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Résumé de l'article

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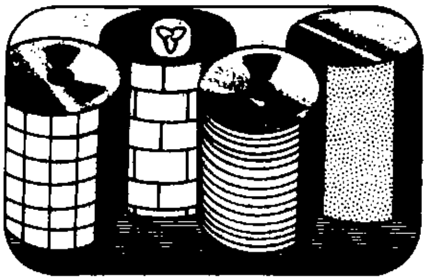

Radioactive Waste Disposal in the Sedimentary Rocks of Southern Ontario

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Summary

This paper is the first published examination of the Paleozoic sedimentary sequence of southern Ontario as a radioactive waste disposal medium. A major asset in siting a repository in such a sequence is the ability to locate zones with favourable geotechnical properties in suitable hydrogeologic environments by application of a large data base to the relatively simple stratigraphic model. A review of the stratigraphy, and the geotechnical and hydrogeologic properties of shales in the sequence reveals several zones of interest for waste disposal purposes. The most significant factor controlling suitability of an area for repository siting is the regional flow pattern. As a start in examining this factor, ten hydrostratigraphic units, distinguished by hydrogeologic properties alone, are proposed and used in a first attempt at evaluating the deep flow regime in southern Ontario.

Introduction

In the past few years the nuclear industry, the scientific community and the general public have become increasingly concerned about the problem of storing and disposing of high-level radioactive waste from nuclear reactors. It is generally accepted that surface storage is not an acceptable long-term solution to this problem. Also many of the more exotic alternatives, such as outer space, deep ocean or polar ice cap disposal and transmutation, have a great many uncertainties associated with them. In recent years a concensus has emerged that a possible solution may be to place solidified wastes in cannisters and dispose of them in mined caverns in geological formations.

The success of the mined cavern concept is dependent on keeping the radioactive materials from returning to the biosphere over very long periods of time. Thus in terms of the degree of isolation provided by a repository there are two main questions: (1) what is the rate, magnitude and direction of groundwater flow in the rock mass where the repository is located, and (2) how will the rock mass and the groundwater flow system respond to the thermal loads imposed by the radioactive decay of the waste?

It is therefore generally required that an acceptable host rock for a nuclear waste repository must have a low rock mass permeability and support stable excavations at the required depth. Internationally, a variety of rock types are being evaluated (Bredehoft *et al.*, 1978) including plutonic rocks, salt domes, bedded salt and shale. In Canada, the emphasis has been on the hard rock option, i.e. plutonic rocks. The soft rock option, i.e. shales and salt, has received relatively little attention. Since most Canadian nuclear generating stations are located in southern Ontario, the logical first place to examine the soft rock alternative is in the Paleozoic rocks in that area.

The soft rock option is normally considered to refer to disposal in salt or shale. The geology of southern Ontario provides for the added options of disposal in massive "strong" beds (e.g. limestone) enclosed within a shale sequence and for disposal in plutonic rocks beneath sedimentary cover (see Figure 1). The common factor is shale. The continued integrity of a bedded salt deposit depends on a seal, usually shale, preventing groundwater dissolution. The option involving burial in "strong" rocks isolated by shale clearly depends on the seal, provided by the shale, to keep groundwater velocities and flux to a minimum.

A number of different countries are conducting research into the use of shale as a host medium for high level nuclear waste (Lomenick and Laughton, 1979; Brondi, 1979). As shown by this research, other workers (e.g. Franklin, 1981), and this paper, there is significant variability in the properties, physical-chemical behaviour and mineralogy of shale; hence the transfer of research results and experiences from one country to another is limited. Thus in order to determine the potential of shale either as a host rock or as an isolating medium one must undertake regional and site-specific studies. In this paper, we examine the suitability of the shale units of southern Ontario by examination of their stratigraphy and their mineralogical, hydrological and geotechnical characteristics.

Geology of Southern Ontario Shales

Stratigraphic and Tectonic Setting. A first step in investigating the use of shales as nuclear waste hosts is to examine their regional setting. The structural geology

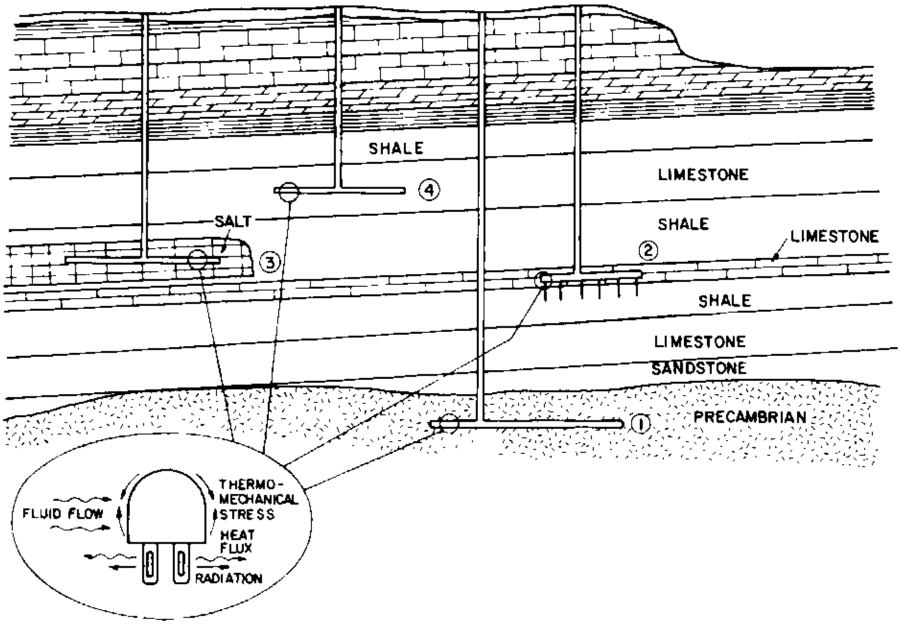

Figure 1 *Mined cavern storage of nuclear waste - options involving the sedimentary sequence 1. In PreCambrian rocks beneath thick sedimentary cover. 2. In shale, using strong overlying beds for the mined opening. 3. In salt. 4. In strong beds overlain and underlain by shale.*

