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NUCLEAR FUEL WASTE DISPOSAL:
LONG-TERM STABILITY ANALYSIS

EVACUATION DES DECHETS DE COMBUSTIBLE NUCLEAIRE:
ANALYSE DE STABILITE A LONG TERME

G. J. Merrett, P. A. Gillespie

Whiteshell Nuclear Research
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Etablissement de recherches
nucléaires de Whiteshell

Pinawa, Manitoba R0E 1L0
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RÉSUMÉ

Dans le présent compte-rendu, on examine les événements et les conditions susceptibles de nuire à la stabilité à long terme d'une enceinte d'évacuation de déchets de combustible nucléaire ou aux régions de la lithosphère et de la biosphère que pourraient atteindre les radionucléides provenant d'une telle enceinte, par suite de leur migration.

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ABSTRACT

This report discusses events and processes that could adversely affect the long-term stability of a nuclear fuel waste disposal vault or the regions of the geosphere and the biosphere to which radionuclides might migrate from such a vault.

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1. INTRODUCTION

Canada is at present studying the concept of immobilization of its nuclear fuel waste and burial in a pluton in the Canadian Shield. The safety studies include an analysis of how radionuclides might escape from the disposal vault and migrate through the geosphere and biosphere to man. Preliminary analyses predict transit times of tens of thousands of years to over a million years; however, these analyses do not account for events and processes that could adversely affect the long-term stability of the system.

This report discusses the following mechanisms that could adversely affect long-term stability:

- disruptive activities of man
- vault-related events
- natural phenomena

The primary objective is not to predict detailed geological and ecological environments far into the future, but rather to conduct a probabilistic analysis that could be used to estimate the ranges of values that the major system parameters might assume during the time under consideration.

2. DISRUPTIVE ACTIVITIES OF MAN

In this report it is assumed that a disposal vault would be located at a depth of one kilometre in granite. Drilling and mining and the use of explosives are activities of man which could breach the vault or affect the geosphere barrier. Only the possibility of man's breaching the vault is considered here, because its consequences would be more serious than any effects on the geosphere barrier.

2.1 DRILLING AND MINING

The most likely way that a future generation could come into contact with the vault contents would be during a drilling or mining operation that impinges on the vault accidentally or deliberately. It is unlikely, however, that a vault would be breached accidentally during such an operation, as granite is quite plentiful at the earth's surface so deep mining to obtain its minerals would not be necessary.

Deliberate disruption of a vault by these methods could occur as a result of sabotage or curiosity. This is unlikely, however, considering the magnitude of the mining or drilling operation that would be required, the vast amount of material that would have to be removed, and the length of time this would take.

Deliberate disruption could also occur if the materials emplaced became valuable enough to make a deep mining operation economically feasible. For example, plutonium in an immobilized fuel vault might become a valuable resource. It is assumed, however, that any society with a technology advanced enough to want the plutonium would understand the hazards involved.

It is also possible that other materials placed in a vault, such as the container or the substance used to immobilize the fuel, might some day be very scarce. This could result in a future generation attempting to recover such materials without any knowledge of the radiation hazard involved. However, careful choice of the materials to be emplaced could reduce the likelihood of this happening. Also, the radioactivity of material in a vault would decrease with time. After a few hundred years, the average toxicity of the vault would be comparable to that of high-grade uranium ore bodies [1], so exposure to the vault contents after this period would be no more hazardous than exposure to these uranium ores.

2.2 USE OF EXPLOSIVE DEVICES

A disposal vault for irradiated fuel could be breached if a sufficiently large nuclear bomb were detonated at the surface above it. This might occur accidentally during a nuclear war, or deliberately, as an act of sabotage. In either case, it would require a far more powerful bomb than any yet developed [2]. In the event of such an explosion, the effect of exposing the vault contents would be insignificant compared to the widespread radioactive release produced by the bomb itself.

3. VAULT-RELATED EVENTS

A disposal vault and its contents would cause several changes in the surrounding rock. In addition to short-term effects during the construction and operation phases of the vault, there could be long-term changes due to the excavation, the presence of a heat source, and the presence of a radioactive source.

This assessment considers the disposal of irradiated fuel in a single-level, room-and-pillar mine at a depth of one kilometre in granite. Fuel containers would be emplaced within the rooms and completely surrounded by a buffer material. Rooms, tunnels, and shafts would later be backfilled.

In this report, the area of the vault is assumed to be 2.6 km^2. The spacing of the rooms is described by the extraction ratio (ER), which is defined as the width of a room divided by the width of a room plus pillar (see Figure 1). The spacing of the rows of containers in a room is called the pitch.

3.1 EXCAVATION

When the vault is excavated, the stress concentrations created in the walls, roof, and floor of each opening will depend on the in situ stress levels. The in situ vertical stresses are assumed to be due to the weight of the overlying rock, while the in situ horizonal stresses can

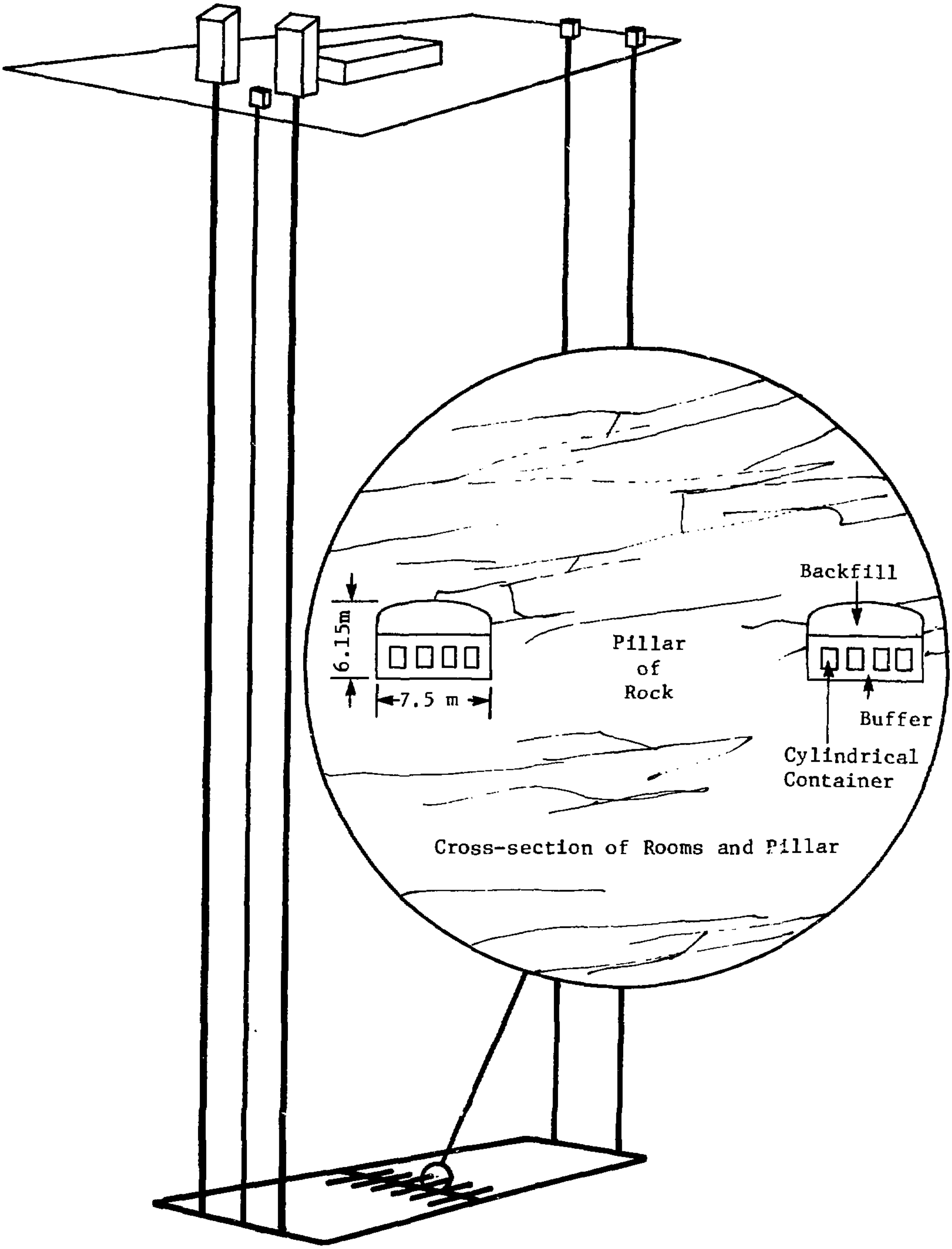


FIGURE 1: Waste Disposal Vault

arise from a Poisson effect (due to the vertical stresses), from the structural inhomogeneity of the region, from the tectonic history of the region, and from "residual" anomalies (due to erosion, metamorphism, thermal effects, and moisture effects). The relationship between the in situ horizontal stress (δ_H) and the in situ vertical stress (δ_V) is described by $\delta_H = K_o \delta_V$, where K_o is the coefficient of lateral earth pressure. K_o can be assumed to be constant, or to vary with depth.

Wiles and Mahtab [3] used a finite-element code to perform rock mechanics analyses for the case where a blast-fractured zone (BFZ) surrounds the vault and extends 0.5 m into the rock. K_o was assumed to be constant. In each element of rock, the strength ratio (SR), defined as the ratio of the Mohr-Coulomb shear strength to the local shear stress, was computed. If the shear stress exceeds the Mohr-Coulomb shear strength ($SR<1$), failure will occur. Figure 2 shows that the region of strength failure around a room is limited to the 0.5 m thick BFZ for time=0 (no heat effect). This is similar to what can be expected in a hard-rock mining situation, so the region of strength failure can be supported by conventional rock-bolting.

3.2 PRESENCE OF A HEAT SOURCE

The heat output from a typical irradiated fuel container decreases with time from an initial value of 260 W, as shown in Figure 3. The initial container power, the number of containers, the extraction ratio, and the pitch all determine the gross thermal loading (GTL), which is defined as the total initial heat generated per unit plan area of the vault. A more localized measure is the panel thermal loading (PTL), which is defined as the total initial heat generated in a room divided by the plan area of one room and one pillar.

Osnes and Brandshaug [4] used the data from Figure 3 to calculate the temperature distributions in the vault and in the surrounding granite. Figure 4 shows how the temperature rise at the mid-point of the vault would vary with time; at 20 to 50 years after emplacement a first peak would occur, and at 10 000 years a second peak would be caused by the actinide groups present in the unreprocessed fuel. The maximum temperature rise is shown to increase with the PTL. Figure 5 shows the temperature rise isotherms in the surrounding granite for times of 30, 200, and 10 000 years after emplacement. It can be seen that the region of elevated temperatures enlarges with time, and the temperatures within that region continue to increase through 10 000 years.

