RESERVOIR SCREENING CRITERIA FOR DEEP SLURRY INJECTION

by

Muhammad Nadeem

A thesis

presented to the University of Waterloo

in fulfilment of the

thesis requirement for the degree of

Master of Science

in

Earth Sciences

Waterloo, Ontario, Canada, 2005

ABSTRACT

Deep slurry injection is a process of solid waste disposal that involves grinding the solid waste to a relatively fine-grained consistency, mixing the ground waste with water and/or other liquids to form slurry, and disposing of the slurry by pumping it down a well at a high enough pressure that fractures are created within the target formation.

This thesis describes the site assessment criteria involved in selecting a suitable target reservoir for deep slurry injection. The main goals of this study are the follows:

- Identify the geological parameters important for a prospective injection site
- Recognize the role of each parameter
- Determine the relationships among different parameters
- Design and develop a model which can assemble all the parameters into a semi-quantitative evaluation process that could allow site ranking and elimination of sites that are not suitable
- Evaluate the model against several real slurry injection cases and several prospective cases where slurry injection may take place in future

The quantitative and qualitative parameters that are recognized as important for making a decision regarding a target reservoir for deep slurry injection operations are permeability, porosity, depth, areal extent, thickness, mechanical strength, and compressibility of a reservoir; thickness and flow properties of the cap rock; geographical distance between an injection well and a waste source or collection centre; and, regional and detailed structural and tectonic setup of an area. Additional factors affecting the security level of a site include the details of the lithostratigraphic column overlying the target reservoir and the presence of overlying fracture blunting horizons. Each parameter is discussed in detail to determine its role in site assessment and also its relationship with other parameters.

A geological assessment model is developed and is divided into two components; a decision tree and a numerical calculation system. The decision tree deals with the most critical parameters, those that render a site unsuitable or suitable, but of unspecified quality. The numerical calculation gives a score to a prospective injection site based on the rank numbers and weighting factors for the various parameters. The score for a particular site shows its favourability for the injection operation, and allows a direct comparison with other available sites. Three categories have been defined for this purpose, i.e. average, below average, and above average. A score range of 85 to 99 of 125 places a site in the “average” category; a site will be unsuitable for injection if it belongs to the “below average” category, i.e. if the total score is less than 85, and the best sites will generally have scores that are in the “above average” category, with a score of 100 or higher. One may assume that for sites that fall in the “average” category there will have to be more detailed tests and assessments.

The geological assessment model is evaluated using original geological data from North America and Indonesia for sites that already have undergone deep slurry injection operations and also for some possible prospective sites. The results obtained from the model are satisfactory as they are in agreement with the empirical observations.

Areas for future work consist of the writing of a computer program for the geological model, and further evaluation of the model using original data from more areas representing more diverse geology from around the world.

ACKNOWLEDGEMENTS

I am thankful to my supervisor Dr. Maurice Dusseault for his valuable guidance and financial support.

I am also thankful to my committee members Dr. David Rudolph and Dr. Stephen Evans for their valuable comments and review of this thesis.

I would like to acknowledge the financial support that I received from the Natural Science and Engineering Research Council (NSERC) of Canada and Terralog Technologies Inc. (Calgary) in the form of an Industrial Postgraduate Scholarship.

I would like to thank Roman Bilak, President Terralog Techonogies Inc for suggesting this thesis topic and also for the generous access to the company's data archives.

I would also like to thank Karsten Michael and Matt Grobe of Alberta Geological Survey, Edmonton for helping me to learn and use GeoOffice V.3.4 software and thereby retrieve valuable information through it.

My thank also goes to all other persons at University of Waterloo and also Terralog Technologies offices who provided me ideas and support and helped me to spend my time in a memorable way, especially Yiqiu Ma (Michael), Suzanne Olmstead, and Betty Dusseault.

DEDICATION

To my adoring mother and father, thanks for all the love and support.

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Chapter 1: Introduction

1.1 General

Deep slurry injection is a process of solid waste disposal that is being used by the petroleum industry to permanently dispose of non-hazardous oil field solid waste (Veil and Dusseault, 2003). The idea of deep biosolids injection and methane generation is a continuation and advancement of this existing technology. This process consists of grinding the solid waste to a relatively fine consistency, mixing the cutting with water and/or other waste liquids to form a slurry, and disposing of the slurry by pumping it down a vertical well at a high enough pressure that fractures are created within the target reservoir. The injected slurry is then emplaced in the fractures created by the force of injection.

Deep under the subsurface, waste is injected into a suitable reservoir where it can be entombed permanently, isolated from the biosphere (hydrosphere and atmosphere). Selection of a suitable target reservoir predominantly depends upon the geology of an area and the reservoir characteristics of a target geological rock unit, for example porosity, permeability, reservoir thickness, reservoir depth, and so on. In the case of municipal or agricultural (biosolids) waste, at great depth the material would undergo a natural process of anaerobic biodegradation, similar to the process of diagenesis that naturally deposited organic layers experience over time after deposition and burial in a sedimentary basin. High temperature and pressure plus biological activity convert the biosolids mainly into methane with some carbon dioxide. The carbon dioxide will be dissolved and sequestered in the formation brine, while relatively high purity methane will migrate upward as a result of density contrast with the formation brine to become trapped in a zone. Therefore, in the case of biosolids injection an additional provision is made in the site selection criteria; i.e. a suitable trap, structural or stratigraphic, which can collect the produced methane gas so that it could be recovered as a clean fuel for beneficial use at the surface.

The parameters recognized as the most important for an injection site are permeability, porosity, depth and volume of reservoir, tectonic setup, the existence of alternating sand-shale sequence, and so on. A prospective injection site requires certain quantitative or qualitative value for every parameter involved in a selection criterion. To select a suitable site for injection a comprehensive geological site selection model is required which can take account of all the important parameters. Using the model, it will be possible to more easily rank and select a suitable disposal site for a given project on a commercial basis.

1.2 Goals and Methodology

The main goals of this study are as follows:

- Identify the geological parameters important for a prospective injection site
- Recognize the role of each parameter and how it can affect the decision making, also its limitations with reference to technical, non-technical, and economical issues
- Determine the relationship between different parameters and how they can influence each other
- Determine the importance of every parameter and assign a ranking on the basis of their

quality

- Determine the weighting factors for the parameters
- Design and develop a model which can assemble all the parameters on the basis of their ranks and weighting factors
- Evaluate the model by applying on different areas to determine their potential for slurry injection operations

To achieve these goals, the published and unpublished literature was reviewed, and also the available professional papers discussing deep slurry injection were consulted. A decision tree and a semi-quantitative and qualitative numerical relationship were developed to assemble the parameters in the form of a geological model. The geological model was applied on different geographical locations representing diverse geology to evaluate its validity.

1.3 Thesis Organization

This thesis consists of five chapters and two appendixes. After the general introduction and the description of goals and methodologies for this research, Chapter 2 begins with the in-depth study.

Chapter 2 identifies the required important quantitative and qualitative parameters for a suitable reservoir for deep slurry injection operations. Each of the identified parameters is discussed in detail, establishing relationships between different parameters and determining how they may affect each other.

Chapter 3 describes the proposed geological assessment model. The model is composed of two segments: a decision tree and a numerical calculation system. This model integrates all the parameters based on their quality and importance.

In Chapter 4 the geological model is evaluated using the geological data that represents a number of geographical locations in Canada, USA, and Asia.

Conclusions and recommendations are presented in Chapter 5.

Appendix A shows the procedure used to calculate the required surface area for a target reservoir.

Appendix B contains a more detailed geological assessment of southwestern Ontario. For this assessment, drilling data were studied from 64 wells covering eight counties.

1.4 Hydraulic Fracturing

Hydraulic fracturing is a mature technology and the petroleum industry has been using hydraulic fracturing treatment since 1947 for stimulating oil and gas wells to increase well productivity from reservoirs (USEPA, 2004).

1.4.1 Introduction

Hydraulic fracturing is the process of breaking a target reservoir such that a large crack or fracture is produced. For this purpose a fluid that does not contain any solids, called a “pad”, is pumped down into a wellbore at a high injection rate. The injection rate is kept too high for the reservoir to accept this fluid in a radial flow pattern, and as a result of the resistance to flow, the pore pressure starts building up around the well because the fracturing fluid can not leak-off as quickly as it is being injected. When pressure in the wellbore reaches a value which is more than the breakdown pressure of the target reservoir, a fracture is created in the reservoir, and the fluid moving from the wellbore down the fracture continues to propagate the fracture.

In conventional treatments, most hydraulically produced fractures are single fractures and oriented vertically. The fracture grows in two opposite directions from the wellbore at 180° apart; it is usually assumed that both wings of the fracture are more or less the same in shape and size. In an isotropic rock properties case, the created fracture grows dominantly away from the wellbore in the vertical direction because the fluid in the fracture is water, and it has a lower pressure gradient than the horizontal minimum stress gradient. Continuous injection into a low-stiffness (high porosity) rock with leak-off creates a fracture that is wide in aperture. Once the injection is stopped the pressure inside the fracture decreases and the fracture closes. In the petroleum industry propping agents are usually introduced into the fluid as the fracture is propagated from the wellbore; propping agents are strong granular solids, for example sand or ceramic beads, and the purpose of the propping agent is to prop open the fracture when the fluid injection is ceased.

Traditionally, hydraulic fracturing treatment has been used to increase oil and gas production rates from low permeability reservoirs; the petroleum industry also uses this treatment to deal with different production-related problems, for example overcoming of near-wellbore damage, reducing sand production by introduction of resin-coated sand proppants, reducing asphaltene or paraffin deposition near the wellbore by reducing the pressure drop, encouraging more rapid coalbed methane production, and so on. Hydraulic fracturing technology has now been used for solid waste disposal for more than a decade.

Pseudo 3-dimensional (P3D) fracturing models are used to design hydraulic fracturing treatments; the P3D models require some critical parameters as input. The most critical input parameters required are the in-situ stress profile, the permeability profile of the target reservoir, and the type of overlying and underlying rock layers of the reservoir (USEPA, 2004). Information regarding the most critical parameters and the other parameters, for example reservoir porosity, reservoir pressure, reservoir depth, Poisson's ratio, reservoir modulus, reservoir lithology, and so on, can be obtained from geophysical logs, drilling data, pressure transient tests, etc.

1.4.2 Mechanics of Hydraulic Fracture

Rock mechanics plays an important role in designing a hydraulic fracture treatment. The in situ stresses control the fracture orientation, and Young's modulus affects the fracture aperture. The stresses and the elastic properties are the most important rock parameters used in hydraulic fracturing theory and design.

1.4.2.1 In-situ Stresses

Geological formations in the subsurface are subject to compressive stress from all directions and exist under a natural stress state that arises because of gravitational and tectonic loading. Stresses are normally reported as the three principal compressive stresses: maximum stress (σ_1), intermediate stress (σ_2), and minimum stress (σ_3) ($\sigma_1 > \sigma_2 > \sigma_3$), and these principal stresses act at right angle to each other. Usually, in the absence of any compressive tectonic forces, σ_1 is the vertical stress, whereas σ_2 and σ_3 act as the maximum and minimum horizontal stresses respectively (Figure 2.1). In the presence of compressive tectonic forces, for example a thrust fault or strike-slip fault environment, σ_1 can be a horizontal stress. The principal stress magnitudes vary with depth and can also vary somewhat within a reservoir (USEPA, 2004). The magnitude and direction of the principal stresses control the following:

- The pressure required to create and propagate a fracture,
- The shape, orientation, and dimensions of a fracture, and
- The contraction of the solids present inside the fracture after injection ceases.

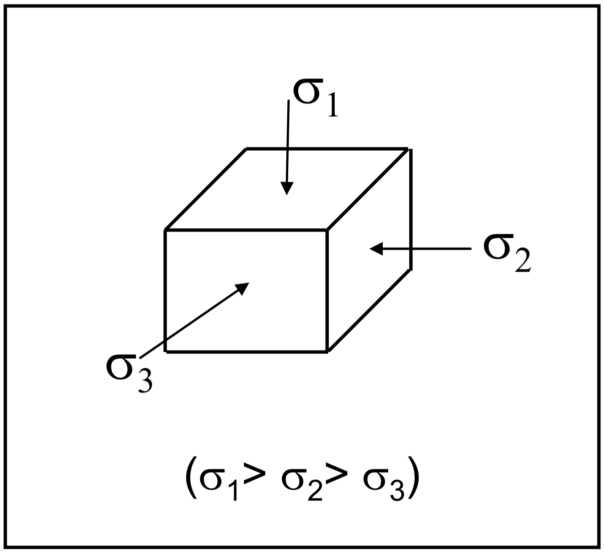


Figure 1.1: In-situ stresses acting on a geological material at depth

The minimum principal stress (σ_3) direction controls the orientation of a fracture, as well as its attitude (horizontal or vertical). A fracture always propagates perpendicular to the least principal stress (σ_3) direction (Figure 2.2) because σ_3 provides the least resistance against fracture opening. Therefore, if σ_3 is horizontal, the fracture will be vertical and if σ_3 is vertical, the fracture will be horizontal. In the case of a shallow target reservoir, it is commonly observed that the overburden (vertical) stress has become the least principal stress ($\sigma_v = \sigma_3$), whereas at a greater depth, it is the intermediate or major stress (σ_2 or σ_1). The magnitude of the vertical stress is controlled by the density of the overlying rocks.

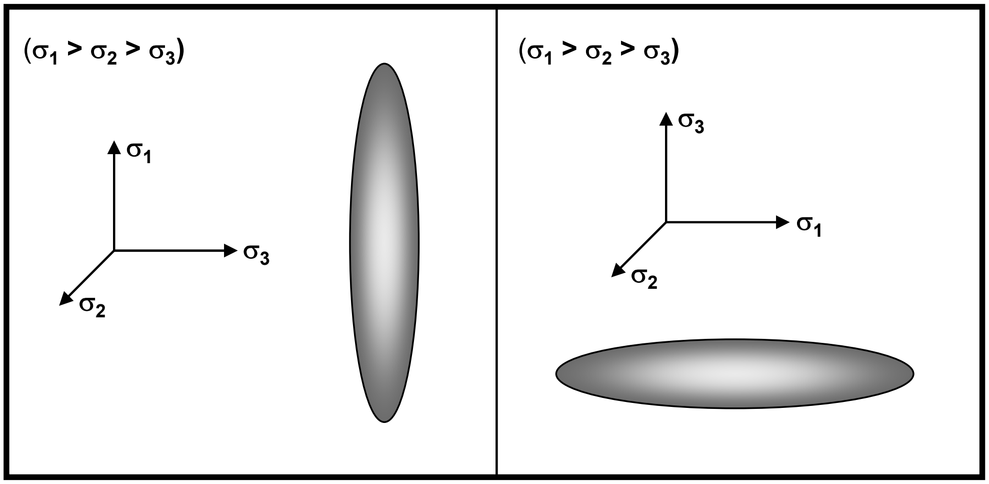


Figure 1.2: Minimum principal stress (σ_3) and fracture orientation

In a tectonically passive area, poroelastic theory can be used to estimate the magnitude of σ_3. Injection tests are generally carried out to measure σ_3 (USEPA, 2004).

1.4.2.2 Young's Modulus

Young's modulus is the rock mechanics deformational property that is important for designing a hydraulic fracture.

Young's modulus is used to calculate the fracture dimension using the theory of linear elasticity. Young's modulus of a rock is a function of the lithology, porosity, fluid type and so on, and it specifies the stiffness of the material. A material behaves stiffly if the modulus is large and vice versa. Other factors being equal, a stiff rock produces narrow and long fractures, whereas a rock of low stiffness produces wide and short fractures (Figure 2.3).

1.4.3 Fracture Monitoring

Hydraulically produced fractures can be continuously monitored to allow estimation of the orientation, shape and dimensions of the fractures, and also to make sure that the injected fluid is entrapped in the target reservoir and is not a potential threat to drinking water aquifers. Geophysical techniques, wellbore techniques, pressure transient tests, injection data, and so on are used for monitoring.

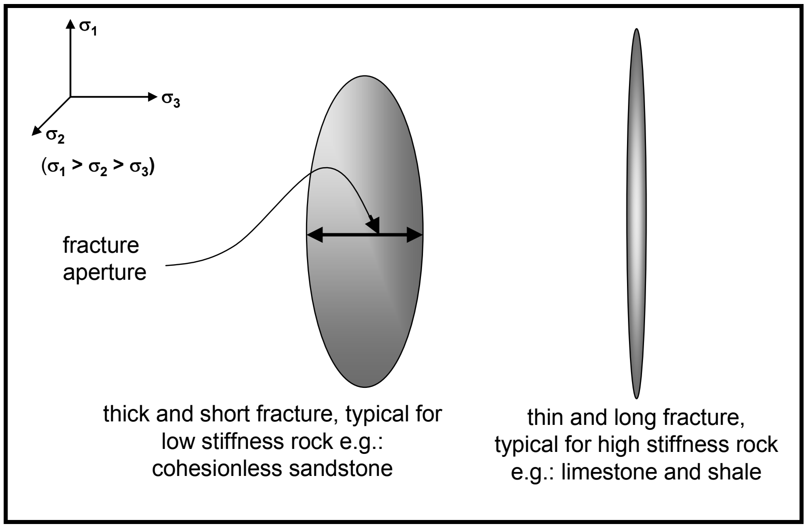


Figure 1.3: Rock stiffness and contrast in fracture geometry

Tiltmeters and microseismic fracture mapping are the main remote geophysical techniques that are used for fracture monitoring. A deformation field is induced in the earth around the created fracture because of the opening and fracture volume. A tiltmeter is a delicate geophysical instrument capable of measuring the earth's deformation (actually inclination at a point, or tilt) to values of tilt as small as 10^{-8} radians. Usually tiltmeters are installed in shallow boreholes (~6-12 m deep) in an array around the injection wellhead to continuously measure the tilt response over a prolonged period of injection. This information is processed and analyzed to measure the fracture orientation and its approximate size.

Tiltmeters can also be placed inside special monitoring wellbores near the target reservoir; the wellbore tiltmeter data combined with the surface data provides more precise information regarding orientation, dimension, and height of the created fracture.

The fracturing also produces noise as a result of shear slippage in natural joints and cracks in a zone around the hydraulically produced fracture. Microseismic techniques use sensitive arrays of down-hole geophones to record this noise data. The data is processed and analyzed to determine the orientation, dimension, and height of the created fracture more accurately than through the use of tiltmeters alone. Microseismic monitoring is relatively more expensive than tiltmeter monitoring, therefore is used only for a higher level of precision if it is considered necessary.

Different type of well logs are run in the wellbore to locate the created fracture, for example tracer logs, temperature logging, borehole image logging, down-hole video logging, and so on. These techniques are effective only in a small diameter around the wellbore, i.e. 2-3 wellbore diameters, and due to this reason can not provide information about fracture dimension. These techniques also provide information regarding any fluid leakage if it happens through the annulus spacing along the wellbore, and therefore provide environmental security and wellbore integrity information.

Injection rates, density of injected fluids, bottom-hole pressure, surface injection pressure, and so on are also continuously monitored during an injection project. Such data, along with regular pressure transient test analyses, are also used to determine the shape and dimension of the hydraulic fracture and the conditions in the target reservoir. Such data can also be analyzed using a 3D reservoir simulator to determine better “images” of the created fracture.

1.5 Deep Slurry Injection

Deep slurry injection technology is based on hydraulic fracturing technology. The petroleum industry uses propping agents to prop open created fractures, whereas in case of deep slurry injection, solid waste replaces the propping agents. For deep slurry injection, the fracture is produced hydraulically deep inside a geological formation far below any drinking water aquifers. As the fracture is propagated, solid waste is introduced in the injection fluid similar to the propping agents in conventional hydraulic fracturing. The fluid carries this solid waste far inside the fracture where it is permanently deposited. The monitoring methods that are described earlier are used in case of slurry injection to provide greater security to the injection project.

Rock mechanics assessment of hydraulic fracturing shows that chances of a created vertical fracture to reach near the surface is close to zero because of the control of principal stresses on the orientation of a fracture and because the fractures will be de-watered by the permeable strata. A fracture growing vertically upward will reach a shallow depth and can not further propagate in the same upward direction because the orientation of the principal stresses is usually different near the surface. The fracture becomes horizontal at some depth because the vertical stress acts as the minimum principal stress at shallow depth, and the further growth of the fracture becomes horizontally dominated. A horizontal fracture tends to stay in a single litho-unit and can not intercept the overlying lithostratigraphic unit that might carry drinkable water sources.

1.5.1 Injection Methodology

A deep slurry injection well is drilled using modern drilling technology, which is also used by the petroleum industry. The well is lined with a steel casing and to set the casing the annulus space is filled with non-shrinking cement; the cement provides hydraulic isolation to the overlying geological litho-units that may carry economic minerals or drinkable water resources. The steel casing is perforated at the target depth in the reservoir with 20-25 mm diameter holes. An injection tubing (66-88 mm diameter) is attached inside the steel casing and is sealed with a packer at the target depth. Down-hole pressure transducers are also set and they continuously measure the pressure on both sides of the packer to maintain constant vigilance on the integrity of the injection well.

Initially, at the beginning of a slurry injection episode, water is pumped down at a rate of about 2 m^3/min in the tubing so that the system acquires full fluid momentum and also achieves the fracturing pressure. This may take several minutes (5-15) before it is clear that a fracture is initiated. Waste material is then introduced into the liquid and gradually its amount is increased so that the desired slurry density is achieved over the next 10-15 minutes, and then follows the steady-state waste slurry injection phase.

One injection episode lasts for perhaps 6-12 hours into a single well. At the end of the injection episode the waste feed content is gradually dropped in the fluid until it reaches a zero concentration over a period of about 20 minutes. Clear water is flushed through the system before the well is shut-in so that the well and perforations are free of solids and any potential blockage problem could be avoided during the next injection phase. The shut-in phase lasts for 12-24 hours, or more if necessary, and allows the pressure to dissipate in the target reservoir; down-hole pressure is continuously monitored during the shut-in period. Figure 2.4 shows an original pressure-time plot for a slurry injection well explaining the injection cycles and different phases of injection.

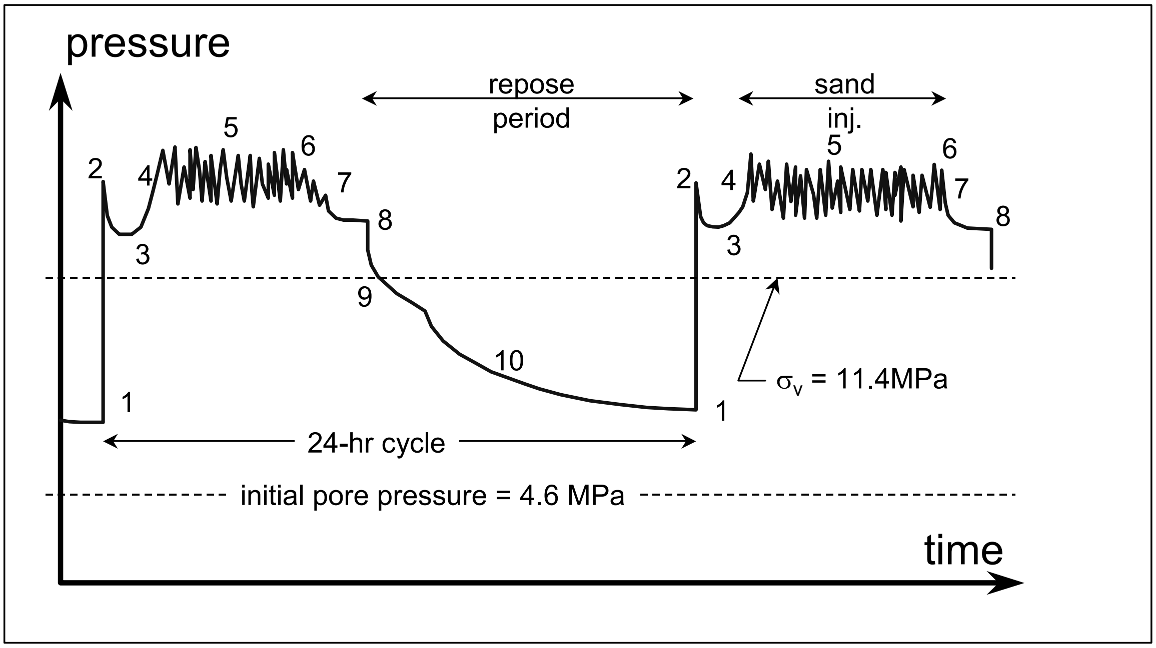


Figure 1.4: Pressure-time plot for a deep slurry injection well: 1- start injection; 2- fracture achieved; 3 and 4- switch to injecting slurried solids; 5- steady injection; 6- decrease solids; 7- clear water flush; 8- shut-in well; 9 and 10- monitor and analyze pressure decay (After Dusseault, 2004)

Chapter 2: Important Parameters for Deep Slurry Injection

2.1 Introduction

The important parameters recognized by different workers for selection of deep slurry injection zones are the following:

- Permeability: The capacity to flow fluids will affect both the fluid leak-off rate from the injected slurry, as well as the rate of flow of generated gases upward through the host medium in the case of biosolids injection with methane generation. The capacity to leak-off slurry liquid will depend more on horizontal permeability, the efficacy of gas segregation will depend on vertical permeability and on capillarity (gas-liquid surface tension effects and pore throat diameters).
- Porosity: The storativity of any geological material depends upon the porosity. High porosity is important to accommodate the liquid phase of the injected waste slurry.
- Thickness and Areal Extent: A large thickness and a large areal extent of reservoir rock are necessary to keep induced fractures contained within the target zone, and to help provide sufficient volume of storage for the expelled fluids (volumetric capacity with perfect displacement = thickness × width × length × porosity).
- Reservoir Depth: The injection depth must be sufficient to eliminate all reasonable risk of potable water contamination, yet not so deep as to require massive pumping

capability to sustain fracture injection.

- Alternating Sequence of Sandstone and Shale: A shale layer acts as a flow and a stress barrier, whereas a sandstone layer acts as a rapid fluid leak-off zone. An alternating sequence of sandstone and shale will limit upward fracture growth because permeable beds above the injection horizon will enhance leak-off and arrest vertical fracture growth.
- Geographical Distance: The geographical distance between a waste disposal and a waste collection site should be short; this will make an injection operation economical and more environmentally secure (reduced transportation risk).
- Cap Rock and its Thickness: A thick layer of cap rock (low permeability strata) will act as a confining unit above the reservoir rock. It will act as a flow and a stress barrier.
- Reservoir Strength: An ideal reservoir rock should be weak in tension (low cohesion or intensely fractured); it will then offer less resistance against breaking (tensile parting) at low values of effective stress.
- Reservoir Compressibility: A highly compressible rock will more easily produce thick (wide aperture) fractures during injection; therefore, it will more easily accommodate large volumes of solid waste.
- Structural/Tectonic History: A structurally and tectonically passive disposal site will more securely contain injected waste in the target stratum by eliminating the chances of upward fluid migration paths through pre-existing fractures and faults.

Some of these parameters can be described quantitatively, but others can only be described semi-quantitatively to qualitatively.

2.1 Permeability

Permeability is defined as the ability of a material (generally an earth material/rock) to transmit fluids (water, gas, oil) through its pores. It is the most important factor in site selection criteria for deep slurry injection.

Both horizontal and vertical permeability (k_h, k_v) are of potential importance to waste disposal. Given that most disposal strata will be approximately flat-lying or of gentle dip, k_h is the most important determinant of the liquid phase leak-off potential, whereas k_v is more important to assess the potential gravitational segregation speed of any generated gas phase that may arise, for example, after biosolids injection. Therefore, if only solids waste disposal is being assessed without methane (CH_4) generation and collection, k_h controls this evaluation, and if biosolids injection with methane generation is being assessed, k_v must also be considered, although with a substantially lower weighting factor. Furthermore, making the assessment yet more complex, the injection process itself is a fracturing process which will likely cut across horizontal clay or shale laminae, and thereby affect the propensity for the vertical migration of a gas phase. Thus, the distance for vertical migration of a gaseous phase may affect the use of k_v as a parameter.