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and stratigraphy, and therefore the near and far-field response to a disposal facility at any particular site, is best predicted and understood in relation to the wider stratigraphic and tectonic context. Without this knowledge, site-specific geotechnical, hydrogeological and other detailed testing programs will be of significantly lesser value. The following summary is derived from numerous sources, including: Beards (1967), Brigham (1971), Franklin (1981), Guillet (1967, 1977), Liberty (1969), Liberty and Bolton (1971), Sanford (1961), Winder and Sanford (1972).

The Lower Paleozoic sequence of southern Ontario can be thought of as a system of carbonate/shale cycles, complicated by periods of evaporite or coarse clastic sedimentation (Figure 2). Argillaceous units of interest in the context of disposal-in-shale or important in the integrity of salt beds are, in ascending stratigraphic order: Whitby Formation, Georgian Bay Formation, Queenston Shale, Cabot Head Shale, Rochester Shale, shales of the Salina Formation, Hamilton Group, Kettle Point Formation.

The Whitby Formation is poorly exposed but underlies a large area extending from Georgian Bay to Lake Ontario and consists mainly of blue and grey calcareous shales with minor limestone interbeds. The middle part consists mainly of brown shales. Its thickness varies from 50 m in the north to 80 m at the south end of its outcrop. The Georgian Bay Formation is similar in lithology, but is less bituminous and richer in limestone and sandy bands. It underlies most of the Toronto area so its performance in excavations and tunnels is well documented. The total thickness ranges from over 125 m near Georgian Bay to over 175 m at Toronto. The upper contact with the overlying Queenston Shale is gradational. This latter formation of red calcareous mudstone outcrops along the slopes of the Niagara Escarpment for most of its length. Green-grey, highly calcareous mudstone or shaly limestone bands and nodules, and crystals and blebs of gypsum are important features which affect its behaviour (Russell, 1982). The Queenston Shale ranges in thickness in its outcrop area from 85 m in the north to over 135 m west of Toronto. The top is a major disconformity separating Ordovician, predominantly shale, units from resistant dolostones of the Lower Silurian.

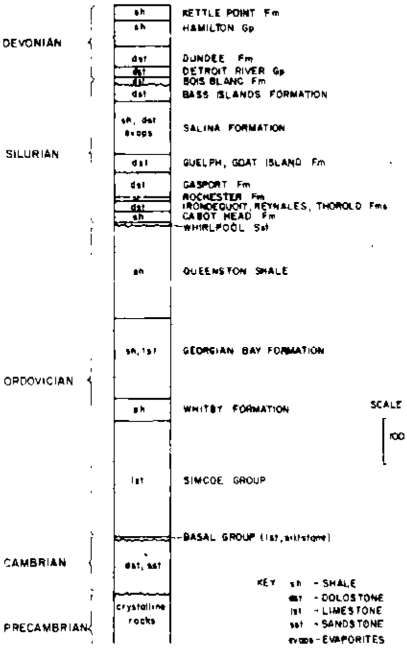

Figure 2 *The Paleozoic sedimentary sequence of the Niagara Peninsula area. After Sanford, 1969.*

The Cabot Head and Rochester Formations are argillaceous interruptions in predominantly carbonate Lower and Middle Silurian strata. The Cabot Head, (11-15 m thick), which lies between the Manitoulin Formation below and the Reynales Formation above, is predominantly soft shale, both red and green, with some limestone interbeds. The Rochester shale (0-17 m thick) underlies the scarp-forming Guelph-Lockport carbonates south and west of Hamilton. It is a grey and blue-grey shale with thin limestone interbeds. Due to its non-resistant lithology (predominantly shales, shaly carbonates and evaporites), the Salina Formation does not outcrop widely, so most data concerning its stratigraphy is derived from well records. It is divided into units labelled A to G, not all of which occur in all areas due to nondeposition or dissolution of salt beds. The major salt beds are units A-2 and B, while units D and F contain significant halite associated with dolostone and shale. Unit C and the upper part of unit F are predominantly shale, but they are extremely dolomitic (Guillet, 1977).

The Middle and Upper Devonian sequence consists of over 300 m of blue-grey, fairly soft shales with calcareous zones. The Hamilton Group is divided into several formations dominated volumetrically by shale. The Kettle Point Formation is a fissile, somewhat bituminous, black and grey shale which overlies the Hamilton Group, but is poorly exposed and probably does not extend deep enough in Ontario to be considered as a host rock for high level waste disposal.

Although this report is primarily concerned with shales, brief mention should be made of the stratigraphic controls on the disposal-in-salt option. The Salina Formation was laid down in an area of restricted circulation centred on the Michigan Basin. Thus, salt beds thicken in a westerly direction (Sanford, 1975). Another influence on salt occurence is the effect of post-deposition dissolution (Grieve, 1955; Sanford, 1975). Brigham (1971) discusses the distribution of salt solution features and their timing. Anomalous thinning of the B-salt occurs in the Lambton County area and elsewhere, caused by dissolution during Middle Devonian time. Since this dissolution controls the distribution of salt and may give an indication of the potential integrity of salt beds, a detailed knowledge of their configuration is required before further study of the salt option (see Figure 1, option 3).