3.2.1 Stress Analysis

3.2.1.1 Room-and-Pillar Analysis

The heat created by the irradiated fuel would cause stress concentrations in the rock surrounding each room. Thermal-rock mechanics analyses were done by Acres Consulting Limited [3], assuming K_o to be constant and using design parameters of 25% for ER and 14 W/m^2 for PTL. The results showed that the room and pillar would be stable throughout the thermal cycle to 20 000 years after emplacement. This is illustrated by Figures 6, 7, and 8, which show SR contours for times of 50, 10 000, and

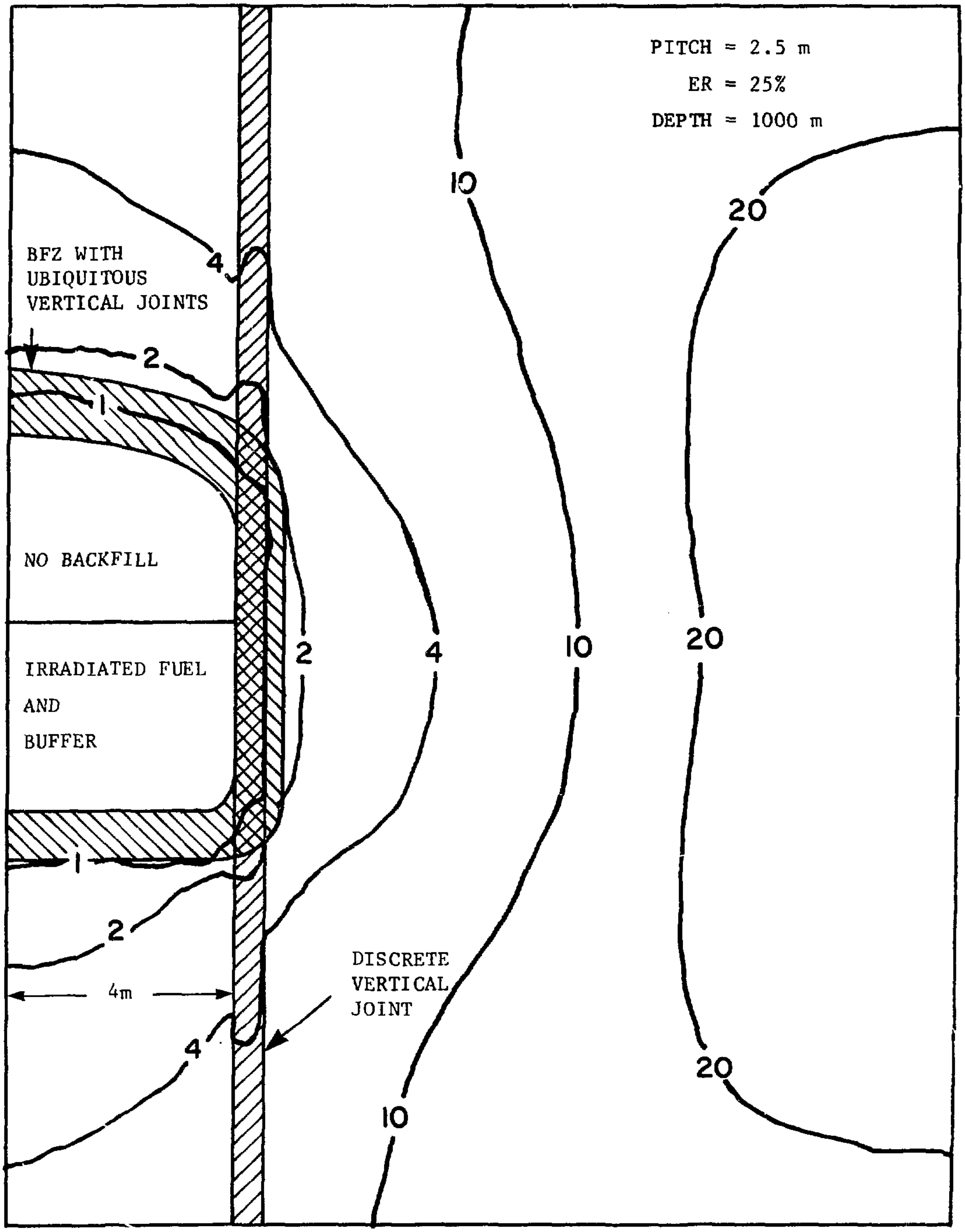


FIGURE 2: Contours of Strength Ratio in Granite Surrounding a Room in an Irradiated Fuel Disposal Vault [3]. Time = 0 years after emplacement.

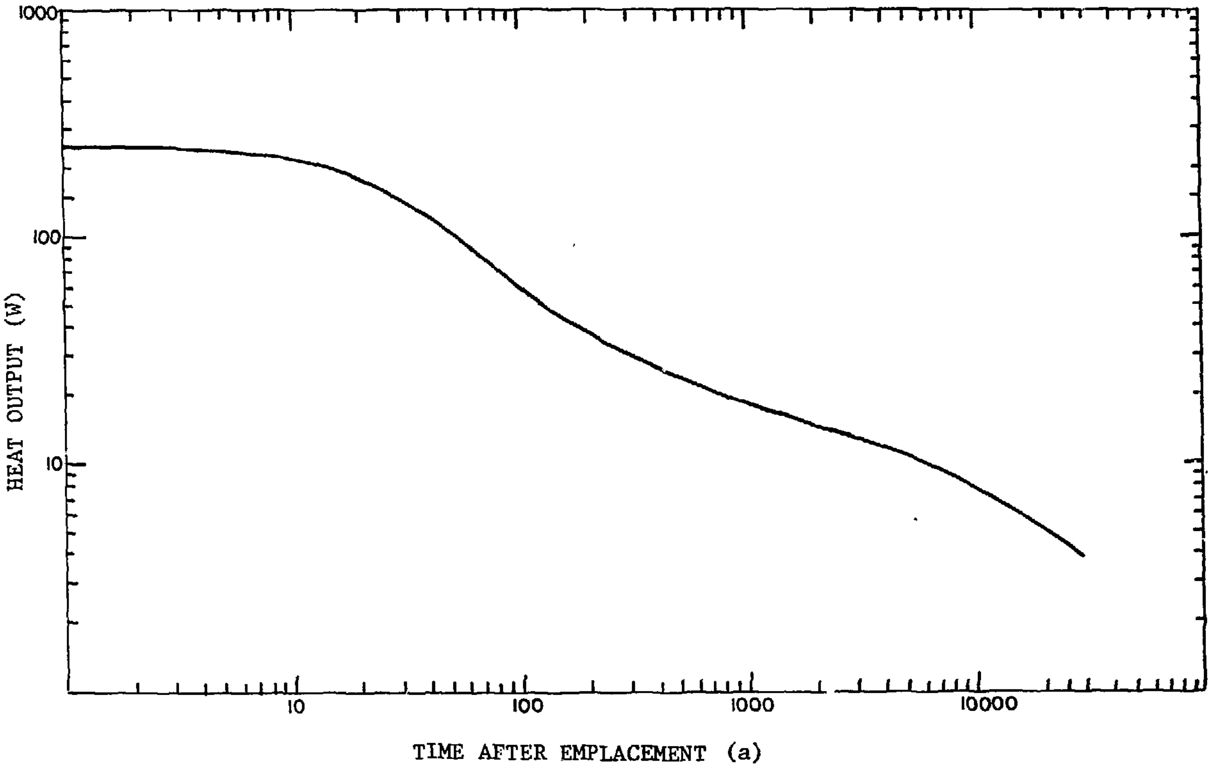


FIGURE 3: Heat Output from a Container of Irradiated Fuel

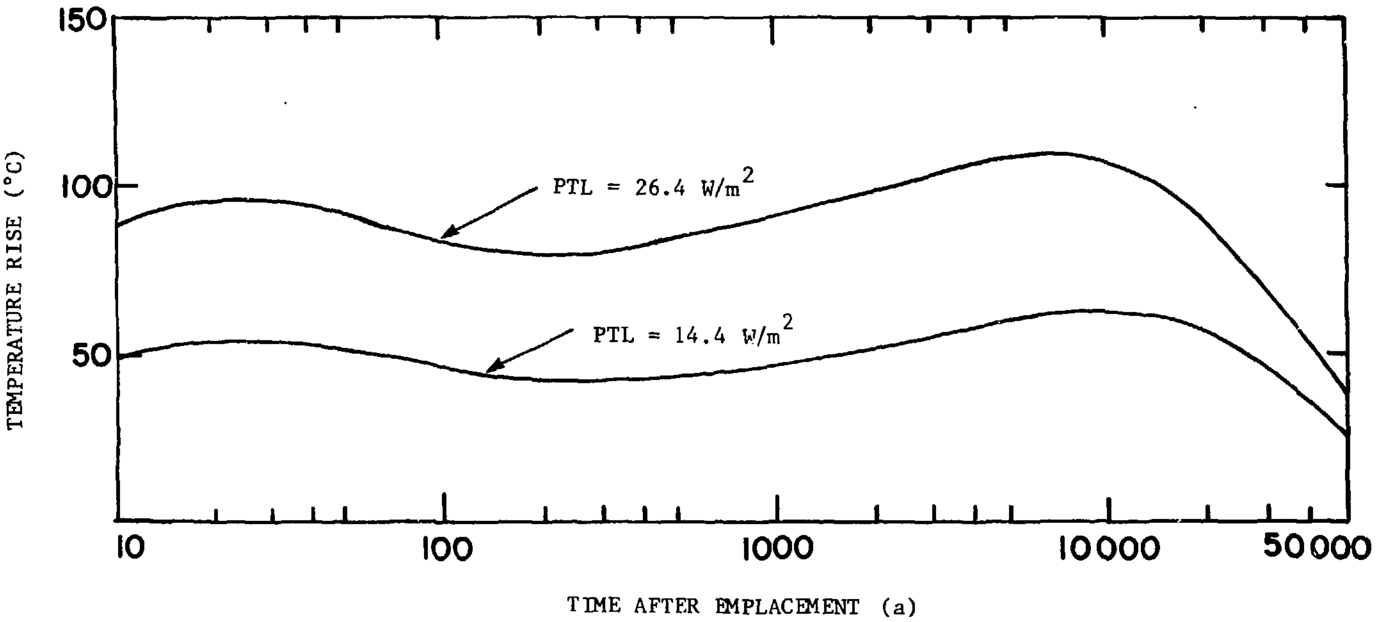


FIGURE 4: **Mid-Point Temperature Rise in an Irradiated Fuel Disposal Vault Located at a Depth of 1000 m in Granite [4]**

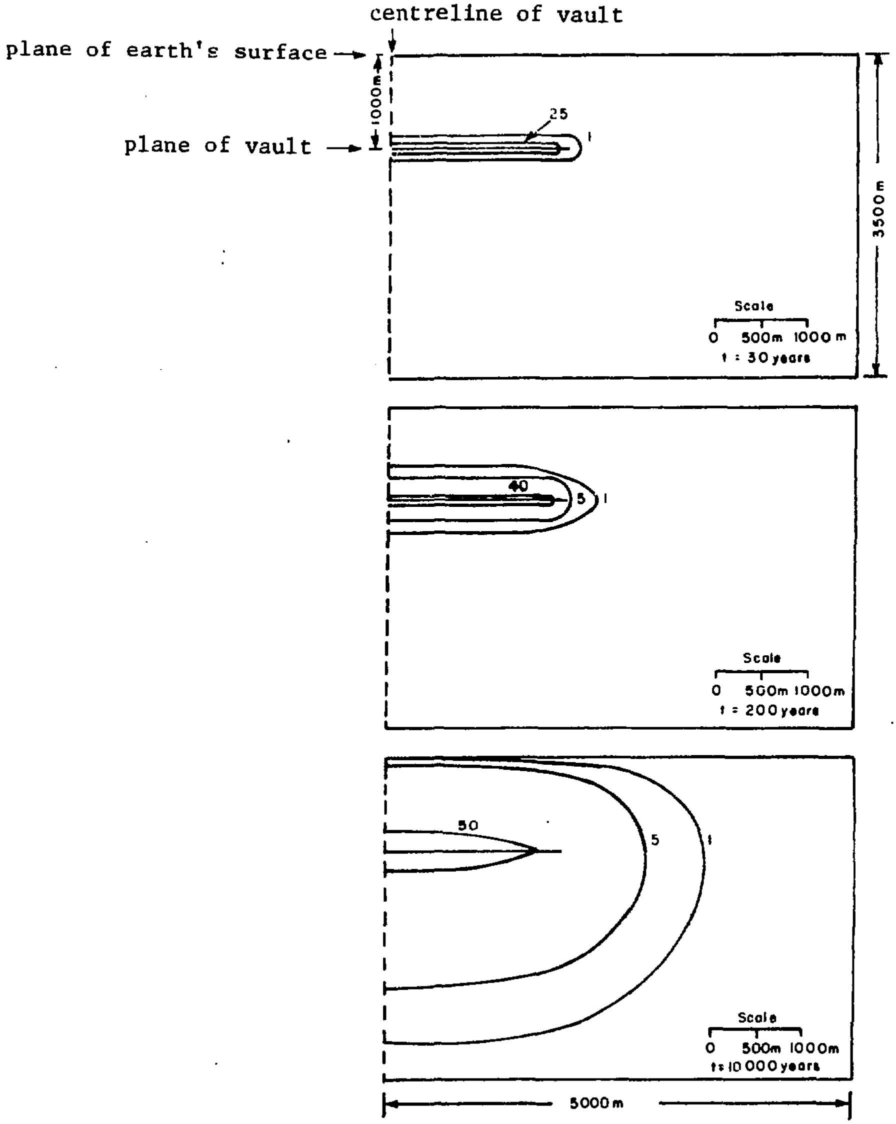


FIGURE 5: Temperature Rise Isotherms (°C) in Granite Surrounding an Irradiated Fuel Disposal Vault [4]. PTL = 14.4 W/m^2.

