Some analogies exist with Opalinus Clay in Switzerland, where geomechanical stability was demonstrated in spite of the existence of horizontal excess stresses. (FEP 34)

- The maximum temperatures to which the formations were exposed during diagenesis are not precisely defined but most likely in the order of 60 - 100 °C. These temperatures are similar to those expected to occur in the near field of heat-emitting spent fuel. In the Swiss safety case for Opalinus Clay (T_{max} = 85 °C), it was concluded that the thermal pulse from the waste (max. 100 °C over max. 1000 a) has no negative effects on the surrounding rock (such as degassing, adverse changes of pore-water composition, substantially changed pore pressures and/or geomechanical properties resulting in water flow). (FEP 31, 33)

- A repository in the sedimentary formations of southern Ontario will encounter brines. Salinity effects on swelling properties of clay minerals (in the geosphere and in the bentonite backfill) will require special attention. The extent to which self sealing of faults occurs in such an environment is yet to be demonstrated, given the small proportion of expandable clay minerals in the shales. While no site-specific investigations are available for southern Ontario, a large body of information on this topic is available from the German waste disposal programmes. (FEPs 41, 42)

- The mechanisms by which repository-generated gas would be transported through the host formations are not presently known and would require repository design-specific, as well as, site-specific experimental and modelling work. Depending on the gas release rate and formation properties, transport in solution or via two-phase flow may be sufficient, otherwise processes that alter the mechanical and hydraulic properties of the geosphere (pathway dilation, gas fracs) must be envisaged. (FEPs 45 - 48)

- The coupling of thermo-hydro-mechanical (THM) and thermo-hydro-mechanical-chemical (THMC) processes is not currently characterised for the Upper Ordovician shales and requires site-specific consideration. The relevance of these processes in limestones is limited by current understanding. (FEP 40)

- The geometric and hydraulic characterisation of the excavation-disturbed zone is not currently available. Given the large *in situ* stresses, detailed experimental and modelling work would be required. Such work would be more demanding for shales than for limestones, but considerable shale-specific experience is available on an international level. (FEPs 35, 38, 39)

7.3 FEP CATEGORY C: LONG-TERM EVOLUTION

- Southern Ontario is located in a tectonically quiescent region outside continent-scale lineaments. Historic earthquakes are weak and infrequent. (FEPs 53, 54)

- Recurrent Quaternary glaciations and periods of permafrost left no resolvable chemical signature in the deeper parts of the sedimentary sequence, and evidence that would indicate deep penetration of oxidising water (as observed in some crystalline-basement environments) is lacking. (FEP 52)

- The northern part of southern Ontario is currently uplifting in response to the retreat of the Laurentide ice sheet. A stable equilibrium typical of cratonic settings is expected to be re-established within thousands of years. (FEP s 57, 59)

- Erosion rates are not quantified in the literature. Due to the long-term stability of the craton, it is probably insiginificant over time scales relevant for waste disposal. Deep glacial erosion focussed in valleys did not occur in southern Ontario. The Devonian and Silurian carbonate formations form a erosion-resistant protective lid for the underlying shales, exemplified by the topographic relief of the Niagara Escarpment. (FEP 57)

- The presence of a stress regime with high horizontal stresses favours the closure of (typically steeply dipping) faults that penetrate the target formations. (FEPs 42, 55)

- Hydrocarbons and salt are the main subsurface natural resources in southern Ontario. While the spatial distribution of salt is well known, the avoidance of hydrocarbon reservoirs should be an explicit part of the evaluation strategy.

7.4 CONCLUSIONS

A substantial body of geoscientific information is available on the sedimentary sequence of southern Ontario. To date, such geoscientific information has been collected for academic or industrial purposes, (*i.e.* investigations for long-term radioactive waste management purposes have not been conducted). The available information is in general regionally based and, as a consequence, background material is in certain instances limited in number and geographic distribution. Issues of site-specific representativity and spatial heterogeneity are items that would require confirmation. However, at least a part of the information gaps can be filled by extrapolating experience from other disposal programmes in sedimentary rocks, and from general knowledge of such systems.

Based on currently available data and interpretations, the suitability of Middle and Upper Ordovician shale and limestone formations in southern Ontario was assessed against an internationally accepted compilation of relevant FEPs (Features, Events and Processes) for argillaceous media. The key conclusions include:

- The thickness of the host formation(s) well exceeds 100 m, a value generally regarded as a siting preference.

- The degree of vertical and horizontal heterogeneity of geological and hydrogeological attributes in the potential host formations is limited and reasonably well known.

- Hydrochemical evidence indicates very long underground residence times of formation waters and no resolvable cross-formational flow at depth over geological periods of time.

- A surficial flow system is underlain by a stagnant hydrogeological regime. Given the absence of exfiltration areas for deep ground waters, flow does not occur or is very limited. Solute transport is probably dominated by diffusion.

- Tunnelling in deeply buried shales and limestones appears to be feasible in spite of high horizontal stresses.

- Sedimentary rocks, specifically clays and shales, are considered as the preferred host formations for spent fuel and vitrified high-level waste in several countries.

Based on current knowledge, there is no evidence that would *a priori* seriously question the feasibility and long-term safety functionality of a nuclear used fuel repository in deeply buried Ordovician shales and limestones in southern Ontario. There are a multitude of independent arguments that suggest this environment is highly suitable. From a purely technical point of view, the chance of success to complete a convincing safety case is substantial. One very positive aspect is the potential for using multiple lines of evidence (*e.g.* predictive flow/transport modelling *vs.* hydrochemical evidence *vs.* understanding of the hydrogeological system) to strengthen the safety case.

In contrast to several European disposal projects in sedimentary rocks, the host formations (whether Ordovician shales or limestones) are not directly bounded by aquifers containing young, fresh waters. Currently, there is no clear evidence that advection is taking place even in higher-permeability formations such as Silurian and Devonian dolomites, most likely due to the absence of large-scale hydraulic gradients. Therefore, a substantial part of the sedimentary sequence and not only the host rocks could be considered as a transport barrier in a safety case. Alternatively, they could be conservatively ignored and left as "reserve FEPs" (in analogy to Nagra 2002b).

The main safety functions of the geosphere ("pillars of safety": isolation, transport barrier, long-term confinement) can be more easily demonstrated for the Upper Ordovician shales than for the Middle to Upper Ordovician limestones, which have a higher degree of heterogeneity and less favourable retardation characteristics. The possibility to plan for a repository in the limestones and rely on the safety function of the overlying shales appears to be a realistic option, even though it means that two different rock systems would need to be characterised to a high degree of detail. In spite of a more challenging geotechnical situation, the positioning of the repository in the shales themselves is the simplest design from the viewpoint of safety strategy and demonstration. Such a repository system would also be directly aligned with other national waste management programmes and could benefit from co-operation with international Research and Development projects.

8. CHARACTERISTICS OF MIDDLE TO UPPER ORDOVICIAN FORMATIONS IN SOUTHERN ONTARIO IN THE INTERNATIONAL CONTEXT

8.1 HOST-ROCK TYPES

Clays and shales

Deep geological disposal in clays and shales is an option pursued in several European countries. Soft clays are studied in Belgium (Boom Clay at Mol, Ypresian Clay at Doel) and Spain (Spanish Reference Clay in the Duero Basin). Moderately indurated shales have been or are the main focus of investigations in France (Callovo-Oxfordian at Bure, Toarcian-Domerian at Tournemire, Couche Silteuse at Marcoule) and Switzerland (Opalinus Clay in the Zürcher Weinland). Highly consolidated shales have been investigated in Switzerland (Palfris Formation at Wellenberg) and in Hungary (Boda Clay Formation). Other, less well developed projects targeted at clays and shales exist in other countries (see Witherspoon & Bodvarsson 2001 for a world-wide overview). National or international rock laboratories are in operation in Switzerland (Mont Terri, Opalinus Clay), Belgium (Mol, Boom Clay) and France (Tournemire, Toarcian-Domerian). Another laboratory is being constructed in France (Bure, Callovo-Oxfordian). Various efforts in clay-related research are co-ordinated by the Nuclear Energy Agency (NEA) of the OECD, namely under the auspices of the Working Group on the Characterisation, the Understanding and the Performance of Argillaceous Rocks as Repository Host Formations ("Clay Club"; see Chapter 4).