A further possibility involving sedimentary rocks is the excavation of a repository in Precambrian rocks beneath thick sedimentary cover (Cherry and Gale, 1979; option 1 Figure 1). PreCambrian rocks in southern Ontario occur at depths of up to 1500 meters. However, relatively little is known of the lithologic and structural conditions which would be encountered in any part of the area were a repository to be sited in the crystalline basement. In addition, groundwater gradients at, and hydrological properties of, the Precambrian/Palaeozoic interface would be of importance in examining this option. The Cambrian rocks are dominantly sand stones; the overlying basal Ordovician strata are typically silty. This interface is therefore a critical area of interest if this option is to be persued.

Deep excavations in shale are not common, due to generally undesirable geotechnical properties of shale, such as low strength. To use the supposedly advantageous hydrological properties of shales and to construct a repository at significant depth, we suggest that the facility could be excavated in one of the many stronger carbonate-rich layers overlying the shale beds (option 2, Figure 1). This provides a geotechnically preferable material in which to construct the semi-permanent opening and allow access to the shale beneath for emplacement of waste canisters. Zones where this lithological contrast occurs are (see also Table I): 1) the base of the Queenston Shale overlying the Georgian Bay Formation shales, north of the Shelburne area; 2) the Manitoulin Formation and lateral equivalents overlying the Queenston Shale; 3) the Decew Dolostone overlying the Rochester Formation; 4) the Fossil Hill Formation overlying the Cabot Head Formation; 5) the top of the Salina C unit shale underlying the E unit, where the D-salt has been removed by dissolution, and 6) the base of the Salina

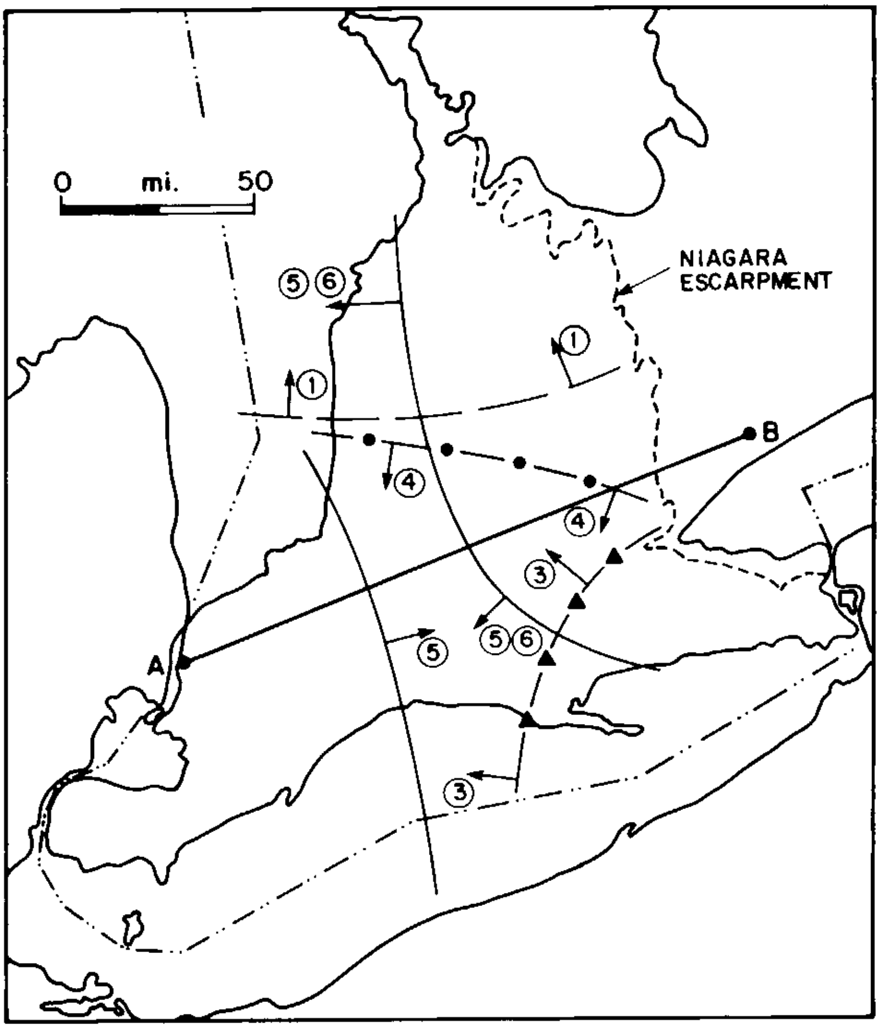

Figure 3 *Sketch map of southern Ontario showing geographic limits on stratigraphic zones of interest. See text and Table 1 for explanation.*

Zone	Stratigraphy	Geographic Limits
1	Queenston Shale Georgian Bay Fm	Southern limit of thick limestone at base of Queenston: escarpment
2	Manitoulin Dst Queenston Shale	Not determined: see text
3	Reynales Dst Cabot Head Shale	Southern limit of Reynales Dst: escarpment
4	Decew Dst Rochester Shale	Northern limit of Rochester Shale: escarpment
5	Salina E-Carb. Salina C-Shale	Erosional edge on east: eastern limit of D-Salt on west
6	Salina G-Dst Salina F-Shale	Erosional edge of Salina on east

Table 1 *Zones where massive carbonate beds overlie shale in the Paleozoic sequence of southern Ontario, (see Figure 3).*

G unit or Bass Island (Bertie) Formations overlying F unit shale.