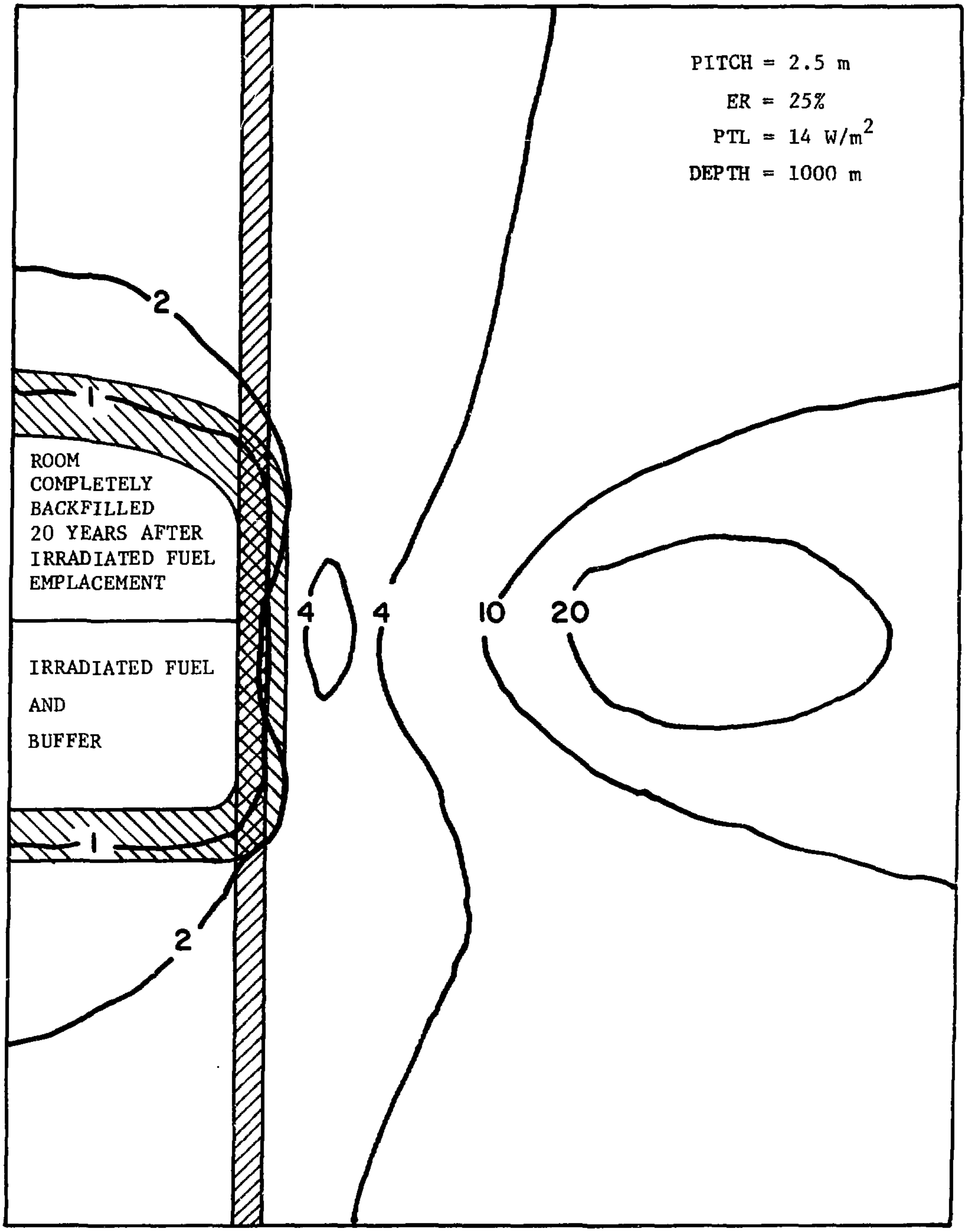


FIGURE 6: *Contours of Strength Ratio in Granite Surrounding a Room in an Irradiated Fuel Disposal Vault [3]. Time = 50 years after emplacement.*

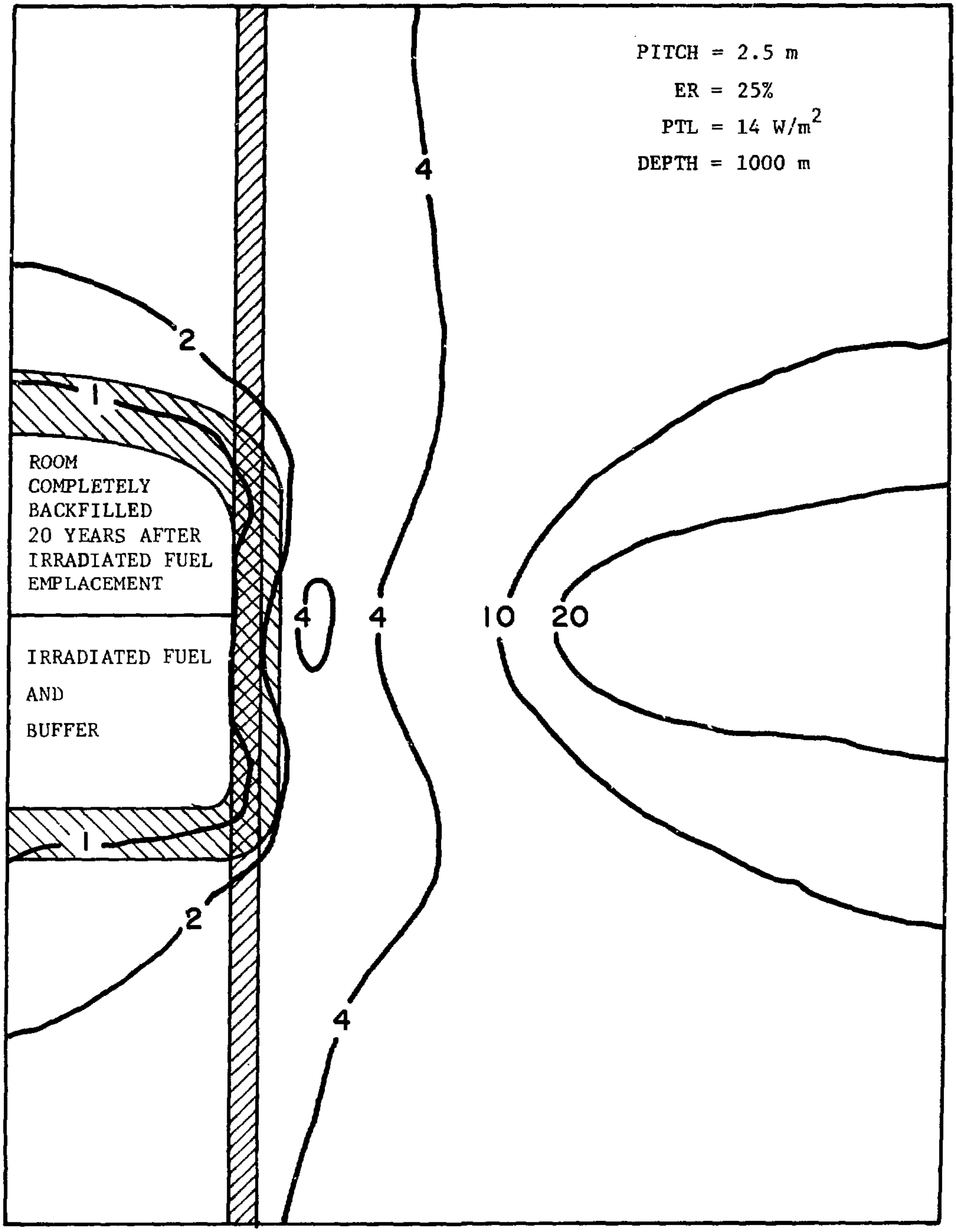


FIGURE 7: Contours of Strength Ratio in Granite Surrounding a Room in an Irradiated Fuel Disposal Vault [3]. Time = 10 000 years after emplacement.

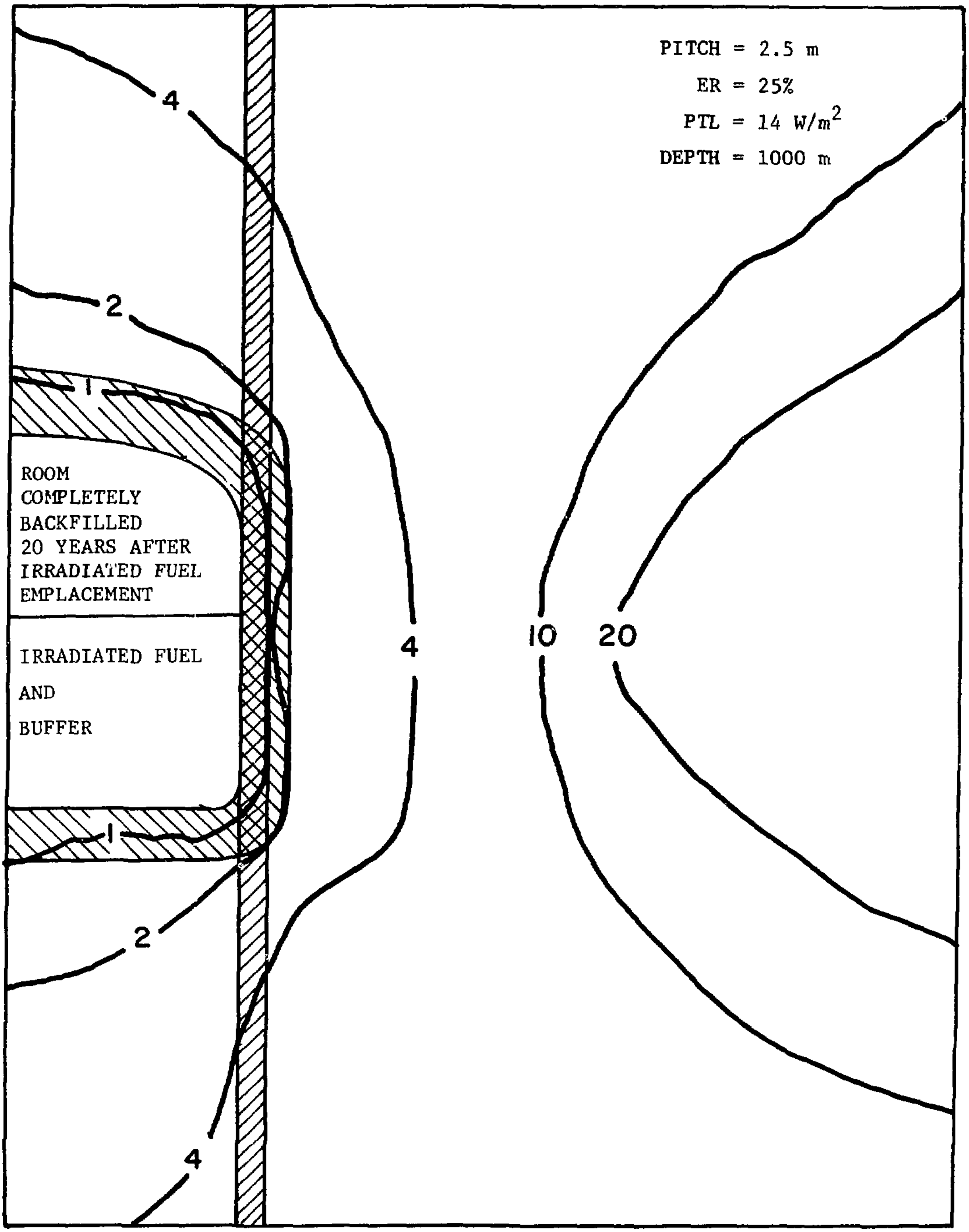


FIGURE 8: Contours of Strength Ratio in Granite Surrounding a Room in an Irradiated Fuel Disposal Vault [3]. Time = 20 000 years after emplacement.