2.1.1 Geomechanical Issues

When waste slurry is injected under high pressure into a subsurface formation, a zone of abnormally high pore pressure can be generated in-situ. This high-pressure zone and its outward growth could reactivate existing faults or trigger slip along bedding planes; therefore, it is important that induced pressure at a distance from the injection point be dissipated quickly after each interval of injection. Permeability plays an important role in the process of dissipation of pressure; a high permeability allows the injected liquid to leak off rapidly from the point of injection, allowing rapid pressure decline, reducing the risk of slip.

High permeability usually means many big pore spaces among the rock grains, at least in the case of granular media such as sandstones. Many large pores make the reservoir rock more compressible under changes in effective stress; therefore, high permeability in sandstones is often associated with high compressibility, which is an aid to solids injection.

High pressure injection leads to hydraulic fracturing in rocks. It is not considered possible to inject any significant amount of solids in aqueous slurry without the generation of hydraulic fractures. In general, porous, permeable materials (unconsolidated and poorly consolidated sandstones or cohesionless sandstones) generally evidence thick (wide aperture) and short (in length) fractures; whereas, low porosity, low permeability materials (typically stiff shales and limestones) tend to produce thin and long fractures (Figure 1.3). This contrast in fracture geometry comes in part because of the different values of stiffness of the materials, as well as because of the different fluid leak-off rates associated with the permeabilities. Shales and limestones are usually stiffer than cohesionless sandstones, and stiffness usually is strongly related to porosity for porous, non-fractured rocks.

Permeability can affect the shape and orientation of the induced fracture (Veil and Dusseault, 2003). High permeability can make fracture injection difficult through a rapid solids screen-out process (a filtration process). This phenomenon also limits lengthwise growth of the fracture and is more likely to produce a wide “disposal domain” in the target formation through creation of multiple fractures (Veil and Dusseault, 2003; Reed, 2001).

This disposal domain of multiple fractures (Figure 2.1) allows a larger volume of solid waste to be disposed close to the injection well (Srinivasan, 1997); therefore, a high permeability is good for the disposal of high volumes of waste, in spite of the potential greater difficulty in generating and sustaining a fracture during injection. In the case of small waste volumes, high permeability is not considered as favourable because a single hydraulic fracture is sufficient for small volumes of waste (Veil and Dusseault, 2003).

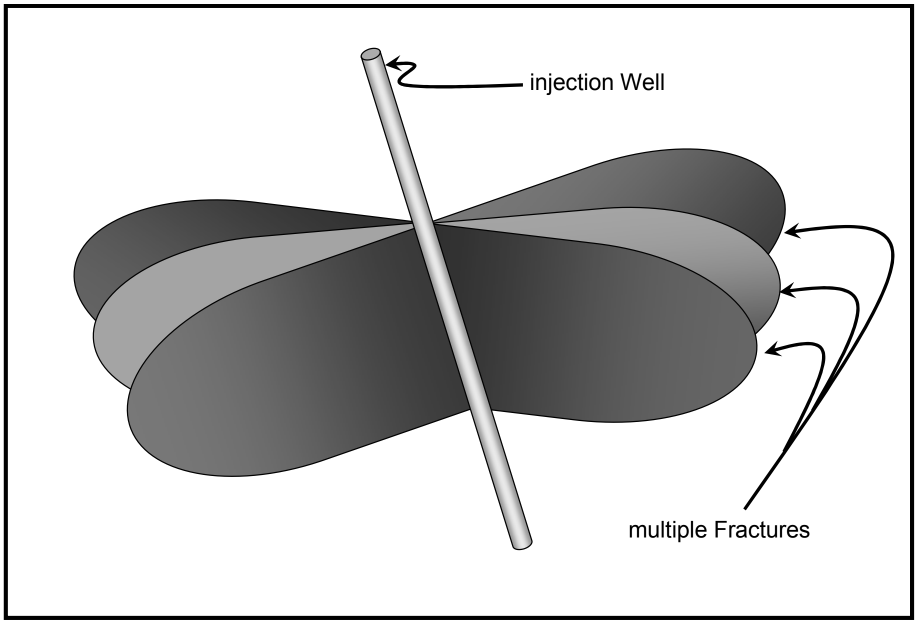


Figure 2.1: Disposal domain of multiple fractures

A pressure above the value of the local minimum total horizontal stress σ_{hmin} is required to fracture the formation and to push the waste inside the fracture. In case of strata of quite high permeability, for example more than 10 Darcy, build-up of enough pressure during a clear (no solids) water injection initiation phase is difficult because of high and rapid leak off; therefore, permeability greater than 10 Darcy is considered as a negative factor for slurry fracture injection.

2.1.2 Fluid Flow Issues

High permeability allows the liquid phase of the injected slurry to leak off rapidly; permitting the liquid phase to move away into the porous medium (Figure 2.2). In the porous rock, the liquid phase will displace the natural waters and experience dispersion and diffusion. This will allow polyvalent cations and other dissolved constituents, present in the liquid phase, to become diluted, dispersed, and absorbed on clays and other minerals, and therefore be attenuated with distance from the injection site. Even potential biodegradation of dissolved organic constituents will be favoured by dispersion and diffusion of the fluids.

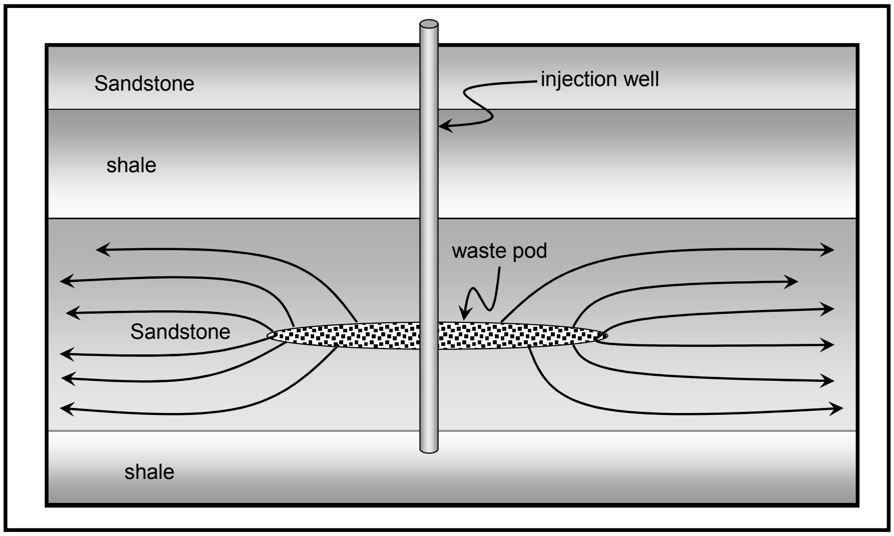


Figure 2.2: Rapid leak-off of the injected fluid away from injection well in the target reservoir, sandwiched in shale layers

Based on previous slurry injection practice (Reed, 2001; Srinivasan, 1998; Srinivasan, 1997; Bruno[1], 1995; Bruno[2], 1995; Dusseault, 1995; Dusseault, 1994), multiple layers of shale (low permeability) and sandstone (high permeability) are considered best as a general geological target stratigraphy for solid waste disposal. When injection takes place into one of the lower sandstone layers in such a sequence, the upper layers of high and low permeability help to arrest upward fracture growth. The low permeability layer acts as a barrier for fluid flow by Darcian advection, whereas the high permeability layer acts as a rapid fluid leak-off zone which will tend to arrest ("blunt") upward fracture propagation and perhaps also help to create a solids screen-out blunting process whereby a high permeability rapidly dehydrates the slurry (Abou-Sayed *et al.* 2000), causing sudden formation of a solid with shear strength that can no longer flow within the fracture.

The permeability of the reservoir rock surrounding the injection well, and particularly the value of k_v for the rocks above the injected solids mass, will be an important factor when methane gas will be generated through biodegradation processes acting on injected biosolids. A high k_v will provide an easy vertical migration path for gravitational segregation of the methane, and a good horizontal path (k_h) will also help allow the methane to travel towards a suitable trap to accumulate in an economical reserve (Figure 2.3).

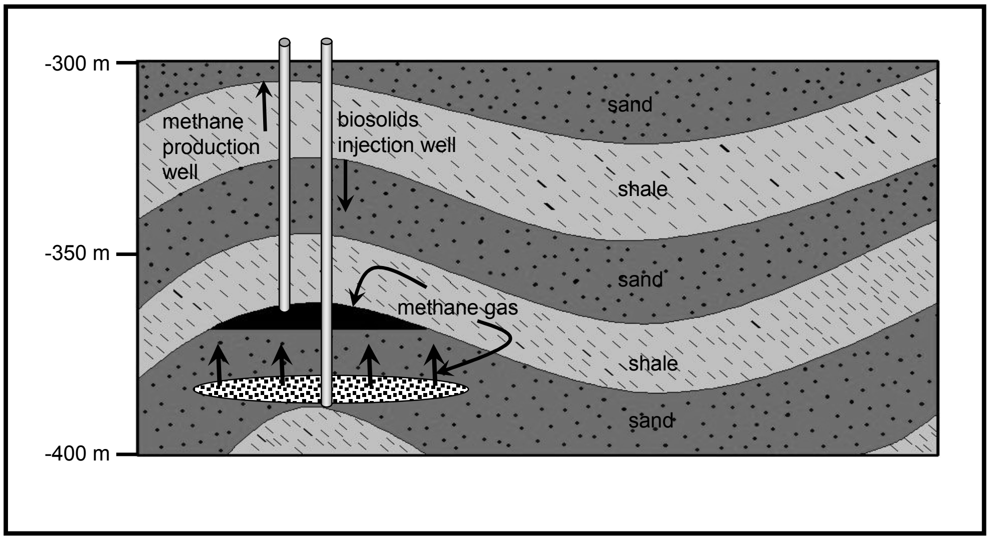


Figure 2.3: Methane generation, trapping, and production in alternating sequence of sandstone and shale (not to scale)

Pressure transient tests are used to obtain reliable information about in-situ reservoir properties in the petroleum industry; for example, reservoir pressure, permeability, porosity, reserves, reservoir and fluid discontinuities, and so on can be obtained. Examples of pressure transient testing techniques are pressure build-up tests, pressure drawdown tests, pressure interference tests among wells, injectivity tests, and so on (Earlougher Jr., 1977). Usually in a geological formation or reservoir, the vertical permeability has a lower value as compared to the horizontal permeability. This permeability anisotropy is a typical characteristic for both homogeneous and heterogeneous reservoirs. Macroscopic features related to depositional environments such as shale-sand inter-bedding, clay dustings on bedding planes, and other factors lead to reduced vertical permeability. Tectonics (faults and fractures etc.) and post depositional compaction (digenesis etc.) can also be major contributors to permeability anisotropy. Pressure transient testing methods are capable of providing information about both horizontal and vertical permeability, k_h and k_v (Earlougher Jr., 1977).

Pressure interference testing is quite useful to determine the vertical permeability caused by vertical fractures; it also helps to determine the orientation of vertical fractures in a reservoir (Earlougher Jr., 1977). Fracture diagnosis, that is whether the fracture is natural or induced, is also possible by combining the test results with other information, for example production logs, stimulation history, core description, geological data about reservoir lithology and continuity, and so on. This helps to distinguish between directional permeability and fracture-induced permeability. (Note that these decisions are aided by data and that such data are more likely to be available in the case of an old oil or gas reservoir).

Shale cap rock (low to negligible permeability strata) will also serve as a barrier to upward migration of methane that will be generated from the injected biosolids, helping to trap the gas to allow it later to be recovered (Figure 2.3). Because of capillarity between gaseous and aqueous phases, probably a vertical permeability in a non-fractured rock of less than perhaps 5-10 mD is enough to stop much of the upward segregation.

2.2 Porosity

Porosity is defined as the fraction (or percentage) of non-mineral volume or void space in rocks. It represents the volume fraction within a rock that can contain fluids (gas, oil, water). Porosity can be primary and secondary in nature; primary porosity, especially in sedimentary rocks, represents the intergranular space (granular porosity) that was original and has not been destroyed by compaction; secondary porosity develops at a later stage of the geological life of a stratum through geochemical and tectonic processes. The intergranular porosity can be further divided into effective porosity and total porosity; effective porosity is the interconnected pore volume, and it contributes to fluid flow in any rock; total porosity is the total pore volume in a rock, and it includes all isolated and interconnected pore volume. Isolated pores do not contribute to fluid flow and must not be considered in assessment of fluid storativity at a site.

Fracture porosity is an example of secondary porosity; it is produced by the tectonic or diagenetic fracturing of a rock. Fractures enhance permeability significantly, particularly if there is a well-developed and interconnected fracture network (joint system) of reasonable aperture (several microns or more). Although fractures enhance permeability greatly, they contribute little to storativity because they are usually much less than 1% of the total volume of the rock mass.

2.2.1 Permeability Issues

Porosity plays an important role in making any stratigraphic unit a suitable target stratum to accept solid waste. According to a general rule of thumb for the same rock type (e.g. sandstone), the higher the porosity, the higher the permeability. Exceptions arise of course when a rock unit has a fine-grained texture like silt and clay etc., because of the small pore sizes. Also, silt and clay fractions in otherwise coarse-grained sandstones (Figure 2.4) can invalidate attempts to establish a link between porosity and permeability.

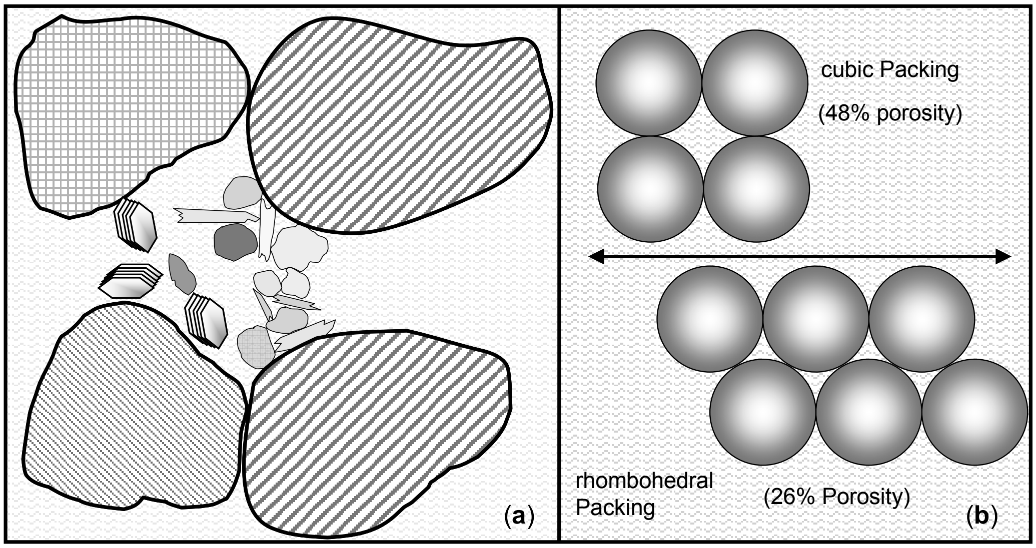


Figure 2.4: Porosity changes (a) big pore filled with fine particles (After Singh and Dusseault, 2003); (b) geometrical arrangements of grains and porosity variation

According to Poiseuille's Law, discharge (Q) through a circular opening in a porous medium is directly proportional to the pore throat radius (r) to the fourth power, and inversely proportional to the viscosity of the fluid (μ).

$$Q = \frac{-r^4 \pi F}{8\mu}$$

F = $(\Delta P + \rho g \Delta z)/\Delta L$ and
Δ = change
P = pressure
ρ = density
g = gravitational acceleration
z = depth
L = distance
μ = viscosity

This equation demonstrates clearly why the permeability of shale (or clay) is orders of magnitudes less than that of sand, even though the porosities may be similar: the pore throat diameter dominates flow rate capacity in a particulate medium, not the pore volume nor the pore size. Also, in a clay-rich material such as shale, the specific surface area is very large, and there is water absorbed electrostatically on the clay surfaces. This water is not fully mobile, and therefore the pore throats in shale have an even lower flow capacity than expected because of immobile water layers.

Both fracture and granular porosities are important to produce high permeability, especially in rocks that have a low matrix permeability such as jointed limestones and jointed shales. Fracture porosity is more important in the case of low intergranular porosity, but even with a high intergranular porosity, fractures can enhance the permeability substantially, particularly in fine-grained sandstones.

Discharge per unit width per unit pressure drop through an individual fracture in geological materials is directly proportional to the third power of the fracture aperture (b); therefore, the fracture's permeability depends strongly upon the fracture width "b".

$$Q = \frac{-2Fb^3}{3\mu}$$

Because natural fractures have apertures that can be in the range of 5-100 microns and have a substantial length, they can dominate the macroscopic flow capacity of the target stratum. Slurry injection produces high pressure in the target formation during injection operations, and it also causes strains and some bending of the overlying strata; this helps natural fractures to open by reducing the effective stress and by bending, even to the point of hydraulic fracture opening of the natural fractures. The network of these open fractures provides an easy conduit for liquid flow and therefore helps to dissipate the pressure more rapidly, which can be an advantage if the overall condition of permeability is not good in a target geological material.

In an actual injection process, the tendency of such a natural fracture system to plug with the solid phase must be assessed as well, as this may negatively affect the capacity of the site to accept solids and liquids.

2.2.2 Geomechanical Issues

When an increase in effective stress is applied to a porous medium, compression can occur because of the compressibility of the grain-to-grain contacts, the compressibility of the mineral grains themselves, the capacity for rearrangement of the mineral grains, and the tendency for the grains or of the pore spaces (porosity) to collapse. Practically, compressibility of mineral grains and fluids plays a negligible role in total compressibility; grain contacts, grain reorientation, and pore collapse and grain crushing are the major contributors for reduction in porosity as effective stress increases. Note that the hydraulic injection process will increase the pore pressure near the fracture temporarily so that the effective stresses will drop, making grain crushing and pore collapse less likely, and even leading to a small expansion of the rock. Once injection ceases and leak-off occurs so that pressures are equilibrated to the original values, the horizontal effective stresses in particular may have been substantially increased.

Cubic packing of identical ideal spheres gives 48% porosity, whereas rhombohedral packing of the same spheres gives only 26% porosity (Figure 2.4). This reduction in porosity is due to the different geometrical packing and comes by rearrangement of grains only, which demonstrates in a simple manner that packing pattern can compress the material markedly. In general, for a dense ($\phi < 32\%$) but uncemented sandstone, it is unlikely that a denser packing could develop during injection; it is far more likely that a looser packing will develop because of shear and dilation when the pore pressures are elevated. However, once injection ceases, the horizontal effective stresses may have been increased substantially to develop the denser packing.

In the waste material, however, a denser geometrical packing may be generated by the shearing that takes place during continuous slurry injection, as compared to a process of pluviation for example (sedimentation). When injection ceases, further compaction occurs as pore pressures equilibrate, and if the grains themselves are deformable, as in the case of biosolids, a much lower porosity can be generated than would be expected in a "normal" granular medium.

2.2.3 Storage Capacity

The storage capacity of any geological material depends upon its void spaces, thus high porosity gives high storativity; therefore, high porosity geological material helps to accommodate the liquid portion of the injected slurry. Space for placing the solid waste (volume of hydraulic fracture after compaction) in the target geological material depends extremely weakly on the porosity of the material because the solid material is “stored” in induced fractures, not within the pore space. According to Reed (2001); the volume of solids containing in the waste pod can be estimated using the following equation: in this equation, V_{solids} is the volume of solids stores, and a, b, and c are the major axes of the best-fit ellipsoid.

$$V_{solids} = ({}^{4}\!/_{3}\,\pi abc)(\phi + C_t \Delta\sigma)\,ff$$

a = fracture half length
b = fracture half width
c = fracture half height
ϕ = porosity
C_t = formation compressibility
$\Delta\sigma$ = stress change
ff = empirical coefficient which can be determined by measurements in practice

2.3 Reservoir Depth

Depth of a target formation for a slurry injection operation needs considerable consideration of the following issues: environment, economics, and waste type. The target formation should be located far below drinking water aquifers and distant from any other site of economic interest, for example petroleum reservoirs or mines. The target formation must be separated from them by a number of appropriate flow barriers, as well as adequate distance.

Based on hydrogeological data, the great majority of drinking water aquifers are located within 200 m from the ground surface; therefore, any depth less than 200 m is considered as a negative factor for slurry injection. It must be emphasized, however, that this figure is also strongly location-dependent, and in some climates and geological conditions the depth of potable water is far greater than 200 m. However, for many reasons, 200 m seems to be a reasonable minimum depth to guarantee security of waste placement.

2.3.1 Environmental Issues

Deep injection into a confined target stratum eliminates any chances of leachates leakage through conventional flow in the porous medium (this assumes that the well has a high-quality cement sheath that serves as a full barrier to any flow along the borehole). Any breach in flow barriers, for example as created by natural or induced seismic activity, could allow liquids to move towards the ground surface or into potable water sources through created fractures or faults. If the well is quite deep, the liquids would take an extremely long time to reach aquifers, even if a path is generated, because of slow flow rates, storage, modest pressure gradients, and so on. The risks of interaction with shallow potable waters appear to be exceedingly small for deep injection, even for long periods of time, but these values have to be estimated on a site-specific basis. For example, even in the case of seismic activity, it is likely that any fracture or fault would be closed as a preferential flow path shortly after the seismic activity, particularly if it passes through shale, salt, other evaporite beds etc.

The interaction of a liquid containing dissolved constituents with a solid involves complex geochemical processes, but there are processes such as sorption and cation exchange that would serve to reduce the content of species such as heavy metals or organic molecules, especially polar molecules, when liquid flows through porous media during and after injection operations. These processes would serve to purify or “decontaminate” the leaking liquid through adsorption at the walls of the fracture and the surrounding porous medium, while migrating upward or in a lateral direction (Piwoni and Keeley, 1990). Therefore, the resultant upward moving liquids would become clean far before reaching the ground surface or potable water sources.

According to Bruno (1999), it is unlikely that fluid would migrate out of a suitably chosen injection interval for the following reasons:

- The pressure and stress gradients required for migration to shallower depths can not be sustained in the permeable disposal formation. The geomechanics involved with fracturing into weak, unconsolidated, and permeable formation serves to effectively dissipate pressures and stresses generated during injection.
- A competent shale barrier overlying the disposal zone will act as a flow and stress barrier to upward fracture propagation, and it also serves as a barrier to Darcy flow.
- Intervals that tend to be approved for injection of biosolids or solid wastes generally include a buffer zone of multiple sand-shale sequences to absorb fluid and arrest any upward fluid migration.
- Extensive monitoring to insure that hydraulic isolation is maintained during injection operations takes place, providing real-time assurance of flow security.

2.3.2 Cost Related Issues

Pressure is required to fracture the target formation and to push the injected slurry inside the hydraulic fracture. To produce a hydraulic fracture in a geological material at a certain depth, the injection pressure must be greater than the minimum stress, σ_3, and if the two horizontal stresses are σ_1 and σ_2 respectively, the vertical stress gives the lower limit to fracture pressure (i.e. $\sigma_v = \sigma_3$). By this argument, the maximum fracture initiation pressure at depth will be slightly larger than the vertical stress, but may of course be lower in regions of relaxed stresses (i.e. non-tectonic areas). Also, as more solids are placed, the horizontal stresses tend to increase until the vertical stress is the least (see below), and this controls the fracture pressure after some volume of injection. Regionally, the vertical stress is directly proportional to the depth:

$$\sigma_v = \rho \cdot g \cdot z$$

If the target formation for slurry injection is quite deep, high pumping surface pressures will be required for the injection process in order to generate hydraulic fracture; this means that great depth leads to high pump horsepower and pressure requirements, high energy consumption, and ultimately a higher cost for injection operations.

$$P_{surf} = P_{frac} - \rho \cdot g \cdot z, \text{ and generally, } P_{frac} \sim 1.15 - 1.25 \times \sigma_v$$

Therefore, it can be concluded that great depth is a negative factor from an economic point of view, with heavier equipment needs and more energy consumption.

2.3.3 Issues of Waste Type

The issue of depth limits also has a relationship with the amount and type of a waste: i.e. non-hazardous or hazardous waste. In case of non-hazardous waste material, for example non-toxic municipal waste, a shallow depth of the target reservoir does not pose any serious environmental threat; also small amounts of the waste could be disposed at a depth shallower than the described limit, i.e. less than 200 m, depending upon the depth of the water aquifers in an area. On the other hand, hazardous waste, for example nuclear and toxic waste, requires a high level of security. For hazardous waste, environmental protection agencies already have certain specific regulations for deep injection operations, depending upon the nature of the hazardous material. For that reason, a deep target reservoir, with multiple impermeable to semi-permeable rock layers in-between the reservoir and the water aquifer, would be the best candidate to receive hazardous waste injection, and also in this case a limit of minimum depth could be much greater than the described limit, i.e. more than 200 m. Therefore, the numerical limiting values must be re-assessed in specific cases on the basis of engineering judgment and available data.

2.4 Areal Extent and Reservoir Thickness

2.4.1 General

The waste volume that can be disposed by hydraulic fracturing depends upon the volume of a target reservoir rock; i.e., the thickness and lateral areal extent (surface area) of the contiguous reservoir body. An ideal target geological formation should be thick and areally wide spread; this will help to accommodate a large volume of waste without pressure build-up. A thick and areally wide-spread target unit will help to accommodate the huge amount of liquid associated with the solid waste. This will be convenient, in that it will also allow access to the target formation from different surface geographical locations, provided that it has a sufficient areal extent (Figure 2.5). A thick geological formation composed of alternating litho-units of high and low permeability will be more conducive to the identification of zones of multiple layers of suitably porous and permeable beds at different depths for injection operations (Figure 2.5).

2.4.2 Issues of Storage

According to Veil and Dusseault (2003), periodic injection of large waste volumes in a poorly consolidated sandstone not only produces a disposal domain of vertically oriented hydraulic fractures (when direction of minimum stress is horizontal), but also produces a horizontal component in the hydraulic fractures. The periodic injection of slurried solid waste produces a local zone of high stresses around an injection well; this changes the original stress environment around the waste pod by making the horizontal stress maximum and the vertical stress minimum. Under this local condition of minimum vertical stress the hydraulic fracture changes its inclination, and becomes horizontal (Figure 2.6); therefore, it would be unlikely for a fracture to grow vertically a great distance. As the fracture starts developing in horizontal direction, it tends to stay in the target formation in the case of a thick injection zone. This demonstrates that a large volume of target formation (a thick and wide-spread reservoir) would be able to accommodate a huge amount of both solid and liquid waste material.

On average, the volumetric fraction of solids in a waste slurry may range from 10% to 30%. This means that the 70% to 90% of the slurry that is liquid will for the most part have to be accommodated in the pore volume of a target formation, whereas the rest of the slurry composed of solids will stay in produced fractures where solid waste will remain arrested forever at a porosity of from 10% (for deformable materials) to 35% (for sands and well-sorted granular wastes). By considering a cylindrical volume in a target formation it is possible to calculate the formation surface area that will be required to accommodate the liquid waste. The calculation made to compute the surface area required for an amount of 1,000,000 m^3 (6,250,000 bbl) injected liquid shows that ideally, in case of a homogeneous and isotropic target geological formation, a surface area of 0.17 km^2 (Appendix A) will be required to accommodate this liquid when porosity and thickness of a target reservoir will be 30% and 20 m respectively, and the pore volume is only occupied by brine and does not contain any hydrocarbon. The required surface area becomes 0.5 km^2 when the porosity and the thickness are reduced to 20% and 10 m respectively. In the case of a depleted oil reservoir, the available porosity which accommodates the liquid part of the slurry depends upon the recovery factor (RF) of the oil during the reservoir exploitation phase. In the case of 50% oil recovery factor, somewhat more than half of the reservoir pores volume is still occupied by the immobile oil, trapped by capillary tension; therefore the actual available pore volume of the reservoir will have to be calculated depending upon the previous exploitation history of the reservoir

$$\text{Storage volume for slurry liquid} = \text{Pore volume of a reservoir } (1- \text{RF})$$

This calculation shows that a large areal extent of a target formation is not required to accommodate huge amounts of liquid waste, and similarly, solid waste “storage” also will require quite small volumes of reservoir rock to accommodate the input volumes. It is known that in sedimentary basins formations usually run many kilometres along their trend directions (depending upon the size of a basin); therefore, it can be concluded that areal extent of a target formation is not an important issue in view of waste volume accommodation.