Apart from the Manitoulin/Queenston contact, areas underlain by these zones are indicated in Figure 3. One of the consistent features of the upper contact of the Queenston Shale is its green colouring, taken to imply groundwater alteration which in turn indicates significant groundwater flux at this zone. Other data confirm this. This zone would not, therefore, be considered any further. Each of these stratigraphic zones will require individual study were the 'shale with access from stronger beds' concept to be persued further.

It has been generally held that southern Ontario is virtually aseismic (Basham *et al.*, 1979; Zoback and Zoback, 1981). The nearest significant tectonic zone is the Ottawa-Bonnechere graben, which has probably experienced faulting in the Quaternary Period (Lumbers, 1980). This is reflected in the maps produced by Bowlby (1980) of the seismic events recorded in southern Ontario in historic times. However, away from this zone, numerous events of up to magnitude four have been recorded, for instance in the Hamilton region. The sources of such seismic events are undefined, but may be faults in the basement and/or sedimentary sequence.

Composition and Form of Ontario Shales. The term 'shale' generally means a fine grained sediment composed in part of clay minerals and exhibiting fissility. However, the term is probably one of the least uniformly applied of all rock descriptions. Examples exist of 'shale' which do not contain significant clay minerals, do not exhibit fissility and do not contain significant clay size particles. Even given two 'fine-grained sediments composed in part of clay minerals and exhibiting fissility', there may still exist large differences in geotechnical properties, which are controlled by the degree of consolidation suffered. Since the engineering and thermal response of shales is controlled by their composition and form (or texture), an awareness of the variety of 'shales' that exist is important. If, as is argued (Shemilt, 1980), Canada is to make use of the experience gained in other research programs, the transfer of this experience will only be possible given a detailed knowledge of the properties of the domestic shales.

Table 2 summarizes mineralogical data for southern Ontario shales provided by Guillet (1967, 1977) and from unpublished analyses by the authors. It shows that the main clay minerals are illite and chlorite. Relatively insignificant quantities of expanding clay minerals are present (e.g. see Czurda *et al.*, 1973). Illite and chlorite have cation exchange capacities ranging from 7 to 20 meq/100 gms (Grim, 1968). Since these sediments have undergone significant diagenesis, the lower end of the range would probably be applicable. Nevertheless, this capacity reflects a significant ability to adsorb radionuclides. Swelling due to intraparticle expansion will not be a problem in excavations in these shales. The non-clay mineralogy shown in Table 2 does not include data for pyrite and gypsum which are frequent components of dark shales and Queenston Shale respectively. The data show that "shales" of southern Ontario vary widely in composition, from the samples from the Salina Formation, more accurately labelled a shaly dolomite, to the low carbonate Whitby Formation shales. However, variation in mineral content between units is matched by lateral variation within the shales. For example, the Georgian Bay Formation becomes more dolomitic to the west and the Queenston Shale bcomes coarser and quartz-rich to the south and west. Since variations such as these will have some control on engineering and hydrogeological properties, more study is needed on the sedimentology of those formations.

Most of the shales under study exhibit anisotropy on two scales. First, the ubiquitous calcareous bands within the shales create an anisotropic system over a vertical range of a few metres. Secondly, the microfabric of most shales is anisotropic due to well developed alignment of the platy clay mineral grains. The relevance of the macroscopic and microscopic anisotropies to the flow directions and flow path lengths depends on the influence of cross-cutting discontinuities (discussed below). However, these sedimentary controls will tend to constrict intergranular flow and directions of ionic diffusion parallel to bedding.

Engineering Geology of Southern Ontario Shales

Geotechnical Properties. Compared with the Precambrian rocks normally considered in the 'hardrock' option, shale has four potential geotechnical problems. First it has generally low strength both as intact rock and as a rock mass. Second it 'squeezes', i.e. displays time dependent deformation. Third, it is affected by slaking, i.e. the degradation on exposure to changes in moisture conditions. Last, because of the generally high moisture content, the thermomechanical response of shales may involve a volume decrease which would affect the mass properties (e.g. see McVey *et al.*, 1979).

At this preliminary stage, the determination of parameters needed for repository design and requiring complex and time consuming tests is not warranted. To compare the physical properties of the various shales, the slake durability test (Franklin and Chandra, 1972) was used extensively. This test measures the proportion of shale that passes through a mesh while being agitated in water, and provides an index of shale durability which can be correlated with various aspects of physical behaviour (Franklin, 1981). Results of engineering tests are given in Figure 4.