20 000 years after emplacement. It can be seen that the strength ratio exceeds 1 outside the blast-fractured zone, so failure due to thermal loading effects should not occur.

3.2.1.2 Far-Field Analysis

The presence of a heat source could also affect rock stress beyond the room-and-pillar region of the vault. Osnes and Brandshaug [4] determined the gross thermal loadings that would cause no significant irreversible deformation of the far-field rock structure. The analysis encompassed a region extending from far below the vault through the vault to the surface.

It was found that a GTL of 14.17 W/m^2 (corresponding to a PTL of 14.4 W/m^2) would not produce any strength failure in the far-field region. As shown in Figure 9, however, this heat loading could produce a 100-m-deep perturbed fissure zone (PFZ) at the earth's surface directly above the vault, where pre-existing discontinuities were predicted to open and remain open. The prediction of the PFZ shown in Figure 9 is based on the assumption of pre-existing continuously distributed fissures in the rock mass. Also, K_o is assumed to be a function of depth, which is considered to be more realistic than assuming K_o to be constant, particularly near the earth's surface [4].

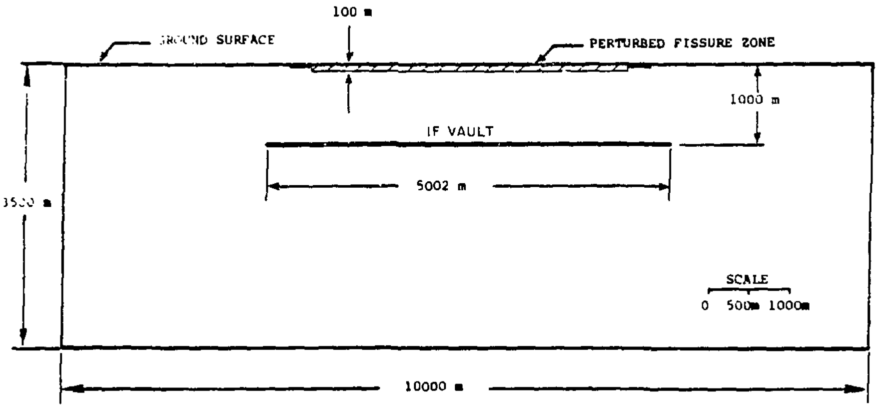


FIGURE 9: Perturbed Fissure Zone Above an Irradiated Fuel Disposal Vault in Granite.
GTL = 14.17 W/m^2.
Time = 10 000 years after emplacement.

This far-field deformation is not expected to affect the integrity of a vault located 1000 m below the earth's surface [4]. Also, the integrity of the host rock near the earth's surface is probably such that the relative increase in permeability due to the perturbation of any fissures is inconsequential [4].

3.2.2 Fracture Mechanics Analysis

Although thermal-mechanical stresses could result in crack propagation, the stress analyses described in Section 3.2.1 do not attempt to account for it. The behaviour of the rock under the predicted thermal-mechanical loads is being further investigated using the fundamental approach of fracture mechanics. As described by B.J.S. Wilkins in Appendix A, laboratory rock crack growth experiments are being performed and then analyzed using linear elastic fracture mechanics.

The results suggest that the vault and its contents would cause no creep/microfracturing in the pluton where the strength ratio is greater than two. As shown in Figures 6, 7, and 8, only small regions of rock above and below each room would have a strength ratio less than two. Thus the increase in permeability of the pluton due to crack propagation would be insignificant.

3.3 PRESENCE OF A RADIOACTIVE SOURCE

Radiation from the fuel waste will not penetrate more than a few tens of centimetres through solid material, so radiation damage would be confined to the container, the buffer, and perhaps a narrow zone of rock. Swedish studies [5] have shown that, with thick copper fuel containers and a 10% bentonite - 90% quartz backfill, the effect of radiation should be minimal. The effect of radiation through other container materials has not been studied.

The presence of a radioactive source could affect or cause chemical reactions, of which the most significant would likely be the radiolytic oxidation of UO_2. A preliminary analysis [6] suggests that this effect would be small.

4. NATURAL PHENOMENA

Natural phenomena can generate very powerful forces which could adversely affect the stability of the geosphere and biosphere. The surface and interior of the earth are slowly and continually changing, but it is the events occurring within the next million years which are of interest when analyzing radionuclide migration from an irradiated fuel vault. These events are considered below.

During this period, the geosphere of the Canadian Shield is expected to be a stable system with respect to global processes such as continental drift, polar wandering, and orogenic episodes. Major chemical changes or major intrusive activity are not expected to occur, as they have not done so for hundreds of millions of years.

4.1 GLACIATION

In recent geologic time, the Canadian Shield was exposed to at least four major glacial advances, the last of these ending about 10 000 years ago. The glacial stages lasted from 20 000 to 50 000 years, separated by interglacial stages of equal or greater length.

These glacial and interglacial stages were triggered by fluctuations in global climate [7]. The major climatic changes over the past 500 000 years have been accounted for by the Milankovitch theory of variations in the orbital geometry of the earth [8,9]. This theory has been used by the U.S. Waste Isolation Safety Assessment Program to model the climate of North America and predict how it might vary in the future [10].

The expected time until the next glaciation is between 4000 and 20 000 years [11,12]; succeeding interglacial and glacial stages could also occur within the next million years. Therefore, future glaciations could affect the stability of a disposal vault and its surroundings. The possible consequences of future glaciation must be considered, as well as the possible consequences of processes still occurring as a result of past glaciations. The subsequent sections discuss the following effects of glaciation:

- subsidence and rebound
- faulting
- erosion
- alteration of hydrological conditions.

4.1.1 Subsidence and Rebound

The mass of an ice sheet causes the land surface to subside as isostatic adjustments take place in the earth's mantle. Bull [11] estimated that the maximum amount of subsidence was 1000 to 1500 m for the Laurentide ice sheet, which had a central thickness of 3000 to 5000 m. This estimate of subsidence agrees well with the theoretical results of Brotchie and Silvester [13].

As an ice sheet retreats, the earth rebounds slowly. This process is still occurring in response to the retreat of the last ice sheet. By studying and dating elevated marine deposits around the Hudson Bay, Walcott [14] estimated that the centre of the uplifted region has risen 140 m since the last ice sheet retreated. From free-air gravity-anomaly maps of the region he predicted that the centre of the uplift must rise another 300 m before equilibrium is reached. If this occurred, the floor of Hudson Bay would be above sea level.

Andrews [15] has derived empirical equations for glacial rebound and has estimated the present rates of uplift to range from 0.2 to 1.3 m per century. His contours for rates of uplift of the Canadian Shield (Figures 10, 11, and 12) show that during the last 8000 years, there has been a decrease in both the maximum rate of uplift and in the area affected by it.

It is evident that glacial subsidence and rebound are capable of significantly altering the present flow systems in the Canadian Shield. Since the analysis of radionuclide transport by groundwater flow is essential to the safety assessment of a disposal vault, the effects of subsidence and rebound should be considered.

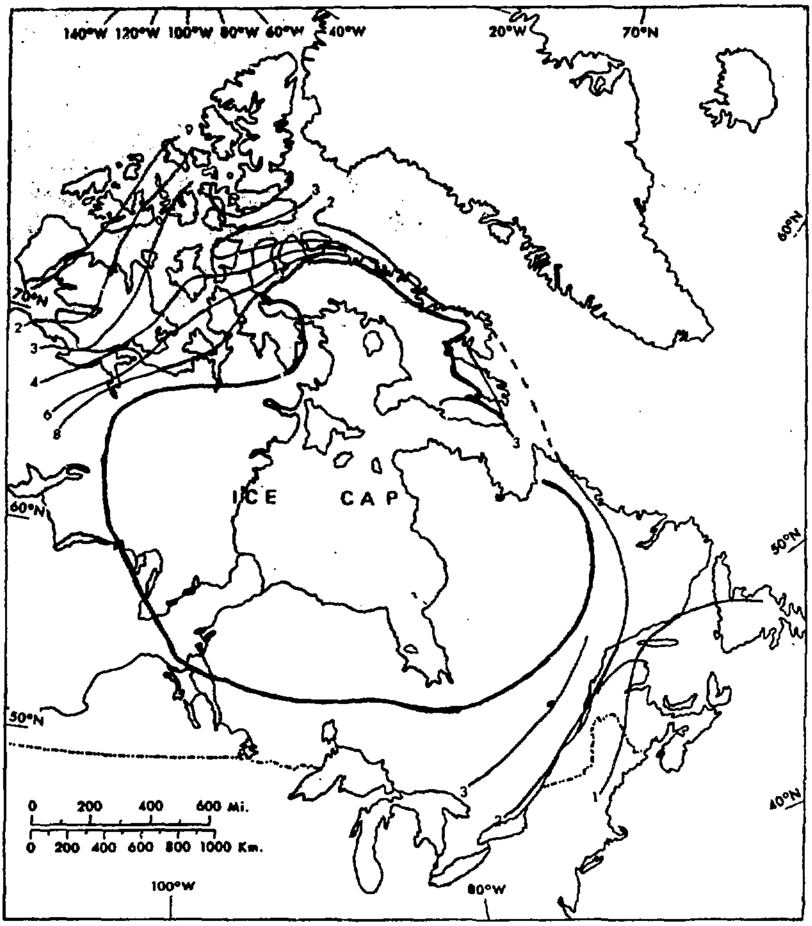


FIGURE 10: Rates of Uplift 8000 Years Ago [15]. Contours at 8,6,4,3, 2,1 m/100 a.

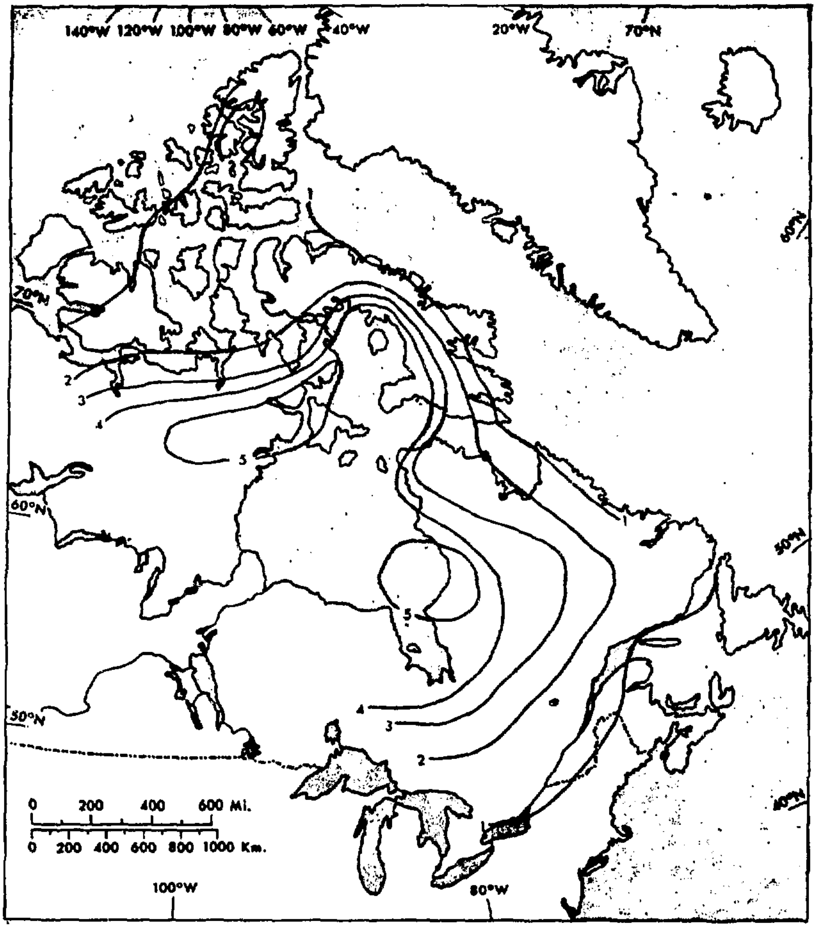


FIGURE 11: Rates of Uplift 6000 Years Ago [15]. Contours every 1 m starting at 1 m/100 a.