There is also the additional storage capacity that may arise in a single well through the use of different injection zones at different depth. Initially, a well may be used, for example, to inject at 1500 m depth into a 30 m thick zone, and after several years, a well re-completion to use an upper zone at 800 m depth could take place. Thus, the capacity of a single well is quite large, providing that the injection process does not impair the well through casing shearing or other effects.

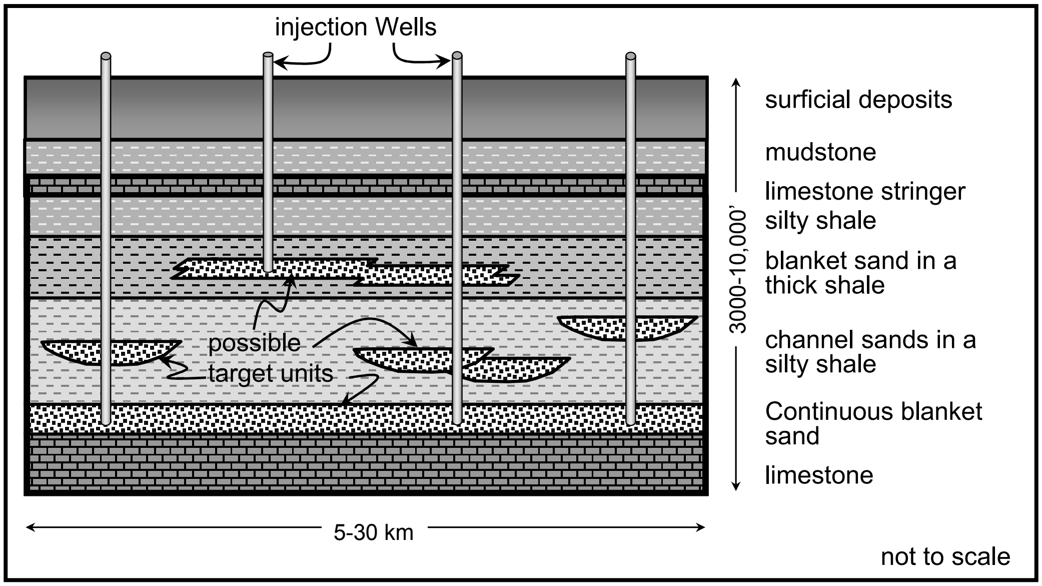


Figure 2.5: Possible target sandstones for slurry injection**,** easily accessible due to large areal extent and multiple levels (Modified from Singh and Dusseault, 2003)

Huge projects for solid waste injection will require more than one injection site. For example, in the case of a giant oil field producing sufficient volumes of waste (sand, sludges, spills, sulphur etc) daily and having an expected life span of 2-3 decades, one injection well will not be sufficient. Depending on waste volumes to be disposed, it will be necessary to drill a new waste injection well, perhaps each 6-24 months. Also, a similar situation can come up in the case of biosolids injection for densely populated urban centres, particularly if the injection zone is relatively thin. This situation will give rise to the issue of injection well distribution or spacing in a given area, and the areal extent will become an important economic factor in this case. In the case of large areal extent of a target formation it will be convenient to drill a number of wells in a single formation, keeping enough distance among them so that the issue of pressure build-up or inter-well interference as a result of a massive injection job can be handled easily. In cases where there are clear volume or rate limits, careful analysis must be undertaken to decide on spacing, completion depth, and number of active wells.

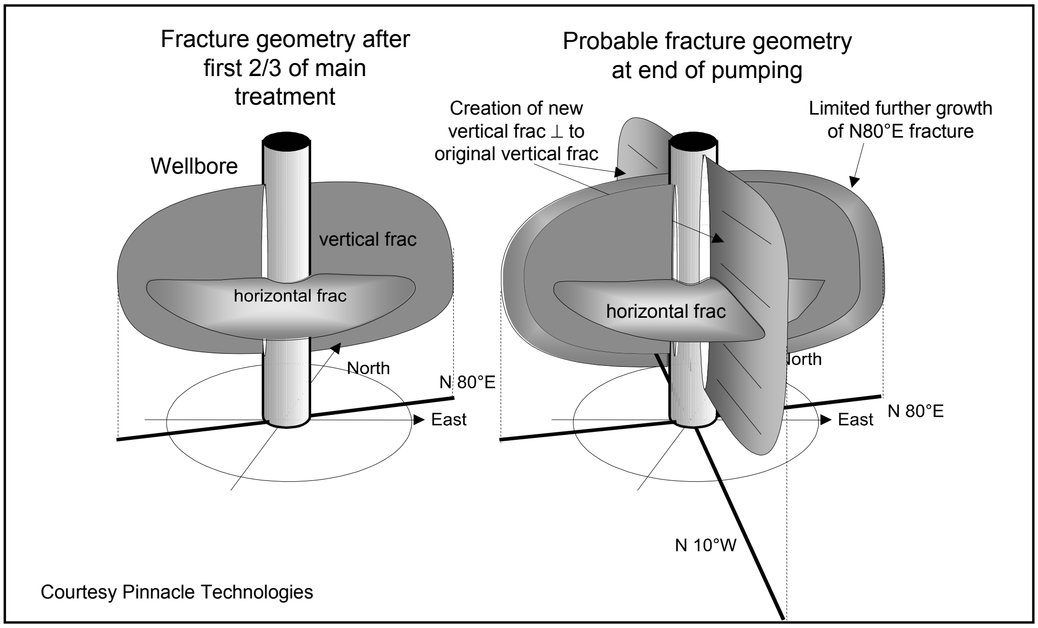


Figure 2.6: Changes in Fracture orientation during injection process (After Singh and Dusseault, 2003)

Naturally reservoirs have heterogeneities and these heterogeneities produce flow restrictions and tend to divide a reservoir into different permeable zones or compartments, separated by low-permeability zones or flow barriers. Sedimentary processes (channel-fill deposits etc.), post-depositional compaction (diagenesis etc.), and tectonics (faults and fractures etc.) are major causes of heterogeneities and compartmentalization. Pressure transient tests are first-order tools to determine the physical barriers to flow and heterogeneities located in a region around a well or in the larger drainage area of a well; they inform the design engineer about the extent of a reservoir in space in which fluid is able to flow (Earlougher Jr., 1977). Furthermore, pressure transient tests can be used to calculate the actual volume of a reservoir which will be capable of receiving injected waste fluids.

2.5 Cap Rock

A successful design of a slurry fracture injection operation requires that there should not be any significant vertical fluid migration from the target reservoir. This eliminates all chances for injected fluids to reach a drinking water aquifer, the ground surface, or the sea floor (for off-shore locations). A fluid displacement process through a porous medium is governed by the breakthrough pressure of the porous medium, and the pressure of the fluid under consideration (Kueper and Frind, 1988).

2.5.1 Fluid Flow Issues

Flow through any granular geological material occurs through the connected pore spaces. As described earlier, discharge through a circular opening in a porous medium is directly proportional to the fourth power of the pore radius ($Q \alpha r^4$). All other factors being the same, flow through a pore with a radius of 1 mm (1000 μm) (undoubtedly found only in a very coarse-grained sand or a gravel) would be $(1000)^4$ $\{1 \text{ x } 10^{12}\}$ times greater than flow through a pore with a radius of 1 μm (probably clay) under the same pressure gradient. Therefore, to arrest the injected liquid in a particular zone, and to eliminate the vertical propagation of the fluid phase, it is important to have a fine-grained rock unit (shale, clay or siltstone of moderate permeability) overlying the target injection stratum to prevent any fluid breach.

The mineral composition of a cap rock is also important. Smectite is a highly swelling, extremely fine-grained mineral, usually in ductile shales; high contents of smectite in a shale cap rock can greatly reduce the ability of fluid flow through it. Therefore, smectite-bearing cap rock can provide greater security to an injection zone than other rock types by keeping the injectate at desired depth. Even sandstone with a few percent of mobile smectite can have a low enough permeability to act as a cap rock because the clay particles block the pore throats.

When a fluid flowing through a porous medium encounters a fine-grained (low permeability) rock unit vertically or laterally, it slows down, and perhaps can not continue to flow unless enough pressure is available to continue to achieve liquid displacement in the fine-grained rock unit. When a low permeability zone is encountered vertically, lateral spreading of the fluid flow front occurs and continues, unless a permeable rock unit is encountered vertically, or until the migrating fluid is dissipated by lateral spreading. Hence, it is important for a cap rock to have wide areal distribution along with a great thickness to prevent vertical fluid movement. The time a fluid takes to reach across a certain rock unit depends upon the hydraulic conductivity and the thickness of the rock unit; hence, a thick cap-rock unit can increase the travel time tremendously.

Boisson *et al.* (2001) and Bradley *et al.* (2001) studied argillaceous rocks (clay, shale etc.) to investigate their fluid flow properties, and concluded that argillaceous rocks behave as semi-permeable membranes, and flow through them can take place as osmotic or diffusive flow, but that diffusive flow is extremely slow. Bradley *et al.* (2001) used undisturbed Cretaceous clay samples from southern Saskatchewan, Canada, and calculated that hydraulic conductivity values range from $(10.7 \pm 7.3) \times 10^{-12}$ m/s to $(3.9 \pm 2.8) \times 10^{-12}$ m/s (on average, one meter in >5000 years) with exceptional values of $(16.5 \pm 1.5) \times 10^{-12}$ m/s; the exceptional high value might represent differences in clay mineralogy or clay fabric. The following two paragraphs describe a summary of the work done by Boisson *et al.* (2001).

The Tournemire tunnel, Aveyron, France was selected to study fluid flow through a Jurassic argillaceous formation (250 m thick) for a nuclear waste disposal program. Both in-situ and laboratory tests were performed to investigate various conditions of fluids flow; for this purpose a number of marl and argillite samples were collected. Numerous laboratory tests were performed to calculate hydraulic conductivity using different test methods (e.g. pulse decay and non-steady-state pulse test) and under different stress conditions, including triaxial stress conditions. The entire tests gave similar values for hydraulic conductivity i.e. in a range of 10^{-14} to 10^{-13} m/s (average 8×10^{-14} m/s: one meter in >390,000 years). This quite low hydraulic conductivity, from different types of laboratory tests, leads to the conclusion that fluid flow is governed by a diffusion process in argillaceous rocks.

In-situ hydraulic conductivity was calculated using suitable tests for very low values of conductivity, for example using a non-steady-state pulse test. Values obtained from the in-situ tests ranged from 6.7×10^{-14} to 5.0×10^{-12} m/s, whereas the average value of the entire clay zone was 1.4×10^{-14} m/s. To understand the effect of faults and joints on argillaceous rocks, cores were analyzed in a laboratory. It was found that fractures were filled with different materials, mainly calcite, but appeared perfectly sealed and impervious. The average value of hydraulic conductivity for the entire clay zone also showed hydraulic conductivity does not change significantly by presence of some fractures.

If a fluid spends a long time in a thick cap-rock (usually shale), on the order of hundreds of thousands of years, it is likely that the sorption processes will take away any contaminant present in the fluid (dissolved salts such as NaCl or $CaCl_2$ are not contaminants in the sense discussed here), and the resultant fluid will be cleaned and will never become a source of any environmental threat. In fact, osmotic effects means that hydrated ions and cations are severely retarded during flow through the semi-permeable clayey shale, so that dissolved salts can lag considerably behind bulk flow. Therefore, a thick and wide-spread unit of shale, mudstone, salt/evaporite, or even a clayey siltstone or sandstone of permeability less than 10 mD can act as a cap rock because these strata possess high required displacement pressure, low hydraulic conductivity, and small pore openings for flow.

Thickness of a cap rock is an important issue, but most particularly in the case of a shallow solids injection target zone. For example, if the injection depth is only 250 m and potable groundwater extends to a depth of 150 m, the possibility of interaction is far greater than if the injection zone is 1500 m deep and the potable groundwater is 300 m deep. Thus, as the depth of a target reservoir becomes quite high, the issue of the thickness of a cap rock layer does not remain important due to the following reasons:

- A deep injection zone usually has many layers of overlying impermeable rocks which make it almost impossible for any upward leak-off of injected fluids;
- Between the deep injection zone and the shallow groundwater, because of porosity,

there is an immense storage capacity that will tend to attenuate concentrations and retard diffusion,

- At great depth rocks behave plastically; therefore, zones of discontinuities (fractures etc.) generally do not exist in shale rocks or become sealed; and,
- Porosity reduces under high stresses so that at depth, due to great thickness of overburden rock column, stresses are quite high and the reduced porosity results in a lowered permeability in the cap rocks.

In the case of a shallow target reservoir (< 1000 m deep), minimum thickness of a cap rock should be three to four times the thickness of a reservoir, for example a 40 m thick cap rock should overlie a 10 m thick reservoir.

Methane gas will be generated through biodegradation processes acting on injected biosolids in the target cohesionless sandstone reservoir. The methane gas will evidence a tendency to migrate upwards in the porous and permeable reservoir due to gravitational segregation because of the density difference between gas and water. A shale cap rock can serve as a barrier to upwards migration of methane, helping to trap the gas and form an economic reserve (Figure 4), and allow it to be recovered. Un-fractured shale is totally impermeable to gas because the fine-grained pores have an extremely high capillary entry pressure for gas.

2.5.2 Geomechanical Issues

According to Bruno (1999), the pressure and stress gradients required for a fluid to migrate towards shallower depths can not be sustained in the target reservoir formation after the injection phase. The geomechanics involved with fracturing into weak, unconsolidated, and permeable formation serves to effectively dissipate pressures and stresses generated during injection; therefore, it is highly unlikely that the fluid would develop enough pressure to breach the cap-rock by fracturing.

A thick cap-rock layer can also act as a stress barrier to counteract vertical propagation of a hydraulic fracture because the shale may have a high stiffness compared to the cohesionless sandstone, and this stress resists fracture penetration into the shale. A fracture climbing through cohesionless sandstone, when it reaches the sand-shale interface, is blunted because as the fracture tends to open the high stiffness of shale it tends to keep the aperture small (Figure 2.7). The sand-shale interface, however, provides a plane of weakness; therefore, as a vertically growing fracture reaches a plane of weakness, it tends to flatten, and may continue its growth along the sand-shale interface (Figure 2.8); therefore, the fracture begins propagation laterally in the horizontal direction, particularly in favourable stress conditions (e.g. when the stresses are all about the same value or if $\sigma_v = \sigma_3$).

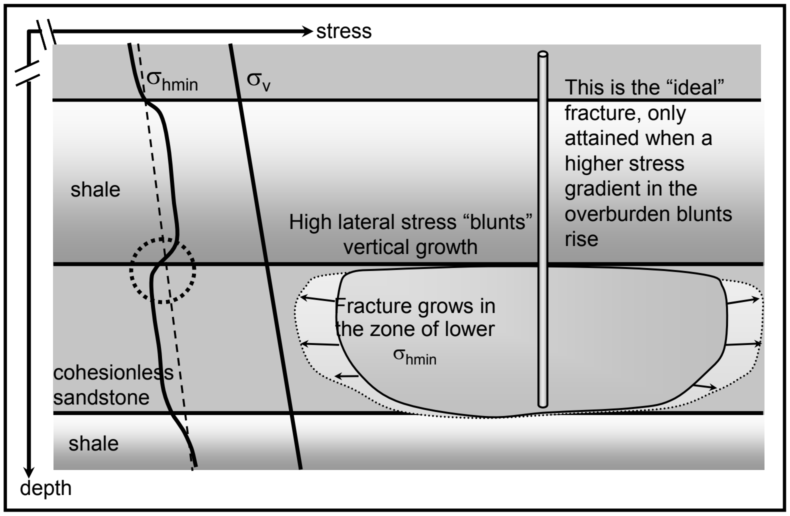


Figure 2.7: Stress barrier (shale) keeps the fracture in sandstone (Modified from Singh and Dusseault, 2003)

2.6 Geographical Distance from Waste Source

The term geographical distance means the distance between a surface disposal facility/site and a waste source or waste collection/generation site. The location of the surface disposal facility is not a fixed place but can vary, and it depends upon many factors both non-technical and technical. Non-technical factors may arise, and this includes public opinion (not-in-my-backyard or no trucks on our road); whereas technical aspects include suitable subsurface geology, hydrogeology, cost, and so on. The disposal facility could be quite near to the waste collection/generation site, on-site (tens to hundreds of meters), or far away from it, off-site.

An example was previously given of the importance of risk assessment for transportation depending on risk of accidents, type of road, and so on. Quantitative risk factors for the probability of accidents can be obtained from insurance companies, and this can help decide some siting issues. For example, it may be decided that an adjacent site is preferred to a distant site, even if the adjacent site is not as geologically and geomechanically suitable.

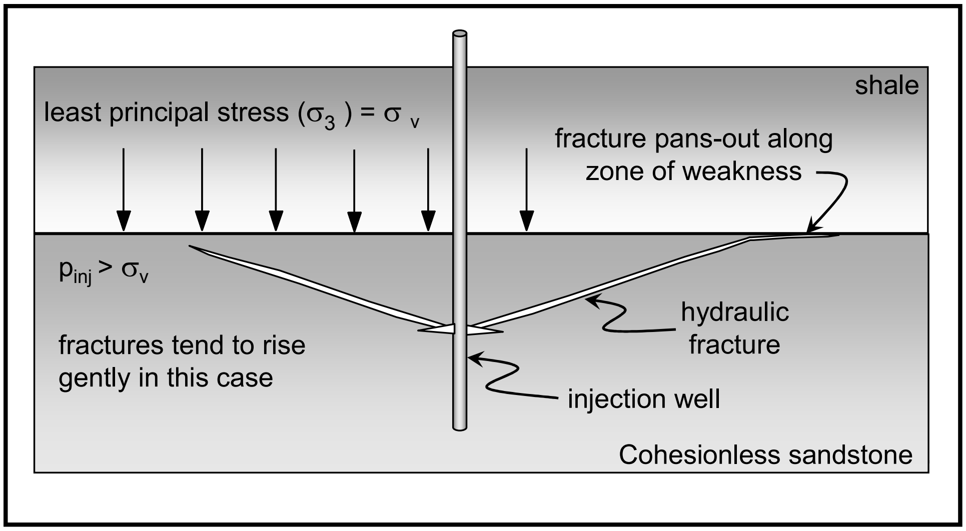


Figure 2.8: Vertically growing fracture tends flatten along sand-shale interface (Modified from Singh and Dusseault, 2003)

2.6.1 Non-Technical Issues

Public awareness is increasing significantly regarding environmental issues. People living in the surroundings of a waste disposal site have fear of potential harmful impacts, which can affect their daily life and also can be possible threats in the future. These potential impacts can be divided into following categories: environmental, social, and economical.

Air and water (both surface and ground water) quality are the key issues of environmental concern, and any change in their quality is not acceptable to the residents of an area, for example odour in air and water, suspended particles/dust in air, change in water colour, and so on. Public health and safety are the major social issues related with waste disposal, and usually caused by the inferior quality air and/or water; other social issues are noise, dust, odour, litter, and volume of truck traffic.

- Noise can be caused by the truck traffic involved in transport of waste to a disposal site and also by the machinery or equipment involved at the site.
- High truck traffic could cause traffic problems and also air pollution due to burning of fossil fuel in their engines, and there is always an increased risk of spills or accidents as the distances travelled go up.
- Odour and littering are also severe social problems that can be caused as a result of a waste disposal operation.
- Potential economic impacts could be related to changes in property values. In view of the previously described issues, new property buyers could avoid purchasing any property in a region around a waste disposal site.

All of the problems described in previous paragraphs are issues related with traditionally practiced methods of municipal waste disposal, for example landfills and sewage treatment sites, sludge spreading in fields, etc. As deep injection can provides environmentally secure disposal, most of the potential impacts will be lessened or will never be encountered during a deep injection operation (e.g. air and surface water pollution, odour, dust generation, and so on.

In spite of this, and because of the activity required for deep injection, for the sake of public opinion and to aid people to recognize the importance of a new method that promises to be more environmentally benign overall, educational activity is necessary to inform all stakeholders in the process. Typically, the following actions can be taken: presentations about deep slurry injection technology, open-house discussion, web sites, site tours and visits for the public, careful and visible monitoring and safety practices, and so on. Local media (electronic and print) can also be a great help to educate the public, therefore a clear and transparent process of engineering and operations must be used and general access made available to media personnel.

2.6.2 Technical Issues

The issues related to suitable subsurface sites have been discussed in detail elsewhere in this document. Assuming that a suitable sub-surface target geological formation is available, an on-site waste disposal operation is likely to be cost effective in comparison to other technologies, but cost-benefit analyses are beyond the scope of this thesis. In the case of on-site waste disposal operation, the solid waste can easily be handled, transported, sized, slurried and injected. For a more distant facility, a pipeline network can carry the slurried waste using slurry pumps towards a disposal well over large distances if necessary (50-100 km pipelines for slurried municipal biosolids after primary treatment is entirely reasonable). Nevertheless, it is to be noted that an on-site waste handling case also will be more environmentally secure as compared to a distant site, even though a pipeline network will provide some environmental advantages as there will be reduced chance of spill, odour, dust, litter, and so on.

It is not always possible to find suitable subsurface geological conditions for waste injection near large urban metropolitan centres; for example the City of New York is located on hard rocks, which are not suitable for injection jobs. Under such a situation the only option left is to seek the nearest suitable subsurface geology. In the case of an off-site disposal facility, transportation of waste will be a critical issue and will increase the operational cost of the disposal project. Possible options for waste transportation can be trucking or a pipeline system. There are risks involved with handling, transferring, and shipping of large waste material by trucking (Bruno, 1999). Long distance truck transportation will consume large amounts of fuel, and the burning of the fuel will generate harmful gases to pollute air, even if the waste handling and transportation can be made environmentally secure by using properly licensed, trained, and approved trucking contractors (Bruno, 1999).

Perhaps, if the economics warrant it, a slurry pipeline system could be implemented for off-site locations, and this would permit the preparation of the optimum mix to be injected before it is transported. Waste slurry can be prepared at a waste collection/generation site and then can be transported on the way to a disposal well using a pipeline network. This would reduce spill risk and provide some environmental advantages over trucking as mentioned earlier.

Regardless of the mode of waste transportation, an off-site surface disposal facility would increase the overall cost of the injection operation. Therefore, the best location for a surface disposal facility would be on-site or near-site if suitable subsurface geology is present.

Geographical distance is an important issue for biosolids injection operation, but in case of drilling and production related waste from the oil industry it does not remain an important factor. Depleted oil fields generally contain good subsurface geology suitable to act as a target for deep waste injection operations; also public opinion is not as serious an issue in the case of oil industry waste, at least in typical remote areas away from population centres.

2.7 Reservoir Strength

A reservoir for solid waste injection can be defined as a subsurface body of sedimentary rocks having sufficient porosity and permeability to store solid and liquid material and transmit fluids. Naturally, rocks have different kinds of flaws present in them, for example joints, pores, fractures, bedding planes, and so on; these flaws provide points of least resistance against breaking, and help to create a large plane of discontinuity, a fracture, in a target rock; therefore, flaws make a rock weaker in terms of strength.

An ideal reservoir rock for solids injection should be weak in tensile strength; it is then easier to induce a fracture in a weak sedimentary rock under low applied stresses. A weak material, for example an unconsolidated or poorly consolidated sandstone, offers less resistance against breaking; also a weak porous and permeable rock limits the fracture’s length due to rapid pressure decline (high k), and this helps contain the injected solid waste nearer to the injection well.

Hydraulic fracturing of hard and stiff materials, for example quartzite and granite, would require high amount of applied stresses; also, such materials would be unable to provide sufficient storage capacity and rapid pressure decline due to their low values of porosity and permeability.

2.8 Reservoir Compressibility

Compressibility of a porous medium is defined as the change in volume of a rock due to a unit change in applied effective stress. Production and injection operations in a reservoir modify the reservoir stresses and cause volumetric change in the pore space in a reservoir. It already has been mentioned in this document elsewhere that compression in a porous medium can take place under high stress by many different ways, for example rearrangement of mineral grains, pore space collapse, grain crushing, and so on.

During the slurry injection phase, pore pressure increases take place around the wellbore region in a reservoir as a result of liquid and solid injection. Increase in pore pressure increases total stresses in a local region around the induced hydraulic fracture because of volumetric expansion, but decreases the effective stresses in the region. This phenomenon of low effective stress and high pore pressure leads to a small expansion in the reservoir rock. Injection of a cold slurry in a reservoir produces thermoelastic shrinkage which also reduces the stresses near the injector; as a result of this phenomenon fracture aperture increases slightly and a small volume is gained as a result of decrease in the reservoir temperature ($-\Delta T$

→ +ΔV). Once injection ceases and leak-off occurs, however, the horizontal effective stresses in particular may have been substantially increased to compress the reservoir rock.

Highly compressible geological material (high porosity rock) will be the best target reservoir for slurry fracture injection; it will help to produce wide fractures, and also will be more capable of accommodating large volumes of waste nearer to the wellbore region.

2.9 Structure and Tectonics

Leakage from the target disposal zone and the surrounding reservoir of injectate is the most critical issue related to deep waste injection operations (it is assumed that the solids are immobilized in the porous medium). Natural faults, fractures, and steeply dipping formations could provide easy flow channels for the fluids to migrate towards the ground surface and interact with any drinking water aquifers present. Potentially, seismic activity could accelerate this process if the deformations are appropriate.

Considering the tectonic setting of a sedimentary basin, possibilities of natural seismicity can be assessed on a broader scale, as for example, basins within active mountain belts, related with salt tectonics, or volcanism can be termed as tectonically complex, whereas examples of tectonically simple basins could be passive continental margin basins (shelf basins), foreland basins, and so on. On the basis of structure and tectonics, an area can be categorized as simple or complex.

An area will be complex if it contains a high density of structural discontinuities, for example fractures, joints, and faults, and or highly tilted (folded and faulted) sedimentary strata. A network of structural discontinuities can provide a conduit for vertical fluid flow towards the biosphere; therefore, injected fluids can use the conduit to escape out of a confined zone. Highly tilted sedimentary strata usually have outcrops on a ground surface, and therefore may provide a passage for fluids to travel through and reach the ground surface. An area will be simple if it is devoid of structural discontinuities and contains an almost flat-lying sedimentary stratum or gently folded stratigraphic unit, preferably bounded by impermeable stratas. A simple area will help to keep the injected liquid at the injected depth for long period of geological time due to the lack of vertical communication.

Detailed study of the local discontinuities (faults, fractures, and so on), inclination of sedimentary strata/folding at the injection site, and regional study of the tectonic framework are necessary to develop a better idea about the disturbance distribution at a proposed injection site and around it (within the greater zone of influence, not simply at the scale of the well). An area can be categorized as complex, intermediate, or simple on the basis of structural and tectonic studies. An ideal site for a deep waste injection project should be tectonically and structurally simple and passive, and have a relatively simple structural fabric.

Nevertheless, tectonic complexity does not automatically disqualify a site. There may be limitations on slurry volumes to be injected, injection rates to be used, or types of materials to be disposed. For example, in a steeply dipping area with some risk of surface outflow of water, the waste materials to be injected may be limited to non-biological and non-hazardous wastes.