Detailed examination of slake durability results for the Queenston Shale and the Georgian Bay Formation show that

FORMATION	QUARTZ (%)	FELDSPAR (%)	CALCITE (%)	DOLOMITE (%)	CLAY MINERALS (%)	CLAY MINERALS Types	Number of samples
KETTLE POINT	33	1	1	0	65	I >C	1
HAMILTON	24-28	0-0.5	6-13	0-0.5	65	I > C	4
SALINA (unit not specified)	27	0-2	5-20	36-37	35	I >C	2
ROCHESTER	12-16	0-1	13-39	19-29	40	I >C	3
CABOT HEAD	20-41	0-1	0-3	0-18	60	I >C	12
QUEENSTON	26(12-34)	2(0-9)	11(2-30)	2(0-8)	60	I >C>>(E)	45
GEORGIAN BAY	28(23-35)	3(0-11)	7(3-17)	1(0-4)	60	I > C	15
WHITBY							
Blue Mt. Sh.	21-28	1-2	0-3	0-3	70	I > C	4
Gloucester Sh.	26-27	2	0	0	70	I> C>> E	2

Table 2 *Mineralogy of southern Ontario shales. A range is given where possible; if sufficient data are available a mean value is also given. I = illite, C = chlorite, E = expanding minerals.*

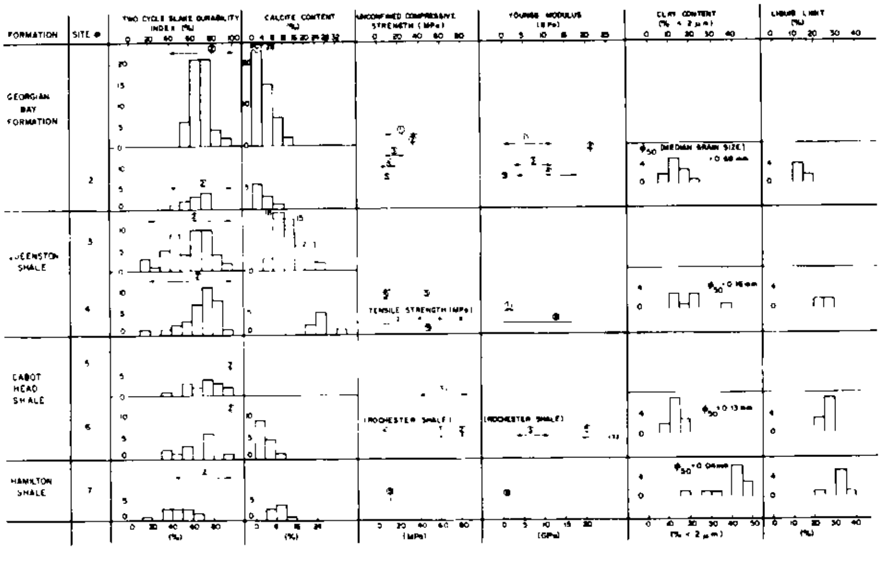

Figure 4 *Summary of engineering data for shales of southern Ontario. Where a histogram is shown, the data was derived in this study. A horizontal line denotes ranges of values given in the literature, a single vertical line gives a single value from the sources noted (1: Lo et al., 1978; 2: Franklin, 1981; 3: Lo and Morton, 1976; 5: This study). Site number refers to different drilling locations.*

the calcite rich bands are distinctly more durable than the majority of the shales. The hard bands in Queenston Shale are thicker, but wider apart than in the Georgian Bay Formation. Since it is generally desirable for underground excavations to be in material of relatively uniform properties, the thinner, more frequent bands of the Georgian Bay Formation may present problems.

In general, the Georgian Bay Formation is the highest quality shale (i.e. most durable and probably strongest), the Queenston and Cabot Head next in quality and the Hamilton shale the lowest. The Hamilton shale may be better regarded as a clay-shale, similar to the Mesozoic shales of the Interior Basin. Shales equivalent to the Hamilton Shale in Michigan are being investigated as disposal media (Lomenick and Laughton, 1979). Results of index tests (Atterberg limits, particle size analyses) are consistent with durability data.

The strength data obtained in this study and from a literature search are given in Figure 4. Strength parameters are affected in a very sensitive way by preparation procedures. As moisture content decreases, strength increases very significantly. This may explain differences in ultimate strength found, for example, in the Queenston Shale samples. Those samples of around 40-60 MPa had their ends ground dry, whereas those with strength less than 10 MPa were cut and ground in the normal way, with water as a lubricant. Dramatic differences between values reported in the literature may be due to this type of feature or to testing different lithologies, rich and poor in calcite. The Brazilian tensile strength test was found to give repeatable results which correlated well with durability. The amount of pretest preparation for the Brazilian test is very small, reducing the possibility of alteration of properties in this phase. This test is preferred to the point load test for comparison purposes of shales since it imposes a failure surface parallel to the core axis, whereas the point load test determines only the minimum tensile strength for a given specimen, regardless of relevance of the orientation of that failure plane.

Hydrogeologic Properties of Shale. In the shales of southern Ontario, the relatively low permeability of intact samples is due to the poor connectedness, and the small number and size of pores. Given the wide range in shale lithology it is not surprising that shale matrix hydraulic conductivities range from 10^{-12} to 10^{-9} meters/sec (m/s) or greater. A search of the literature yielded no representative matrix hydraulic conductivities for southern Ontario shales. The only known systematic laboratory and field testing of any part of the Paleozoic sequence is that associated with an investigation by Nadon and Gale (1981). Obtaining representative samples of shales for laboratory determination of matrix hydraulic conductivities has proven difficult since only the more cemented parts of the shale sections survive the drilling process, subsequent stress release and sample preparation. The porosity and permeability values determined on intact pieces of core from the Amabel Dolostone, Cabot Head shale, Manitoulin Formation, and Whirlpool sandstone are shown in Table 3. The locations of each sample in the vertical section is shown in Figure 5. The hydraulic conductivities of the three Cabot Head shale samples tested range from 10^{-12} m/s to 10^{-9} m/s.