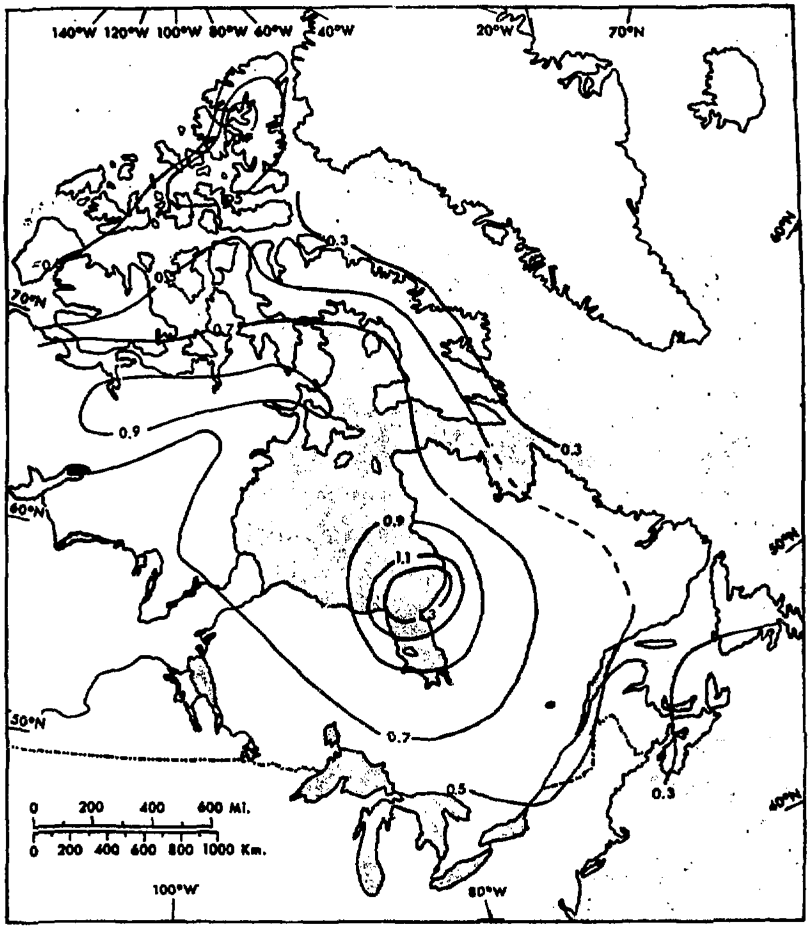


FIGURE 12: Present Rates of Uplift [15]. Contours every 0.2 m starting at 0.3 m/100 a.

4.1.2 Glacially Induced Faulting

The mass of an ice sheet imposes mechanical loads on the underlying rock. These include the gravitational force and the shear force caused by the ice moving over the rock surface.

Pusch [16] studied the effect of the shear forces due to glacial motion. Using a simple analysis of intact rock, he concluded that in the first few metres of rock, fractures would be caused and opened, but at depths of over a few tens of metres, the effect of the shear forces is negligible. Therefore, at vault depth, only the gravitational load need be considered.

The stresses beneath a 3-km thick ice sheet have been calculated assuming three different models of the earth's crust. Pusch [16] assumed that the rock is restrained laterally; Brotchie and Silvester [13] assumed that the earth's crust is a thin spherical shell and is filled with a viscous fluid; Walcott [14] assumed that the earth's crust is an elastic plate and is supported by a viscous fluid mantle. The results of each of these analyses indicate that stresses large enough to cause fracturing should occur near the periphery of such an ice sheet.

It is not known whether such fracturing occurred during previous glaciations. The distribution of fractures in the Swedish bedrock indicates that, in spite of several glaciations, permeability was significantly affected only in the top 100 or 200 m of the bedrock [17]. The deeper rock retained low permeability.

This lack of agreement between calculated and observed effects of glaciation could be due to the inexact models assumed. The earth's crust is not completely restrained, nor does it behave exactly like an elastic medium. Also, the incipient faults in the rock might have dominated the response to the glacial load. Better understanding of the response of the Canadian Shield to glacial loading is required in order to make predictions about effects on a disposal vault.

4.1.3 Glacial Erosion

The massive gouging action of glaciers was documented by Gera and Jacobs [18] and has led to concern about vault integrity during glaciation. White [19] claimed that the Shield areas of the world were actually formed by extensive erosion by ice sheets, possibly to a depth of 1000 m. He also claimed that several bodies of water, such as Lake Michigan, Lake Seneca, and Hudson Bay, were carved out by glacial erosion.

Sugden [20], however, cited evidence that the Shield was exposed long before the first known glaciation. He argued that the geology of the Shield does not support the theory of deep areal erosion, and that only tens of metres were affected over most of the Canadian Shield. Deep "constrained flow" erosion near the edge of the Shield could have created lakes there, but Sugden believed it unlikely that the Hudson Bay basin was formed by glacial erosion. His assertion is supported by the presence of a preglacial valley pattern on paleozoic rocks of the basin floor.

Kaszycki and Shilts [21] have recently studied glacial erosion in the Keewatin district of the Canadian Shield. By evaluating the volume of Dubawnt detritus in till located down-ice from Dubawnt outcrops, they estimated the depth of glacial erosion in this area to be 5.5 to 8.0 m. This is in agreement with the findings of Sugden [20] and Flint [22], which also support the conclusion that erosion was in the order of tens of metres in Shield areas where only areal erosion occurred.

The absence of "relict great lakes" on the Shield led Bull [11] to predict that in the future deep glacial erosion would likely occur only in those areas that have experienced deep erosion in the past. This suggests that if a vault were placed in an area where no deep erosion had previously occurred, only areal erosion need be considered in a safety assessment.

4.1.4 Alteration of Hydrological Conditions

It is clear that surface drainage patterns would be completely changed by both the formation and melting of glaciers. If the existing ice sheets melted, the world sea level would rise by 60 to 70 m [23]. Bull [11] estimated that the probability of the Antarctic ice sheet melting in the next million years is about 0.25, and that the probability of the Greenland sheet melting in that time is much higher.

Hughes [24] discussed a model of surface water conditions at the base of a glacier, and suggested that during the Pleistocene epoch all of Canada and most of the northern United States could have been covered by glacial permafrost.

Bull [11] has considered the possibility of deep groundwater recharge conditions occurring beneath an ice sheet due to strong horizontal gradients of surface hydrostatic pressure. He concluded that conditions were present which could have caused this phenomenon, although there is no direct evidence of it having occurred on the Shield.

If glacial loading were to produce fracturing, the permeability of the rock would be increased.

During glacial and interglacial stages, these and perhaps other changes in hydrological conditions would affect groundwater flow, and thus affect the transport of radionuclides from a vault.

4.2 SEISMIC ACTIVITY

An earthquake could produce jointed rock motion, rapid fault growth, slow fault growth, or new fault formation. Any of these could increase permeability, and thereby affect the transport of radionuclides through the geosphere. A more serious effect would be the disruption of the vault, a possibility that is discussed below for the four categories of fault behaviour.

4.2.1 Jointed Rock Motion

An earthquake occurring in the area of the vault, but not causing any shearing through it, may still have an effect on the vault due to vibratory motion. Studies have shown [25], however, that the vibratory effects of earthquakes are significantly smaller on underground openings than on surface structures. Ontario Hydro is doing a dynamic analysis of vault performance under seismic loading conditions. Since the vault would be designed to withstand these loadings while open, similar conditions would be unlikely to cause container damage after the rooms were backfilled. Wight [26] has suggested that matching the acoustic impedance of the backfill to that of the surrounding rock would minimize the surface wave effects at the buffer/rock interface.

4.2.2 Rapid Fault Growth

Rapid fault growth due to an earthquake could breach the vault by a direct shearing action. A simplified model for determining the probability of container damage under such circumstances has been proposed by Ringdal, Gjöystdal, and Husebye [27]. It is described by

$$P = P(F) \cdot P(A/F) \cdot P(E \geq ?/AF) \cdot P(B/E)$$

where P = probability of damage to a container per unit time

$P(F)$ = probability of at least one fault intersecting a randomly placed disposal vault

$P(A/F)$ = probability of a given fault being active

$P(E \geq ?/AF)$ = probability of an earthquake greater than a given intensity on an active fault per unit time

$P(B/E)$ = probability of container breakage given an earthquake occurrence.

$P(F)$, the probability of at least one fault intersecting a randomly situated disposal vault, is estimated in Appendix B to be 0.75. This is a conservative number since it is likely that a site would be chosen to avoid major fault systems.

$P(A/F)$, the probability of a given fault being active, is more difficult to estimate. The historical data on earthquakes in the regions under consideration are extremely limited, so it is virtually impossible to assign a particular fault to a known earthquake. It may, however, be possible to derive the required probability estimate from dating studies on the fault intrusions in the geological structures of the surrounding area.

$P(E \geq ?/AF)$, the probability of an earthquake greater than a given intensity occurring in a unit time, is also difficult to estimate. The extremely long time period which must be considered precludes the use of current techniques developed to ensure the safety of structures intended to last 50 to 100 years. In order to get a realistic estimate for the probability, an investigation of fundamental tectonic and geologic processes is necessary.

In order to provide some of the information needed to estimate these probabilities, a project has been undertaken by the Earth Physics Branch of Energy, Mines and Resources Canada. This project essentially consists of three parts:

(1) An extension of the seismograph network in the Shield area to enhance the low-magnitude earthquake-monitoring capability in this region.

(2) The investigation of a well-documented seismically active area called the "Gatineau Triangle" [28] (see Figure 13) in order to determine the fundamental tectonic properties of the area and so explain its observed seismicity, and the application of this information in the development of a seismicity model that will estimate the potential for future earthquakes in such areas.

(3) A search for more information on historical seismicity in the Shield.

$P(B/E)$, the probability of container breakage due to an earthquake, describes the effect of faulting on a container. It is proposed that a finite-element computer program be used to determine whether shearing offsets of the room walls will cause damage to a container. The container, buffer material, backfill material, and backfill-rock shearing action should be modelled.