2.10 Rank Allocation

Table 2.1 contains a quantitative description of some important parameters including permeability and porosity of reservoir rock, depth of target stratum, areal extent of reservoir rock, thickness of reservoir and cap rock, and geographical distance between prospective injection sites and source of waste storage or generation, as applicable. Porosity, thickness, and lateral extent of reservoir rock determine the storage capacity of a formation; therefore, this factor has not been included separately in Table 2.1.

Table 2.1 uses a "ranking category" developed in view of evolving a quantitative rating scheme for sites in order to numerically "capture" or rank their suitability for massive slurried waste injection. The upper and lower limits or the range of the each ranking category for every parameter has been selected after discussion with slurry injection experts and reviewing published and unpublished literature for sites which have a successful record of slurry injection (and also those which have not qualified as suitable for the injection operation). At the present time, these values must be considered to be tentative, and furthermore, they have not been "weighted" against each other. For example, a specific factor such as permeability may have a greater impact on ranking than rock strength (or stiffness, etc.), therefore individual parameter weighting factors will have to be developed, based on experience and data, and applied to any overall ranking scheme. This issue is taken up again in Chapter 3.

This table in some cases presents an overly simplistic view that must be clarified and expanded with additional data. For example, in the risks associated with transportation of waste slurry to the disposal site, the following ancillary questions arise:

- Is slurry pipeline transport a viable alternative?
- Is transportation on high traffic or low traffic roads?

- Are roads rural high-speed roads or urban low-speed roads?
- What are the consequences of a spill during transportation?

Clearly, any of these factors will affect the relative importance of the transportation factor in site choice. For example, 20 km transportation of toxic waste in an urban area at high and low speeds carries a great deal of risk, whereas 5 km transportation of “benign” wastes on rural roads represents an extremely low risk.

Table 2.1: Rank allocation and important parameters for deep slurry injection

Factors	**Range**	**Rank**
Permeability (k) (Note that k_h dominates leak-off and k_v dominates gravitational segregation. Note also that too high permeability is a negative factor for initiation of hydraulic fractures)	<10 mD	0
	10 – 100 mD	1
	100 – 500 mD	2
	500 – 1000 mD	3
	1000 – 2000 mD	4
	2000 – 5000 mD	**5**
	5000 – 10,000 mD	3
	> 10,000 mD	0
Porosity **(ϕ)**	0 – 5%	1
	5 – 10%	2
	10 – 20%	3
	20 – 30%	4
	> 30%	**5**
Reservoir Depth (Note that 200 m is arbitrarily selected as the minimum depth, but there are variations in potable groundwater depth and in the risk associated with different injectates)	< 200 m	0
	200 – 300 m	4
	300 – 700 m	**5**
	700 – 1500 m	4
	1500 – 2000 m	3
	2000 – 3000 m	2
	> 3000 m	0
Reservoir Thickness	< 1 m	0
	1 – 2 m	1
	2 – 4 m	2
	4 – 8 m	3
	8 – 20 m	4
	> 20 m	**5**

(PTO)

Table 2.1 (Cont'd)

Factors	**Range**	**Rank**
Geographical Distance from Waste Source (Risk in Transport, rural transport, low toxicity wastes)	>100 km	0
	50-100 km	1
	25-50 km	2
	10-25 km	3
	1-10 km	4
	< 1 km	**5**
Alternating Sequence of Shale – Sandstone (capacity for arresting vertical fracture migration tendencies, t = bed thickness)	One sandstone bed only	0
	One or two overlying sandstone layers > 1m each in thickness, k > 500 mD, t×k > 1 D·m	3
	More than two overlying permeable sandstones, t×k > 5 D·m	**5**
Reservoir Strength **(**tensile strength**)**	Strong	1
	Intermediate	3
	Weak	**5**
Reservoir Compressibility	Low compressibility	1
	Intermediate compressibility	3
	High compressibility	**5**
Structural/Tectonic Setup	Complex	1
	Intermediate	4
	Simple	**5**

Chapter 3: Geological Assessment Model

3.1 Introduction

On the basis of an in-depth assessment of the parameters (Table 2.1) involved in a site selection procedure, the relative significance of each parameter has been evaluated based on its quality and importance. Inter-relationships among different parameters are important factors and are assumed to be relatively well-understood. Using this information, an attempt has been made to create a geological model which can be used for assessment of a prospective disposal site for deep solid waste injection operations. This model consists of two segments; the first segment of the model is composed of a decision tree, whereas the second segment comprises the extraction of a semi-quantitative numerical relationship expressing the quality of the site.

The first segment is composed of the decision tree which deals with the most critical parameters, those that will render a site unsuitable, or suitable but of unspecified quality. These parameters have certain defined limits chosen on the basis of geological and geomechanical considerations, and any site which can not comply with these limits will be discarded completely in a comprehensive site search process. The second segment of the process is involved with calculations which engage the rank and weighting factor of each parameter to obtain a total "score" for a prospective injection site as an indication of quality relative to other sites that passed the decision tress process.

The system delineated here is not foolproof. Cases may arise where a site that does not pass the decision tree screening process will, for other reasons, be chosen. For example, in a case where the depth of the site is close to the minimum depth recommended, and all other parameters are excellent, providing a high degree of security against groundwater contamination, an engineering decision may be made to proceed with the ranking and evaluation process. Similarly, in some regions of the world, potable groundwater is found at considerable depths, therefore a site that passes the minimum depth used herein may be rejected nonetheless. In other words, the numerical limiting values used in this process must be re-assessed in some specific cases; only engineering judgement can be used in these cases, and then new limits must be set on the basis of available data.

3.2 Decision Tree

A decision tree is a graphical representation of the decision process i.e. a postulate of a sequence of events and the possible outcomes of each event. It resembles the structure of a tree, and is considered to be a fundamental analytical tool for decision analysis. A decision tree exposes the logic sequence of a problem solving procedure, and consists of questions and possible responses in the form of branches; these branches extend all the way to the final outcome, highlighting alternative actions that help to lead towards a suitable solution for a defined problem.

3.2.1 Overview

A decision tree represents the formalization of a model which has ability to predict an outcome, choose an optimum path, or classify a given case (Brand, 1998). A decision tree takes an object or a situation representing a set of properties as input, whereas the output decision comes out as GOOD/YES or BAD/NO, representing a Boolean function (AAAI, 2004) or a numerical value. A model created by a decision tree has both predictive and descriptive properties; therefore, it is easy to understand and assimilate a decision tree, particularly because it is amendable to clear visual presentation (Brand, 1998).

Several factors are involved making a decision in the presence of risk and uncertainty. A decision tree is a tool which identifies all the important factors to consider and also relates each factor with different outcomes of the decision. The numbers of levels are not predetermined for a decision tree, but the tree becomes generally more complex (in terms of its depth and breadth) as the number of independent variables increase. The relationship found in data is displayed graphically in decision trees, but the product of a decision tree can be translated into a numerical value or text (tree-to-text rule), for example If $x = a$, and $y > b$ Then z = Yes/Good. This is similar to rule induction algorithms that produce rule sets without a decision tree (AAAI, 2004).

Decision trees are used for two purposes i.e. classification (predicting what group a case belongs to) and regression (predicting a specific value) (Brand, 1998). A classification type decision tree is quite useful for categorization or prediction of outcomes from a data set. A goal of classification tree design is to generate clear rule sets so that the decision process can be easily understood and explained; therefore, classification trees label the information and divide the objects into discrete classes (RSI, 2004).

A classification type decision tree seems suitable for the present problem of site selection for deep slurry waste injection, but it is less suitable for rank-ordering of sites on the basis of quality. The latter task is addressed elsewhere.

Binary recursive partitioning is a process used to build a classification tree; this interactive process splits the data into partitions, this splitting or partitioning is then applied to each of the braches of a tree (RSI, 2004). The splitting process continues until further splits cannot be found. Classification trees are not usually used in the fields of probability and statistics, but are widely used in diverse applied fields such as medicine (diagnosis), computer science (data structures), psychology (decision theory), and botany (classification) (SI, 2004).

3.2.2 Morphology and Anatomy

A decision tree is not drawn on a scale, thus lengths of lines or tree branches have no quantitative significance; similarly, the magnitude of the angles between the lines or branches are meaningless; to sum up, the specific geometry of the skeleton of a decision tree is not important. Decision trees are typically drawn from left to right or top to bottom and also are read in the same order because the actual sequence, decision choices, and chance events occur in the same order as the branch points on the decision structure.

A decision or chance node is a point from which emanate two or more branches and represents a decision or chance. A decision node is surrounded by a square shape and represents a point at which the decision-maker chooses which branch should be followed (and consequently which branches should be rejected). However, a chance node is surrounded by a circle and represents a point where chance (or the calculation of a probability) determines the outcome (Moore and Thomas, 1976; Newendorp, 1975) (Figure 3.1). Any number of lines can emanate from a node because the numbers of decision alternatives or outcomes are not fixed for a problem.

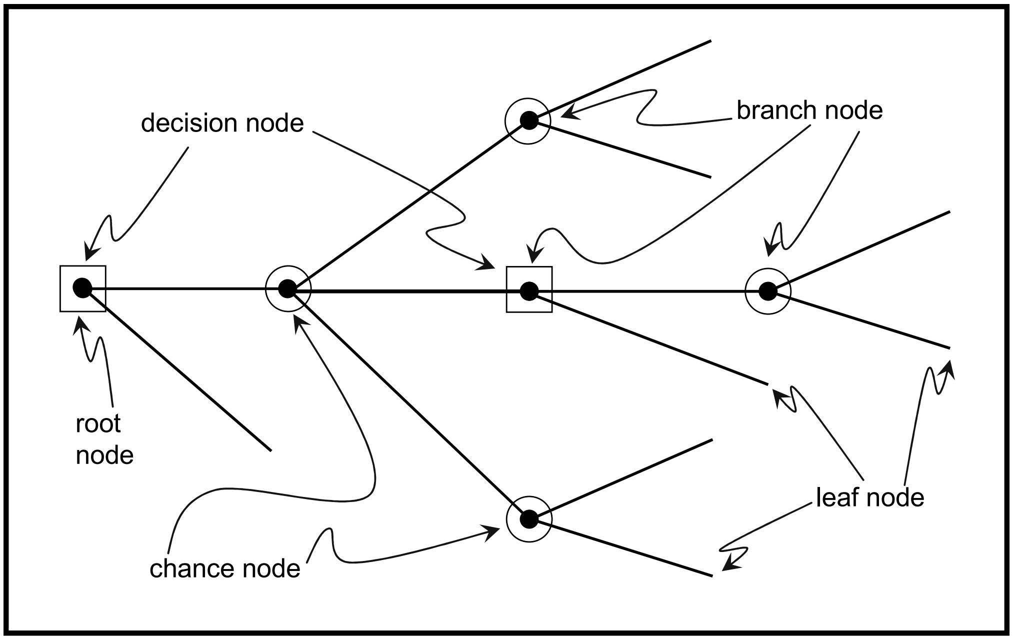


Figure 3.1: General anatomy of a decision tree

Nodes are also classified into root node, decision nodes, chance nodes, branch nodes, and leaf nodes (Figure 3.1). Decision trees begin from a point called the root node and lead towards some leaf nodes through a series of branch nodes. Each non-leaf node emanates two or more branches and is connected to another node through branches that carry an attribute, a particular value, condition, or relationship; in this way each node is associated with a set of possible answers (Hamilton, 2002). No new branch emanates from leaf nodes; therefore, they represent the closing points of a decision tree and are terminal. The leaves of a decision tree, for example, constitute the final classification scheme for the case under investigation.

3.2.3 How to Read the Decision Tree

The decision tree made for deep slurry injection site selection is shown in Figure 3.2. This decision tree belongs to the classification type tree and is capable to predict whether a prospective site is feasible for injection operations or not. The specific values on the tree branches will have to be modified in particular cases, such as for the injection of a particularly toxic material.

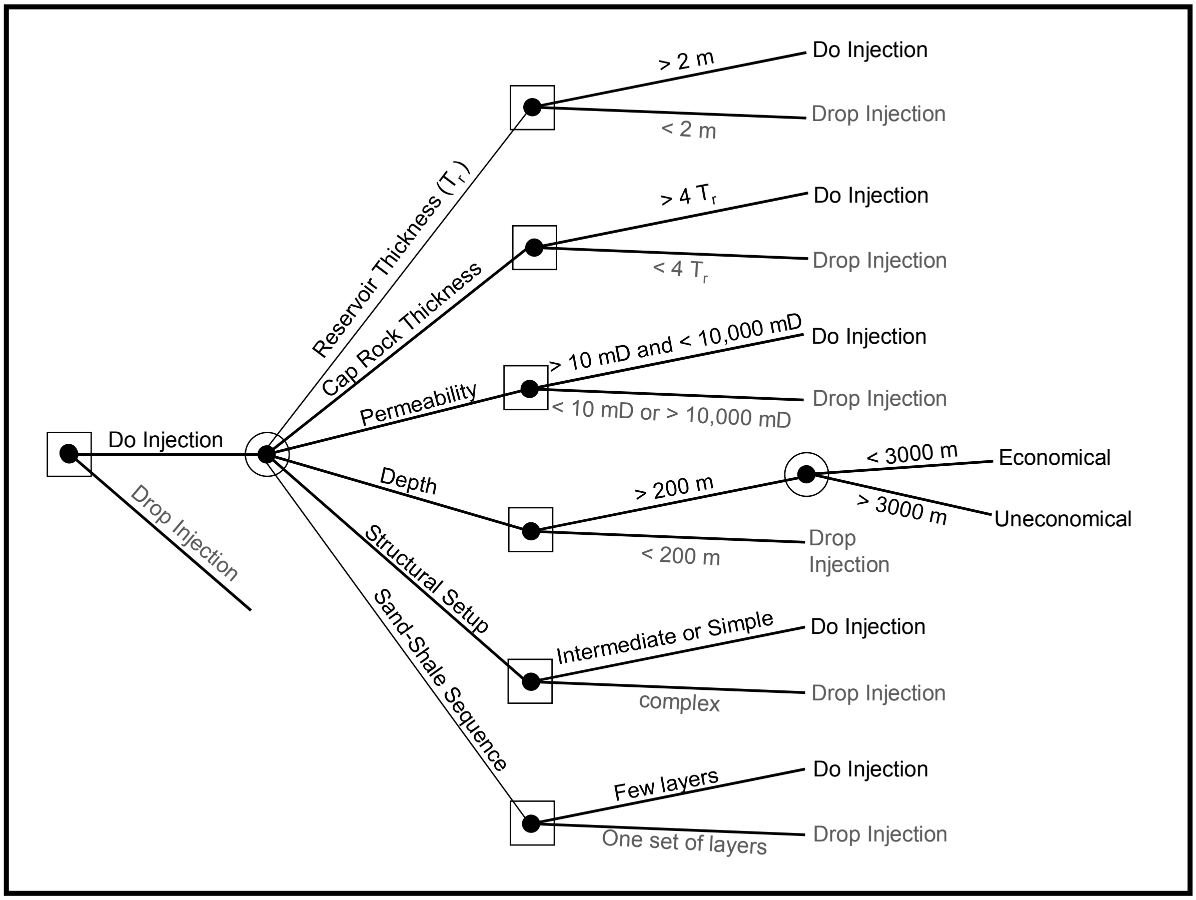


Figure 3.2: Decision tree showing most critical parameters and values limits

The tree is constructed from left to right; towards the left, the first node is a root node which emanates two branches of options i.e. go for or reject an injection operation. In the case of a positive choice, the “Do Branch” terminates at a chance node and emanates five further branches; each branch carries one parameter (Figure 3.2). These parameters are the most critical parameters because they govern the selection criteria and the decision of rejection or acceptance for a prospective site. These parameters are defined in terms of specific limits or values which govern the assessment of the site. For example, permeability is the most important parameter recognized for a suitable injection site, but any value of permeability that is less than 10 mD or more than 10,000 mD disqualifies a prospective disposal site for injection operations, regardless if all of the other parameters are ideal in conditions; therefore, these values of permeability are critical limits. This information can be read from the decision tree as follows:

If permeability = <10 mD or > 10,000 mD, Then injection site = BAD or No Injection, but

If permeability = >10 mD and < 10,000 mD, Then injection site = GOOD or Do Injection

Similarly,

If structural setup = complex, Then injection site = BAD, but

If structural setup = intermediate or simple, Then injection site = GOOD

In case of some parameters, for example depth, first chance node leads to a decision node with two options i.e. Do or Do Not. The Do branch ends up in two leafs that provide some economical constrains. This information can be read as follows:

If depth = < 200 m, Then injection site = BAD, but

If depth = > 200 m but < 3000 m, Then injection site = Economical, and

If depth = >3000 m Then injection site = Uneconomical

A decision as to the economical or uneconomical possibilities is based approximately on present-day technology and cost, but this limit would change in future as a result of improved and economical technologies. Furthermore, in unusual cases, these limits can be changed.

For example, if an ideal reservoir with existing wells at a depth of 3300 m is available, it may be more economical to use existing wells rather than move elsewhere. Nevertheless, in general it is believed that 3000 m is a reasonable depth limit.

Any prospective site which could not pass the decision tree test and gets one BAD grade or No Injection attribute would usually be discarded completely even if all the other parameters will be ideal. Nevertheless, if there is only one failing grade on the decision tree test, the reason for that failure should be examined in the wider context of costs, the quality of the other factors, and so on, to see if the conditions can be relaxed. It is unlikely that a site having two or more failures could be reclassified, however.

On the other hand, any site which passes the decision tree test with all GOOD grades will go to the second segment of the geological model for further evaluation: the scoring criterion based on the ranks and weighting factors, which is explained in the next section.

It can be concluded that a prospective injection site must achieve 100% score in the first segment (decision tree) of the geological model, providing that the limits have been chosen properly, and that due consideration is given for an exceptional set of circumstances.

3.3 Numerical Evaluation

3.3.1 Introduction

Parameters such as permeability, depth, porosity, and so on are allocated a ranking number (P_1, P_2, P_3, …P_n) based on the value or the quality of the conditions with respect to solids injection. This ranking number is not a fixed value, but depends to some degree on the perception of the user, and a different scale may perhaps be used in different geological conditions. Nevertheless, it is a numerical value that can be used to arrive at an overall ranking of sites if used logically and consistently.

Another issue is the relative importance of the parameter. Clearly, some of the parameters have first-order importance, for example permeability, whereas some other parameters may be less or far less important. This leads to the concept of a weighting factor (α_1, α_2, α_3, ..α_n) to be applied to the numerical ranking of the parameters. Then, an overall numerical value in terms of total score (W) for a prospective injection site could be expressed in the form of a mathematical relationship

$$W = \alpha_1 \cdot P_1 + \alpha_2 \cdot P_2 + \alpha_3 \cdot P_3 + \ldots\ldots + \alpha_n \cdot P_n$$

3.3.2 Rank Numbers

Rank numbers are ordinal values (zero as minimum, five as maximum) developed to evolve a quantitative rating for deep slurry injection sites. Table 2.1 describes the rank allocation for different parameters in the form of discrete values; this Table has been used to draw the graphical relationship (Figures 3.3a-e) between the rank and each quantitative parameter using the average values from the Table. These graphs give a continuous relationship between a rank and a parameter, and also are used to find the appropriate rank against a given value of the quantitative parameter to use in the geological assessment model to evolve a quantitative rating for injection sites.

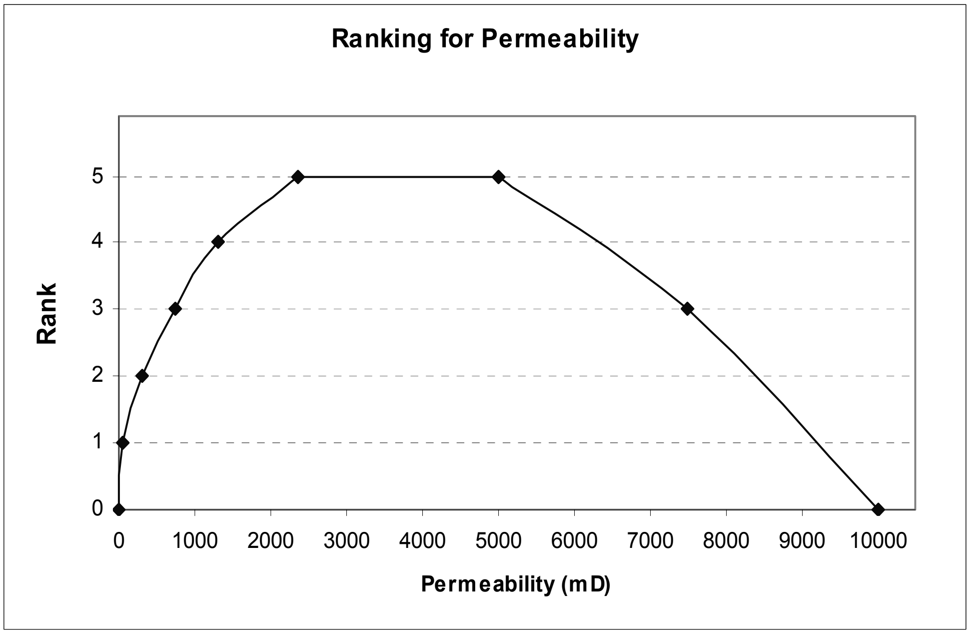


Figure 3.3a: Graph showing rank values for permeability

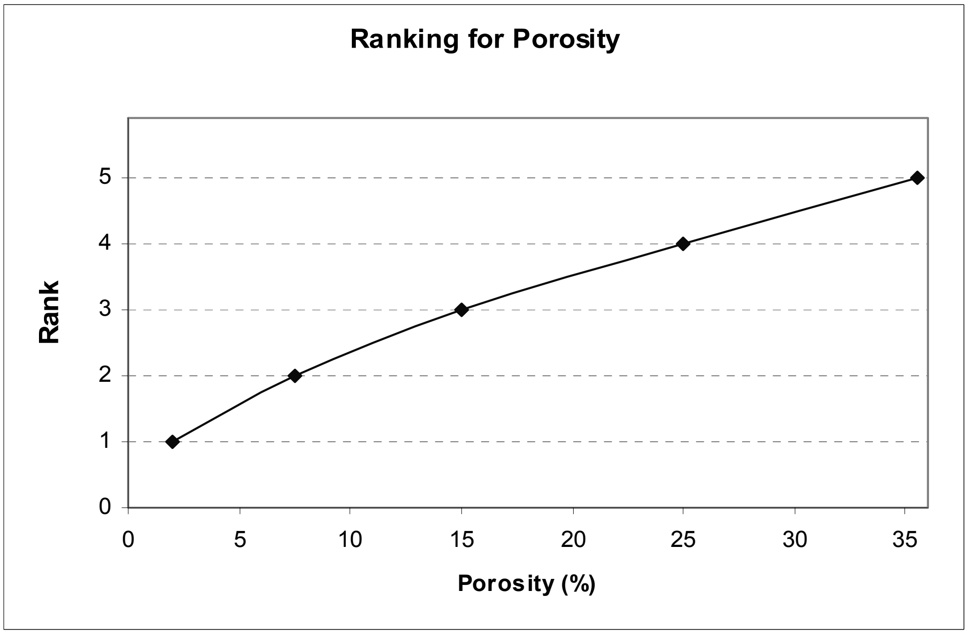


Figure 3.3b: Graph showing rank values for porosity

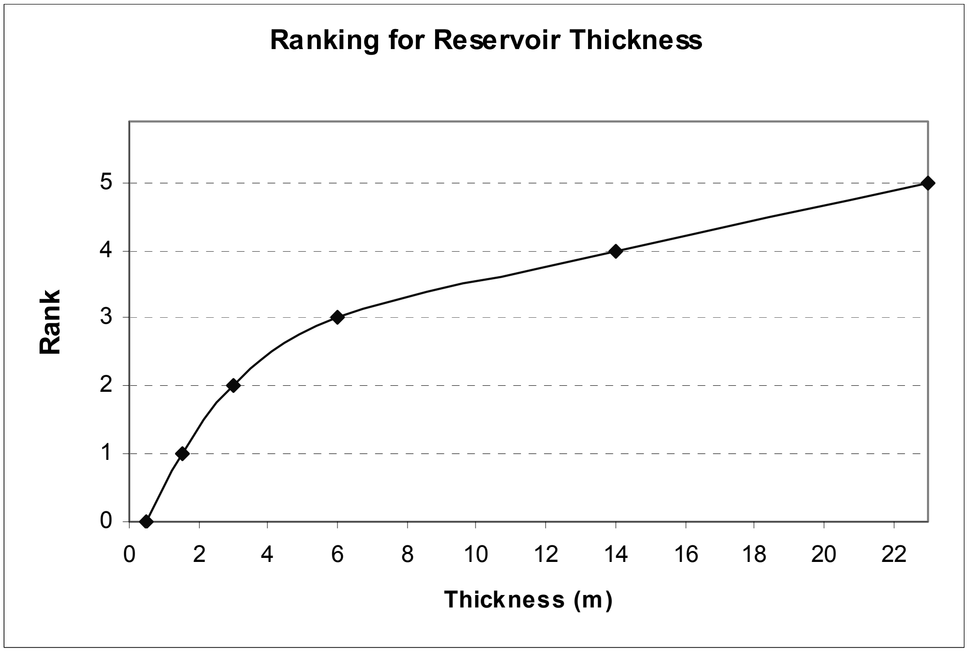


Figure 3.3c: Graph showing rank values for reservoir thickness

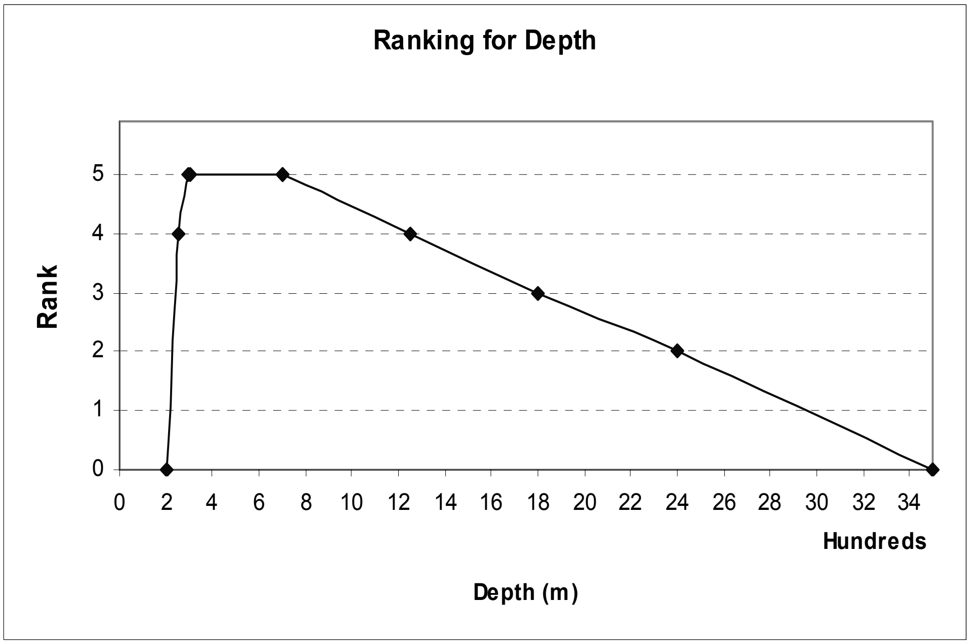


Figure 3.3d: Graph showing rank values for reservoir depth

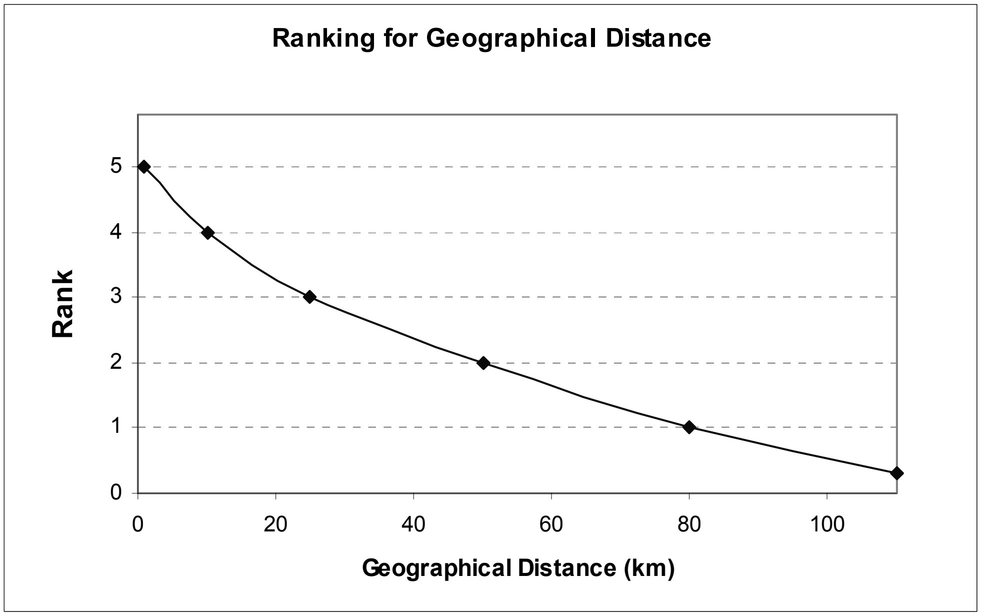


Figure 3.3e: Graph showing rank values for geographical distance

3.3.3 Weighting Factors

Assigning any weighting factor to each parameter requires establishment of criteria which could grade the parameters on the basis of their quality and importance in the form of a priority scale. Therefore, following is the list (Table 3.1) of parameters according to their priority, along with the assumptions and considerations made for each parameter for weighting factor assignment.