Injection tests in the boreholes where the samples were derived, using 2 m packer spacings, gave hydraulic conductivities for the Cabot Head shale that ranged from 10^{-10} m/s to 10^{-9} m/s. Differences in the range of laboratory and field results reflect the contribution of fractures in the shale to the rock mass hydraulic conductivity. This shows that shales and clays are no different from granites and basalt in that their bulk hydraulic properties are dependent to a great extent on the fractures interrupting the primary fabric (see also Williams and Farvolden, 1967; Grisak *et al.*, 1978).

The complexities of extrapolating surface fracture data to the subsurface in hard rock are matched if not exceeded in shales due to the added complications of discontinuities formed during sedimentation and early diagenesis, which are extremely sensitive to stress release. Thus, the overwhelming appearance of fissility seen in outcrops of the Georgian Bay Formation may be of limited relevance in the subsurface compared to a single subvertical fracture. Shear planes formed in the plastic state will tend not to have unmatched irregularities, and if these exist, shale may be deformable enough to close the aperture so formed. While drilling in shale, Rock Quality Designation (the percentage of core recovered in lengths greater than 100 mm long) can vary from 20% to 100% purely because of a change in driller. Interpretation of the form, frequency and effect of

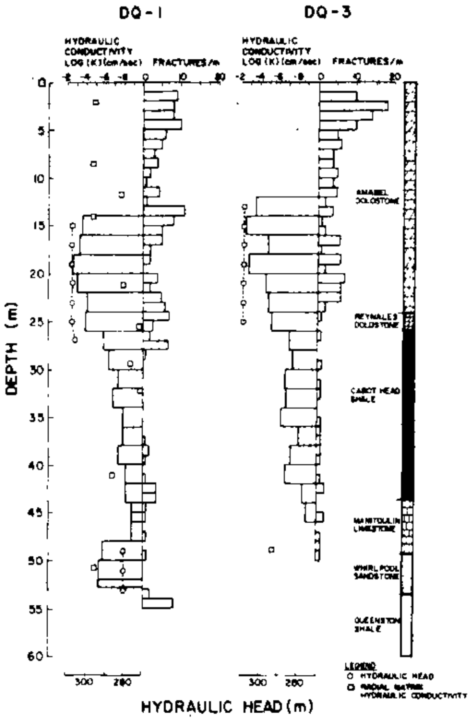

Figure 5 *Hydrogeological data from boreholes in Ordovician and Silurian strata at Milton*

Sample Number	Depth(metres)	Rock Type	Porosity(%)	Hydraulic Conductivity (cm/sec) Radial	Axial
1-1	2.05	Dolostone	7.0	1.6×10^{-5}	2.2×10^{-8}
1-2	8.5	Dolostone	9.0	5.3×10^{-5}	1.2×10^{-8}
1-3	11.7	Dolostone	4.3	4.0×10^{-6}	$<10^{-10}$
1-4	14.1	Dolostone	8.3	3.2×10^{-5}	2.5×10^{-7}
1-5	21.15	Dolostone	3.9	1.2×10^{-8}	3.3×10^{-9}
1-6	29.35	Arg. Dolostone	7.7		4.1×10^{-9}
1-7	32.1	Dol. Shale	6.8	1.2×10^{-10}	9.4×10^{-10}
1-8	41.0	Arg. Dolostone	5.5	1.5×10^{-7}	1.3×10^{-9}
1-9	50.65	Sandstone	13.4	2.8×10^{-5}	1.1×10^{-7}
1-10	55.55	Dolostone	1.5	4.0×10^{-10}	$<10^{-10}$
3-1	48.75	Sandstone	11.1	5.2×10^{-6}	2.0×10^{-8}

Table 3 *Porosity and permeability measurements on core samples of Ordivician and Silurian strata, Milton, Ontario.*

shale discontinuities in the subsurface from either outcrops or drill core must therefore be done with care.

Preliminary observations of fractures in Queenston Shale has revealed seven types (Figure 6) (The first five were observed at the Milton Brick Pit, Ontario), as follows: 1) On weathered surfaces, "slaking fractures" are present, and form small (2-3 cm long) lenticular pieces of shale, reflecting the behaviour of Queenston Shale in the slake durability test; 2) Sigmoidal, sometimes paired, fractures, subhorizontal to 40 degrees from the horizontal, about 0.5 m long, that often terminate when their ends turn towards the vertical and join together;
3) Joints, subvertical to vertical, penetrate red shale and grey green hard bands, often showing distict curvature, length typically 1-2 m. In drillhole cores, vertical fractures have been observed in green bands but not in the overlying and underlying red shale; 4) Major joint clusters, that are typically three to five vertical fractures grouped within a metre, with lengths of at least 7 m; 5) Low angle shears, that are up to 5 m long, dipping 20-30 degrees with crushed hard shale between surfaces 3-5 cm apart; 6) Slickensided curved surfaces found only in drillhole cores and 7) Microfractures, observed with the S.E.M. (Russell, 1982). Fracture types 4 and 5 will cause problems of excavation stability and high permeability. This is clearly a preliminary study; full studies of fracture type, frequency and genesis are required for all shale types as prerequisites for any detailed interpretation of shale mass properties.

Regional Flow Systems in Southern Ontario. Given that radionuclide toxicity decreases with time, repositories must clearly be located in positions which provide for the longest flow paths and lowest radionuclide transit velocities. This is achieved by placing repositories in what are, and will hopefully continue to be, recharge zones for deeper parts of a regional flow system. It is therefore essential to determine where potential repository sites may be located with respect to the three dimensional groundwater flow system in southern Ontario.