Limestones

With one exception, limestones are not considered as host formations for radioactive waste in any of the leading European programmes. The two main reasons for this are:

- European projects are focussed on Mesozoic and Tertiary sedimentary basins, where limestones and dolomites are typically clean, *i.e.* contain only minor amounts of clay minerals. Thus the retardation and self sealing properties are less favourable than in shales.
- Limestones in the investigated basins often have high hydraulic conductivities, and many represent fractured, sometimes karstic aquifers that are being exploited. An example from the Paris Basin (France) is shown in Figure 8-1.

Thus the Paleozoic limestones in southern Ontario with generally very low hydraulic conductivity are exceptional in the context of international repository studies that have characterised limestone lithologies. Possible explanations for their different hydraulic characteristics include:

- Limestones in southern Ontario are frequently argillaceous and often contain shale interbeds, in contrast to the essentially pure limestones studied elsewhere. The reasons for the higher clay-mineral contents are not entirely clear, given the fact that all carbonates considered are shallow marine deposits. One could speculate whether the scarcity of vegetation on the continents in the Paleozoic could have resulted in higher terrigenous input into shelf sediments, when compared with younger sediments.

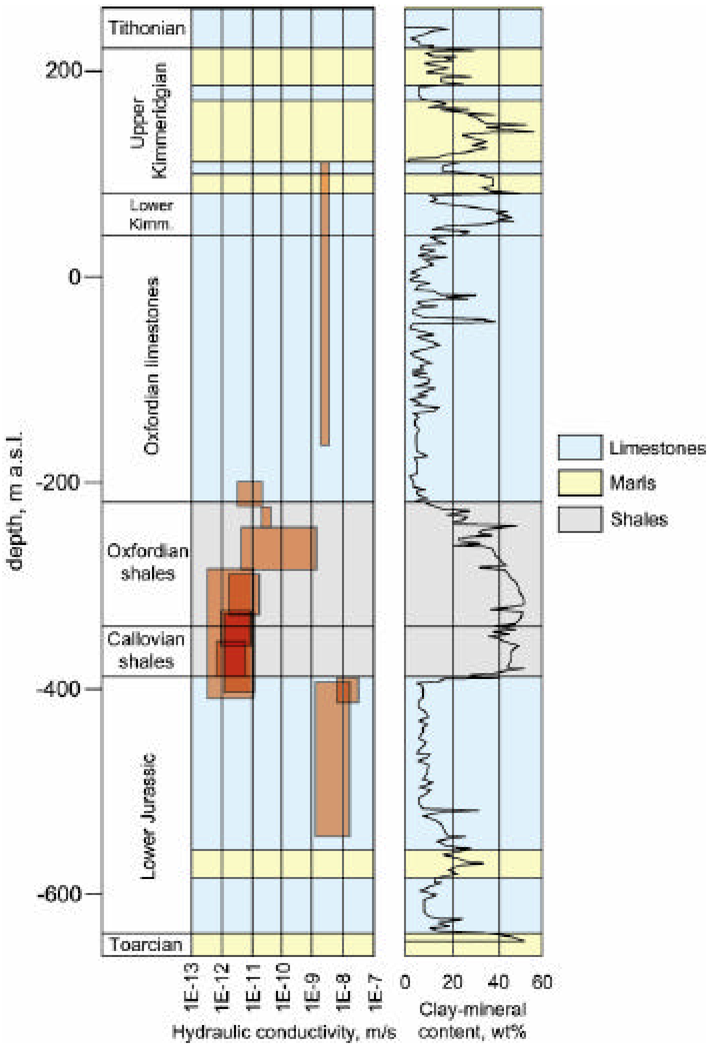

Figure 8-1: Simplified lithologic profile, hydraulic conductivity data and clay-mineral log for borehole MSE 101 at the Bure Site (France). Compiled from Babot (1999) and Andra (1999d). The Callovo-Oxfordian shales with very low hydraulic conductivity are sandwiched between higher-conductivity limestone formations.

- The compressive stress regime that is identified today in the North American Craton (see Chapter 6.7.1) contributes to the closure of steeply dipping fractures, thereby limiting their hydraulic significance. Such a stress regime may have prevailed over geological time scales in the past.

- The Middle to Upper Ordovician limestones in southern Ontario do not show evidence of palaeo-karst features (see Chapter 6.6.4), while many European limestones do.

In the German Konrad project, it is planned to dispose of low- and intermediate-level radioactive waste in a disused, carbonate-hosted iron ore mine in Jurassic limestone (Brennecke 2004). In the safety case for this project, the geosphere barrier is constituted by overlying, 170 - 400 m thick Lower Cretaceous shales, while no barrier function is attributed to the limestones which host the repository. This project was licensed by the German regulatory bodies in 2002.

8.2 GEOMETRIC ASPECTS

The 3D geometry of Paleozoic formations in southern Ontario is simple and relatively well known, thus lateral predictability is good. While there are currently no well-developed geometric design criteria for radioactive waste disposal in sedimentary rocks of southern Ontario, there is a general consensus on an international level regarding host formation thickness (100+ m) and depth below surface (200 m, more frequently 400+ m) of a potential host formation. These aspects are discussed in Chapter 6.9.1 and Table 6-6. Both the Upper Ordovician shales and the Middle to Upper Ordovician limestones in southern Ontario comply with these international criteria. Whatever the specific design criteria and regulatory requirements, there are large potential areas in southern Ontario that would deserve further evaluation, larger than in many European countries.

In addition, an evaluation process should include geoscientific aspects such as

- regional faulting,
- internal heterogeneity (*e.g.* limestone or dolomitic beds in the shales, or dolomitised faults in the limestones),
- economic resources in the subsurface.

These aspects are not fully characterised at the present stage and will require efforts in the future. Overall, the likelihood of finding areas that comply with all geometric design criteria is high, thus, from today's geoscientific perspective, the situation in southern Ontario is very promising in the framework of geological waste disposal.

8.3 HYDRAULIC CONDUCTIVITY AND HEAD

In Table 8-1, hydraulic conductivity data from various European argillaceous formations are compared with data for Middle to Upper Ordovician shales and limestones from southern Ontario. The data are shown graphically in Figure 8-2. The following points can be made:

- Moderately indurated formations, such as Opalinus Clay and all three French formations, have extremely low hydraulic conductivity. This is most likely because flow through the matrix is very limited given the relatively low porosities of 0.1 - 0.15, while fracture flow is also limited due to the scarcity of fractures and efficient self sealing.

- In comparison, weakly indurated clays with high matrix porosity (Belgian and Spanish clays) have somewhat higher (even though still low) hydraulic conductivities because flow occurs through the large interconnected pore space in the matrix.

