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A REVIEW OF RESEARCH INTO THE EFFECTS OF LONG-TERM ENVIRONMENTAL CHANGE ON DEEP LAND DISPOSAL SITES FOR RADIOACTIVE WASTE

DRAFT

FOR
COMMISSION OF THE EUROPEAN COMMUNITIES
AND
UK DEPARTMENT OF THE ENVIRONMENT

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1.0 INTRODUCTION

1.1 SCOPE AND PURPOSE

This report is the first of three documents describing the results of a project entitled: "Modelling the Long Term Evolution of Geological Radwaste Disposal Facilities", sponsored jointly by the Commission of the European Communities (CEC) and the United Kingdom Department of the Environment (DOE). The report presents a review of the status of research into the effects of long term environmental changes on deep land disposal facilities for radioactive wastes. It is intended to provide a sound footing for current and future research into glacial processes, and the incorporation of environmental change modelling into performance assessment.

The review specifically addresses the role of factors which could potentially cause environmental change over a period of approximately one million years in the vicinity of a deep (100m to 1000m) onland waste repository. Changes over several million years, or factors which influence only the near-surface environment, are not generally considered.

Wherever possible we have sought to obtain the most up to date information on the activities of the various research teams active in considering long term environmental changes and their effects on disposal worldwide, by means of both written and oral communications. Background work for the review was carried out between November 1987 and February 1988.

1.2 REPORT STRUCTURE

Following this introduction, Section 2.0 outlines the nature of the environmental system and the changes that can occur within it. This is intended to provide a conceptual background to the specific programmes of work discussed later.

Section 3.0 describes the current status of research into the effects of long term environmental change in the various countries actively engaged in such work. These countries, and also agencies within countries, have invariably adopted different approaches to the study of long term change, partly because of geographic location but also because of the research strategies employed. Comparison of these different approaches is instructive in the evaluation of the importance of different factors which contribute to environmental change.

Research into environmental change modelling carried out at Dames & Moore, funded by DOE as part of the development of a suite of tools for post-closure safety assessment, is outlined in Section 4.0. This section concentrates on the TIME2 computer model of environmental change. Although this model specifically addresses shallow onland disposal, rather than deep disposal, it represents important groundwork for future environmental change modelling.

Section 5.0 addresses the incorporation of environmental change evaluation into performance asssessment. It thus comprises the application of the factors discussed in the preceding sections. In particular, two approaches to evaluation of environmental change are compared and contrasted: the "scenarios approach" and "time dependent performance assessment".

Conclusions from this review are presented in Section 6.0. A glossary of terms follows this section, as well as a list of references. Finally, the Appendix provides a categorised list of source material for the review.

2.0 THE NATURE OF ENVIRONMENTAL CHANGE

2.1 INTRODUCTION

This chapter presents an overview of the nature of environmental change, as a background to the discussion of recent work on the effects of environmental change on the disposal of radioactive waste. We concentrate on issues relevant to deep, onland disposal.

It is important to realise that all the processes and events involved in environmental change act together as a unified system. Our knowledge of this overall system is poor and in many cases we do not understand how different processes interact in detail despite knowing that some linkage exists. In other cases, we are able to model the linkages effectively over very short timescales but these models break down when projected too far into the future (for example large global circulation models which have been constructed to model climatic and weather systems). It is therefore necessary to recognise some basic features of the environment when attempting to model environmental change:

- The interlinking of processes and events;
- The need to model those linkages whenever possible;
- The limitations of our current understanding of the environmental system.

In the following sections the emphasis is, therefore, placed on the discussion of 'systems'. Individual processes and their precise interrelations with the 'system' may be unknown; nevertheless, these processes must be regarded as contributions to the environmental system which we aim to model.

2.2 THE ENVIRONMENTAL SYSTEM

Change is inevitable in the earth's environment. This is evident in the many dynamic processes presently understood in the study of the earth. Two fundamental driving forces can be identified (Plate 1):

- o Astronomical movements;
- o Tectonic movements.

Changes in the earth's climate result primarily from astronomical fluctuations in the earth's orbit and their effects on the atmospheric and surface temperatures of the earth. Changes in processes at the earth's surface (eg. river and groundwater flow) are primarily determined by tectonic processes in the crust. These tectonic processes arise ultimately from radiogenic heat production in the earth's core and mantle. However, the effects of these two primary causes of change are not simple and are supplemented by numerous environmental processes. For example, the global water-circulation system responds slowly (ie with delayed response) to changes in temperature resulting from (solar) insolation effects, and this response is in turn further complicated by the distribution of land masses and the vegetation patterns on them.

Our understanding of these processes follows several pioneering discoveries such as those of Milankovitch (who first established the link between climatic change and planetary orbits, in 1951), Wegener (who initiated the idea of moving continents and their role in changing the face of the planet, in 1919), and Darwin (who pioneered the understanding of living species and their adaptation to the changing environment, in 1859). Since these initial steps in understanding the earth's environment, a vast web of inter-relation has become apparent. individual processes can rarely be considered in isolation.