Unfortunately, no studies of the three dimensional flow system of the study area have been undertaken. Several local studies such as those by Sibul (1969), Haefeli (1970, 1972), Yakutchik and Lammers (1970), and Vandenberg *et al.* (1977) provide useful starting points. The development of even a conceptual regional flow system for southern Ontario is somewhat hampered by the lack of data on the distribution of porosity, permeability and hydraulic head for the lithological units involved. However, Haefeli (1970) has shown how the development of both local and intermediate flow systems between Lake Simcoe and Lake Ontario are controlled to a large degree by the surface topography or water table. Thus it appears that a first step in defining the flow system would be to undertake a fully three-dimensional computer study based on the subsurface stratigraphy and lithologies delineated by Sanford (1969, 1975) and other authors, elevations of local and regional water bodies and the Great Lakes, and the topography.

Based on data from the sources mentioned above, Scott (1967) and publications of the Ontario Water Resources Commission, a first attempt has been made at defining hydrostratigraphic units for the sequence present in southern Ontario. Ten units have been defined and

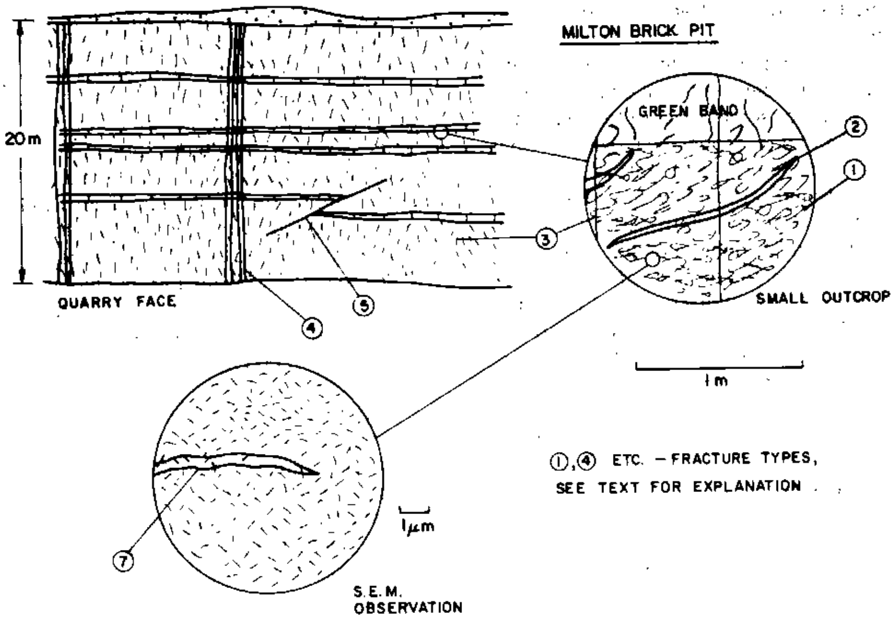

Figure 6 *Fracture types in Queenston Shale. Milton Brick Pit. See test for explanation.*

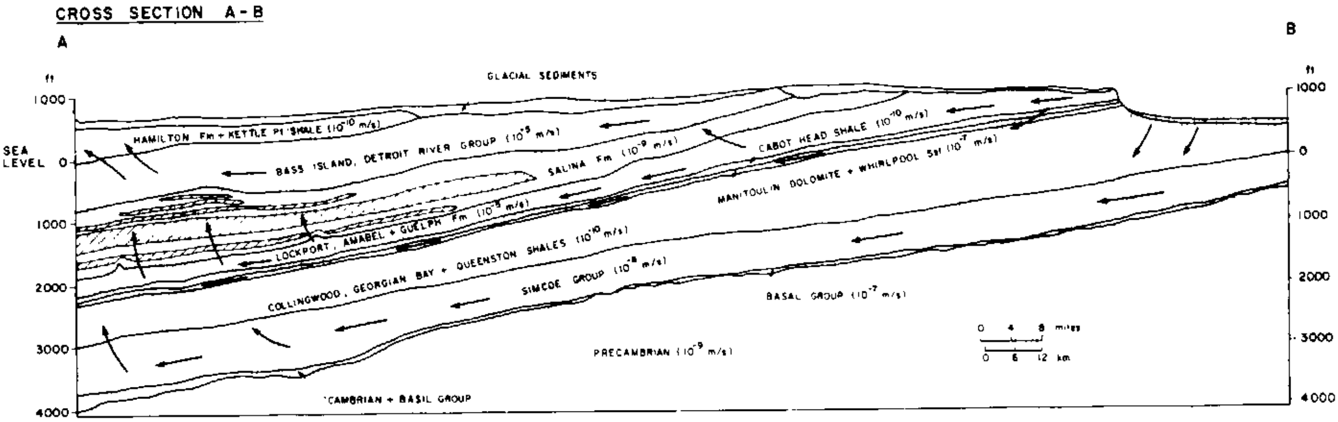

Figure 7 *Cross section of southern Ontario from Toronto to Windsor, showing hydrostratigraphic units, estimated hydraulic conductivities and assumed directions of fluid flow.*

these are shown, along with an estimate of their average hydraulic conductivities in Figure 7. Rather than attempt to show a flow system configuration for this very complex situation we have shown in cross-section a first approximation of the relative hydraulic conductivities of the various units and the assumed directions of groundwater movement. It should be noted that the unconformities and associated regoliths present at the Precambrian/Paleozoic contact and the base of the Silurian and Devonian systems may be significant hydrologic pathways. This is evidenced by the high permeability zone at the contact of the Whirlpool sandstone (Silurian) and Queenston Shale (Ordovican) (Nadon and Gale, 1981; see Figure 5). We have assumed that recharge to the regional system takes place to the northeast with some component of regional flow following the structural trend towards the centre of the Michigan Basin. The presence of the high permeability dolomitic units above and below the Salina Formation is a matter of some concern for disposal in the salt units, especially if disposal operations may increase the rate of salt solution. Some vertical flow must take place in the extreme western parts of southern Ontario as evidenced by the hydrogeochemical characteristics of the groundwaters (Vandenberg *et al.*, 1977; Scott, 1967) and the presence of saline springs in Michigan. However the depth and configuration of the local, intermediate and regional flow systems in southern Ontario cannot be inferred from existing data.