- Permeability: It is the most important parameter, as already has been discussed in this document elsewhere in detail; therefore, permeability must be on the top of the priority scale.

- Reservoir Thickness: The amount of the waste that can be disposed depends to a great degree upon the thickness of a reservoir rock; hence, this parameter is second on the priority scale.

- Tectonics: Tectonics or structural setup is a qualitative parameter for an injection site but is important regarding safety and containment of the waste in a particular zone. It is given a third position on the priority scale.

- Porosity: Other parameters, for example permeability, strength and compressibility of a reservoir, and storage capacity, depend on porosity. All these parameters also carry individual weighting factors, therefore porosity is given fourth position on the priority scale.

- Reservoir Depth: It has been discussed in this document elsewhere that great depth carries a number of technical advantages in terms of fluid flow and environmental security, but is a negative parameter due to economical reasons. Also, in the case of few available sites, it would be difficult to reject a site on the basis of high depth; therefore, its priority is fifth.

- Alternating Sand-Shale Sequence: Alternating sand-shale sequences provide extra mechanical barriers to keep hydraulic fractures in the desired zone; they also provide flow barriers for the fluids and increase environmental security. This parameter is at sixth on the priority scale.

- Reservoir Strength and Compressibility: Both of these parameters strongly depend upon the porosity of a reservoir rock; hence are at the bottom of the priority scale because they have to a considerable degree been incorporated in the porosity assessment.

- Geographical Distance from Waste Source: This parameter is also at the bottom of the priority scale, because in the case of only suitable off-site disposal location there would be no other option.

3.3.3.1 Weighting Factors Development Process

The following procedure is adopted to develop appropriate weighting factors (Table 3.1) for all the parameters involved in a process of site selection for solid waste injection operations:

- Numbers are assigned as a weighting factor for each parameter on the basis of intelligent (experienced) guesses and the priority of each parameter,
- The ranking numbers are generated for each parameter for different hypothetical sites; for this purpose numbers of possible combinations were considered ranging from excellent to worse case scenarios by consulting expert opinion and the published and unpublished literature,
- These weighting factors and ranking numbers are used to calculate the total score for each hypothetical site according to the described mathematical relationship, and
- This exercise is repeated for different sets of weighting factors while keeping all the other conditions and ranking values the same so that the optimum weighting factors could be revealed.

Several examples of hypothetical sites and their ranks are shown in Table 3.2; these ranks are used to determine the weighting factors for each of the parameters, based on the total score that each of the hypothetical sites secured and by comparison of all hypothetical sites with the reference sites. Reference sites include sites which have successful records of deep slurry injection and also those which have been considered as unsuitable for injection. These reference sites belong to different geographical locations and represent somewhat diverse geological conditions; about 15 sites are used as reference sites to develop the weighting factors. It should be emphasized that these sites are all shale-sand sequences, which has undoubtedly had some impact on the ranking and weighting of the factors. The final scale of the weighting factors learned from this process is shown in Table 3.1.

The weighting factor is a dynamic variable that could change from case to case. For example, in a case where all the target reservoirs are of excellent permeability in a certain area, then this parameter is no longer important to the choice of sites, and, surprisingly, it could even be allocated a weight of zero without affecting the ranking outcome! This would allow site choices to be affected only by the remaining parameters, for example reservoir thickness, depth, geographical distance from waste source, and so on. In this case the total score for a suitable site would be redefined: i.e., what range of numerical score will be required to categorize a prospective site into average, above average, or below average category. On the other hand, if a particular parameter for all the target reservoirs in a given area is of excellent quality, than this parameter can be given the maximum ranking number for the purpose of calculation. In this way there will be no need to redefine the range of final numerical scores, which categorize the favourability of a site.

Table 3.1 describes the interdependency of important parameters on each other, and also a priority and weighting factor scale on the basis of their importance in selection of deep slurry injection sites. The priority scale ranges from one to nine where one represents maximum priority.

Table 3.1: Priority and weighting factor scale of important parameters involved in deep slurry injection operation

Parameters	**Priority**	**Remarks**	**Weighting Factors**
Permeability	1	Depends upon porosity	7
Reservoir Thickness	2	Independent variable	4.5
Structural/Tectonic Setup	3	Independent variable	3.5
Porosity	4	Independent variable	3
Reservoir Depth	5	Independent variable	2
Alternating Sequence of Sand-Shale	6	Independent variable	2
Reservoir Strength	7	Depends upon porosity	1
Reservoir Compressibility	8	Depends upon porosity	1
Geographical Distance	9	Independent variable	1

Table 3.2: Few examples of hypothetical sites and their ranks (the data is split into two tables for each row because of too many columns)

Parameters	**WF**	**MR**	**Ranks for hypothetical sites**			
Permeability	7	5	2	2	5	4
Reservoir Thickness	4.5	5	5	4	3	4
Tectonic Setup	3.5	5	5	5	5	5
Porosity	3	5	3	3	5	4
Reservoir Depth	2	5	5	4	3	4
Alternating Sand-Shale Sequence	2	5	5	3	5	5
Reservoir Strength	1	5	3	3	5	5
Reservoir Compressibility	1	5	3	3	3	5
Geographical Distance	1	5	5	5	5	5
Total score		125	94	87	110	108
Category			average		above average	

Table 3.2 (Cont'd)

Ranks for hypothetical sites											
4	5	2	3	1	1	1	2	4	4	2	3
3	2	4	3	4	1	5	2	4	2	3	4
5	5	5	5	5	3	5	5	5	5	5	5
4	4	2	4	1	1	1	3	4	4	3	3
3	2	4	5	4	2	5	4	2	4	4	4
5	5	3	5	3	5	5	5	5	5	5	5
5	5	3	3	1	1	1	3	5	5	3	3
3	3	3	5	1	1	1	3	3	5	1	3
5	5	5	5	5	5	5	5	5	5	5	5
100	101	86	97	67	46	77	79	103	100	85	95
above average		average		below average				above average		average	

WF= Weighting Factor, MR= Maximum Rank

3.4 Conclusions

The geological assessment model is developed to help in selection of prospective sites for deep slurry injection operation; this model is composed of a decision tree based on parameter limits and a numerical relationship calculated from weighted parameter assessments.

First of all, the decision tree is applied to a prospective injection site and it is verified that the values of the most critical parameters for the site are in agreement with the limits defined in the tree. Any prospective site which can not pass the decision tree test would almost invariably be discarded for injection. A site which passes the decision tree segment will then be evaluated using the second segment of the assessment model.

The second segment of the assessment model, numerical evaluation, assigns a score to the site based on parameter ranks and weighting factors. The maximum score a model site can reach is 125 based on the identified nine parameters and their relative importance (Table 3.1). To generally categorize a prospective injection site on the basis of its favourability, three approximate categories have been defined i.e. average, below average, and above average. The score range of the average category is 85 to 99 out of 125; any score less than 85 represents the "below average" category; and, a score equal to or more than 100 represents the "above average" category. A site will be unsuitable for injection operation if it belongs to "below average" category: i.e. the total score is less than 85; whereas the best sites will be those whose total score will be equal to or more than 100 (above average category).

Some minor inconsistencies have been identified in the second segment of this model which can increase or decrease the total score of a site. The correction factor of ±3 is introduced to deal with this discrepancy; application of the correction factor can change the total score of a prospective injection site by utilizing existing site evaluation experience. For example a prospective injection site receives 83 or 84 points that make it unsuitable for injection but site evaluation experience shows that the injection site is favourable for operations, use of the correction factor will make the total score 86 or 87 that is suitable for injection; similarly if the site receives 86 or 87 points that make it suitable for injection but site evaluation experience shows that the site is unsuitable for injection, use of the correction factor will decrease the total score to move the site in no injection category. This correction factor is an attempt to capture the fact that there is always a degree of uncertainty in geological engineering assessments, and that the categories should not be viewed as being completely rigid in nature.

Finally, before proceeding, it is necessary to state clearly that the numerical parameter values in the decision tree and the factors and weights in the numerical assessment part of the model have been chosen by the writer to reflect the information available, combined with knowledge of "typical" conditions. These numbers could well be different in other areas. For example, the minimum depth of injection in an arid climate that has deep but fresh aquifers would be greater than in a moist climate with a thin potable water layer. Similarly, other parameters have to be specified in a rational manner in view of geological conditions.

Chapter 4: Evaluation of the Geological Model

4.1 General

In order to examine the validity of the geological assessment model it is required to apply this model on a number of areas of different geographical locations representing diverse geology. The following areas have been selected for this purpose: the Appalachian Basin, Illinois Basin, Texas Gulf Coast area, Michigan Basin, Alaskan North Slope, and Los Angeles Basin in United States; the Western Canada Sedimentary Basin and southwestern Ontario area in Canada; and the Duri Oilfield in Indonesia. These areas include the sites that already have a successful history of deep slurry injection operations and also include prospective target reservoirs for future injection.

The surface and subsurface geological data regarding the most critical parameters that are used as in-put in the assessment model are collected from public and private organizations, published and unpublished literature, and also from the studies conducted earlier by the author, based on publicly available records. The values for semi-quantitative or qualitative parameters are deduced from overall study of the subsurface geology and tectonics, whereas the values of those parameters which could not be found using publicly available data, for example reservoir strength, reservoir compressibility, and so on, are determined as intelligent estimates. Such estimates are based on the relationship of the unknown parameters with other known parameters; for example, compressibility depends upon the porosity, and so on. The rank numbers and the weighting factors are used to calculate the total score for an injection site according to the defined numerical relationship.

Initially, at the feasibility stage of a study, the quantitative parameters required for evaluation of an injection site are permeability, porosity, depth, and thickness of the target reservoir, and these can be collected using geophysical logs and drilling data; these techniques are quite reliable to calculate porosity, depth, and thickness of the reservoir, whereas permeability can be calculated more precisely using cores data. Information regarding the tectonic fabric and structural setting of an area can be obtained from geological reports and maps, combined with subsurface structural and stratigraphic cross-sections. The other parameters that are used as input in the assessment model can be estimated based on their relationship with the known parameters and intelligent (experienced) estimates.

4.2 Evaluation of Terminal Island, Los Angeles

The city of Los Angeles and Terralog Technologies Inc. (TTI) are working on an innovative technology for biosolids disposal and energy generation. The technology involves biosolids conversion into clean energy (CH_4 - methane) by thermal biodegradation at great depth. A slurry of partially treated biosolids and water will be injected into a suitable geological formation, above the fracturing pressure. Terminal Island Treatment Plant operated by Los Angeles city has been selected as injection site, where more than 1000 m deep sandstone litho-units will act as target reservoirs to receive the slurry.

Structural geological and sedimentary development of the Los Angeles Basin began in the late middle Miocene age as a result of the movement along the San Andreas fault system (TTI[1], 2001). The Los Angeles Basin is divided into four major structural blocks bounded by major active faults, and the Los Angeles City Terminal Island Treatment Plant is located within the southwestern structural block of the Los Angeles Basin, away from the active bounding faults.

A generalized stratigraphic column of the Los Angeles Basin is shown in Figure 4.1; the Tar, Ranger, and Upper Terminal Zones of the Repetto and Puente Formations have been selected by TTI experts as target reservoirs for biosolids injection. These target reservoirs are late Miocene to early Pliocene age rocks representing deltas, shallow marine sheet sands, and turbidite sequences. The target zones are composed of intercalated fine- to coarse-grained, poorly sorted sandstones and siltstones with interbedded shales and clays. Reservoir characteristics of all the zones shown in Figure 4.1 are given in Table 4.1. All of these zones are evaluated using the geological assessment model (Table 4.2) to determine their suitability to act as target reservoirs for deep slurry injection operations.

From bottom to top in the stratigraphic column the Ford and Union Pacific Zones (Figure 4.1) of the Puente Formation secure 80 and 83 points out of 125 on the geological assessment model, which grade the zones into the below average category, not suitable for injection. However, the rest of the four upper zones, the Lower and Upper Terminal, Ranger, and Tar zones, belong to the above average category, as they secured 103, 108, 119, and 112 points respectively (Table 4.2). These results show that the upper three zones selected by the TTI experts are also the most favourable target reservoirs from top to bottom according to the geological assessment model i.e. the Tar, Ranger and Upper Terminal zones. The Lower Terminal zone although belongs to the “above average” category but has not been selected due to the availability of enough best target reservoirs at relatively shallow depth. These results show the model is in-agreement with the TTI expert views and shows its credibility.

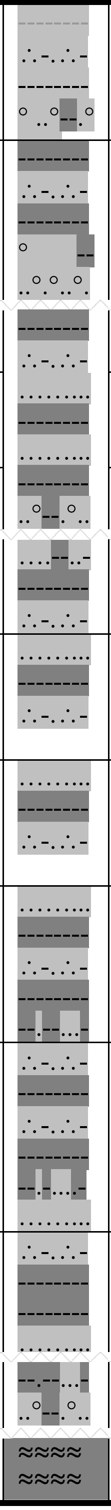
AGE	Million Years	FM.	THICK (feet)	ZONE	LITH.	SUBZONES	COMMENTS
Pleistocene	1.8	San Pedro	1800				
Upper Pliocene		Pico				JF,KF *Up Repetto unconf.*	Base of fresh water 2800’
Lower Pliocene	5.3	Repetto	300				
			300	Tar		So,S,T,U DU	Por.35-40%, perm.1000-8000md, temp104-120°F
			300	Upper Ranger		F1,F_0,F,H,X	Por.30-40%, perm. 1000-2500md, temp.114-164°F, 100-200’sand,20-30’shale caps
Miocene / Pliocene	16.4	Puente	300	Lower Ranger		G,G4,G5,G6	
			600	Upper Terminal		HX1,HX_0,HX, HXb,HXc,J,Y, Y4K,Z,WA	Por.30-40%,perm.500-1000md, temp.132-175°F, 60’sd, sd/sh:60/40
			600	Lower Terminal		AA,AB,AC,A DADI	Por.25-35%,perm.400-700md, temp.145-168°F, 60’sd, sd/sh:60/40
			800	Union Pacific		AE,AF,AI,AK 1AK,AL1,AM	Por.20-25%,perm.40-200md, temp.183-211°F, 30’sd, sd/sh:35/65
			1200	Ford		AO,AO1,AR, AR1,AU,AU2. AV,AX,AY,A Y1,AZ	Por.20-25%,perm.10-100md,temp.183-211°F, 30’sd, sd/sh:35/65
			1300	237		BA,BB,BC	Por.20-25%,perm.10-200md, temp.264-280°F
Middle Miocene		Monterey					
?		Catalina Schist					

Figure 4.1: Generalized stratigraphic column of the Terminal Island (After TTI[1], 2001)

Table 4.1: Data for different reservoirs at the Terminal Island

Target Reservoir	Tar	Ranger	Upper Terminal	Lower Terminal	Union Pacific	Ford
Permeability (mD)	4000	1800	800	600	140	70
Reservoir Thickness (m)	-	150	20	20	10	10
Porosity (%)	38	35	35	30	23	23
Depth (m)	1200	1400	1600	1700	2000	2200
Alternating Sand -Shale Sequence	2	> 2	> 2	> 2	> 2	> 2
Geographical Distance (km)	< 1	< 1	< 1	< 1	< 1	< 1

Table 4.2: Evaluation of different reservoirs for the Terminal Island

Parameters	WF	Ranks						
		MR	Tar	Ranger	Upper Terminal	Lower Terminal	Union Pacific	Ford
Permeability	7	5	5.0	4.5	3.2	2.7	1.3	1.0
Reservoir Thickness	4.5	5	4.8	5.0	4.8	4.8	3.7	3.7
Tectonics Setup	3.5	5	5.0	5.0	5.0	5.0	5.0	5.0
Porosity	3	5	5.0	4.9	4.9	4.5	3.8	3.8
Depth	2	5	4.0	3.7	3.4	3.2	2.7	2.3
Alternating Sand-Shale	2	5	5.0	5.0	5.0	5.0	5.0	5.0
Reservoir Strength	1	5	5.0	5.0	5.0	5.0	3.0	3.0
Reservoir Compressibility	1	5	5.0	5.0	5.0	5.0	5.0	5.0
Geographical Distance	1	5	5.0	5.0	5.0	5.0	5.0	5.0
Total Score		125	122	119	108	103	83	80
Category			above average				below average	

WF = Weighting Factor, MR = Maximum Rank

4.3 Evaluation of SW Ontario

A study was conducted by the author to determine the potential of different towns of SW Ontario for deep waste slurry injection. Drilling data from some 64 petroleum wells was studied covering eight counties for this purpose (Appendix B).

It was discovered from the study that the critical parameters required for a suitable site for deep slurry injection operation, for example permeability, porosity, reservoir thickness, and so on, were of quite low values in all the studied counties; also, where some parameters were in acceptable ranges, others were totally unacceptable. This judgment was made by comparing the geological data of SW Ontario with other injection sites around the world which already have successful records of slurry waste injection. On the basis of this study, it was empirically concluded that the slurry injection potential of SW Ontario is below average; therefore, the area is not suitable for a commercial waste slurry injection operation.

The geological model developed for an assessment of a prospective injection site is applied on some counties of SW Ontario to check the performance of the model. The evaluation results are shown in Table 4.3. It is evident from the results that all of the counties selected for evaluation belong to the "below average" category by achieving less than 85 points of 125. This demonstrates that these sites are not suitable candidates for deep slurry injection operation. These results are in-agreement with the empirical results which were concluded at the time of the study, and it gives an idea about the credibility (and consistency) of the geological assessment model.

Table 4.3: Evaluation of different townships of SW Ontario

Parameters	WF	Ranks				
		MR	Tilbury East	Sombra	Moore	Dawn
Permeability	7	5	1.0	0.5	0.5	0.3
Reservoir Thickness	4.5	5	4.1	3.0	3.4	5.0
Tectonics Setup	3.5	5	5.0	5.0	5.0	5.0
Porosity	3	5	1.4	2.0	2.0	2.2
Depth	2	5	5.0	5.0	5.0	5.0
Alternating Sand-Shale Sequence	2	5	5.0	5.0	5.0	5.0
Reservoir Strength	1	5	1.0	3.0	3.0	3.0
Reservoir Compressibility	1	5	1.0	1.0	1.0	1.0
Geographical Distance	1	5	5.0	5.0	5.0	5.0
Total Score		125	74	70	71	77
Category			below average			

Table 4.3 (Cont'd)

Parameters	WF	Ranks				
		MR	Enniskillen	Tilbury West	Dunwich	Blenheim
Permeability	7	5	0.3	1.2	0.5	1.2
Reservoir Thickness	4.5	5	5.0	2.5	2.8	2.5
Tectonics Setup	3.5	5	5.0	5.0	5.0	5.0
Porosity	3	5	3.2	2.0	2.0	2.2
Depth	2	5	5.0	5.0	4.0	4.0
Alternating Sand-Shale Sequence	2	5	5.0	5.0	5.0	5.0
Reservoir Strength	1	5	3.0	3.0	3.0	3.0
Reservoir Compressibility	1	5	1.0	1.0	1.0	3.0
Geographical Distance	1	5	5.0	5.0	5.0	5.0
Total Score		125	80	72	67	72
Category			below average			

WF= Weighting Factor; MR= Maximum Rank

4.4 Evaluation of Duri Oilfield, Indonesia

The Duri Region in Indonesia is part of a sedimentary basin constituting the northeastern half of Sumatra. Geologically the basin is quite young in age and immature, and is composed of alternating sand and shale litho-units. The sands are loose and unconsolidated, therefore are suitable candidates for deep slurry injection operations. In some parts, the Duri oilfield is a faulted anticlinal structure producing the oil from the structural traps.

Based on the geological data, different well tests, and geophysical logs, experts of Terralog Technologies Inc selected sandstones of the Pematang and Dalam Formations as target reservoirs for deep slurry injection operations in the Duri oilfield, Indonesia (TTI^2, 2001), and presently TTI is performing successful injection of slurried oilfield waste in these formations. These formations are evaluated using the assessment model; the important characteristics of the Pematang and Dalam Formations and their evaluation results from the assessment model are shown in Table 4.4 and 4.5 respectively. The evaluation results show that both the Pematang and Dalam Formations belong to the "above average" category, and these results again confirm the credibility of the model.

Table 4.4: Data for target reservoirs in Duri oilfield

Target Reservoir	Pematang Formation	Dalam Formation
Permeability (mD)	1800	4700
Reservoir Thickness (m)	21	13
Porosity (%)	18	30
Depth (m)	394	370
Geographical Distance (km)	~10	~10

Table 4.5: Evaluation of target reservoirs in Duri oilfield

Parameters	WF	Ranks		
		MR	Pematang	Dalam
Permeability	7	5	4.5	4.9
Reservoir Thickness	4.5	5	4.9	4.1
Tectonics Setup	3.5	5	5.0	5.0
Porosity	3	5	3.3	4.5
Depth	2	5	5.0	5.0
Alternating Sand-Shale Sequence	2	5	5.0	5.0
Reservoir Strength	1	5	5.0	5.0
Reservoir Compressibility	1	5	3.0	5.0
Geographical Distance	1	5	3.7	3.7
Total Score		125	113	118
Category			above average	

WF = Weighting Factor, MR = Maximum Rank

4.5 Evaluation of Port Fourchon, Louisiana

The coastal area of Louisiana is a downwarped sedimentary basin formed by deltaic progression. This basin consists of thick stratigraphic sections of clastic sediments of Miocene and younger ages (<24 million years) that dominantly progress and thicken seaward. Sedimentary formations present in the subsurface of southern Louisiana area consist of alternating layers of sand and shale litho-units having gentle regional dips in the southward direction.

Salt tectonism is a characteristic feature of the southern Louisiana area. Originally, salt was buried at an approximate depth of 6,000 m, but differential loading on the salt layer caused the salt to move upward in a buoyant manner, penetrating the overlying sedimentary strata in the form of salt domes and salt ridges, accompanied by major normal faults above the domes and ridges (evidence of extensional deformation).

The deltaic progression contains one of the world's thickest sections of clastic sediments, and the gross lithologic facies recognized in the progression are massive sandstone facies, interbedded facies, and massive shale facies. The massive sandstone facies are composed of 50% to 75% sandstone with interbedded thin shale beds; the interbedded facies consist of alternating units of sandstone and shale where sandstone content ranges from 10% to 50%; and the massive shale facies dominantly consist of dark marine shales commonly interbedded with thin erratic sandstones, sandstones make less than 10% of the total volume of the massive shale facies (TTI, 2000).

Chevron used two sandstone reservoirs in Port Fourchon area to successfully dispose one million barrels of the oilfield waste containing small amounts of naturally occurring radioactive material (NORM) using deep slurry injection technology (Reed *et al*, 2001). Table 4.6 shows the important characteristics of the two target injection zones collected from Terralog Technologies Inc. Calgary and Table 4.7 shows their evaluation results using the geological assessment model. According to the results both of the reservoirs belong to the "above average" category and it is in-agreement with the performance of the target reservoirs.

Table 4.6: Data for target reservoirs in Fourchan, Louisiana

Target Reservoir	Completion 1	Completion 2
Permeability (mD)	2000	3000
Reservoir Thickness (m)	34	13.2
Porosity (%)	-	23
Depth (m)	1469	1352
Geographical Distance (km)	~ 1 km	~ 1 km

Table 4.7: Evaluation of target reservoirs in Fourchan, Louisiana

Parameters	WF	Ranks		
		MR	Completion 1	Completion 2
Permeability	7	5	4.7	5.0
Reservoir Thickness	4.5	5	5.0	4.1
Tectonics Setup	3.5	5	5.0	5.0
Porosity	3	5	3.0	3.8
Depth	2	5	3.6	3.8
Alternating Sand-Shale Sequence	2	5	5.0	5.0
Reservoir Strength	1	5	5.0	5.0
Reservoir Compressibility	1	5	3.0	5.0
Geographical Distance	1	5	5.0	5.0
Total Score		125	112	115
Category			above average	

WF = Weighting Factor, MR = Maximum Rank

4.6 Evaluation of Western Canada Sedimentary Basin

In a cross-sectional view, the Western Canada Sedimentary Basin is a thin northeastward tapering wedge of supracrustal rocks of Phanerozoic age that overlap the Precambrian crystalline basement of North American Craton (Price, 1994). The Phanerozoic sedimentary wedge thickens southwestward from exposed Canadian shield rocks where the thickness of the wedge is zero, and reaches a thickness of 3-6 km at the northeast margin of the foreland fold and thrust belt. The maximum thickness of sediments is more than 6000 m in the Liard Basin, more than 3000 m in the Canadian portion of the Williston Basin, and more than 5500 m in the Alberta Basin (Wright, 1994). Two distinct tectonics settings have been recognised in the Western Canada Sedimentary Basin, based on knowledge of the sedimentary record for Phanerozoic strata, i.e. the Paleozoic to Jurassic Platformal succession and middle

Jurassic to Paleocene foreland basin succession (Mossop and Shetsen, 1994). The Paleozoic to Jurassic age sequence marks a period of a stable craton that was present adjacent to the ancient margin of North American plate; and dominantly carbonate rocks were deposited on the passive craton during this succession. The Middle Jurassic to Paleocene age marks a period of active orogeny and the formation of a foreland basin, which evolved into the Canadian Cordillera; dominantly clastic rocks were deposited in the foreland basin during this tectonic phase.

The North American plate began to drift westward with the opening of the Atlantic Ocean in the Middle Jurassic period. This drift caused collisions between the western margin of North American plate and large oceanic terrains, and produced a compressional regime on the western margin of the plate. As a result of the collisions, layers of platformal sedimentary rocks deposited on the ancient margin of collided continental and oceanic plates compressed, and were thrust eastward over the western margin of the continental plate forming imbricate thrust slices. The Canadian Rocky Mountains and the Rocky Mountains Foothills evolved as a result of these processes. This emplacement increased the thickness of the crust and also down-warped the foreland to form an eastward migrating foredeep basin on the east of the Canadian Rocky Mountains. Erosional processes acting upon the rising mountains in the west provided the source of clastic detritus to fill the foreland basin.

Stratigraphically, the rocks of the foreland basin are divided into four major groups and from bottom to top they are as follows: Vanguard Group of Jurassic age, Mannville Group of Lower Cretaceous age, and Colorado and Montana Groups of Upper Cretaceous age. The Mannville Group of Lower Cretaceous age is dominantly composed of sandstones, whereas the Colorado and Montana Groups of Upper Cretaceous age are dominantly shales.