Table 8-1: Hydraulic conductivity in argillaceous formations

Formation		*In situ* tests		Laboratory tests		Data source
		K_{min}, m/s	K_{max}, m/s	K_{min}, m/s	K_{max}, m/s	
Queenston Formation, SW Ontario	shales	2.5E-13	1.0E-9			1
Georgian Bay Formation, SW Ontario		1.0E-13	4.0E-12			1
Blue Mountain Formation, SW Ont.		1.0E-12				1
Lindsay Formation, SW Ontario	limestones	6.3E-14	4.0E-11			1
Verulam Formation, SW Ontario		2.0E-14	7.0E-9			1
Bobcaygeon Formation, SW Ontario		1.0E-13	6.3E-9			1
Gull River Formation, SW Ontario		2.5E-14	6.3E-9			1
Opalinus Clay at Benken, Switzerland		1.0E-14	6.0E-14	2.0E-14	1.0E-13	2
Opalinus Clay at Mont Terri, Switzerland		2.0E-14	1.0E-12			2
Palfris Formation at Wellenberg, Switz.		1.0E-13	1.0E-10			3
Callovo-Oxfordian at Bure, France		1.3E-13	1.7E-11	1.0E-14	4.0E-14	2
Toarcian/Domerian at Tournemire, France		6.7E-14	1.3E-12	1.0E-14		2
Spanish Reference Clay, Spain		1.3E-12	2.1E-11			2
Boom Clay at Mol, Belgium		1.0E-12	1.0E-10			2
Yper Clay at Doel, Belgium		4.0E-10				3
Boda Clay Formation, Hungary		1.0E-12	1.0E-10			2

Data sources: 1 = Chapter 6.3 (this document), 2 = Mazurek *et al.* (2003), 3 = NEA (in prep.).

- Highly indurated, strongly over-consolidated[13] shales (Boda Clay, Palfris Formation) also have higher hydraulic conductivities. In this case, flow occurs in a fracture network, whereas matrix flow is irrelevant because porosity is very small.

- Judging from their porosity (Figure 8-2) and burial history (Chapter 6.6.1), the Upper Ordovician shales are moderately over-consolidated and belong to the group of argillaceous formations with very small hydraulic conductivities. Such very small values were actually measured *in situ*.

- Some relatively high values for the Queenston Formation are probably due to the fact that the measurement intervals were all located at shallow levels (overburden <140 m, see Appendix 1), and lower values would be expected at depths of several hundreds of metres (see discussion in Chapter 6.3.1).

- The Middle to Upper Ordovician limestones show a very large variability of hydraulic conductivity. The lowest values are comparable to those of very low-permeability shales,

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[13] The over-consolidation ratio is the maximum effective stress to which the formation was exposed during burial divided by the present-day effective stress. Because the Boda Clay and the Palfris Formation were buried to depths of several km but occur at depths < 1 km today, they are highly over-consolidated. Strong over-consolidation triggers the formation of fracture networks in argillaceous rocks.

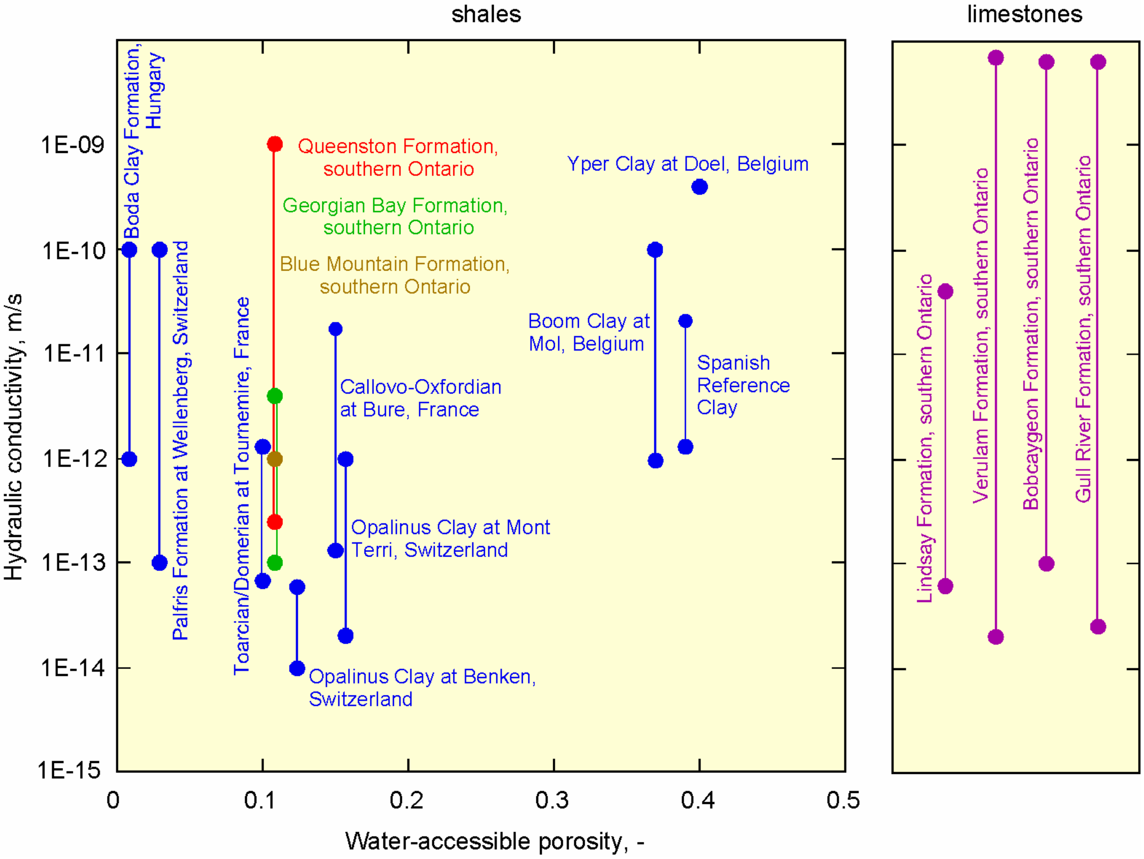

Figure 8-2: Water accessible porosity *vs.* hydraulic conductivity (only *in situ* data considered) of various argillaceous formations compared with shales and limestones from southern Ontario. Data taken from Table 8-1 and Table 8-3.

while the highest values around 1E-8 m/s are ca. 2 orders of magnitude higher than in the shales. The heterogeneity of porosity and hydraulic conductivity of the limestones was addressed in Chapter 6.11.

- In shales, hydraulic conductivity is anisotropic, and *in situ* tests characterise the value parallel to bedding. Conductivity normal to bedding is typically 2 to 5 times smaller.

- Laboratory data for hydraulic conductivity of French and Swiss formations (no laboratory measurements are available from southern Ontario) generally yield similar or smaller values when compared to *in situ* values (see Table 8-1). This could be due to the fact that fractures occur in the formation while laboratory tests are conducted with intact rock samples. However, it is also possible that *in situ* measurements are affected by the presence of a higher-conductivity skin (excavation-disturbed zone of the borehole) and thus overestimate the real *in situ* values. On several occasions, such skin effects were observed.

- Available hydraulic measurements from southern Ontario were not adapted to the study of very low-permeability rocks. The lower ends of the ranges typically represent experimental detection limits and not actual values.

In low-permeability formations of southern Ontario, anomalous formation pressures were reported (Chapter 6.3.2). Similar observations were made in Opalinus Clay at Benken and in the Callovo-Oxfordian at Bure (slight overpressures) and in the Palfris Formation at Wellenberg (heavy underpressures). Several hypotheses were put forward to explain such anomalous pressures (*e.g.* osmosis, horizontal strain, gas migration, erosional or postglacial unloading). However, none of the hypotheses is conclusive due to substantial data uncertainty and limited understanding of coupled processes. In any case, anomalous pressures are taken as evidence of very small hydraulic conductivity on a large scale.