Discussion

Locating a nuclear waste repository in sedimentary rock will involve identifying a suitable stratigraphic zone within a favourable hydrological environment. The first step must be the determination of the flow systems operating in the sedimentary sequence and upper part of the Precambrian basement at the regional level, to delineate relatively large zones of interest. After this framework has been established, preliminary selection of suitable stratigraphic horizons (as in Table 1 and Figure 3) should be made. Then more localized studies of flow regimes should be made, concentrating on the hydrological environment (permeabilities, flowpath lengths) of the stratigraphic sections selected.

Since the geology of southern Ontario has been studied for over a century, the data exist for the stratigraphic selection procedure, as has been attempted at a preliminary level in this work. Although the "layer-cake" model of sedimentary sequences is often a gross oversimplification, the lateral continuity of sediment layers provides a frame of reference allowing reliable identification and extrapolation of major vertical and horizontal discontinuities. It is in this respect that the first stage of site selection in sediments will be more reliable than in plutonic rocks of northern Ontario. In addition, the flow paths of groundwater are, to a large degree, constrained by the layering. Thus, if and when basic hydrogeological work is carried out, prediction of flow directions at a given site will probably be more reliable in sediments than in a plutonic rock environment. Over 12,000 well records exist, providing an extensive data base readily available for stratigraphic analysis. An undesirable corollary of this abundance of data is an abundance of vertical fluid pathways - poorly plugged boreholes. Clearly, detailed knowledge of all historic drilling is required.

Based on the available data, no single shale unit can be ruled out as a possible waste host. The thinner formations may be unsafe due to the short distances from the waste to potentially more permeable units. However, flow paths (and directions of ionic diffusion if that were the significant mode of solute transport) will be constrained by the sedimentary fabric if major discontinuities are not present. Since this generally anisotropic fabric will impose flow perpendicular to that required for rapid leakage (i.e. along bedding), the bed thickness may not be a problem.

Although we have assumed that the main opening for a repository will be in rock types other than shale, some examples of large excavations in 'shale' exist, e.g. Poatina, Tasmania (Endersbee and Hofto, 1963). Whether or not a structurally stable repository could be constructed in southern Ontario shales would be determined only by detailed investigations. Whether such a repository would be safe from a radionuclide containment aspect would depend to a large degree on the response of the shales to the perturbation caused by the excavation; this will be controlled by their behaviour upon stress release (i.e. changes in fracture intensity, aperture), exposure to new moisture conditions (i.e. slaking breakdown) and their thermomechanical behaviour. Shale surrounding the emplaced canister will be subject to a complex set of conditions affecting its physical properties. Even if temperatures of the waste are kept below 100° C, some contraction of the shale will take place due to dehydration. Opposing this process is the tendency for rock squeeze to decrease the diameter of an opening. Backfill materials being considered exert swelling pressures in all directions. There will, therefore, be a complex interaction of stresses and associated deformations affecting the near-field hydrogeologic character of a shale repository.

As suggested above, the flow regimes in southern Ontario are poorly understood. One of the most important problems to solve in defining the hydrostratigraphy is to determine the relative stability of the salt beds in the Salina Formation. That these salt beds suffered a period of dissolution relatively soon after deposition can be determined from well records. However, we do not know if any dissolution is taking place today and, if so, at what rates. Salt beds are bounded, in certain geographic and stratigraphic zones, by carbonates that appear to have fairly high permeabilities. The increase in dissolved solids in groundwater with increasing depth reported by Vandenberg *et al.* (1977) for water wells located in the Dundee and Detroit River Formations along the southeast shore of Lake Huron suggests leakage from deeper bedrock formations. Thus in order to determine if the salt beds in the Salina Formation are a suitable host rock it is necessary to determine the magnitude of the groundwater flux in both the horizontal and vertical directions in the higher permeability zones above and below the Salina Formation and their level of saturation with respect to Na and Cl.

In any study related to regional flow systems, it must be remembered that there have been major changes in the hydrodynamic boundary conditions in southern Ontario since the last glaciation. It is expected that these changes will have had a major impact on the configuration of the groundwater flow system and the current flow system may still reflect these past events. If we are serious about isolating wastes for many thousands of years, the likelihood of another change in boundary conditions, should be taken into account by placing the repository in a zone where low groundwater flux is caused by low permeability rather than low hydraulic gradient.

It is obvious that the Canadian nuclear waste disposal effort will continue to be directed towards the crystalline hard-rock option with only minor support for an evaluation of the suitability of the sedimentary sequences as waste host rocks. However it should also be obvious that the 'layer-cake' geology of southern Ontario provides for the rapid selection of candidate sites and target horizons that meet necessary thickness, depth, lithologic and isolation criteria. Thus a small research commitment will yield a disproportionate amount of information which will help determine (a) whether use of the sedimentary sequence in question is possible and (b) where (geographically and stratigraphically) to persue more detailed investigations.

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