The Mannville Group forms one of the major sedimentary rocks wedges into the foreland basin, and extends throughout the Western Canada Sedimentary Basin. This group has great significance for the oil and gas business since it hosts a significant proportion of the basin's conventional oil and gas deposits, and also practically all of the prodigious bitumen resources of the oil sands deposits (Mossop and Shetsen, 1994). The Colorado Group of Upper Cretaceous age is dominated by marine shales; a few thin but extensive sandstones layers interrupt these shales sequences and have enormous economic importance as petroleum reservoirs, such as the Viking Sandstone of Upper Cretaceous age in southern Alberta and southwestern Saskatchewan, which contains significant oil and gas reserves.

Terralog Technologies Inc. (TTI) Calgary has carried out a number of deep slurry injection operations to dispose of oilfield sand, slop, and tank-bottom sludge for a number of petroleum companies at different locations of Alberta and Saskatchewan (TTI 1996; TTI^1, 1997; TTI^2, 1997). TTI provided the required geological data for some target sandstone reservoirs in the Western Canada Sedimentary Basin for the evaluation of the geological assessment model. Table 4.8 and 4.9 show the important characteristics and the evaluation of the Clearwater and Lloydminster-Rex Formations for the Charlotte Lake area in Alberta, the Rex Unit for the Elk Point area in Alberta, and the Dina Unit for the Edam area in Saskatchewan. The evaluation results using the assessment model are in-agreement with the performance of the target reservoirs in different parts of the Western Canada Sedimentary Basin.

Table 4.8: Data of target reservoirs in Western Canada Sedimentary Basin

Target Reservoir	Clearwater	Lloydminster-Rex	Rex	Dina
Permeability (mD)	3000	70	988	1000
Reservoir Thickness (m)	>25	23	18	>25
Porosity (%)	-	30	-	-
Depth (m)	411	373	536	563

Table 4.9: Evaluation of target reservoirs in Western Canada Sedimentary Basin

Parameters	WF	Ranks				
		MR	Clearwater	Lloydminster-Rex	Rex	Dina
Permeability	7	5	5.0	1.1	3.5	3.5
Reservoir Thickness	4.5	5	5.0	5.0	4.6	5.0
Tectonics Setup	3.5	5	5.0	5.0	5.0	5.0
Porosity	3	5	4.5	4.5	4.0	4.0
Depth	2	5	5.0	5.0	5.0	5.0
Alternating Sand-Shale Sequence	2	5	5.0	5.0	5.0	5.0
Reservoir Strength	1	5	5.0	3.0	5.0	5.0
Reservoir Compressibility	1	5	3.0	3.0	3.0	3.0
Geographical Distance	1	5	5.0	5.0	5.0	5.0
Total Score		125	122	92	108	110
Category			Above average	average	above average	

WF = Weighting Factor, MR = Maximum Rank

4.7 Evaluation of North Slope of Alaska

Giant oil fields of the North Slope of Alaska make it one of the most important energy producing areas in the US; the Prudhoe Bay and Kuparuk River oil fields are among the ten largest oil fields in the US (Gibson, 2004). The Prudhoe Bay field is located to the east of the Kuparuk River field and they are approximately 32 km apart from each other.

The Kuparuk River Field was discovered in 1969; its estimated areal extent is more than 520 square kilometres with recoverable reserves of around 1.6 billion barrels and oil-in-place estimates range from 18 to 40 billion barrels (Masterson and Paris, 1987; Werner, 1987). The presence of heavy oil in the Alaskan North Slope is known since early exploratory drilling; in 1982 a comprehensive production program was initiated to produce the shallow oil sands (Werner, 1987). It is known that oil sand production technologies generate huge volumes of solid waste along with oil production, and the rules and regulations defined by environmental protection agencies require the proper environmentally safe disposal of this waste. Deep slurry injection technology has been practiced in different areas of Alaskan North Slope to permanently dispose the solid oil field waste (as well as other wastes).

According to Veil and Dusseault (2003), the North Slope of Alaska has received the largest number of slurry injection job permits (i.e. 129, whereas 334 is the total number of such jobs in the world in their report). Three successful cases of the North Slope injection operations are selected from the Veil and Dusseault (2004) work and the geological assessment model is applied on them for the purpose of their evaluation. Available data (Table 4.10) for these cases provide basic information that is required to use as input in the geological assessment model. Table 4.11 shows evaluation results in the form of “total score” that each site achieved from the model. These results show that all the injection sites of the Alaskan North Slope selected for the evaluation belong to the “above average” category and have excellent reservoirs to receive slurried waste. These results are also in-accordance with the performance of the target reservoirs.

Table 4.10: Data for different sites in Alaskan North Slope

	Kenai	North Star (1)	North Star (2)	Prudhoe Bay
Permeability (mD)	Ave. 700 (300-1000)	Ave. 2500 (250-4500)	Ave. 1400 (150-2500)	~ 1000
Reservoir Thickness (m)	>25 Sterling sand	>25 Brookian age Sand	>25 Schrader Bluff Formation	>25 Friable Ugnu sand
Porosity (%)	Ave. 28 (25-30)	Ave. 32 (29-34)	Ave. 30 (28-32)	Ave. 30 (20-42)
Depth (m)	1561	1739	2499	2011

Table 4.11: Evaluation of different sites in Alaskan North Slope

Parameters	WF	MR	Ranks			
			Kenai	North Star (1)	North Star (2)	Prudhoe Bay
Permeability	7	5	2.9	5.0	4.1	3.5
Reservoir Thickness	4.5	5	5.0	5.0	5.0	5.0
Tectonics Setup	3.5	5	5.0	5.0	5.0	5.0
Porosity	3	5	4.3	4.7	4.5	4.5
Depth	2	5	3.4	3.1	1.8	2.6
Alternating Sand-Shale Sequence	2	5	5.0	5.0	5.0	5.0
Reservoir Strength	1	5	5.0	5.0	5.0	5.0
Reservoir Compressibility	1	5	5.0	5.0	5.0	5.0
Geographical Distance	1	5	5.0	5.0	5.0	5.0
Total Score		125	105	120	111	108
Category			above average			

WF = Weighting Factor, MR = Maximum Rank

Hitherto the application of the geological assessment model on data from different geographical locations representing diverse geology is shown to be robust and it demonstrates that the model can be used to predict the deep slurry injection potential for the future prospective sites. For this purpose the geological assessment model is applied on some prospective sites in US and Canada to determine their slurry injection potential.

4.8 Prospective Reservoirs in Alaskan North Slope

The geological assessment model is applied on the West Sak Sands, the Ugnu Sands, and the Kuparuk River Formation of the North Slope area to determine their slurry injection potential; Table 4.20 shows values for the required parameters for these stratigraphic horizons as given by Werner (1987) and Masterson and Paris (1987). Although the values were calculated for the oil bearing sand zones but it is expected that similar values would be encountered in other parts of the litho-units along their lateral extensions that do not contain any hydrocarbons, and such oil barren segments of the sand-units or the depleted oil reservoirs could be used as target reservoirs for deep slurry injection operations. The following paragraphs present a summary of the work done by Werner (1987) for the West Sak Sands and Ugnu Sands, and Masterson and Paris (1987) for the Kuparuk River Formation.

The West Sak Sands of Late Cretaceous age are equivalent to the Schrader Bluff Formation. In the Kuparuk area the average thickness of the West Sak Sands is 90 m, 1231 m and 1141 m represents the top and bottom depths of the stratigraphic unit, although thickness ranges from 81-182 m along its lateral extension. The West Sak stratigraphic interval is classified as litharenites and lithic wackes; it is composed of very fine- to fine-grained sandstone and silty sandstone with interbedding of siltstone and mudstone. Due to the lack of cementing material the West Sak Sand is very friable; values of porosities and permeabilities obtained from core data range from 25 to 35% and from 10 to 800 mD respectively.

Stratigraphically, the Ugnu Sands directly overlie the West Sak Sands and belong to the Upper Cretaceous-Paleocene boundary; in the Kuparuk area a 30-45 m thick extensive mudstone sequence separates these two sands from each other. Total thickness of the Ugnu stratigraphic interval is 167 m in this area, the top and bottom of the stratigraphic interval are at depths of 827 and 994 m respectively. In general, sandstone beds are laterally continuous and thick, separated by siltstone and mudstone layers, with thickness ranging from 3-30 m. The fine- to medium-grained Ugnu Sands are also unconsolidated, having no significant amount of cement. Porosity and permeability values of the Ugnu Sands obtained from core data range from 30 to 35% and 200 to 3000 mD respectively.

The Kuparuk River Formation belongs to the Ugnuravik Group of the Lower Cretaceous period. This formation is divided into upper and lower members by an unconformity, which is an erosional remnant of the lower member. The lower member is mainly composed of interbedded sandstone, siltstone, and mudstone, whereas the upper member is a coarsening upward sequence mainly composed of sandstone and siltstone. The well 1A-13 data shows that total thickness of the formation is about 109 m, the lower member is about 70 m thick, and 1809 m and 1918 m depths respectively mark the top and bottom of the formation. Average values of porosity and permeability for reservoir sandstones in the lower and upper member are 23% and 100 mD and 130 mD respectively; whereas maximum values of porosity and permeability for the lower and upper member are 30% and 33% and 500 mD and 2600 mD respectively.

Table 4.13 shows the "score" for each stratigraphic interval secured from the geological assessment model. The results show that the West Sak and Ugnu Sands can act as the best candidates for slurry injection operation, whereas the Kuparuk River Formation falls in the "average" category due to its low permeability and high depth.

Table 4.12: Data for West Sak Sands, Ugnu Sands, and Kuparuk River Formation

Target Reservoir	West Sak Sands	Ugnu Sands	Kuparuk River
Permeability (mD)	500	1600	120
Reservoir Thickness (m)	>25	>25	>25
Porosity (%)	30	33	23
Depth (m)	1141	994	1918

Table 4.13: Evaluation of West Sak Sands, Ugnu Sands, and Kuparuk River Formation

Parameters	WF	Rank			
		MR	West Sak Sand	Ugnu Sand	Kuparuk River
Permeability	7	5	2.5	4.3	1.3
Reservoir Thickness	4.5	5	5.0	5.0	5.0
Tectonics Setup	3.5	5	5.0	5.0	5.0
Porosity	3	5	4.5	4.7	3.8
Depth	2	5	4.2	4.5	2.8
Alternating Sand-Shale Sequence	2	5	5.0	5.0	5.0
Reservoir Strength	1	5	3.0	5.0	3.0
Reservoir Compressibility	1	5	5.0	5.0	3.0
Geographical Distance	1	5	5.0	5.0	5.0
Total Score		125	102	118	87
Category			above average		average

WF = Weighting Factor, MR = Maximum Rank

4.9 Prospective Reservoirs for Some Major US Cities

A geological study was conducted by the author to determine the slurry injection potential of some of the more populous metropolitan areas of the United States using publicly available data by comparing it with other successful slurry injection cases, and carried out initially for Terralog Technologies Inc (Calgary) on a work term. Geological data for some of the areas provide values for the most important parameters required for an injection site; such areas have been selected for evaluation using the geological assessment model, and their relevant available data is shown in Table 4.14. It was discovered that some of the major urban areas in the US are not located directly above suitable geology, but some distance away from sedimentary basins; therefore, in such cases the near-by basins have been selected and studied for slurry injection. Exact geographical distances between the prospective injection sites and the major metropolitan centres vary and also are unknown; therefore, a rough estimate has been used for this parameter in the geological model.

Most of the populous cities in the eastern US are located in a broad belt of the Coastal Plain areas along the Atlantic Ocean, for example New York, Washington, Atlantic City, and so on. The suitable disposal locations identified for the eastern US cities are unconsolidated sedimentary sequences of the Atlantic Coastal Plain areas and the shallow depleted petroleum reservoirs of the Appalachian Basin. Geological data available for the Atlantic Coastal Plain areas does not provide values for all the required parameters, therefore only some litho-units of the Appalachian Basin are evaluated with the geological model (Table 4.14 and 4.17).

Major populous cities of the State of Texas are Houston, Dallas, and San Antonio. The sedimentary strata of the Texas Coastal Plain area are composed of unconsolidated sequences of Cretaceous and Cenozoic age. Underneath the fresh water aquifers in the Coastal Lowland and Coastal Upland area around the Houston area, there are many sandstone beds with good porosity (20-25%) and permeability (250 mD to > 1000 mD) (Nadeem, 2003). Also, salt tectonism in this area has produced a lot of excellent traps for hydrocarbon entrapment, which are quite suitable for biosolids or industrial solid waste injection operation. The city of Dallas is located just outside the Coastal Plain geographical and hydrogeological area. The subsurface geology of Dallas is not suitable for deep slurry injection; the nearest geologically suitable area for Dallas could be the Coastal Plain area to the southeast of the city. The South Texas Gulf Coast Basin has many sandstone units, for example San Miguel-Olmos sandstone, Wilcox sandstone, Frio fluvial/deltaic sandstone, and so on, which have acted as petroleum reservoirs (Table 4.15). The depleted sandstone units of the basin can serve as convenient targets for deep slurry injection for the region of the city of San Antonio. Table 4.17 shows the total score and the category that some of the litho-units in the state of Texas secured using the geological assessment model.

Chicago is the third largest metropolitan area of the United States and the most populated city of the state of Illinois. This city is located on rocks of Silurian age which carries potable ground water; therefore, it might be difficult to find any suitable geological strata to inject biosolids in the area. The most favourable injection site near to Chicago is in the Illinois Basin. The oil and gas fields of the Pennsylvanian system are the oldest in the Illinois Basin and can be assumed to be totally depleted; therefore, they can act as good reservoirs for slurry injection operation, but due to lack of the data they are not evaluated using the geological model. The sandstone unit present at the Pennsylvanian - Mississippian system boundary in Crawford County is evaluated using the geological model for the city of Chicago (Table 4.16 and 4.17) because of the availability of data.

The city of Detroit is the most populated city of Michigan State and the tenth largest metropolitan area in the US. The subsurface sedimentary column under Detroit is about 1200 m thick. Shallow rocks form aquifer system in the region, whereas deep parts of the strata contain high concentration of dissolved solids, increasing towards the centre of the basin, and becoming more than 300,000 mg/litre in the basin centre (Nadeem, 2003). Such zones of high salt concentrations could be appropriate candidates for deep slurry injection. There are multiple layers of thick and continuous shale units present in the sedimentary column of the Michigan Basin which serve to sandwich sandstone units and act as cap rocks for injection zones. Structural closures in the form of folds are also present in some parts of the basin and could be useful to help trap the methane gas that would be generated from biodegradation of injected biosolids. Values of required geological parameters are only available for Mt. Simon Sandstone in the Michigan Basin (Table 4.16); Table 4.17 shows total score for Mt. Simon Sandstone on the geological assessment model.

Table 4.14: Data for some litho-units of the Appalachian Basin

Target Reservoir	Pottsville, New River, & Lee Ss.	Mauch Chunk Gr.	Big Injun Ss.	Berea Ss.	Venango Ss.	Bradford Ss.
Permeability (mD)	90	25	150	300	300	500
Reservoir Thickness (m)	1.5 - 60	3 - 12	27 – 60	24 – 70	12 – 60	6
Porosity (%)	12	12	15	12	8	9
Depth (m)	168 - 611	220 - 1044	300 - 912	270-1200	640-795	593-1016

Table 4.15: Data for some litho-units of South Texas area

Target Reservoir	San Miguel Ss.	Wilcox Fluvial Ss.	Frio Fluvial Ss.	Blossom Ss.	Paluxy Ss.
Permeability (mD)	18	488	432	1000	250
Reservoir Thickness (m)	111	20	47	20	120
Porosity (%)	23	24	25	25	20
Depth (m)	1135	2060	1718	-	1050

Table 4.16: Data for some litho-units of Illinois and Michigan Basins

Target Reservoir	Pennsylvanian-Mississippian Boundary Ss.	Mt. Simon Ss.
Permeability (mD)	550	32
Reservoir Thickness (m)	20	> 30
Porosity (%)	14	15
Depth (m)	360	1400

Ss.= Sandstone, Gr.= Group

Table 4.17: Evaluation of target reservoirs for major cities in US

Parameters	WF	Ranks					
		MR	Pottsville & Lee Ss.	Mauch Gr.	Big Injun Ss.	Berea Ss.	Venango Ss.
Permeability	7	5	1.2	0.5	1.4	2.0	2.0
Reservoir Thickness	4.5	5	5.0	3.3	5.0	5.0	5.0
Tectonics Setup	3.5	5	5.0	5.0	5.0	5.0	5.0
Porosity	3	5	2.6	2.6	3.0	2.6	2.0
Depth	2	5	5.0	5.0	5.0	4.9	5.0
Alternating Sand-Shale Sequence	2	5	3.0	3.0	3.0	5.0	5.0
Reservoir Strength	1	5	3.0	3.0	3.0	3.0	3.0
Reservoir Compressibility	1	5	3.0	3.0	3.0	3.0	1.0
Geographical Distance	1	5	4.0	4.0	4.0	4.0	4.0
Total Score		125	82	70	85	92	88
Category			below average			Average	

(PTO)

Table 4.17 (Cont'd)

Parameters	WF	Ranks					
		MR	Bradford Ss.	San Miguel Ss.	Wilcox Ss.	Frio Ss.	Blossom Ss.
Permeability	7	5	2.5	0.1	2.4	2.3	3.5
Reservoir Thickness	4.5	5	3.0	5.0	4.8	5.0	4.8
Tectonics Setup	3.5	5	5.0	5.0	5.0	5.0	5.0
Porosity	3	5	2.2	3.8	3.9	4.0	4.0
Depth	2	5	4.8	4.2	2.6	3.2	5.0
Alternating Sand-Shale Sequence	2	5	5.0	5.0	5.0	5.0	3.0
Reservoir Strength	1	5	3.0	3.0	3.0	3.0	5.0
Reservoir Compressibility	1	5	1.0	3.0	3.0	3.0	5.0
Geographical Distance	1	5	4.0	5.0	5.0	5.0	5.0
Total Score		125	83	82	94	95	107
Category			below average		average		above average

Table 4.17 (Cont'd)

Parameters	WF	Ranks			
		MR	Paluxy Ss.	Pennsylvanian-Mississippian Boundary Ss.	Mt. Simon Ss.
Permeability	7	5	1.9	2.6	0.9
Reservoir Thickness	4.5	5	5.0	4.8	5.0
Tectonics Setup	3.5	5	5.0	5.0	5.0
Porosity	3	5	3.5	2.9	3.0
Depth	2	5	4.4	5.0	3.7
Alternating Sand-Shale Sequence	2	5	5.0	3.0	5.0
Reservoir Strength	1	5	3.0	3.0	3.0
Reservoir Compressibility	1	5	3.0	3.0	3.0
Geographical Distance	1	5	5.0	0.0	5.0
Total Score		125	93	88	84
Category			average		below average

WF = Weighting Factor, MR = Maximum Rank

4.10 Prospective Reservoirs for Major Cities of Alberta

Calgary, Edmonton, and Red Deer are the three major population and industrial centres of Alberta, Canada. To determine the deep slurry injection potential of these metropolitan areas, subsurface geological data around the areas were collected and evaluated using the geological assessment model. The data for these areas was collected from the Edmonton office of the Alberta Geological Survey.

General standard well reports of nine wells were selected for this purpose; four for the Calgary area covering the eastern and southeastern quadrants of the city (Well # 00/03-27-025-23W4-0 (C-1), 00/03-08-026-23W4-0 (C-2), 00/12-34-020-25W4-0 (C-3), and 00/07-22-025-28W4-0 (C-4)), two for the west Edmonton area (Well # 03/06-32-050-26W4-0 (E-1) and 00/12-30-052-25W4-0 (E-2)), and three for the Red Deer area covering the eastern and northeastern quadrants of the city (Well # 00/03-05-039-26W4-0 (R-1), 00/04-07-039-26W4-0 (R-2), and 00/12-33-038-26W4-0 (R-3)).

Well C-1, C-2, and C-4 are located on the eastern side of the City of Calgary, outside the city limits, whereas well C-3 is situated in the southeast of Calgary. Sandstones of the Glauconitic Formation of the upper Mannville Group are target reservoirs in well C-1 and C-2, whereas the Ellerslie (Basal Quartz) Formation of the lower Mannville Group is a suitable target reservoir in well C-3 and C-4.

Wells E-1 and E-2 both are situated in the western part of the City of Edmonton. The E-1 is situated outside the city limit whereas the E-2 is located inside the metropolitan area; both of these wells are being used as water disposal wells, and receiving target reservoirs are carbonates of the upper Devonian period. Well R-1, R-2, and R-3 are abandoned oil wells, the R-1 is located in east of Red Deer city, whereas the R-2 and R-3 are located in the northeast of the city. Target reservoirs in all of the wells are Viking sandstones of the Colorado Group.

Tables 4.18 and 4.19 show values of the important parameters for Calgary, Edmonton, and Red Deer areas, whereas Tables 4.20 and 4.21 show the score each area attained from the geological assessment model.

Table 4.18: Data for target reservoirs for different wells around Calgary area

	Well C-1	Well C-2	Well C-3	Well C-4
Permeability (mD)	894 Ave. (300-1850)	123 Ave. (1-427)	537 Ave. (3-1850)	142 Ave. (3-3801)
Reservoir Thickness (m)	18	10	5	12
Porosity (%)	21 Ave. (12-23)	15 Ave. (9-25)	13 Ave. (8-18)	11 Ave. (8-13)
Depth (m)	1577	1528	1810	2146

Table 4.19: Data for different wells around Edmonton and Red Deer areas

	Well E-1	Well E-2	Well R-1	Well R-2	Well R-3
Permeability (mD)	844 Ave. (20-1400)	61 Ave. (1-568)	201 Ave. (70-368)	327 Ave. (100-570)	660 Ave. (200-1345)
Reservoir Thickness (m)	27	18	10	10	9
Porosity (%)	9 Ave. (1-18)	14 Ave. (6-21)	12 Ave. (9- 4)	12.3 Ave. (8-16)	14.5 Ave. (11-18)
Depth (m)	1655	1411	1577	1519	1616

Table 4.20: Evaluation of Calgary area

Parameters	WF	Rank				
		MR	C-1	C-2	C-3	C-4
Permeability	7	5	3.3	1.3	1.3	2.5
Reservoir Thickness	4.5	5	4.6	3.7	4.0	2.7
Tectonics Setup	3.5	5	5.0	5.0	5.0	5.0
Porosity	3	5	3.6	3.0	2.5	2.8
Depth	2	5	3.4	3.5	2.4	2.9
Alternating Sand-Shale Sequence	2	5	5.0	5.0	5.0	5.0
Reservoir Strength	1	5	5.0	3.0	3.0	5.0
Reservoir Compressibility	1	5	5.0	5.0	3.0	3.0
Geographical Distance	1	5	4.0	4.0	4.0	4.0
Total Score		125	103	81	77	84
Category			above average	below average		

Table 4.21: Evaluation of Edmonton and Red Deer areas

Parameters	WF	Rank					
		MR	E-1	E-2	R-1	R-2	R-3
Permeability	7	5	3.2	1.0	1.7	2.1	2.8
Reservoir Thickness	4.5	5	5.0	4.6	3.7	3.7	3.6
Tectonics Setup	3.5	5	5.0	5.0	5.0	5.0	5.0
Porosity	3	5	2.2	2.9	2.6	2.6	3.0
Depth	2	5	3.3	3.7	3.4	3.5	3.3
Alternating Sand-Shale Sequence	2	5	5.0	5.0	5.0	5.0	5.0
Reservoir Strength	1	5	5.0	3.0	3.0	5.0	5.0
Reservoir Compressibility	1	5	3.0	3.0	3.0	3.0	3.0
Geographical Distance	1	5	5.0	5.0	5.0	5.0	5.0
Total Score		125	99	83	82	87	92
Category			average	below average		Average	

WF = Weighting Factor, MR = Maximum Rank

The evaluation results indicate that some wells have better waste injection potential as compared to other wells in the same area. There can be many reasons for these differences; for example, the values of porosity, permeability, and reservoir thickness are taken from core analysis and the cores were taken only from selective and limited intervals of the wells. It is possible there are much better litho-units present in these area which are suitable to act as target reservoirs and could be recognized through careful analysis of geophysical logs; therefore, it is important in these cases, as well as others, to undertake more detailed investigation to locate good stratigraphic horizons.

4.11 Preferable Injection Site

A selection process for a subsurface slurry injection site is based on a number of important geological and engineering parameters, which have been discussed in detail in this document and elsewhere. Considering the various factors, a depleted oilfield seems to be a preferred candidate choice for waste injection operations, as compared to a virgin area.

4.11.1 Depleted Oilfields

A depleted oilfield is an area which has gone through different phases of petroleum exploration and production operations. Therefore, it is likely that detailed information regarding subsurface geological and engineering parameters, required for a slurry injection site selection procedure, would be easily available for an oilfield.

The following information could be collected for an oilfield using available geological, geophysical, and engineering data:

- Subsurface stratigraphy: Employing drilling data and geophysical logs lithology, thickness, depth, position, and distribution of each litho-unit in a sedimentary basin can be recognized.
- Subsurface structural/tectonics setup: Information about reservoir geometry and dimensions, inclination of strata, and structural discontinuities caused by tectonic forces can be determined using structural-tectonics maps and seismic time-depth plots.
- Stratigraphic sections: Lithologic correlation of stratigraphic units between adjacent wells and study of lateral and vertical changes in litho-facies can be accomplished by using geophysical logs and drilling data.
- Storage capacity and flow properties: Porosity and permeability of an injection zone or any other stratigraphic horizons can be determined utilizing core data, geophysical logs, and pressure transient tests; permeability helps to understand flow behaviour of a litho-unit, whereas porosity combined with other parameters can be used to calculate storage capacity of a reservoir.
- Permeability anisotropy: Flow barriers create hydraulically isolated compartments in a reservoir and produce permeability anisotropy; pressure transient tests are useful tools to identify these barriers.

All of this information is quite useful and will play an important role in selection of a suitable site for deep solid waste injection.

Oil and gas reservoirs usually have the following properties: good porosity and permeability, ample areal extent and thickness, excellent cap rock, and so on. An excellent cap rock acts as a seal which overlies the reservoir and keeps the oil and gas confined in it, whereas other positive qualities, for example, good porosity and permeability and huge reservoir volume, provide better flow conditions and storage capacity for injected wastes.

A depleted oilfield also generally has an essential basic infrastructure which can be used during an injection operation, depending upon its condition and suitability. For example, abandoned wells, pipeline networks, roads, water sources, and so on, might all represent valuable assets to an injection facility.

4.11.2 Virgin Area

A virgin area on the other hand has limited or no detailed record of geological and geophysical investigations, and also has not gone through any phase of deep drilling operations. In the absence of required geological and engineering work, it becomes more difficult to access critical information regarding the important parameters that are necessary for initial assessment of an injection site. Therefore, deficiencies in the required geological and engineering data make decision-making processes difficult for a virgin area regarding potential slurry injection operations.

High uncertainty and risk is involved in assessments of a new virgin area without a history of oil and gas development. This makes a depleted oilfield a relatively favourable site for waste injection operations because there is almost certainly enough useful information at first hand to determine the injection potential and long term behaviour. This allows a decision to be made, and if a new well is drilled for injection, additional information can be collected as needed.

Chapter 5: Conclusions and Recommendations

This study contributes to the understanding of geological selection criteria for identifying suitable target reservoirs for deep slurried waste injection operations, and also to the quantification of the geological properties required for continued injection operations. The following conclusions are made based on this study:

- The important parameters that must be quantified before making a decision regarding a target reservoir for deep slurry injection are:
    - Permeability, porosity, depth, thickness, mechanical strength, and compressibility of a reservoir;
    - Thickness and flow properties of cap rock;
    - Geographical distance between an injection well and a waste source or collection centre; and,
    - Regional and detailed structural and tectonic setup of an area.
- Most of the parameters can be described quantitatively, but others are available only as qualitative measures (e.g. tectonic fabric, jointing…).
- Permeability, porosity, reservoir thickness, reservoir depth, and tectonic setup are the most important parameters for a prospective slurry injection site.
- Some of the critical parameters require the definition of certain suitable upper and lower limits for their values; for example:
    - Permeability and depth of a reservoir should all be defined within limits, as both too small and too large values can be handicaps.