4.2.3 Slow Fault Growth

The strain energy of an earthquake can be released by a slow creep type of motion, which could also cause a shearing effect on a vault. The probability of container damage under these circumstances has been described by Ringdal et al. [27] by the equation

$$P = P(F) \cdot P(A/F) \cdot P(C \geq ?/AF) \cdot P(B/C)$$

where P = probability of container damage per unit time and container

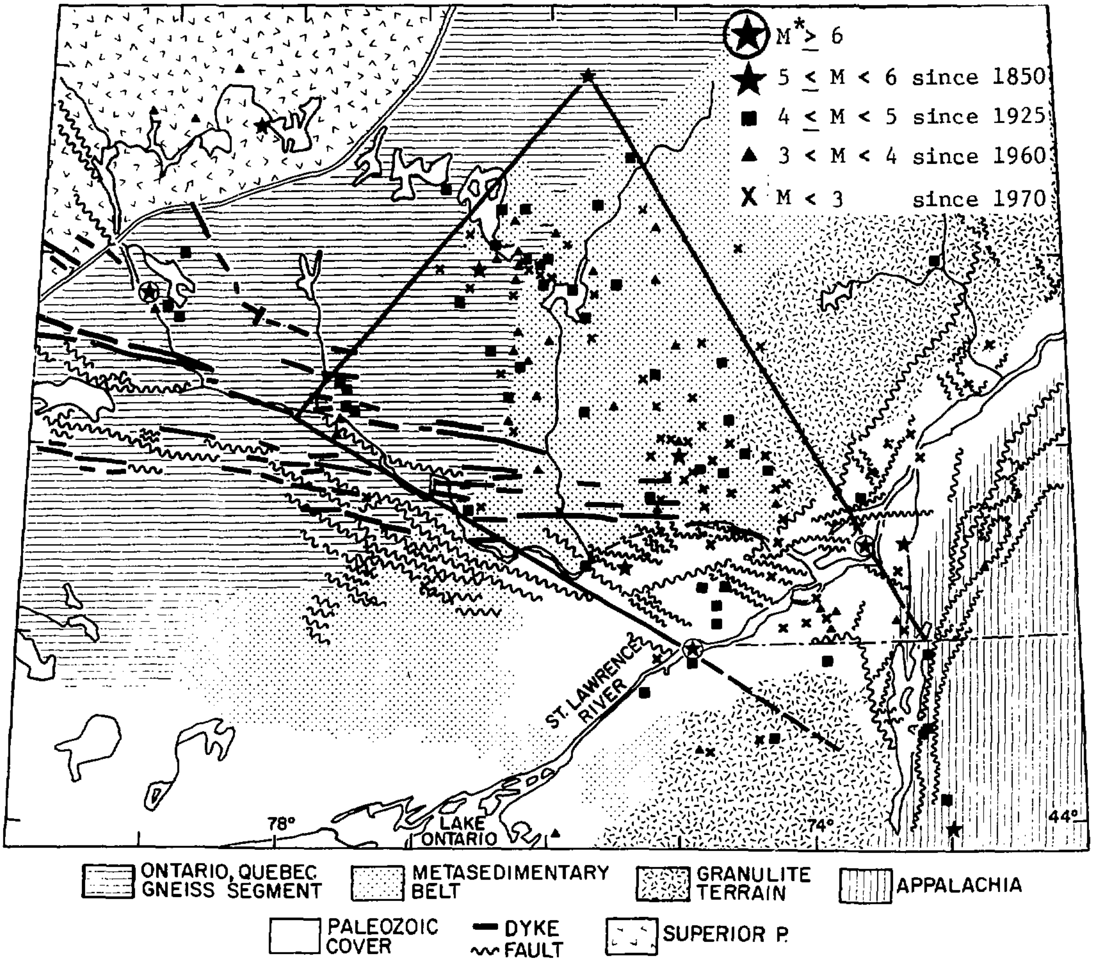
$P(F)$ = probability of at least one fault intersecting a randomly situated disposal vault (discussed in Section 4.2.2)

$P(A/F)$ = probability of a given fault being active (discussed in Section 4.2.2)

$P(C \geq ?/AF)$ = probability of significant creep on an active fault per unit time

$P(B/C)$ = probability of container damage given creep movement.

$P(C \geq ?/AF)$, the probability of significant creep occurring on an active fault, must be determined by studying the tectonics and geology of the Canadian Shield. This could involve modelling the creep motion due to the cumulative effect of a series of small earthquakes.



*M is the earthquake magnitude on the Richter scale

FIGURE 13: Seismicity of Western Quebec and Eastern Ontario Superimposed on Geological Provinces and Structural Features of the Region [28]. The triangular zone indicates the so-called "Gatineau Triangle".

P(B/C), the probability of container damage given creep movement, is expected to be low. The container will probably be embedded in a buffer material that will behave plastically under a slow external deformation. According to experiments done by Pusch [29], the vault could undergo a relatively large displacement before any damage would be done to an embedded container.

4.2.4 New Fault Formation

The probability of a new fault forming within the disposal area can be estimated if it is assumed that the rate of fault formation will be the same in the future as it has been in the past. Approximately 1.4 major faults are expected to exist at the site of a randomly placed disposal vault (see Appendix B). If these faults are assumed to have occurred randomly in time over the lifetime of the newest geological province in the Canadian Shield (0.95×10^9 a), then the frequency of new fault formation at a vault is

$$P(F) = \frac{1.4}{0.95 \times 10^9} = 1.5 \times 10^{-9}/a$$

The assumption of a random rate of fault formation is probably not a good one. It has been suggested [30] that fault formation occurred mainly during the relatively short periods when tectonic activities were intense. If this is true, and if one of these periods of high activity were to occur after waste emplacement, the frequency of new fault formation at a vault could be higher than that given above.

4.3 VOLCANIC ACTIVITY

A volcanic eruption near a storage vault could seriously weaken, or perhaps destroy, the engineered and geological barriers. Fortunately, volcanic activity usually occurs in well-defined patterns. Almost all volcanic activity is confined to the boundaries of the great drifting plates that make up the earth's surface. Since North America forms part of one large plate, there is no plate boundary in the Canadian Shield.

However, volcanic activity occasionally occurs in the interior of a plate, and the presence of lavas in the Canadian Shield indicates that volcanic activity occurred prior to or during its formation. This is consistent with the general belief that the Shield was the scene of intense mountain-making episodes in Precambrian time [31]. Volcanic activity can occur in the interior of a plate at a hot spot or at a rift system.

4.3.1 Hot-Spot Volcanic Activity

Hot spots are small regions of isolated volcanic activity. They are believed to be caused by jets of hot material that rise from deep within the earth's mantle, force their way through the crust, and emerge at the surface as volcanic centres such as Hawaii [32]. There is no evidence of hot-spot activity in the Shield.

The probability (P) of a hot-spot volcano affecting a vault can be calculated using the method of Smith [33], and is described by

$$P = f_{occ} \cdot \frac{A_t}{A_{occ}}$$

where f_{occ} = the frequency of occurrence of volcanoes on an area A_{occ}

A_t = the area in which a volcano would have to occur in order to affect at least part of a vault.

Smith made the following assumptions:

(1) The frequency of formation of new volcanoes will remain the same in the future as it has been in the past.

(2) The radius (r_a) of the area affected by a volcano is about 1 km.

(3) The radius (r_t) of the area A_t is given by $r_t = r_v + r_a$, where r_v is the radius of a circular area equal to the area of the vault.

In his calculations, Smith used the following data to calculate the area A_{occ}:

(1) The diameter of the earth is 12 600 km.

(2) Continental areas constitute 30% of the total surface of the earth.

According to Burke and Wilson [32], 69 hot-spot volcanoes have occurred on continents in the past 10 million years, so $f_{occ} = 6.9 \times 10^{-6}$/a for $A_{occ} = 0.3\ \pi(12\ 600)^2$ km^2. If the area of a vault is assumed to be 2.6 km^2, then $r_v = 0.91$ km, and $A_t = \pi r_t^2 = \pi(0.91 + 1)^2$ km^2. The probability of a hot-spot volcano affecting at least part of a vault located on a continent is

$$P = 6.9 \times 10^{-6} \cdot \frac{\pi(0.91 + 1)^2}{0.3\ \pi\ (12\ 600)^2} = 5.3 \times 10^{-13}/a$$

4.3.2 Rift System Volcanic Activity

There are two known major rift systems on the Shield, one of which, the Kapuskasing High, is Precambrian and has long been inactive. The other rift system, the Ottawa-Bonnechere graben, is younger and has experienced intrusive activity as recently as 125 million years ago [34]. Kumarapeli and Saull [35] studied the current seismicity of the region and concluded that the rift system might still be active. A significant amount of the seismic activity in eastern Canada lies to the northeast of the

Ottawa-Bonnechere graben [35] in an area known as the Gatineau Triangle (Figure 13), but it is not known whether this seismicity is due to the active rift system or other tectonic forces.

The frequency of occurrence of magmatic activity near a rift system is probably orders of magnitude greater than for hot-spot formation on the Shield. Any magmatic activity due to rift system activity would be highly site-specific. Indeed, for locations away from the actual rift systems the frequency of magmatic activity should decrease so rapidly as to be of no concern. If, in spite of the high seismicity, it still seemed desirable to locate a disposal vault in the Ottawa region, a more thorough understanding of these activities would be required.

4.4 DENUDATION AND FLUVIAL EROSION

4.4.1 Denudation

Denudation refers to the general lowering of the land surface caused by chemical weathering, wind erosion, and precipitation runoff. This areal type of erosion would affect the surface above a disposal vault no matter where the vault was situated, so the rate of denudation should be considered.

Dole and Stabler [36] estimate denudation rates of 16×10^{-6} m/a for the Laurentian Basin and 6.5×10^{-6} m/a for the Hudson Bay Basin. These rates are strongly affected by elevation, climate, overburden type, and especially human activity, which can vary the rates by an order of magnitude [37]. Even these larger rates for denudation are very small, so with careful vault siting the effect of denudation should not be a problem.

4.4.2 Fluvial Erosion

Although a disposal vault would not be built beneath a major river, a waterway could subsequently be formed over the vault. Potential local erosion due to rivers should therefore be considered.

The rates of fluvial erosion are usually significantly larger than those for denudation. For example, Gera and Jacobs [18] estimated rates of fluvial erosion for the Grand Canyon which were approximately five times the rate of erosion of the surrounding area. On the other hand, Pearce and Elson [38] obtained fluvial erosion rates of 7.78 and 12.5×10^{-6} m/a for the Mont St. Hilaire region of Quebec, and these are within the range of denudation rates given by Dole and Stabler [36] for the Shield. Thus it is not clear whether the rate of fluvial erosion exceeds the rate of denudation in the Shield. Further studies are required on this subject.

4.5 METEORITE IMPACTS

Small meteorites continually bombard the earth's surface, but large meteorites rarely do. However, since a large meteorite could crush the vault or fracture the rock above it, the probability of these occurrences is of interest.

4.5.1 Determination of Impact Frequencies

The frequency of impact of large meteorites is estimated by counting the craters produced over a long period of time. It is likely that the frequency of impacts has been decreasing slightly throughout most of the life of the solar system [39]; however, the work reported here is based on the conservative assumption that the frequency is constant. Latitude dependencies of meteorite impacts are small [40], so they have not been accounted for.

The Canadian Shield is an ancient and relatively stable land mass, so it was used by Hartmann [39] as a counting surface for meteorite craters. Grieve and Dence [41] used the entire North American craton, half of which is the exposed part of the Shield. Both studies involved establishing a cutoff crater diameter above which meteorite structures would have survived for the age of the Shield. Hartmann used a cutoff diameter of 10 km, while Grieve and Dence used 22.5 km.

Meteorite impact frequencies were determined for craters exceeding the cutoff diameters. These were then converted to frequencies for smaller craters by using a frequency/diameter relationship. Hartmann used the relationship $N_D \propto D^{-2.4}$ where N_D is the number of craters of diameter larger than D km. This relationship is valid even for small craters because it is derived from lunar data and the moon is essentially unaffected by erosion. Grieve and Dence used the relationship $N_D \propto D^{-2}$, which was derived from data for planets where erosion is also not significant.

4.5.2 Probability of Damage

Figure 14 shows a typical cross-section of a meteorite crater in granite gneiss. It can be seen that the crushed rock extends beneath the original plain to a depth of about 1/3 the crater diameter. Therefore, a meteorite landing directly above a vault and causing a crater exceeding 3 km in diameter could crush the vault and result in an immediate release of radioactive material. The impact frequency of such a meteorite is calculated to be 3×10^{-13}/a, using the relationships given by Hartman [39]. A similar value of 4×10^{-13}/a is given by the method of Grieve and Dence [41].

Figure 14 also shows that a meteorite creates a zone of fractured rock to a depth of twice the crater diameter below the crater floor. Therefore, a meteorite causing a crater 430 m in diameter could create fractures to the depth of a vault, thus seriously reducing the retardation capability of the geosphere barrier. The frequency of occurrence of such a crater is calculated to be 2×10^{-11}/a, using the method of Grieve and Dence. Thus meteorite impact is not likely to affect the transport of radionuclides during the time required for the longest-lived fission products to decay.