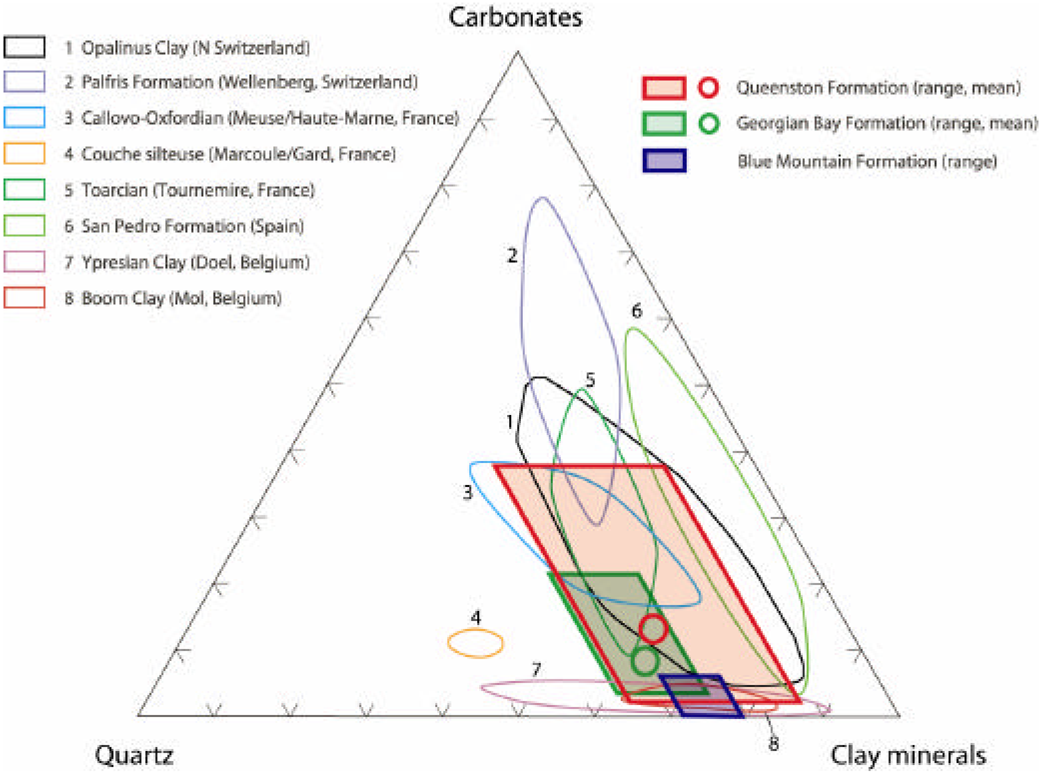

Figure 8-3: Mineralogical composition of various argillaceous formations compared with that of Upper Ordovician shales in southern Ontario. Adapted from Nagra (2000a), Ontario data from Russell & Gale (1982). Data represent weight proportions.

8.4 MINERALOGY

The mineralogical composition of the Upper Ordovician shales in southern Ontario is given in Table 6-7. In Figure 8-3, these data are compared with European shale formations considered in the framework of radioactive waste disposal. It is evident that there is a high degree of overlap, namely with the Callovo-Oxfordian at Bure (France) and with Opalinus Clay in northern

Switzerland. While detailed clay-mineralogical data are not reported in the literature, available information suggests that the proportion of swelling clays is lower in the Upper Ordovician of Ontario when compared to the European formations. Another difference is the presence of minor proportions of vermiculite and the absence of kaolinite.

Mineralogical data for the Middle to Ordovician limestones are not available. Based on lithologic descriptions (*e.g.* Johnson *et al.* 1992), variable amounts of clay minerals are present.

8.5 PORE-WATER COMPOSITION

The composition of formation water in the Middle to Upper Ordovician limestones in southern Ontario is discussed in Chapter 6.4 and summarised in Table 6-3. The pore-water composition of the overlying shales is not known. However, given the long residence times, it is likely that it is similar to the compositions of those in the under- and overlying units where water samples could be taken. Table 8-2 shows the available data, together with compositions of other argillaceous formations considered in the framework of radioactive waste disposal. The following observations can be made:

Table 8-2: Chemical characteristics of ground- and pore waters in argillaceous formations

Formation	Total dissolved solids, g/L	Water type	Data source
Thorold Fm / Grimsby Fm / Whirlpool Fm, SW Ontario	191 - 325	Na-Ca-Cl to Ca-Na-Cl	Frape *et al.* (1989), McNutt *et al.* (1987)
Trenton Gp / Black River Gp, SW Ontario	140 - 243	Na-Ca-Cl	
Opalinus Clay at Benken, Switzerland	13	Na-Cl-(SO_4)	Various sources: Mazurek *et al.* (2003), NEA (in prep.), internal documents
Opalinus Clay at Mont Terri, Switzerland	18	Na-Cl-(SO_4)	
Palfris Formation at Wellenberg (upper part), Switz.	1.0	Na-HCO_3	
Palfris Formation at Wellenberg (lower part), Switz.	12	Na-Cl	
Callovo-Oxfordian at Bure, France	5	Na-Cl-(SO_4)	
Couche Silteuse at Marcoule, France	10	Na-Cl-SO_4	
Toarcian/Domerian at Tournemire, France	0.9	Na-Cl-HCO_3	
Spanish Reference Clay, Spain	3.0	Na-SO_4	
Boom Clay at Mol, Belgium	1.7	Na-HCO_3	
Yper Clay at Doel, Belgium	19	Na-Cl	
Boda Clay Formation, Hungary	2.0	Na-HCO_3-SO_4	
Konrad mine (Lower Cretaceous), Germany	160	Na-Ca-Cl	Klinge *et al.* (1992)

- The salinities of most European argillaceous formations are 1 - 2 orders of magnitude lower than those of shales and limestones in southern Ontario. Potential reasons for this contrast are 1) the absence of salt at many sites, and 2) the presence of active lime- or sandstone aquifers above and below the shale unit. For example, Opalinus Clay in the Zürcher Weinland (northeastern Switzerland) is underlain by 3 aquifers containing glacial and interglacial waters (Nagra 2002a), which results in ongoing out-diffusion from the shale (Waber *et al.* 2001).

- The only site where pore waters similar to those in southern Ontario are observed is the German Konrad mine, which is undelain by Upper Permian salt. At this site, a quasi-linear increase of salinity from 160 g/L in Lower Creaceous shales to 220 g/L in Upper Jurassic limestones is observed. This situation is interpreted to represent a stagnant, diffusion-dominated system (Klinge *et al.* 1992).

- Reducing conditions (negative Eh values) prevail in all European formation waters that were considered. No published data are available for southern Ontario. However, given the presence of organic matter, sulfide minerals and chlorite, reducing conditions are inferred as well. S. Frape (pers. comm. 2004) reported elevated levels of H_2S (up to 5 - 15 g/L) at least in Devonian formations, and methane throughout the sedimentary column.

The high salinities in formation waters from southern Ontario lead to the following issues when dealing with geological disposal of radioactive waste:

- The higher rate of corrosion of repository materials, such as waste canisters, requires special attention. In the Swedish safety case, a maximum salinity of 100 g/L is a design criterion for siting a repository.

- The capability of clay minerals to swell and self seal (in bentonite backfill, in the excavation disturbed zone and in natural faults of the host formation) at high salinity needs to be addressed on a site-specific basis. Extrapolations from other sites may not be valid due to the materially different hydrochemical environments.

- Geochemical calculations (*e.g.* speciation, disolution/precipitation and sorption equilibria) may be more complex than in dilute systems due to substantial deviations of activity coefficients from ideal behaviour.