    - Similarly, cap rock thickness; structural setup; and sand-shale sequence must be given limits, although these will necessarily be of a non-quantitative nature.
- These limits depend upon many factors, for example, the depth and thickness of the surficial drinkable aquifer, the storage capacity and flow properties of a target reservoir, the thickness and mechanical integrity of the overlying flow barrier, and so on. The limits are not a fixed quantity but can be re-assessed in specific cases depending upon the geological and hydrogeological conditions in an area.
- A geological assessment model is developed for the assessment of a prospective injection site and is composed of two components: a decision tree and a numerical calculation system. The decision tree deals with the most critical parameters, those that render a site unsuitable or suitable but of unspecified quality, whereas a numerical evaluation system gives a score to a site based on the rank number and weighting factor of each parameter. On the basis of the total score a site can be classified into three broad categories, i.e. above average, average, or below average category, to indicate its favorability for the long-term injection operations.
- The geological assessment model is evaluated using available and original data collected for a number of sites in Canada, US, and Indonesia. Some of these sites have a successful history of deep slurry injection, and some of the sites have been considered as unsuitable for such injection operations. The geological assessment model is shown to be robust with respect to this data base because the results obtained are in agreement with the empirical assessments for injection use. This demonstrates that the model is capable of evaluating the deep slurry injection potential for future prospective sites. To this end, some prospective sites in Canada and US are also

evaluated using the model.

- Depleted oilfields are preferred sites for deep injection operations as compared to a virgin area. It is easy to obtain the required data for the purpose of site assessment from depleted oilfields, and also such sites provide the ideal geological conditions that are considered to be a prerequisite for a site for slurry injection operation.

This work can be further advanced by pursuing the following recommendations:

- Writing a computer program for the geological model, this will make it easy and more efficient to use the model.
- Further evaluation of the geological model using data from more areas around the world could improve the performance of the model and help identify any remaining shortcomings.
- The geological assessment model has mainly been evaluated using sandstone reservoirs present in a sand-shale sequence and this is because all existing cases of slurry injection belong to the sand-shale sequence environment. The behaviour of the model is somewhat uncertain in fractured sedimentary rocks and carbonate sequences. Nevertheless, if the rocks fulfil the defined criteria of the decision tree and the numerical ranking evaluation, even in the absence of an overlying sand-shale lithostratigraphy, it is likely that these targets would be of interest. Further work in these areas of carbonate sequences and fractured strata could improve the reservoir screening criteria for solids injection.

APPENDIX A

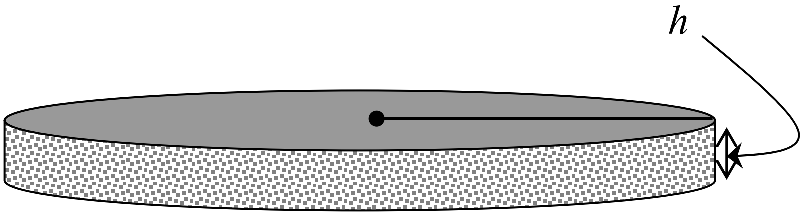
Calculation for Surface Area

Volume of liquid part of slurry = 1,000,000 m^3

Thickness of target reservoir (h) = 20 m

Porosity of target reservoir (ϕ) = 30%

Required areal extent = ?



We know that

Volume of a cylinder = $\pi r^2 h$

Also

Volume of voids = Unit bulk volume × Porosity

Therefore

Volume of liquid part of slurry = $\pi r^2 h \phi$

$$1{,}000{,}000 = \pi r^2 \times 20 \times 0.3$$

$$r = 230.33m$$

We also know that

Surface area of a cylinder = πr^2

Required areal extent = $3.14 \times (230.33)^2$

$= 1, 66{,}667.48\ m^2$

$= 0.166\ km^2$

Waste Volume	Required Areal Extent
500,000 m^3 (3,125,000 bbl)	0.08 km^2
1,000,000 m^3 (6,250,000 bbl)	0.166 km^2

APPENDIX B

B. Geological Assessment of SW Ontario

Southwestern Ontario is characterized by a thin veneer of sediments overlying a part of the southern margin of the Canadian Shield. The sedimentary strata are flat lying Paleozoic sediments and evaporate of the Upper Cambrian to Upper Devonian Age. Because of a very low regional dip and scarcity of outcrops in this region, most of the structural and stratigraphic information is available only from the records of wells drilled in the area for oil and gas exploration and production. Using this data, an attempt has been made to describe the regional stratigraphy and the reservoir characteristics of some litho-units to determine the potential of the area for deep biosolids injection.

Drilling data of some 64 wells from Oil Gas and Salt Resources Library, London, Ontario, have been studied for this project. The data cover eight counties of Southwestern Ontario including Norfolk, Oxford, Huron, Elgin, Middlessex, Kent, Lambton and Essex Counties (Figure B.1).

B.1 Structure and Tectonics

B.1.1 Regional Tectonics

Plates movement and related orogenic activities, centred at or beyond the craton margins, are responsible for basement arch movement in the Canadian Craton.

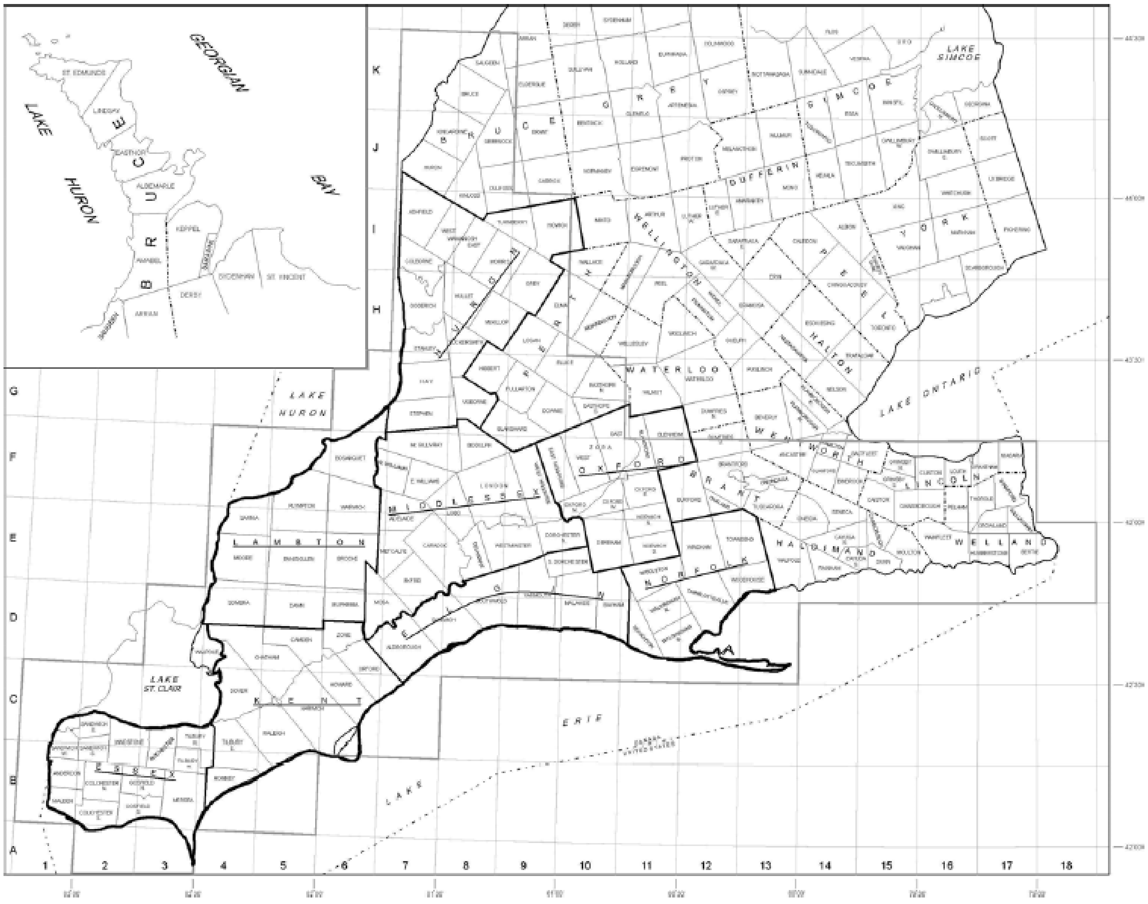


Figure B.1: Geographical map of SW Ontario showing studied counties in dark boundaries.

"Phanerozoic epeirogeny of the Canadian Craton was an intermittent tectonic process, presumably initiated from time to time by more intensive plates movement and associated orogenies centred on the east, west, north, and south margins of the continent" (Sanford, 1985). Tectonic processes that affected the southeastern part of the Canadian Craton have been divided into two cycles by Sanford (1985). The first tectonic cycle extends from the Late Precambrian to Late Palaeozoic while the second extends from the Early Mesozoic to present. Extensional tectonics, rifting, and eventual separation of the continental mass by seafloor spreading occurred during Late Precambrian to Early Ordovician times in the first part of the first tectonic cycle. During the second part of the first tectonic cycle, tectonic forces reversed and an extensional regime was converted to a compressional regime, which resulted in closing of the proto-Atlantic and eventual collision of the continents.

During the second tectonic cycle, which started in the Triassic and still continues, seafloor spreading again became dominant. Rifting and pulling apart of the continent at the onset of each of the two Phanerozoic tectonic cycles initiated uplift, faulting and dyke and pluton emplacement over a wide region of the southern craton. It is believed that most wide spread and intensive cratonic movements have been associated with orogenic events triggered by the compressional tectonic phase during Early Ordovician to Late Palaeozoic.

Much of the resulting cratonic uplift was along the axes of the arches (positive basement trends) that criss crossed the continent (Figure B.2) in dominantly northeast (e.g. Henrietta Maria Arch, and Findlay / Algonquin Arch etc.) and northwest directions (e.g. Severn Arch and Saguenay Arch etc). In response to the succession of positive basement high trends, there was corresponding down warping of the intervening crust to form cratonic basins, and these two complementary processes of high and low continued to evolve over long periods of the geological time. Due to intense tectonic activity associated with Appalachian and Greenland Orogenies, the most intensive arch movements were along the southeast and northwest margins of the craton. The succession of paleogeological models (Sanford, 1985) shows (Figure B.3) structural deformation associated with repeated positive and negative movements in the geological time.

It is evident from this model of the Phanerozoic epeirogeny involving arch rejuvenation and associated basin subsidence that broad segments of the Canadian Craton were intermittently tectonically active throughout much of the Palaeozoic time. Higher concentrations of earthquake epicentres that either follows the axes or the margins of several basement arches suggest that certain segments of the craton are still tectonically mildly active.

B.1.2 Algonquin Arch

Southern Ontario straddles a broad, northeast–southwest trending Precambrian basement high known as Algonquin Arch. The Algonquin Arch is a southwestward plunging anticlinal structure and is a continuation of the Findlay Arch, separated from each other by the Chatham Sag (Powell, 1984) (Figure B.2). The Chatham Sag, formed by mutual plunging sections of the two arches Algonquin and Findlay, has a regional trend of northwest to southeast. This arch complex initiated in the Late Precambrian time and was reactivated (Stanford, 1985; Carter[1], 1996) from time to time during the Palaeozoic to form a broad platform between the more rapidly subsiding Michigan Basin on the west and the Allegheny trough to the southeast (part of the Appalachian Basin). The Algonquin Arch divides the Ontario Palaeozoic succession into two parts, one continues westward and northward into the Michigan Basin while other continues southward and eastward into the Appalachian Basin. The Michigan Basin is nearly circular and has a maximum depth of about 4,267 m, while the Appalachian Basin is elongate, has maximum depth of about 12,000 m (Brigham, 1971; Easton, 1992) (Figure B.2). The Palaeozoic sequences that overlie and flank the arch complex are up to 1500 m (Stanford, 1985) thick and consist of a variety of carbonates, shales, evaporites, and minor sandstones.

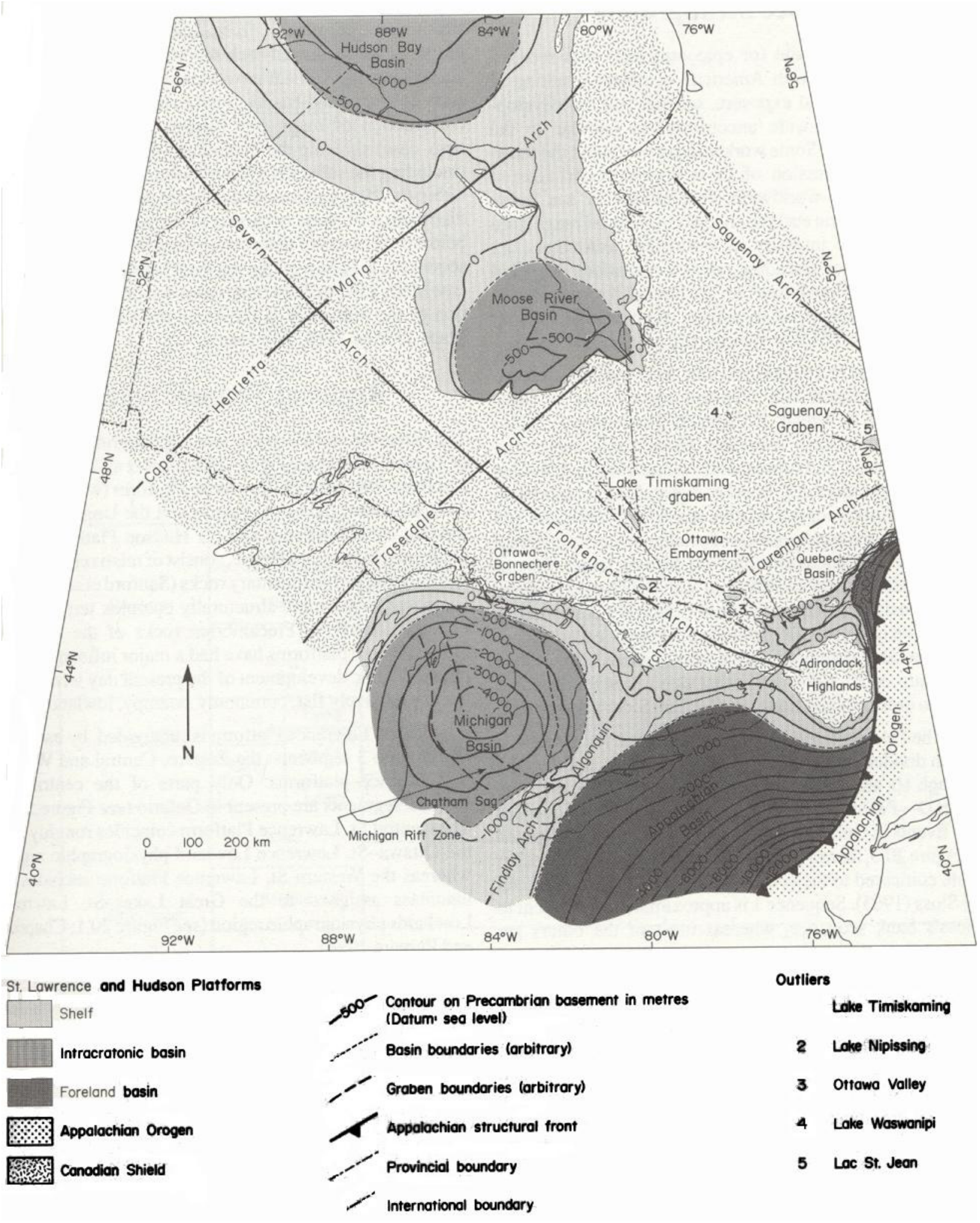


Figure B.2: Principal Paleozoic and Mesozoic tectonic elements of Ontario and adjacent regions (After Easton, 1992).

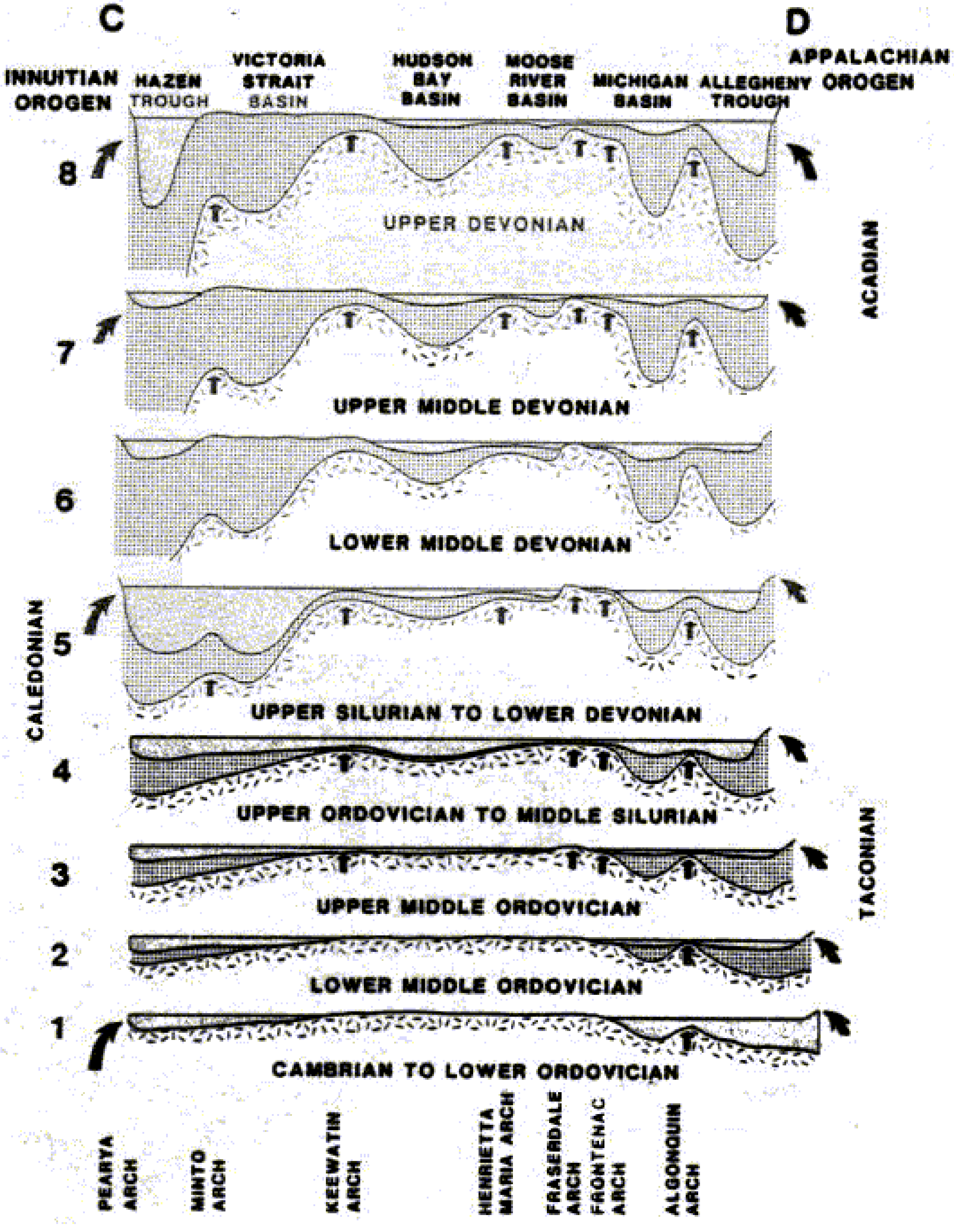


Figure B.3: Paleozoic depositional cycles and tectonics elements (After Sanford, 1985).

B.2 Geology of SW Ontario

B.2.1 Introduction

Southern Ontario is underlain by a succession of Palaeozoic sedimentary rocks ranging in age from the Late Cambrian to Late Devonian and locally Mississippian. These strata thin, pinch out, or have been eroded away over the crest of the Algonquin Arch (Carter[2], 1996).

The sedimentary sequence in southern Ontario extends over about 10^5 km^2 with about one-third of this area beneath Lakes Ontario, Erie, St. Clair and Huron. The sequence is 1475-1500 m (Carter[2], 1996; Baker, 1984) thick, but pinches out against the Precambrian Shield to the north and northeast. The Algonquin and Findlay Arches divide the Palaeozoic strata of Ontario into two parts, one in the Michigan Basin and other in the Appalachian Basin. The general strike of the strata is northwest - southeast in the study area and the strata lie almost horizontally with a regional inclination of 6 - 9 m / 1000 m (Powell, 1984) towards the southwest.

Surface exposures of the Palaeozoic succession in southern Ontario are poor, but due to intensive drilling for exploration of oil and gas in this area, enough borehole data are available to build an excellent stratigraphy of southwestern Ontario. Dominantly, the stratigraphic units appear to be of shallow platformal origin, essentially carbonate sequences punctuated by minor terrigenous units, with the exception of the evaporite sequence of the Salina Group of the Late Silurian age. The only periods of prolonged clastic deposition are the Upper Ordovician (Queenston shale) and Upper Devonian (Kettle Point – Port Lambton shales) resulting from the uplift of the Appalachian orogenic belt (Powell, 1984). Southward and eastward into the Appalachian Basin, abrupt lateral facies change are common. The widespread regional unconformities in southern Ontario appear closely related to periodic uplift and tectonic activity within the time of the Appalachian orogen.

B.2.2 Regional Stratigraphy

The study area is composed of Palaeozoic sedimentary cover. Mainly it is a sequence of carbonates and shales with minor amounts of evaporites and sandstones (Table B.1). Based on the drilling data collected for this study, the maximum drilled thickness is 1469 m in Lambton County in the Sarnia area. Lambton County is located where the Algonquin and Findlay Arches plunge to form the Chatham Sag, hence it is the site of the thickest sedimentary accumulation in Southwestern Ontario. The depth and individual thicknesses of each formation / rock unit respective to the County are given in Table B.2 & B.3. The stratigraphic nomenclature (Table B.1) used in this study is that of the petroleum industry, as noted in their drilling logs.

Table B.1: Subsurface stratigraphic column of southwestern Ontario

Standard Reference		Group	Formation / Unit	Dominant Lithology
DEVONIAN	Upper		Kettle Point Fm.	Shale
	Middle		Hamilton	Calcareous Shale & Limestone
			Dundee Fm.	Limestone
		Detroit River	Lucas Fm.	Carbonate and Anhydrates
			Amherstburg Fm.	Dolomite & Limestone
	Lower		Bois Blanc Fm.	Dolomite & Limestone
			Springvale Mem.	Sandstone
SILURIAN	Upper		Bass Island Fm.	Dolomite
		Salina	G Unit (Shale)	Shale
			F Unit (Shale)	Shale
			E Unit (Carbonate)	Carbonate
			D Unit (Salt)	Salt
			C Unit (Shale)	Shale
			B Unit (Marker)	
			B Unit (Salt)	Salt
			B Unit (Anhy.)	Anhydrite
			A-2 Unit (Carb.)	Carbonate
			A-2 Unit (Shale)	Shale
			A-2 Unit (Anhy.)	Anhydrite
			A-1 Unit (Carb.)	Carbonate
			A-1 Unit (Evap.)	Evaporite
	Middle		Guelph Fm.	Dolomite
		Amabel	Goat Island Fm.	Dolomite
			Gasport / Wiarton Fm.	Dolomitic Limestone
			Rochester Fm.	Dolomitic shale
			Irondequoit	
			Reynales / Fossil Hill Fm.	Dolomite
	Lower	Cataract	Cabot Head Fm.	Shale & few Dolomite
			Manitoulin Fm.	Dolomite
ORDOVICIAN	Upper		Queenston Fm.	Shale & Dolomite
			Meaford - Dundas Fm.	Shale & few Sandstone and Limestone
			Blue Mountain-Collingwood Fm.	Shale
	Middle	Trenton	Cobourg Fm.	Limestone
			Sherman Fall/Verulam Fm.	Limestone and Shale
			Kirkfield Fm.	Limestone
		Black River	Coboconk Fm.	Limestone
			Gull River Fm.	Limestone and Dolomite
			Shadow Lake Fm.	Dolomite and Shale
CAMBRIAN	Upper			Sandstone & few Carbonate

Table B.2: Geological record showing top (m) of formations from different wells in SW Ontario

Formation / Unit	Norfolk (Walsingham)	Oxford (Blanford)	Oxford (Blenheim)	Oxford (Blanford)
Kettle Point Fm.				
Hamilton				
Dundee Fm.	92.5			54.9
Lucas Fm.				62.5
Amherstburg Fm.	127.0			125.0
Bois Blanc Fm.	149.0	11.0		140.5
Springvale Mem.	167.5			
Bass Island Fm.	179.5	16.8		153.0
G Unit (Shale)	198.0			159.7
F Unit (Shale)	202.7	37.5	55.7	192.9
E Unit (Carb.)	240.7	76.2	79.3	
D Unit (Salt)		98.5		
C Unit (Shale)	263.5	99.5	92.0	226.2
B Unit (Marker)	280.3	112.8	106.7	
B Unit (Salt)				
B Unit (Anhy.)	288.5	118.9		246.0
A-2 Unit (Carb.)	293.7	125.0	121.9	246.9
A-2 Unit (Shale)				
A-2 Unit (Anhy.)		139.5		260.6
A-1 Unit (Carb.)	304.7			262.7
A-1 Unit (Evap.)				
Guelph Fm.	309.3	140.2	136.5	268.2
Goat Island Fm.	324.2	222.5		298.7
Gasport / Wiarton Fm.	371.1	237.7		358.7
Rochester Fm.	382.7	250.5	242.5	361.5
Irondequoit	396.1			377.0
Reynales / Fossil Hill Fm.	398.6	262.1	254.5	379.8
Cabot Head Fm.		272.8	256.0	383.4
Manitoulin Fm.		287.0	277.0	402.0
Queenston Fm.		295.7	280.4	410.6
Meaford - Dundas Fm.				595.3
Blue Mountain-Collingwood Fm.		426.7	624.9	730.0
Cobourg Fm.		647.2	660.5	779.4
Sherman Fall/Verulam Fm.			671.2	836.4
Kirkfield Fm.			769.9	887.6
Coboconk Fm.		806.5	812.0	925.1
Gull River Fm.				945.8
Shadow Lake Fm.		873.0	881.8	1012.2
Cambrian		874.7	883.0	1016.2
Precambrian				1023.5

(PTO)

Table B.2 (Cont'd)