4.6 BIOSPHERE CHANGES

Gradually occurring biosphere changes include evolution and succession. Evolution is the process of genetic changes in organisms due

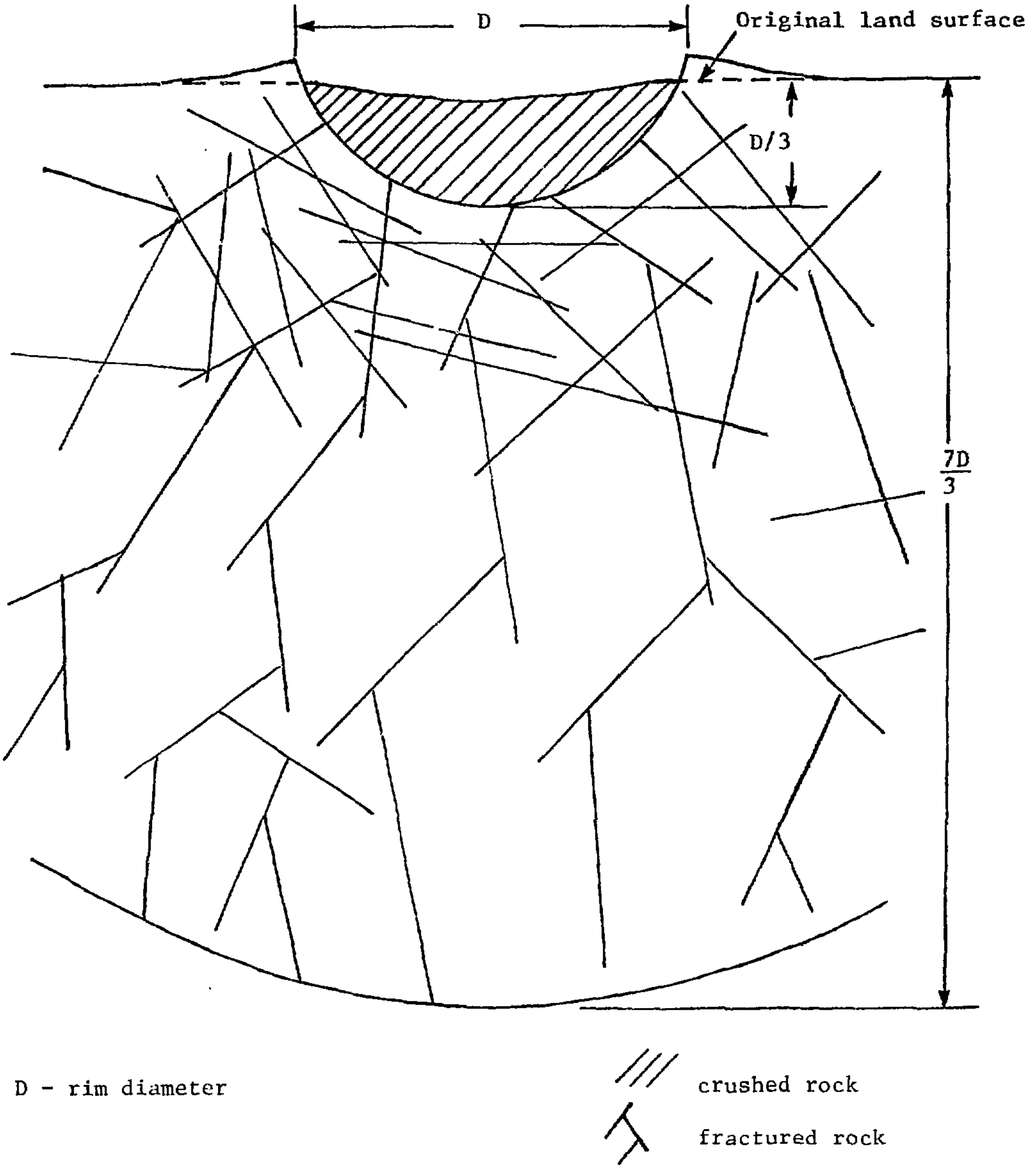


FIGURE 14: Cross-Section of a Simple Meteorite Crater in Granite Gneiss

to selective pressures. Succession is the process of replacing one kind of community by another. Both of these processes will modify the biosphere during the period under consideration. An idea of the changes that might occur can be obtained from the history of the formation of the present biosphere.

After the last major ice sheet retreated about 6000 years ago, the surface of the land was relatively barren of life. Revegetation occurred in stages, according to Krebs' analysis of a glaciated area in Alaska [42]. He found that lowland glacial till was initially colonized by mosses, Dryas, and small shrubs. Over a period of time, these turned the lakes into bogs, which gradually filled in and became grasslands, which in turn changed to forests. The present Shield biosphere is a combination of all these stages of succession, so lake area is gradually decreasing and forested area is gradually increasing.

Analysis of the periods before, during and after the next ice age could be based on the following assumptions:

(1) The lake-bog-grassland-forest succession will continue until another glacial advance occurs. (The influence of man on this process could be significant.)

(2) The biosphere will react to the next ice advance as it did to the last one.

(3) The same type of succession will begin after the ice retreats.

This discussion of succession is only a brief introduction to the complex subject of biosphere changes. Some of the other topics that need to be considered are:

(1) The possible interaction between disruptive processes, such as fires and glaciers, and the process of succession.

(2) Refugia, and how the relocation of species will contribute to the evolutionary pressures.

(3) The importance of the formation of new species or the extinction of existing ones.

(4) Changes in soil chemistry and their effects on the biosphere.

5. CONCLUSIONS

Several events that could adversely affect long-term stability have been discussed. They are categorized here according to whether they are likely to be unimportant or they require further consideration.

5.1 EVENTS THAT ARE LIKELY TO BE UNIMPORTANT

Drilling and Mining: Drilling and mining are unlikely to result in accidental breaching of the vault or in deliberate disruption due to sabotage or curiosity. Deliberate recovery of radioactive materials is not expected to have adverse consequences. Careful choice of other materials to be emplaced should reduce the likelihood of any recovery attempt being made by people unaware of the radiation hazard involved.

Use of Explosive Devices: The effect of exposing the vault contents by the explosion of a nuclear bomb would be insignificant compared to the widespread radioactive release produced by the bomb itself.

Excavation of the Vault: When the vault is excavated, the region of strength failure can be supported by conventional rock-bolting.

Presence of a Heat Source in the Vault: The vault would be designed so that failure due to thermal-mechanical loading would not occur outside the blast-fractured zone. Any increase in permeability due to the perturbation of fissures near the surface is expected to be inconsequential. The results of preliminary fracture mechanics analyses suggest that the increase in permeability of the pluton due to crack propogation would be insignificant.

Volcanic Activity: The probability of a hot-spot volcano affecting at least part of a vault located on a continent is conservatively estimated to be 5.3×10^{-13}/a. For locations away from rift systems, the frequency of magmatic activity should decrease so rapidly as to be of no concern.

Meteorite Impacts: The frequency of meteorites landing over a storage vault and being large enough to crush it is calculated to be less than 4×10^{-13}/a. The frequency of impacts causing a fracture zone beneath the crater to vault depth is about 2×10^{-11}/a. These frequencies are orders of magnitude less than one occurrence during the age of the earth.

5.2 EVENTS THAT REQUIRE FURTHER CONSIDERATION

Glaciation: Glacial activity is likely to be a major factor in modifying the geosphere and biosphere in the next million years. The transport of radionuclides from a vault could be affected by subsidence and rebound, glacially induced faulting, glacial erosion, changes in the amount of water on the earth, permafrost, and perhaps by deep groundwater recharge conditions beneath an ice sheet.

Glacial erosion seems to have caused deep scouring only near the periphery of an ice sheet, so with careful vault siting only areal erosion need be considered. However, further studies are necessary on the effects of subsidence and rebound on the drainage patterns of the Shield, the effects of glacial loading on the integrity of the underlying rock mass, and the effects of a glacier on the hydrogeology of the Shield.

Seismic Activity: An earthquake could result in jointed block motion, fault growth, or new fault formation, any of which could change the hydrogeology. More needs to be known about these possible changes to the geosphere of the Shield. Fault growth or new fault formation could also breach the vault by a direct shearing action. The probability of container damage due to seismic activity is as yet unknown.

Biosphere Changes: Better theories should be developed to describe the evolution of the environment.

Denudation and Fluvial Erosion: Denudation and fluvial erosion need to be studied in more detail, but would not seem to be a serious problem with careful vault siting.

Presence of a Radioactive Source in the Vault: The effects of radiation damage and of radiation-induced chemical reactions need to be studied further, but are expected to be small.

ACKNOWLEDGEMENTS

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APPENDIX A

SLOW CRACK GROWTH

by

B.J.S. Wilkins

The stress intensity factor (K_I) at a crack tip increases with applied stress and crack size. Above a critical value of the stress intensity factor (K_{Ic}), the crack is unstable and will propagate rapidly. At values of $K_I < K_{Ic}$, slow crack growth may occur, leading to the phenomenon of "delayed failure". Slow growth of cracks has been demonstrated in Lac du Bonnet (LDB) granite. For materials such as soda-lime glass and fused quartz (and probably granitic rocks), growth is due to a stress-dependent corrosion mechanism at the crack tip. The extent of crack growth in a given time can be predicted using fracture mechanics.

Obtaining some of the fracture data that may be required for predicting crack growth is difficult, as the loading of cracks will probably be in modes II and III, i.e., in in-plane and antiplane shear. The cracks will also be subjected to overburden and confining pressures. There have been no reported measurements of the critical values of the stress intensity factor in mode II or mode III (K_{IIc} or K_{IIIc}) or of crack growth velocity as a function of the stress intensity factor in mode II or mode III (K_{II} or K_{III}). Most probably, the intervention of tensile failure (mode I) will prevent or, at least,make difficult such measurements. Therefore, the approach [A.1] to estimating time-dependent disturbance of cracks in the rock considers changes due to tensile stress components only. This should produce an overestimate of crack growth while avoiding the difficulties of the complex stress system.

The essence of the initial approach is to consider the potential growth of planar circular cracks subjected to tensile stress. A stress is calculated that will produce a given percentage crack extension in a given time. Reference is then made to the stress distribution around the vault to fix the position of an envelope outside of which the percentage crack growth will be less than a given value. The conservative nature of the estimate will be further enhanced by ignoring the stress relaxation due to cracking.

A statistical experiment is being used to measure the relationship between slow crack growth and the stress intensity factor [A.2]. Time-to-failure (t_f) is measured for a large number of rock specimens stressed to a fraction of their instantaneous breaking stress. From these data the relationship between K_{Ii}/K_{Ic} and t_f is found, where K_{Ii} is the initial stress intensity factor at the crack destined to grow to the size for fast fracture. The ratio K_{Ii}/K_{Ic} is the same as the ratio of applied to instantaneous breaking stress. It provides a direct link to the geotechnical approach as it is essentially the reciprocal of the strength ratio. Also, from these data the constants A and n are found for the expression

$$dL/dt = A\ K_I^{\,n}$$

where dL/dt is crack velocity.

To date, results have been obtained for LDB granite in water and in brine at 80°C, and in air (relative humidity ∽ 50%) at 20°C. The brine composition used was typical of many found in the Canadian Shield. The results are represented by [A.3]

$$dL/dt = 7.7 \times 10^{-189}\ K_I^{31.04} \quad \text{(brine, 80°C)}$$

$$dL/dt = 1.5 \times 10^{-190}\ K_I^{30.96} \quad \text{(water, 80°C)}$$

$$dL/dt = 3.0 \times 10^{-339}\ K_I^{56} \quad \text{(dry, 20°C)}$$

where: dL/dt is in $m \cdot s^{-1}$ and K_I is in $Pa \cdot m^{1/2}$ units. These relationships show that sub-critical crack growth in LDB granite in brine is not significantly different from that in water. The percentage of the instantaneous tensile breaking stress that causes ∽20% crack extension in 1000 years of application is calculated to be ∽45% in both cases. This is an encouraging result for it suggests that the vault and its contents would cause no creep/microfracturing in the pluton where the SR is greater than two.

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APPENDIX B

PROBABILITY OF A FAULT IMPINGING ON A RANDOMLY PLACED DISPOSAL VAULT

The probability, P(F), of having at least one fault intersecting a randomly placed disposal vault can be calculated using the assumptions below:

(1) The distribution of future fault lengths is similar to the existing distribution, and the spatial distribution and orientation are assumed to be homogeneous.