8.6 POROSITY AND DIFFUSION COEFFICIENTS

Porosity data of the Upper Ordovician shales in southern Ontario are comparable to those of Opalinus Clay as well to those of all French sites (Table 8-3). There is a good correlation between porosity and diffusion coefficients, exemplified in Figure 8-4 for ^3H. The shales from Ontario fit reasonably well into the general pattern. The following points can be made:

- For formations in southern Ontario, only diffusion coefficients for Cl are available. Based on international experience, values for ^3H are ca. 4 times higher than those for Cl because water molecules can access a larger pore volume than Cl, which is repelled by negatively charged clay-mineral surfaces (Pearson 1999). However, such anion exclusion effects are probably less important in the case of shales in southern Ontario because of their very

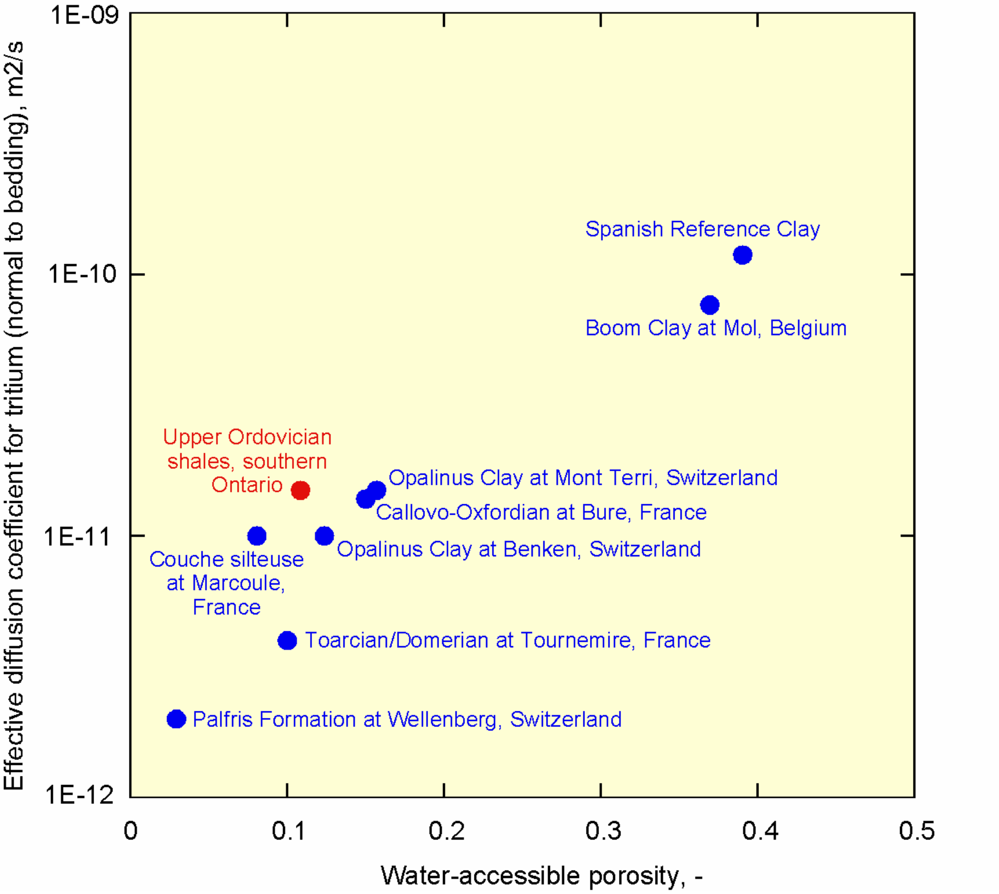

Figure 8-4: Water accessible porosity *vs.* effective diffusion coefficient for ^{3}H (values normal to bedding if specified in the original data) of various argillaceous formations compared with data of shales from southern Ontario. For shales from southern Ontario, the effective diffusion coefficient for Cl^{-} is shown (no data for ^{3}H available). Data taken from Table 8-3.

high pore-water salinity. The thickness of the electric double layer adjacent to clay surfaces, *i.e.* the zone from which anions are repelled, is much smaller in saline environments when compared to pore waters with small ionic strength.

- Similar to hydraulic conductivity, diffusion coefficients are anisotropic in shales. The values parallel to bedding are typically 2 to 5 times higher than normal to bedding.

8.7 GEOMECHANICAL PROPERTIES

Basic geomechanical parameters of Upper Ordovician shales in southern Ontario were set in an international context in Chapter 6.10.3, with some tentative conclusions regarding geomechanical stability. Geomechanical data from limestones in southern Ontario are not available, but underground constructions in this rock type are generally less critical.

Table 8-3: Porosity and effective diffusion (De) coefficient for ^{3}H in argillaceous formations

Formation	Water-accessible porosity, -	De for ^{3}H (normal to bedding), m^{2}/s	De for ^{3}H (parallel to bedding), m^{2}/s
Upper Ordovician shales, SW Ontario	0.108	1.5E-11[1]	
Opalinus Clay at Benken, Switzerland	0.124	1.0E-11	5.0E-11
Opalinus Clay at Mont Terri, Switzerland	0.157	1.5E-11	6.3E-11
Palfris Formation at Wellenberg (upper part), Switz.	0.029	2.0E-12	n.d.
Callovo-Oxfordian at Bure, France	0.15	1.4E-11	2.0E-11
Couche Silteuse at Marcoule, France	0.08	1.0E-11	
Toarcian/Domerian at Tournemire, France	0.10	4.0E-12	1.5E-11
Spanish Reference Clay, Spain	0.39	1.2E-10	n.d.
Boom Clay at Mol, Belgium	0.37	7.7E-11	1.5E-10
Yper Clay at Doel, Belgium	0.40	n.d.	

[1] Value for Cl (no data for ^{3}H available).

Data sources: Mazurek *et al.* (2003), NEA (in prep.) and various unpublished documents.

9. CONCLUSIONS

Geometry and structural features

- The 3D geometry of sedimentary rock formations in southern Ontario is simple and reasonably well known. Lateral variability of rock formations is either limited or known, thus the lateral predictability is good.

- A regional network of faults with vertical displacements typically in the range of dekametres occurs in the sedimentary rocks of southern Ontario. Major lineaments were not observed.

- Faults and other structural complications occur in units overlying the partially dissolved salt of the Salina Formation.

Hydrogeology and flow system

- The sedimentary sequence of southern Ontario consists of alternating low-permeability units (*e.g.* shales, limestones) and higher-permeability formations (*e.g.* dolomites, sandstones). Regional water flow would be expected to occur within individual formations and not across them.

- Deep infiltration of meteoric water into the deep underground appears unlikely because of the absence of obvious exfiltration areas (and therefore small regional hydraulic gradients) and because the high density of the brines renders infiltration of fresh water physically difficult.

- At the present state of knowledge, it is concluded that a shallow flow system containing fresh water exists, and flow is topographically driven towards the lakes that bound the area of investigation. The deeper subsurface of southern Ontario contains stagnant water, and solute transport is expected to be dominated by diffusion even in those formations that have higher permeability.

Hydrogeochemistry

- Except for the shallow flow system, the subsurface of southern Ontario is characterised by brines. The geometry of the interface to the shallow fresh water flow system is not well characterised.

- Chemical and isotopic signatures suggest very long subsurface residence times of deep ground waters, with no resolvable young components (except at very shallow levels). Formation-specific characteristics of some hydrochemical tracers suggest that there has been no resolvable cross-formational flow at depth over geologic periods of time. Limited evidence suggests the possibility of cross-formational flow at shallow levels along known faults.

- After several Quaternary glaciations, hydrochemical evidence that would indicate glacial signatures in deep ground waters is lacking.

- The possible presence of methane and H_2S dissolved in deep ground water requires special attention when designing and operating a repository.

Stress state and neotectonics

- Southern Ontario is located in the southeastern part of the North American Craton and thus tectonically very stable. Active faulting and seismicity are very limited.

- The regional stress field in southern Ontario is characterised by horizontal excess stresses. This feature is beneficial from the point of view of fault sealing. Its effects on the geotechnical feasibility of shafts and tunnels in the deep subsurface, as well as, on the development of instabilities and an excavation-disturbed zone will require special attention.

- The neotectonic evolution is affected by Quaternary glaciations, including transient vertical movements, glacial erosion and minor faulting at shallow levels. Effects on the deeper subsurface appear to be negligible.

- The central and northern part of southern Ontario is currently uplifting in response to post-glacial isostatic re-equilibration. The re-establishment of stable conditions is expected over geologically short periods of time.