Formation / Unit	Huron (Goderich)	Elgin (Aldborough)	Elgin (Dunwich)	Elgin (Aldborough)
Kettle Point Fm.				
Hamilton			61.6	
Dundee Fm.	59.8	76.0	78.6	71.4
Lucas Fm.	75.9	134.0	107.6	129.2
Amherstburg Fm.	156.0		153 / 56.7	
Bois Blanc Fm.	205.8	173.7	209.7	174.9
Springvale Mem.				238.3
Bass Island Fm.	255.5	256.0	236.2	251.1
G Unit (Shale)	350.6	330.2	263.7	
F Unit (Shale)	357.3	338.0	271.6	329.1
E Unit (Carb.)	403.2	366.2	298.4	363.3
D Unit (Salt)				
C Unit (Shale)	448.7	406.3	336.8	396.2
B Unit (Marker)	454.9	418.5		
B Unit (Salt)		430.0		420.6
B Unit (Anhy.)		476.0	360.6	
A-2 Unit (Carb.)	457.9	480.3	363.0	474.3
A-2 Unit (Shale)				
A-2 Unit (Anhy.)	507.5	505.7	383.4	
A-1 Unit (Carb.)	516.1	508.3	386.2	504.7
A-1 Unit (Evap.)	523.0		407.8	513.3
Guelph Fm.	526.4	518.3	409.7	517.2
Goat Island Fm.	591.3	551.7	429.8	
Gasport / Wiarton Fm.	600.7	573.6	434.6	
Rochester Fm.	615.1	598.3	473.7	
Irondequoit				
Reynales / Fossil Hill Fm.	619.4	613.5	484.0	
Cabot Head Fm.	638.2	616.5	492.9	
Manitoulin Fm.	659.1	646.2	506.0	
Queenston Fm.	668.8	654.6	528.2	
Meaford - Dundas Fm.		772.4	665.7	
Blue Mountain-Collingwood Fm.		906.0	793.1	
Cobourg Fm.	885.4	943.6	831.5	
Sherman Fall/Verulam Fm.	941.3	968.7	882.4	
Kirkfield Fm.	985.5	1035.0	922.3	
Coboconk Fm.	1029.3	1082.0	976.3	
Gull River Fm.	1039.2	1109.8	1001.6	
Shadow Lake Fm.	1119.4	1206.6	1086.9	
Cambrian	1124.0	1207.3	1090.0	
Precambrian		1230.1	1099.7	

(PTO)

Table B.2 (Cont'd)

Formation / Unit	Norfolk	Middlesex (Ekfrid)	Kent (Romney)	Lambton (Dawn)
Kettle Point Fm.			56.4	22.3
Hamilton		57.0	67.4	79.2
Dundee Fm.	92.5	69.0	87.0	150.9
Lucas Fm.		106.0	130.5	170.7
Amherstburg Fm.	127.0	151.6	156.4	
Bois Blanc Fm.	149.0	195.0	182.2	257.6
Springvale Mem.	167.5			
Bass Island Fm.	179.5	224.3	215.4	295.7
G Unit (Shale)	198.0	258.4	263.8	323.1
F Unit (Shale)	202.7	267.2	270.5	341.4
E Unit (Carb.)	240.7	313.8	297.0	367.6
D Unit (Salt)		333.3		
C Unit (Shale)	263.5	335.2	341.3	415.7
B Unit (Marker)	280.3	349.6		430.1
B Unit (Salt)			371.1	441.4
B Unit (Anhy.)	288.5	358.7	378.0	488.6
A-2 Unit (Carb.)	293.7	362.0	380.1	488.9
A-2 Unit (Shale)				523.0
A-2 Unit (Anhy.)		387.0	399.8	547.7
A-1 Unit (Carb.)	304.7	390.7	403.4	550.8
A-1 Unit (Evap.)		409.0		586.4
Guelph Fm.	309.3	411.0	414.6	591.0
Goat Island Fm.	324.2	429.8	441.9	604.4
Gasport / Wiarton Fm.	371.1	465.4	513.9	
Rochester Fm.	382.7	471.2	518.0	
Irondequoit	396.1			
Reynales/Fossil Hill Fm.	398.6	487.7	525.0	
Cabot Head Fm.		489.2	528.1	
Manitoulin Fm.		517.1	567.0	
Queenston Fm.		525.9	578.0	
Meaford - Dundas Fm.			667.6	
Blue Mountain-Collingwood Fm.		651.0	785.2	
Cobourg Fm.		819.0	822.3	
Sherman Fall/Verulam Fm.		849.0	844.3	
Kirkfield Fm.		904.4	890.6	
Coboconk Fm.		968.2	947.7	
Gull River Fm.		991.7	977.3	
Shadow Lake Fm.		1075.2	1059.3	
Cambrian		1076.4	1061.5	
Precambrian		1084.4	1090.2	

(PTO)

Table B.2 (Cont'd)

Formation / Unit	Lambton (Sarnia)	Lambton (Sarnia)	Essex (Mersea)	Essex (Mersea)
Kettle Point Fm.	36.0			
Hamilton	51.7	47.5		
Dundee Fm.	146.4	123.7	24.0	22.0
Lucas Fm.		154.8	56.0	49.6
Amherstburg Fm.		242.0	70.0	73.7
Bois Blanc Fm.	287.2	288.6	91.0	89.3
Springvale Mem.			113.0	
Bass Island Fm.	346.7	324.0	122.0	127.7
G Unit (Shale)	428.8	363.3	177.0	176.8
F Unit (Shale)	435.4	369.7	184.0	184.9
E Unit (Carb.)	572.6	477.6	204.0	208.3
D Unit (Salt)	594.9	505.7		
C Unit (Shale)	605.7	523.3	249.7	251.0
B Unit (Marker)	624.8	537.7		263.7
B Unit (Salt)	632.2	548.6		
B Unit (Anhy.)			280.5	278.5
A-2 Unit (Carb.)	725.0	634.9	285.7	286.0
A-2 Unit (Shale)	759.1	678.2		
A-2 Unit (Anhy.)	775.9	708.7	304.2	302.6
A-1 Unit (Carb.)	809.8	711.4	306.3	
A-1 Unit (Evap.)	845.0	751.0		
Guelph Fm.	850.5	756.8	314.7	319.2
Goat Island Fm.	856.2	762.0		
Gasport / Wiarton Fm.	863.8	766.3	405.6	375.0
Rochester Fm.	877.3	778.8	469.1	464.2
Irondequoit				
Reynales/Fossil Hill Fm.	879.0		474.7	469.8
Cabot Head Fm.	880.6		478.9	474.8
Manitoulin Fm.	918.5		518.2	512.5
Queenston Fm.	939.4		528.5	522.7
Meaford - Dundas Fm.			615.5	
Blue Mountain-Collingwood Fm.	1024.6		729.0	607.7
Cobourg Fm.	1128.6		771.0	763.7
Sherman Fall/Verulam Fm.	1160.0		792.3	785.0
Kirkfield Fm.	1209.2		833.8	819.5
Coboconk Fm.	1278.0		870.6	863.1
Gull River Fm.	1315.5		901.4	889.4
Shadow Lake Fm.	1428.0		1007.1	1000.8
Cambrian	1431.2		1011.0	1004.0
Precambrian	1469.0		1055.0	1049.5

Table B.3: Lithological thicknesses (m) based on drilling record from different wells in SW Ontario

Formation / Unit	Norfolk (Walsingham)	Oxford (Blanford)	Oxford (Blenheim)	Oxford (Blanford)
Hamilton				
Dundee Fm.	34.5			7.6
Lucas Fm.				62.5
Amherstburg Fm.	22			15.5
Bois Blanc Fm.	18.5	5.8		12.5
Springvale Mem.	12			
Bass Island Fm.	19	20.7		6.7
G Unit (Shale)	4.7			33.2
F Unit (Shale)	38	38.7	23.6	33.3
E Unit (Carb.)	22.8	22.3	12.7	
D Unit (Salt)		1		
C Unit (Shale)	16.8	13.3	14.7	19.8
B Unit (Marker)	8.2	6.1	15.2	
B Unit (Salt)				
B Unit (Anhy.)	5.2	6.1		0.9
A-2 Unit (Carb.)	11	14.5	14.6	13.7
A-2 Unit (Shale)				
A-2 Unit (Anhy.)		0.7		2.1
A-1 Unit (Carb.)	4.6			5.5
A-1 Unit (Evap.)				
Guelph Fm.	14.9	82.3	106	30.5
Goat Island Fm.	46.9	15.2		60
Gasport / Wiarton Fm.	11.6	12.8		2.8
Rochester Fm.	13.4	11.6	12	15.5
Irondequoit	2.5			2.8
Reynales / Fossil Hill Fm.		10.7	1.5	3.6
Cabot Head Fm.		14.2	21	18.6
Manitoulin Fm.		8.7	3.4	8.6
Queenston Fm.		131	344.5	184.7
Meaford - Dundas Fm.				134.7
Blue Mountain-Collingwood Fm.		220.5	35.6	49.4
Cobourg Fm.		159.3	10.7	57
Sherman Fall/Verulam Fm.			98.7	51.2
Kirkfield Fm.			42.1	37.5
Coboconk Fm.		66.5	69.8	20.7
Gull River Fm.				66.4
Shadow Lake Fm.		1.7	1.2	4
Cambrian				7.3

(PTO)

Table B.3 (Cont'd)

Formation / Unit	Huron (Goderich)	Elgin (Aldborough)	Elgin (Dunwich)	Elgin (Aldborough)
Hamilton			17	
Dundee Fm.	16.1	58.4	29	56.4
Lucas Fm.	80.1	39.7	45.4	45.7
Amherstburg Fm.	49.8		56.7	
Bois Blanc Fm.	49.7	82.3	26.5	63.4
Springvale Mem.				12.8
Bass Island Fm.	95.1	74.2	27.5	70.4
G Unit (Shale)	6.7	8	7.9	
F Unit (Shale)	45.9	28	26.8	34.2
E Unit (Carb.)	45.5	40.1	38.4	32.9
D Unit (Salt)				
C Unit (Shale)	6.2	12.2	23.8	24.4
B Unit (Marker)	3	11.5		
B Unit (Salt)		46		53.7
B Unit (Anhy.)		4.3	2.4	
A-2 Unit (Carb.)	49.6	25.4	20.4	25.6
A-2 Unit (Shale)				
A-2 Unit (Anhy.)	8.6	2.6	2.8	
A-1 Unit (Carb.)	6.9	10	21.6	8.5
A-1 Unit (Evap.)	3.4		1.9	3.9
Guelph Fm.	64.9	33.4	20.1	7+
Goat Island Fm.	9.4	21.9	4.8	
Gasport / Wiarton Fm.	14.4	24.7	39.1	
Rochester Fm.	4.3	15.2	10.3	
Irondequoit				
Reynales / Fossil Hill Fm.	18.8	3	8.9	
Cabot Head Fm.	20.9	29.7	13.1	
Manitoulin Fm.	9.7	8.4	22.2	
Queenston Fm.	216.6	117.8	137.5	
Meaford - Dundas Fm.		133.6	127.4	
Blue Mountain-Collingwood Fm.		37.6	38.4	
Cobourg Fm.	55.9	25.1	50.9	
Sherman Fall/Verulam Fm.	44.2	66.3	39.9	
Kirkfield Fm.	43.8	47	54	
Coboconk Fm.	9.9	27.8	25.3	
Gull River Fm.	80.2	96.8	85.3	
Shadow Lake Fm.	4.6	0.7	3.1	
Cambrian		22.8	9.7	

(PTO)

Table B.3 (Cont'd)

Formation / Unit	Norfolk	Middlesex (Ekfrid)	Kent (Romney)	Lambton (Dawn)
Hamilton		12	19.6	71.7
Dundee Fm.	34.5	37	43.5	19.8
Lucas Fm.		45.6	25.9	86.9
Amherstburg Fm.	22	43.4	25.8	
Bois Blanc Fm.	18.5	29.3	33.2	38.1
Springvale Mem.	12			
Bass Island Fm.	19	34.1	48.4	27.4
G Unit (Shale)	4.7	8.8	6.7	18.3
F Unit (Shale)	38	46.6	26.5	26.2
E Unit (Carb.)	22.8	19.5	44.3	48.1
D Unit (Salt)		1.9		
C Unit (Shale)	16.8	14.4	29.8	14.4
B Unit (Marker)	8.2	9.1		11.3
B Unit (Salt)			6.9	47.2
B Unit (Anhy.)	5.2	3.3	2.1	0.3
A-2 Unit (Carb.)	11	25	19.7	34.1
A-2 Unit (Shale)				11.3
A-2 Unit (Anhy.)		3.7	3.6	3.1
A-1 Unit (Carb.)	4.6	18.3	11.2	35.6
A-1 Unit (Evap.)		2		4.6
Guelph Fm.	14.9	18.8	27.3	13.4
Goat Island Fm.	46.9	35.6	72	
Gasport / Wiarton Fm.	11.6	5.8	4.1	
Rochester Fm.	13.4	16.5	7	
Irondequoit	2.5			
Reynales / Fossil Hill Fm.		1.5	3.1	
Cabot Head Fm.		27.9	38.9	
Manitoulin Fm.		8.8	11	
Queenston Fm.		125.1	89.6	
Meaford - Dundas Fm.			117.6	
Blue Mountain-Collingwood Fm.		168	37.1	
Cobourg Fm.		30	22	
Sherman Fall/Verulam Fm.		55.4	46.3	
Kirkfield Fm.		63.8	57.1	
Coboconk Fm.		23.5	29.6	
Gull River Fm.		83.5	82	
Shadow Lake Fm.		1.2	2.2	
Cambrian		8	28.7	

(PTO)

Table B.3 (Cont’d)

Formation / Unit	Lambton (Sarnia)	Lambton (Sarnia)	Essex (Mersea)	Essex (Mersea)
Hamilton	94.7	76.2		
Dundee Fm.	140.8	31.1	32	27.6
Lucas Fm.		87.2	14	24.1
Amherstburg Fm.		46.6	21	15.6
Bois Blanc Fm.	59.5	35.4	22	38.4
Springvale Mem.			9	
Bass Island Fm.	82.1	39.3	55	49.1
G Unit (Shale)	6.6	6.4	7	8.1
F Unit (Shale)	137.2	107.9	20	23.4
E Unit (Carb.)	22.3	28	45.7	42.7
D Unit (Salt)	10.8	17.7		
C Unit (Shale)	19.1	14.3	30.8	12.7
B Unit (Marker)	7.4	11		14.8
B Unit (Salt)	92.8	86.3		
B Unit (Anhy.)			5.2	7.5
A-2 Unit (Carb.)	34.1	43.3	18.5	16.6
A-2 Unit (Shale)	16.8	30.5		
A-2 Unit (Anhy.)	33.9	2.7	2.1	16.6
A-1 Unit (Carb.)	35.7	39.6	8.4	
A-1 Unit (Evap.)	5	5.8		
Guelph Fm.	5.7	5.2	90.9	55.8
Goat Island Fm.	7.6	4.3		
Gasport / Wiarton Fm.	13.5	12.5	63.5	89.2
Rochester Fm.	1.7		5.6	5.6
Irondequoit				
Reynales / Fossil Hill Fm.	1.6		4.2	5
Cabot Head Fm.	37.9		39.3	37.7
Manitoulin Fm.	20.9		10.3	10.2
Queenston Fm.	85.2		87	85
Meaford - Dundas Fm.			113.5	
Blue Mountain-Collingwood Fm.	104		42	156
Cobourg Fm.	31.4		21.3	21.3
Sherman Fall/Verulam Fm.	49.2		41.5	34.5
Kirkfield Fm.	68.8		36.8	43.6
Coboconk Fm.	37.5		30.8	26.3
Gull River Fm.	112.5		105.7	111.4
Shadow Lake Fm.	3.2		3.9	3.2
Cambrian	37.8		44	45.5

B.3 Porosity and Permeability

Core analysis of some selected formations and selected oil and gas pool data from southwestern Ontario show that there are only few formations that possess both good porosity and relatively high permeability (Table B.4 & B.5).

For deep biosolids disposal, the most promising rock units of the Silurian sequence with some reasonable values of porosity and permeability are A-1 and A-2 carbonates of the Salina Group and Guelph Formation with porosity and permeability ranges of 1.5% – 25% (average 9.9%) and < 0.1 – 1847 mD (average 53.6 mD) respectively.

In the Ordovician sequence, there appears to be no rock unit that is suitable for solids injection, as the porosity and permeability range is 0.88 – 6% and 0.2 – 10 mD respectively.

The Cambrian sequence is much better than the Ordovician sequence in terms of porosity and permeability, as the porosity ranges from 4.86 – 20% and permeability from < 0.1 – 300 mD with average of 8.5% and 69 mD.

In the case of DBI, fracture permeability also plays an important role. As DBI produces high pressure in a target formation during injection, it helps the natural fractures to open. The network of these open fractures provides an easy conduit for liquid flow and therefore it helps to dissipate the pressure more rapidly. This phenomenon can be an advantage in the event of DBI because of the active tectonic history in Southwestern Ontario, even if the overall condition of permeability is not as good as in high porosity sediments. Fracture permeability depends upon a fracture's aperture. The same network of fractures would also be helpful for the generated methane to migrate and accumulate in economic reserves.

It is a usual practice in the petroleum industry to record any mud lost circulation and fluid (water, oil, & gas) encountered during drilling a well. These zones show the presence of porosity and permeability in a qualitative sense. Drilling records studied for this report show some observations in this regard. Available information about fluid encountered and mud lost circulation are summarized in Table B.6.

Table B.4: Porosity and permeability data of oil and gas pools in SW Ontario

County	**Town**	**Pool**	**Rock Type**	**Productive Interval (m)**	**Thickness**	**Porosity %**	**Permeability mD**
Oil & Gas Pools in the Silurian Sequence of Southwestern Ontario							
Lambton	Sombra	Becher west	A-1 Carbonate	561.4 - 564.2	2.8	10 - 25 Ave. 7.5	7.7 (up to 50)
Lambton	Sombra	N/A	A-1 Guelph reef	562 - 570.6	8.6	7.2	170.70
Lambton	Sombra	Terminus	A-1 Guelph reef	491.3 - 495.3	4.0	9.3	46.30
Lambton	Dawn	Bentpath	A-1 Guelph reef	499 - 538.9	39.9	9.6	18.40
Lambton	Dawn	Dawn 47 - 49	A-1 Guelph reef	561.7 - 568.5	6.8	9 - 12.5	N/A
Lambton	Dawn	Dawn 59-85	A-1 Guelph reef	470.9 - 561.1	90.2	11.0	N/A
Lambton	Dawn	Dawn 156	A-2 Carbonate	494.1 - 499.6	5.5	11.0	N/A
			A-1 Guelph reef	524 - 528.5	4.5	N/A	
Lambton	Dawn	Dawn 167	A-1 Guelph reef A-2 Carbonate	493.2 - 502.3	9.1	11.0	N/A
Lambton	Enniskillen	Rosedale	A-1 Guelph reef	502.6 - 589.2	86.6	7.5	13.00
Lambton	Enniskillen	Enniskillen 28	A-1 Guelph reef	571.8 - 620.3	48.5	11.0	N/A
Lambton	Moore	Payne	A-1 Guelph reef	599.8 - 612.6	12.8	11.0	N/A
Lambton	Moore	Brigden	A-1 Carbonate	642.5 - 646.2	3.7	3.5	25.10
Lambton	Moore	Corunna	A-1 Guelph reef	655 - 664.8	9.8	7.3	57.90
Kent	Raleigh	D'clute	A-1 & A-2 Carb. & Guelph	432.8 - 474.6	41.8	8.0	N/A
Kent	Chatham Gore	Chatham A	Guelph & A-1 Carbonate	444.4 - 445	0.6	10.0	N/A
Kent	Zone	Zone	A-1 & A-2 Carbonate	438.3 - 445.6	7.3	18.6	N/A
Elgin	Dunwich	Cowal	A-1 Carbonate	350.2 - 375.5	25.3	11.0	N/A
Elgin	Malahide, Yarmjuth	N/A	Guelph Carbonate	323.7 - 331	7.3	8.0	N/A
Oxford	Dereham	Brownsville	Guleph Carbonate	274.3 - 274.9	0.6	11.0	N/A
Essex	Tilbury West	Staples	Guelph Reef	354.2 - 356	1.8	8.0	N/A

(PTO)

Table B.4 (Cont'd)

County	Town	Pool	Rock Type	Productive Interval (m)	Thickness	Porosity %	Permeability mD
Oil & Gas Pools in the Ordovician Sequence of Southwestern Ontario							
Kent	Dover	Dover	Trenton Dolomite (TD)	891.5 - 914.4	22.9	N/A	N/A
Essex	Colchester South	Colchester	TD	654.7 - 659.9	5.2	4.0	1.49
Essex	Malden	Malden	T D	670.3 - 677	6.7	6.0	10.00
Essex	Malden	Malden 3-41-IV	T D	733.7 - 751.6	17.9	2.7	N/A
Oil & Gas Pools in the Cambrian Sequence of Southwestern Ontario							
Kent	Orford	Clearville	Cambrian Dolomite & Sand	1206.4-1207.9	1.5	10-20%	5-300
Oxford	Blenheim	Gobles	Cambrian Sandstone	878.7 - 879.3, 880.9 - 881.5 , 882.1 - 882.7	0.6, 0.6, 0.6	11.8	67.00
Oxford	Blandford	Innerkip	Cambrian Sandstone	883.9 - 889.4	5.5	11.6	1.00
Elgin	Dunwich	Willey	Cambrian Sandstone	1095.5-1102.8	7.3	9.2	1-182 Ave. 30.6
All oil and gas reservoirs are shallower than 200 m in the Devonian Sequence of Southwestern Ontario; N/A = Not Available							

Table B.5: Porosity and permeability data from core analysis

County	Town	Rock Type	Core Interval (m)	Thickness	Porosity (%)	Permeability (mD)	Permeability Range
Silurian Sequence							
Lambton	Dawn	A-2 Carbonate	481.8 - 492.6	10.8	1.7	0.08	< 0.01 - 0.34
Kent	Tilbury East	A-1 Carbonate	410.0 - 420.3	10.3	4.3	8.48	< 0.1 - 195
Lambton	Enniskillen	A-1 Carbonate	494.0 - 502.6	8.6	1.5	1.9	< 0.1 - 24
Essex	Tilbury West	Guelph	353.1 - 359.3	6.2	5.4	114.62	2.5 - 475
Kent	Tilbury East	Guelph	420.3 - 445.3	25.0	4.6	122.27	< 0.1 - 1847
Lambton	Dawn	Guelph	568.1 - 598.3	30.2	8.4	3.89	0.09 - 11.8
Lambton	Enniskillen	Guelph	502.9 - 589.2	86.3	7.8	13.67	< 0.1 - 145
Lambton	Dawn	Goat Island	598.6 - 604.1	5.5	6.1	2.2	< 0.1 - 11.6
Lambton	Enniskillen	Goat Island	628.8 - 646.5	17.7	0.7	< 0.1	very low
Lambton	Enniskillen	Gas Port	646.8 - 662.0	15.2	3.2	2.46	< 0.1 - 31.5
Lambton	Enniskillen	Rochestor	662.0 - 666.9	4.9	2.7	10.67	1.1 - 46.3
Ordovician Sequence							
Lambton	Sombra	Coboconk	1038.6 - 1053.6	15.0	1.3	1.99	< 0.01 - 16
Kent	Dover	Gull River	1106.0 - 1131.6	25.6	0.9	0.2	< 0.1 - 1.0
Cambrian Sequence							
Lambton	Sarnia	Cambrian	1467.0 - 1471.6	4.6	4.9	0.83	< 0.1 - 6.05
Elgin	Aldborough	Cambrian	1211.6 - 1229.0	17.4	6.1	5.06	< 0.1 - 47
Elgin	Dunwich	Cambrian	1096.4 - 1100.0	3.6	7.8	21.19	0.11 - 134
Elgin	Dunwich	Cambrian	1094.9 - 1100.8	5.9	7.4	9.87	0.15 - 39
Oxford	Blenheim	Cambrian	873.5 - 877.6	4.1	8.9	117.45	0.1 - 804
Oxford	Blandford	Cambrian	872.5 - 877.5	5.0	9.8	5.19	< 0.1 - 135

Table B.6: Data of fluid encountered and lost circulation during drilling in SW Ontario

County	Town	Formation / Unit	Interval (m)	Thickness	Initial Water Record	Initial Oil Record	Initial Gas Record	Mud Lost Circulation
Kent	Romeny	Bois Blanc	205.0 - N/A	N/A			Show	
			210.0 - N/A	N/A			Show	
		Collingwood	796.0 - N/A	N/A		Show		
		Sherman Fall	847.8 - 878.8	31		Show		
			850.0 - 853.0	3		Show		
Lambton	Dawn	Lucas	217.9 - N/A	N/A	Show			
		Cambrian	1438.0 - N/A	N/A	Show			
Essex	Mersea	Guelph	320.0 - N/A	N/A	Show			
		Kirkfield	848.0 - 851.0	3	Show			
			863.0 - 866.0	3	Show			
		Coboconk	892.0 - N/A	N/A	Show			
			896.0 - N/A	N/A	Show			Lost
			925.0 - 930.0	5	Show			
Elgin	Dunwich	Shadow Lake & Cambrian	1089.1 - 1099.7	10.6		Show		
	Aldborough	Springvale	237.7 - 265.2	27.5	Show			
		A-2 Carbonate	486.1 - 487.7	1.6			Show	
		A-1 Carbonate	506.3 - 508.4	2.1			Show	

B.4 Discussion

In the case of possible Deep Biosolids Injection (DBI), the most important geological considerations for a target formation are its porosity, permeability, thickness, depth, and nature of the overlying stratigraphic column. To select a particular formation all of these parameters are important. For example, based on previous slurry injection practice in Western Canada, porosity of 30%, permeability of 2 – 4 Darcy, thickness of 20 m, depth of about 500 m, and a sequence of 2 - 3 overlaying layers of impermeable rock units would be considered ideal for DBI.

The stratigraphic column of Southwestern Ontario (Table B.1) shows there are multiple layers of shale and salt present in Upper Silurian and Devonian which can act as perfect caps for underlying target formations, and also these rock units are quite persistent through out the area studied (Table B.2). However, the salt is not present as persistently as the shales.

It is clear from the data collected that porosity and permeability values in Southwestern Ontario are low, compared to an ideal case. If there are relatively good porosity and permeability in a rock unit, the thickness is low, as in the thin Cambrian Sandstones.

To come up with a reasonable combination of thickness, porosity and permeability, the following criteria have been applied:

- Eliminate any strata less than 5% porosity,
- Eliminate any strata less than 11 mD permeability, and
- Eliminate any strata less than 2 m thickness.

The results are shown in Table B.7 and a relative ranking of the strata of Southwestern Ontario for DBI operation. Table B.7 shows that A-1 & A-2 carbonates of the Salina Group and underlying Guelph Formation of the Silurian sequence, as well as the Cambrian Sandstone, are relatively better candidates for DBI operation as compared with other rock units in the area. The Table B.7 also shows a ranking of counties and preferable areas in each county, in descending order.

Horizontal flow of ground water is quite helpful for the liquid squeezed from the biosolids to move away and remain at the same depth at which the injection took place. It eliminates the chances of upward escape of the liquid and also mixing with the fresh ground water aquifers. Because of quite low regional dip, about 6 – 9 m / 1000 m for the sedimentary cover of Southwestern Ontario, the strata are lying almost horizontal; therefore, this helps the ground water to flow horizontally. The natural flow barriers present persistently throughout the area in the form of shale and salt layers will also force horizontal flow. These will help the slurry liquid phase to remain isolated in the target formation at the depth.

Table B.7: Ranking of Southwestern Ontario for DBI based on average values (priority decreases from top to bottom)

Town	Formation/Rock Type	Thickness (m)	Porosity %	Permeability (mD)
1. KENT COUNTY				
Tilbury East	A-1, Guelph Carbonate	10.3 - 25.0	4.4	65.4 (max. 1847)
Raligh	A-1, A-2, Geulph Carbonate	41.80	8.0	N/A
Zone	A-1, A-2 Carbonate	7.30	18.6	N/A
2. LAMBTON COUNTY				
Sombra	A-1, Guelph Carbonate	2.8 - 8.6	8.0	74.90
Moore	A-1, Guelph Carbonate	3.7 - 12.8	7.3	41.50
Dawn	A-1, A-2, Geulph Carbonate	4.5 - 90.2	9.5	12.00
Enniskillen	A-1, Guelph Carbonate	48.5 - 86.6	17.1	13.34
3. ESSEX COUNTY				
Tilbury West	Guelph Carbonate	1.8 - 6.2	6.7	114.62
4. ELGIN COUNTY				
Dunwich	Cambrian	3.6 - 7.3	8.1	20.55
Malahide	Guelph Carbonate	7.3	11.0	N/A
Dunwich	A-1 Carbonate	25.3	8.0	N/A
5. OXFORD COUNTY				
Blenheim	Cambrian	4.1	8.9	117.45

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