(2) The fault-length distribution of the area is known and any lineaments under a certain length are considered as joints, which would not be involved in earthquake faulting.

(3) The fault-length distribution can be represented as a log-normal distribution. This follows from linear breakage theory [B.1] and has been shown by Ringdal et al. [B.2] to be a valid assumption for faulting in Sweden.

Using the properties of the log-normal distribution, the expected number of faults of length less than L in a unit area becomes

$$N(<L) = \frac{N}{A} \int_0^L \frac{\log e}{\sqrt{2\pi}\cdot\delta\cdot x} \cdot \exp\left[-\frac{(\log(x)-\mu)^2}{2\delta^2}\right] dx$$

where logarithms are to the base 10

N = number of faults in area A

x = fault length variable

μ = mean of the log-normal distribution

δ = standard deviation of the log-normal distribution.

The probability of a fault impinging upon a circular area equivalent to the vault area (see Figure B-1) is given by

$$Pr = \begin{cases} 1.0 \text{ if } r < R_V \\ 2\theta_1/\pi \text{ if } R_V < r < \sqrt{R_V^2 + (L/2)^2} \\ 2\theta_2/\pi \text{ if } \sqrt{R_V^2 + (L/2)^2} < r < R_V + L/2 \\ 0 \text{ if } R_V + L/2 < r \end{cases}$$

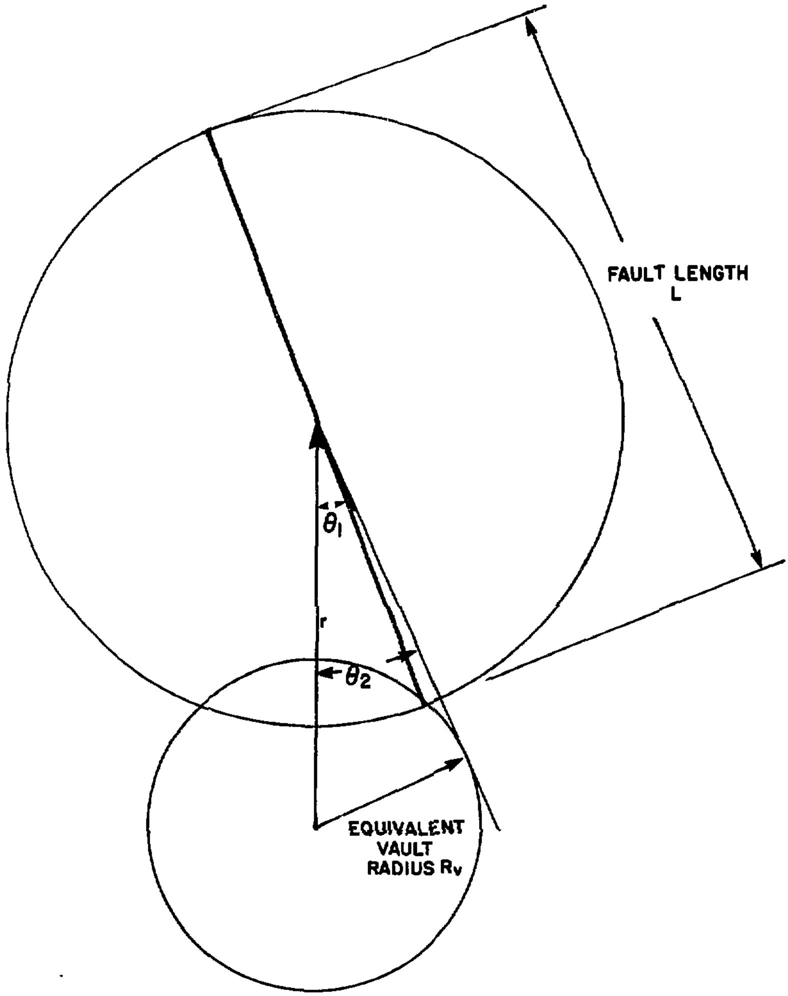

FIGURE B-1: Interaction of a Fault with a Storage Vault where r = the distance of the fault midpoint from the vault centre

R_V = the equivalent radius of the storage vault

L = fault length

$$\theta_1 = \arccos \frac{r^2 + (L/2)^2 - R_V{}^2}{r \cdot L}$$

$$\theta_2 = \arcsin (R_V/r)$$

These equations can be used to determine the expected number (E_N) of faults less than length L_o that would intersect the vault:

$$E_N = \int_o^{L_o} \int_o^{R_V + L/2} \Pr \cdot \frac{d}{dL} [N(<L)] \cdot 2\pi r \, dr \cdot dL$$

The distribution of faulting in the area of a storage vault is, of course, very site-specific. In an attempt to demonstrate how this method would apply, the lineament study of Brown and Thivierge [B.3] has been used. As small lineaments are not likely to be associated with potentially active faults, an arbitrary minimum length of 2 km was chosen. The resulting accumulative lineament distribution for five plutons is shown in Figure B-2. The 2-km cutoff length resulted in a distribution that is obviously not a good log-normal fit, but this poor fit can be ignored since this calculation is primarily intended to demonstrate the method of analysis. The statistical parameters for these data are:

$N = 77$ $A = 667 \text{ km}^2$

$\mu = 0.70$, with x in km $\delta = 0.134$

Using an equivalent-area vault radius of $R_V = 0.91$ km to represent a 2 km x 1.3 km vault, the expected number of major faults impinging on a randomly placed disposal vault is:

$E_N = 1.4$

In order to determine the probability of one or more faults intersecting the vault area, use is made of the assumption of random spatial distribution of the faults and of the fact that the expected number of occurrences of intersections is relatively small (1.4). The probability distribution for this event can be approximated by a Poisson's distribution with a mean of 1.4. This distribution is shown in Figure B-3 from which it is apparent that the probability of no faults intersecting a disposal vault is 0.25. The probability of one or more intersections is, therefore,

$P(F) = 0.75$

This is a conservative number since the vault would not be randomly situated, but rather a site would be chosen so as to avoid major fault systems.

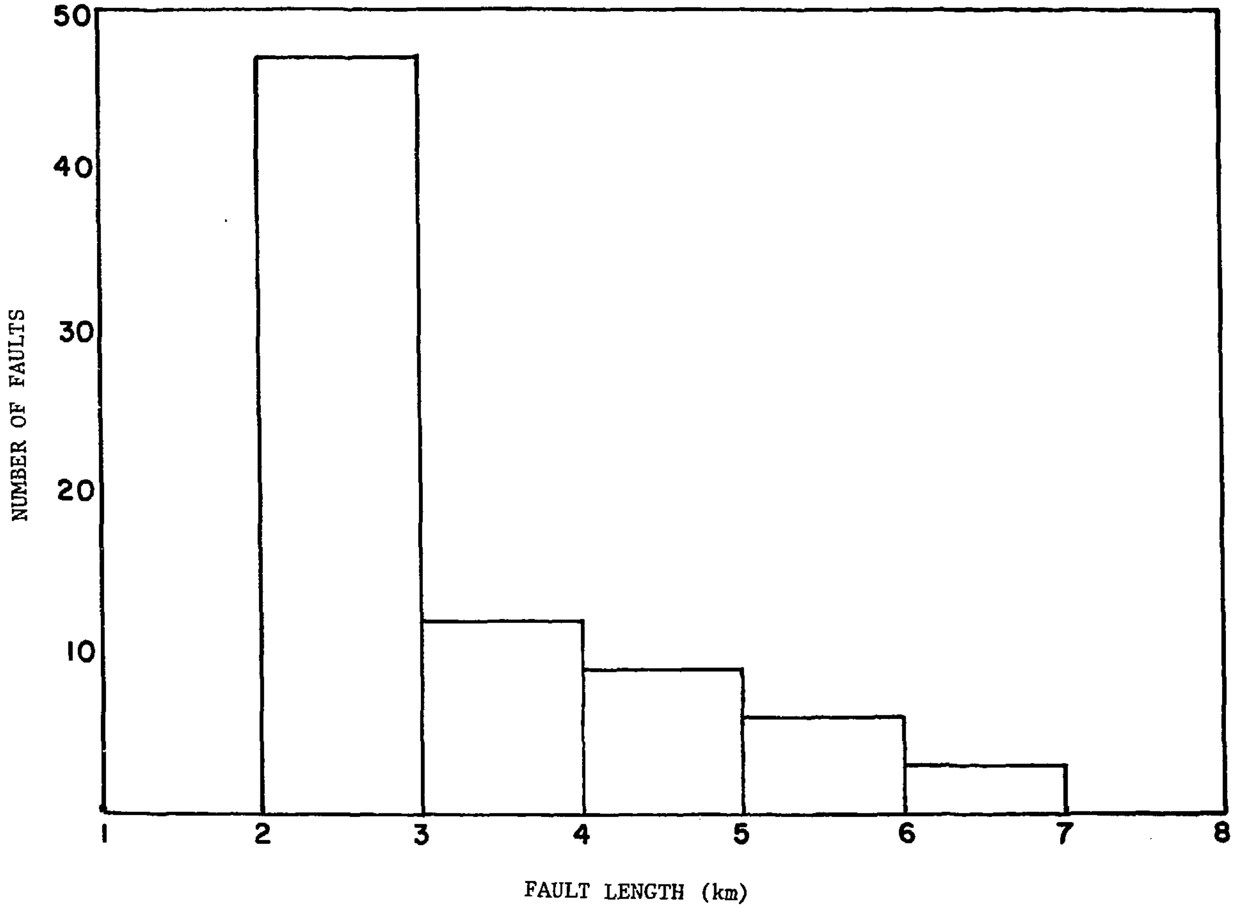

FIGURE B-2: Representative Lineament Distribution in Igneous Rock Formations of Northern Ontario

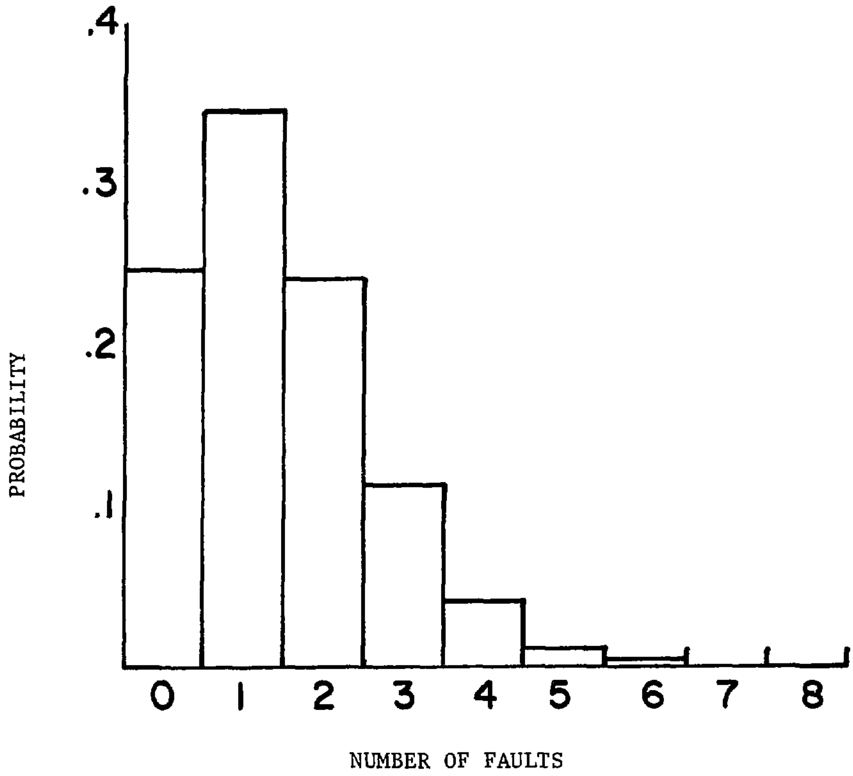

FIGURE B-3: Probability Distribution for the Number of Faults Intersecting a Random Vault Site

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