Assessment of potential host formations and regions

- Based on a number of simple assessment criteria (hydraulic conductivity, depth below surface, thickness, homogeneity), Upper Ordovician shales and Middle to Upper Ordovician limestones have been identified as potential formations to host a deep geological repository for spent fuel in southern Ontario.

- The Middle to Upper Ordovician formations occur in sufficient thickness and at favourable depth in large parts of southern Ontario. Substantial parts of the Bruce Megablock could be considered in future studies, mainly due to the absence of major lineaments, the presence of a simple fault pattern, the absence of mapped faults in the underlying crystalline basement, and very low seismic hazard. Hydrocarbon resources are much less frequent in the Bruce Megablock when compared to the Niagara Megablock, yet this issue should be further pursued in future assessments.

Suitability of Middle to Upper Ordovician shales and limestones as host formations for a used nuclear fuel repository, international context

- The hydrogeological, geochemical and geomechanical properties of Upper Ordovician shales show many similarities with European argillaceous formations that are currently being investigated in the framework of radioactive waste disposal. Such properties include key parameters such as hydraulic conductivity, porosity, diffusion coefficient and compressive strength. The main difference in comparison to European projects is the expected high salinity of pore water.

- The geotechnical feasibility of a deep repository in highly stressed shales is yet to be demonstrated, once a higher level of understanding of the material constitutive laws and of coupled hydro-mechanical processes has been reached. To some degree, the situation is analogous to Opalinus Clay in northeastern Switzerland, where geotechnical feasibility has recently been established.

- With one exception, limestones as host formations do not have international precedents, and the generally very low hydraulic conductivity of the Middle to Upper Ordovician limestones in southern Ontario is a somewhat unique situation. Lateral heterogeneity introduces some uncertainty, given the fact that steeply dipping, dolomitised and potentially permeable faults occur, have acted as pathways for hydrocarbon migration in the past and produce water in some wells today. The explorability of such features from the surface may be difficult. In other areas, the limestones act as caprocks for hydrocarbons, which indicates very low hydraulic conductivity.

- A spent fuel repository could be hosted by the Upper Ordovician shales, which would also act as a geosphere barrier. Alternatively, the repository could be located in the underlying Middle to Upper Ordovician limestones. In such a case, the main geosphere barrier in the safety case would be the overlying shales and not the limestones themselves (an analogous situation exists in the German Konrad project). The choice between these options is a trade-off between a possibly simpler geotechnical situation in the latter option and the possibility to focus all efforts on one single rock type in the former option.

- The available knowledge from southern Ontario was tested against a FEP list that was compiled on the basis of the integrated experience of European waste disposal programmes in argillaceous rocks. The conclusion is that there is no evidence that would *a priori* seriously question the feasibility and long-term safety functionality of a spent fuel repository in deeply buried Ordovician formations in southern Ontario. On the other hand, a multitude of arguments suggest that the environment is highly suitable. One very positive aspect is the potential for using multiple lines of evidence (*e.g.* predictive flow/transport modelling *vs.* hydrochemical evidence *vs.* understanding of the hydrogeological system) to strengthen the safety case.

10. OPEN QUESTIONS AND SUGGESTIONS FOR FUTURE WORK

The data base on which the conclusions presented above are based is sufficient for general understanding and as a basis for further decision making. However, not all conclusions are supported by observations and measurements of adequate number, quality and spatial distribution. The representativity of available data and conclusions (often derived only from specific parts of the region of interest) is yet to be established on the basis of more localised and purpose-designed investigations. The degree of knowledge is higher in the Niagara Megablock when compared to the Bruce Megablock. What follows is a possibly incomplete list of open issues that became evident in the preceding Chapters.

Geometry

- The detailed deterministic geometry of the fracture framework as proposed by Sanford *et al.* (1985) requires further substantiation.

- Geological profiles along and across the Algonquin Arch should be constructed.

- More generally, an improved visualisation of the 3D geometry of geological units, regional structures and economic resources would be of great help for the evaluation process. Ideally, such a 3D model would be established on a GIS platform, where various pieces of information (*e.g.* topographic elevation, locations of existing deep boreholes, neotectonic features, location of oil and gas reservoirs) could be organised in superposed layers. A potentially suitable GIS platform, together with a comprehensive data base on petroleum boreholes, is available at the Petroleum Resources Centre of the Ontario Ministry of Natural Resources.

- The avoidance of conflicts with the ongoing and future exploitation of existing resources, such as hydrocarbons, salt and metals, requires special attention.

Host-rock characterisation

- Properties of the Upper Ordovician shales that are relevant for the quantification of retardation of solute migration are not well characterised at the present stage. Relevant aspects would include mineralogy, porosity, diffusivity ion exchange and sorption characteristics, pore-water composition and redox state.

- The Upper Ordovician shales show some degree of heterogeneity, mainly in the vertical dimension (limestone and dolomite beds, red beds, etc.). A more detailed characterisation of such heterogeneities with respect to their significance for solute transport and retardation on the formation scale is currently outstanding.

- The geomechanical and coupled hydro-mechanical rock characteristics that are needed as input for the derivation of material constitutive laws for short- and long-term deformation are open issues. Namely in the case of the shales, such laws are needed for the demonstration of geotechnical feasibility by model calculations.

- Rock properties relevant for the quantification of gas transport mechanisms should be addressed.

Understanding of the flow system

- Minor admixtures of young meteoric waters to the brines would not be recognised on the basis of the available data set. Dating techniques using radioactive isotopes (such as ^{14}C) would be useful to constrain the age structure of the deep ground waters.

- The depth of the interface between the surficial fresh-water flow system and the deep, stagnant brines is yet to be characterised.

- Increasing the data base of formation pressures and head distributions, explicitly considering depth-dependent fluid density, would help in the evaluation of potential regional flow fields.

Salinity effects

- The effects of the expected high pore-water salinity need special attention in the context of
  - corrosion of repository materials,
  - efficiency of clay swelling and self sealing in the bentonite backfill, in the excavation-disturbed zone and in natural faults,
  - efficiency of sorption on clay surfaces,
  - availability of thermodynamic and kinetic data needed for the modelling of solute-water-rock interactions.

Long-term evolution

- Few data exist on the rate and nature of erosion in southern Ontario. A better understanding will be required for the development of long-term scenarios that would include climatic change, glaciations and vertical movements.

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APPENDICES

		Raven et al. (1992)							Raven et al. (1992)						
Lithology	Formation	Borehole	[illegible]	[illegible]	[illegible]	K, min (m/s)	K, max (m/s)	Comments	Borehole	[illegible]	[illegible]	[illegible]	K, min (m/s)	K, max (m/s)	Comments
Shale	Kettle Point Shale	MDMW-1, Sarnia	34	47	13	1.0E-10	1.0E-10	Formation is partially eroded							
Limestone/ Dolomite	Ipperwash & Widder Limestone	MDMW-1, Sarnia	47	82	35	7.9E-11	7.9E-07								
Shale	Arkona Shale	MDMW-1, Sarnia	82	120	38	1.0E-12	1.0E-12								
Limestone	Rockport Quarry Limestone	MDMW-1, Sarnia	120	126	6	1.0E-12	4.0E-08								
Shale	Bell Shale	MDMW-1, Sarnia	126	145	19	1.0E-12	6.3E-12								
Limestone	Dundee Limestone	MDMW-1, Sarnia	145	189	44	4.0E-13	1.3E-07								
Limestone/ Dolomite	Lucas Dolomite	MDMW-1, Sarnia	189	281	92	2.5E-09	3.2E-07								
Limestone/ Dolomite	Amherstburg Limestone	MDMW-1, Sarnia	281	304	23	3.2E-11	7.9E-09								
Dolomite	Bois Blanc Formation														
Dolomite	Bass Island Formation														
Various, incl. evaporites	Salina Formation														
Dolomite	Guelph Dolomite	USNI-1, Niagara Falls	5	23	18	1.6E-07	1.0E-05	Top eroded	NI-1, Niagara Falls	8	44	36	7.9E-09	6.3E-05	Top eroded
Dolomite	Lockport Dolomite	USNI-1, Niagara Falls	23	42	19	3.2E-08	1.0E-05	Only partial information	NI-1, Niagara Falls	44	64	20	3.2E-09	2.0E-05	
Dolomite	Decew Dolomite	USNI-1, Niagara Falls	42	48	6	1.0E-13	1.0E-13	Only partial information	NI-1, Niagara Falls	64	67	3	2.0E-08	2.0E-08	Only partial information
Shale	Rochester Shale	USNI-1, Niagara Falls	48	62	14	1.0E-13	2.5E-07	Only partial information; max value is an outlier, other data are Š2.5E-11 m/s	NI-1, Niagara Falls	67	84	17	1.3E-09	1.3E-09	Only partial information
Various	Clinton Group (below Rochester Shale)	USNI-1, Niagara Falls	62	75	13	1.0E-12	2.5E-11	Only partial information	NI-1, Niagara Falls	84	97	13	3.2E-09	3.2E-09	Only partial information
Shale/ Sandstone	Grimsby Sandstone	USNI-1, Niagara Falls	75	91	16	4.0E-11	4.0E-10	Only partial information	NI-1, Niagara Falls	97	114	17	6.3E-11	3.2E-09	Only partial information
Shale	Power Glen Shale	USNI-1, Niagara Falls	91	101	10				NI-1, Niagara Falls	114	121	7	6.3E-11	6.3E-11	Only partial information
Sandstone	Whirlpool Sandstone	USNI-1, Niagara Falls	101	107	6	1.3E-08	1.3E-08	Only partial information	NI-1, Niagara Falls	121	127	6	6.3E-11	6.3E-10	
Shale	Queenston Shale	USNI-1, Niagara Falls	107	115	8	2.5E-13	2.0E-11	Uppermost 10 m only	NI-1, Niagara Falls	127	137	10	4.0E-11	1.0E-09	Uppermost 10 m only
Shale	Georgian Bay Shale	OHD-1, Missisauga / Lakeview	5	172	167	1.0E-13	4.0E-12	Lowermost ca 50 m only; top eroded							
Shale	Whitby Shale	OHD-1, Missisauga / Lakeview	172	186	14	1.0E-12	1.0E-12								
Limestone	Lindsay Limestone	OHD-1, Missisauga / Lakeview	186	233	47	1.0E-13	6.3E-12		UN-2, Darlington / Bowmanville	22	70	48	6.3E-14	1.6E-11	Uppermost 5 m not tested (even though present)
Limestone	Verulam Limestone	OHD-1, Missisauga / Lakeview	233	277	44	2.0E-14	1.3E-12		UN-2, Darlington / Bowmanville	70	157	87	1.0E-13	7.0E-09	1 outlier at 7E-9 m/s, else 1E-10 or below
Limestone	Bobcaygeon Limestone	OHD-1, Missisauga / Lakeview	277	331	54	1.0E-13	4.0E-12		UN-2, Darlington / Bowmanville	157	176	19	1.0E-13	4.0E-12	
Limestone/ Dolomite	Gull River Limestone	OHD-1, Missisauga / Lakeview	331	367	36	2.5E-14	2.5E-11		UN-2, Darlington / Bowmanville	176	203	27	1.0E-13	1.0E-12	
Shale/ Sandstone	Shadow Lake Sandstone	OHD-1, Missisauga / Lakeview	367	376	9	1.0E-13	1.0E-09		UN-2, Darlington / Bowmanville	203	210	7	1.0E-13	1.0E-12	

		Golder Associates (2003)						Nowakowski & Lapcevic (1988				Intera (1988)		
Lithology	Formation	Borehole	[illegible]	[illegible]	K, min (m/s)	K, max (m/s)	Comments	Site	[illegible]	K, min (m/s)	K, max (m/s)	Site	K, min (m/s)	K, max (m/s)
Shale	Kettle Point Shale											Boreholes in Sarnia region	<1.0E-10	
Limestone/ Dolomite	Ipperwash & Widder Limestone											Boreholes in Sarnia region	1.0E-08	1.0E-05
Shale	Arkona Shale													
Limestone	Rockport Quarry Limestone											Boreholes in Sarnia region	1.0E-08	1.0E-05
Shale	Bell Shale													
Limestone	Dundee Limestone											Boreholes in Sarnia region	5.0E-12	1.0E-09
Limestone/ Dolomite	Lucas Dolomite											Boreholes in Sarnia region	1.0E-08	1.0E-07
Limestone/ Dolomite	Amherstburg Limestone	Bruce	0	100	5.0E-11	9.0E-05						Boreholes in Sarnia region	1.0E-11	1.0E-09
Dolomite	Bois Blanc Formation													
Dolomite	Bass Island Formation													
Various, incl. evaporites	Salina Formation													
Dolomite	Guelph Dolomite							Niagara		1.4E-08	2.8E-04			
Dolomite	Lockport Dolomite							Niagara		7.8E-11	5.5E-04			
Dolomite	Decew Dolomite							Niagara		1.0E-11	1.7E-06			
Shale	Rochester Shale													
Various	Clinton Group (below Rochester Shale)													
Shale/ Sandstone	Grimsby Sandstone													
Shale	Power Glen Shale							Niagara	<	1.0E-11	2.0E-07			
Sandstone	Whirlpool Sandstone													
Shale	Queenston Shale							Niagara	<	1.0E-11	2.4E-10			
Shale	Georgian Bay Shale													
Shale	Whitby Shale													
Limestone	Lindsay Limestone	DDH01/02, Bowmanville	22	70	1.3E-12	4.0E-11								
Limestone	Verulam Limestone	DDH01/02, Bowmanville	70	157	5.0E-13	2.0E-09								
Limestone	Bobcaygeon Limestone	DDH01/02, Bowmanville	157	176	1.0E-11	6.3E-09								
Limestone/ Dolomite	Gull River Limestone	DDH01/02, Bowmanville	176	203	2.0E-11	6.3E-09								
Shale/ Sandstone	Shadow Lake Sandstone	DDH01/02, Bowmanville	203	210	5.0E-09	1.0E-08	No test in this formation only							

		Intera (1988)					Intera (1988)					Intera (1988)					Intera (1988)				
Lithology	Formation	Site	[illegible]	K, min (m/s)	K, max (m/s)	Comments	Site	[illegible]	K, min (m/s)	K, max (m/s)	Comments	Site	[illegible]	K, min (m/s)	K, max (m/s)	Comments	Site	[illegible]	[illegible]	[illegible]	[illegible]
Shale	Kettle Point Shale																				
Limestone/ Dolomite	Ipperwash & Widder Limestone																				
Shale	Arkona Shale																				
Limestone	Rockport Quarry Limestone																				
Shale	Bell Shale																				
Limestone	Dundee Limestone											Ojibway mine	41	1.0E-07	1.0E-06	Inflow, high K					
Limestone/ Dolomite	Lucas Dolomite	Hagersville mine	20	Inflow, high K			Goderich mine	0 - 200	1.0E-07	1.0E-06	Several inflows, high K; porous dolomite	Ojibway mine	64	1.0E-07	1.0E-06	Inflow, high K	Bruce tunnels	50	6.0E-06		Inflows, high K
Limestone/ Dolomite	Amherstburg Limestone																				
Dolomite	Bois Blanc Formation	Nanticoke tunnel	63	1.0E-09	1.0E-08	Up to 1E-3 m/s at shallower levels															
Dolomite	Bass Island Formation						Goderich mine	0 - 200	1.0E-07	1.0E-06	Inflows, high K; dolomite	Ojibway mine	215	1.0E-07	1.0E-06	Inflow, high K; shaly dolomite, contact to Salina Formation					
Various, incl. evaporites	Salina Formation	Drumbo mine	68	Inflow, high K		Dolomitic shale, gypsum, anhydrite	Goderich mine	300 - 500	dry	dry	Dry; various lithologies, incl. evaporites	Ojibway mine	275-300	dry	dry	Various lithologies, incl. evaporites					
Dolomite	Guelph Dolomite	Drumbo mine	142	Inflow, high K		At Salina/Guelph contact, but connected via fractures to Guelph Formation															
Dolomite	Lockport Dolomite	Niagara, Sir Aadam Beck tunnels & shaft		minor seepage																	
Dolomite	Decew Dolomite																				
Shale	Rochester Shale																				
Various	Clinton Group (below Rochester Shale)	Niagara, Sir Aadam Beck tunnels & shaft		dry	dry																
Shale/ Sandstone	Grimsby Sandstone	Niagara, Sir Aadam Beck tunnels & shaft		dry	dry																
Shale	Power Glen Shale																				
Sandstone	Whirlpool Sandstone																				
Shale	Queenston Shale																				
Shale	Georgian Bay Shale	11 geotechnical openings	10 - 30	Only for 2 out of 11, inflows were reported. Weak documentation.																	
Shale	Whitby Shale																				
Limestone	Lindsay Limestone	Darlington Generating Station tunnels	30 - 35	<1E-12		Dry tunnels	Wesleyville excavations and shallow boreholes	Minor inflow at 23 and 40-50 m	1.0E-11	1.0E-08	Completely dry below 150 m	Wesleyville shallow boreholes		2.0E-10	4.0E-06	Bulk: 1E-9					
Limestone	Verulam Limestone																				
Limestone	Bobcaygeon Limestone																				
Limestone/ Dolomite	Gull River Limestone																				
Shale/ Sandstone	Shadow Lake Sandstone																				

Appendix 1: Data base for hydraulic conductivity in the Paleozoic formations of southern Ontario.

FEPs no. & hierarchy		Structured FEPs classification	Related FEPs
	A	**UNDISTURBED SYSTEM**	
	A1	**Transport mechanisms**	
1	A1.1	Advection/dispersion	
2	A1.1.1	*Size and geometry of the host rock and of surrounding units, migration path length*	
3	A1.1.2	*Migration pathways, including heterogeneity and anatomy*	
4	A1.1.3	*Undetected geological features*	
5	A1.1.4	*Hydraulic potentials and gradients in the host rock, including boundary conditions*	
6	A1.1.5	*Hydraulic properties of the host rock*	
7	A1.1.6	*Units over- and underlying the host formation: local and regional hydrogeologic framework*	
	A1.2	Diffusion	A2.1
8	A1.2.1	*Diffusivity*	A2.1.1
9	A1.2.2	*Connected matrix porosity*	A2.1.2
10	A1.2.3	*Ion exclusion*	A2.1.4
11	A1.2.4	*Surface diffusion*	A2.1.5
12	A1.3	Colloid formation, transport and filtration	
	A2	**Retardation mechanisms**	
	A2.1	Matrix diffusion	A1.2
8	A2.1.1	*Diffusivity*	A1.2.1
9	A2.1.2	*Connected matrix porosity*	A1.2.2
13	A2.1.3	*Flow-wetted surface and accessibility of matrix*	
10	A2.1.4	*Ion exclusion*	A1.2.3
11	A2.1.5	*Surface diffusion*	A1.2.4
	A2.2	Sorption (broad definition)	
14	A2.2.1	*Lithology, mineralogy of rocks and fracture infills*	
15	A2.2.2	*Natural organics, complexation*	
16	A2.2.3	*Mineral-surface area*	
17	A2.2.4	*Pore- and fracture water composition*	
18	A2.2.5	*Dissolution / precipitation of solid phases*	
19	A2.2.6	*Solid solutions / co-precipitation*	
20	A2.2.7	*Ion exchange*	
21	A2.2.8	*Surface complexation*	
22	A2.2.9	*Thermodynamic and kinetic modelling data*	
	A3	**System understanding and independent methods / tools to build confidence in predictive models**	
23	A3.1	Palaeo-hydrogeology of the host formation and of embedding units	C1.1.1
24	A3.2	Evolution of pore-fluid (water and gas) chemistry and mineralogy in the host formation and in embedding units	C1.1.2
25	A3.3	Water residence times in the host formation	

FEPs no. & hierarchy	Structured FEPs classification	Related FEPs
B	**REPOSITORY-INDUCED PERTURBATIONS**	
B1	**Chemical perturbations**	
26 B1.1	Oxidation of the host rock	
27 B1.1.1	*Redox buffering capacity of the host rock*	
28 B1.2	Effects of repository components on pore-water chemistry in the host rock	
29 B1.2.1	*Interactions of hyperalkaline fluids and host rock*	
30 B1.2.2	*Organics from waste and their effect on transport properties of the host rock*	
B2	**Thermal perturbations**	
31 B2.1	Thermal effects on mineral stability and pore-water composition	
32 B2.2	Thermal rock properties	
33 B2.3	Thermally induced consolidation of the host rock	
B3	**Geomechanical perturbations**	
34 B3.1	Geomechanical stability	
35 B3.2	Size and structure of the EDZ	
36 B3.3	Effects of bentonite swelling on the host rock	
37 B3.4	Geomechanical rock properties	
B4	**Hydraulic perturbations**	
38 B4.1	Hydraulic properties of the EDZ	
39 B4.2	State of saturation of the EDZ and desiccation cracking	
B5	**Perturbations from coupled processes**	
40 B5.1	Coupled thermo-hydro-mechanic processes	
41 B5.2	Swelling	C2.3
42 B5.3	Self-sealing	C2.4
43 B5.4	Off-diagonal Onsager processes except chemical osmosis	
44 B5.5	Chemical osmosis	
B6	**Perturbations from waste-derived gas**	
45 B6.1	Gas dissolution and chemical interactions between gas and pore water	
46 B6.2	Gas migration through the primary porosity (matrix, natural fractures)	
47 B6.3	Gas migration through stress-induced porosity (gas fracs, pathway dilation)	
48 B6.4	Gas-induced transport in water	
49 B7	**Microbiological perturbations**	

FEPs no. & hierarchy	Structured FEPs classification	Related FEPs
C	**LONG-TERM EVOLUTION**	
C1	**Diagenesis**	
C1.1	Past basin evolution	
23 C1.1.1	*Palaeo-hydrogeology of the host formation and of the embedding units*	A3.1
24 C1.1.2	*Evolution of pore-fluid (water and gas) chemistry and mineralogy in the host formation and in embedding units*	A3.2
50 C1.1.3	*Past burial history*	
C1.2	Ongoing and future processes	
51 C1.2.1	*Present and future geothermal regime and related processes*	
52 C1.2.2	*Future changes in hydrochemistry of the host rock and of surrounding formations (e.g. due to out-diffusion, water-rock interactions, uplift)*	
C2	**Deformation events**	
53 C2.1	Past deformation events	
54 C2.2	Future fault (re)activation, changes in migration pathways; changes of hydraulic parameters; flow events	
41 C2.3	Swelling	B5.2
42 C2.4	Self-sealing	B5.3
55 C2.5	Present-day stress regime	
56 C2.6	Future stress regime	
C3	**Erosion and burial**	
57 C3.1	Geomechanical effects of erosion / unloading	
58 C3.2	Consolidation due to burial	
59 C3.3	Future evolution of hydraulic potentials and gradients (*e.g.* due to erosion or burial)	

Appendix 2: FEP list from the OECD/NEA FEPCAT project (Mazurek et al. 2003).