The task of geological disposal of radioactive waste requires detailed knowledge of many of these aspects of the earth's environment. The repository is located within the geosphere, the behaviour of which needs to be sufficiently understood for long-term assessment of the future performance of the repository. Transport of radionuclides from the repository into the

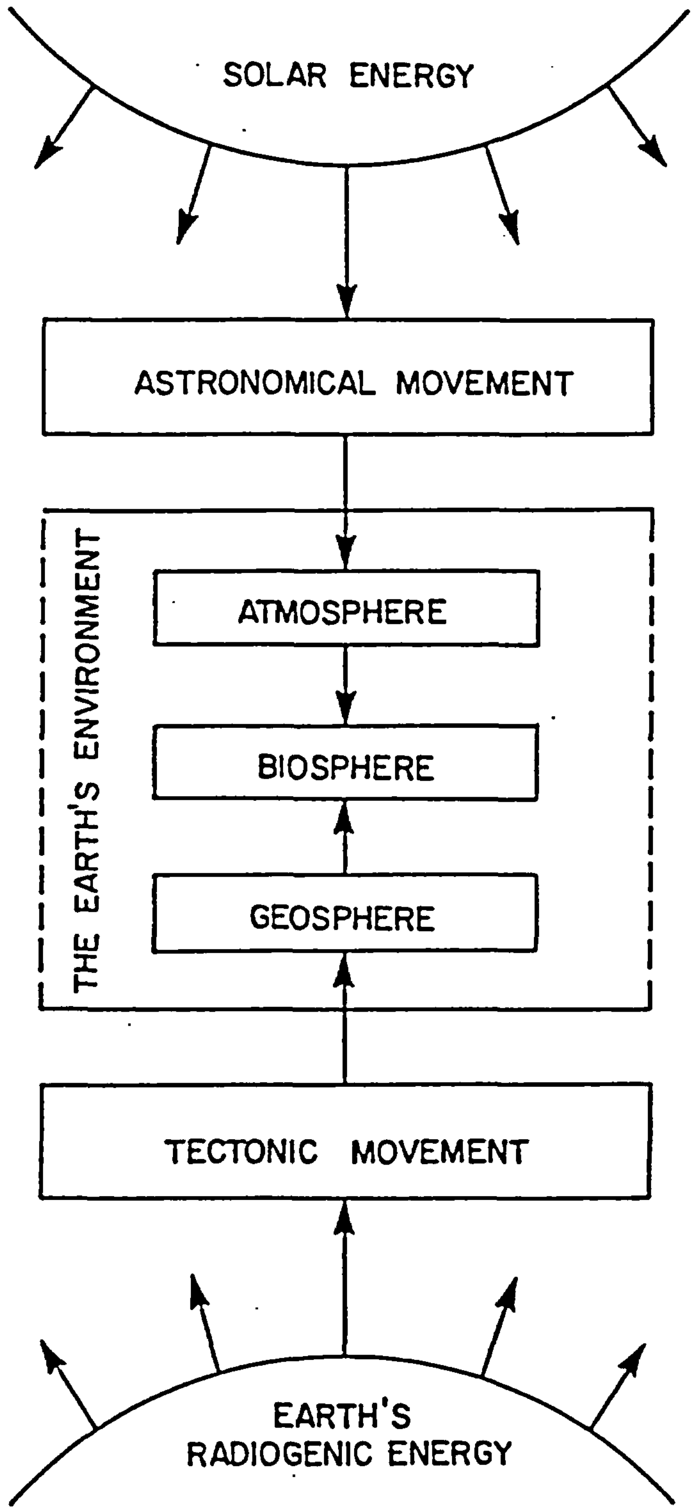

PLATE 1 THE EARTH'S ENVIRONMENTAL SYSTEM

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biosphere is the primary issue in the calculation of potential long-term effects on human, animal and plant life. In this report we do not consider the processes of biosphere transfer or the effectiveness of the engineered repository components (steel, concrete etc.) but consider the geosphere and its effects on both the biosphere and repository. Thus our interest in climatic change, water movement and human activity relate primarily to their effects on the geosphere and its effectiveness in radionuclide containment.

2.3 THE DEEP-DISPOSAL ENVIRONMENTAL SYSTEM

We turn now to consider the specific elements of the environmental system which are of concern to the disposal of radioactive waste at depth within geological formations. Plate 2 illustrates the principal factors which have been identified as influencing the long-term performance of a repository. Two forms of change constitute the primary drivers of the system:

- Climatic change;
- Tectonic change.

The effects of climatic change are especially evident in the processes associated with glaciation. This is partly because recent geological history has been essentially 'glacial', but also because most areas (in Europe) where geological disposal of radioactive waste is proposed are at high latitudes where glacial effects have particular importance. Other aspects affected by climate include sea level change, denudation, water balance and permafrost development.

'Tectonics' refers to the structure and deformation of the earth's crust. It is in many ways analogous to 'climate' in being the total state of the crust, much as climate is the total state of the atmosphere. In terms of radioactive waste disposal, tectonic change is of interest primarily for its influence on the conditions of the geosphere around a repository. Specifically, this involves the state of stress in the rocks, the level of seismicity and associated deformation, and the permeability and degree of fracturing of various rock types (the media parameters).

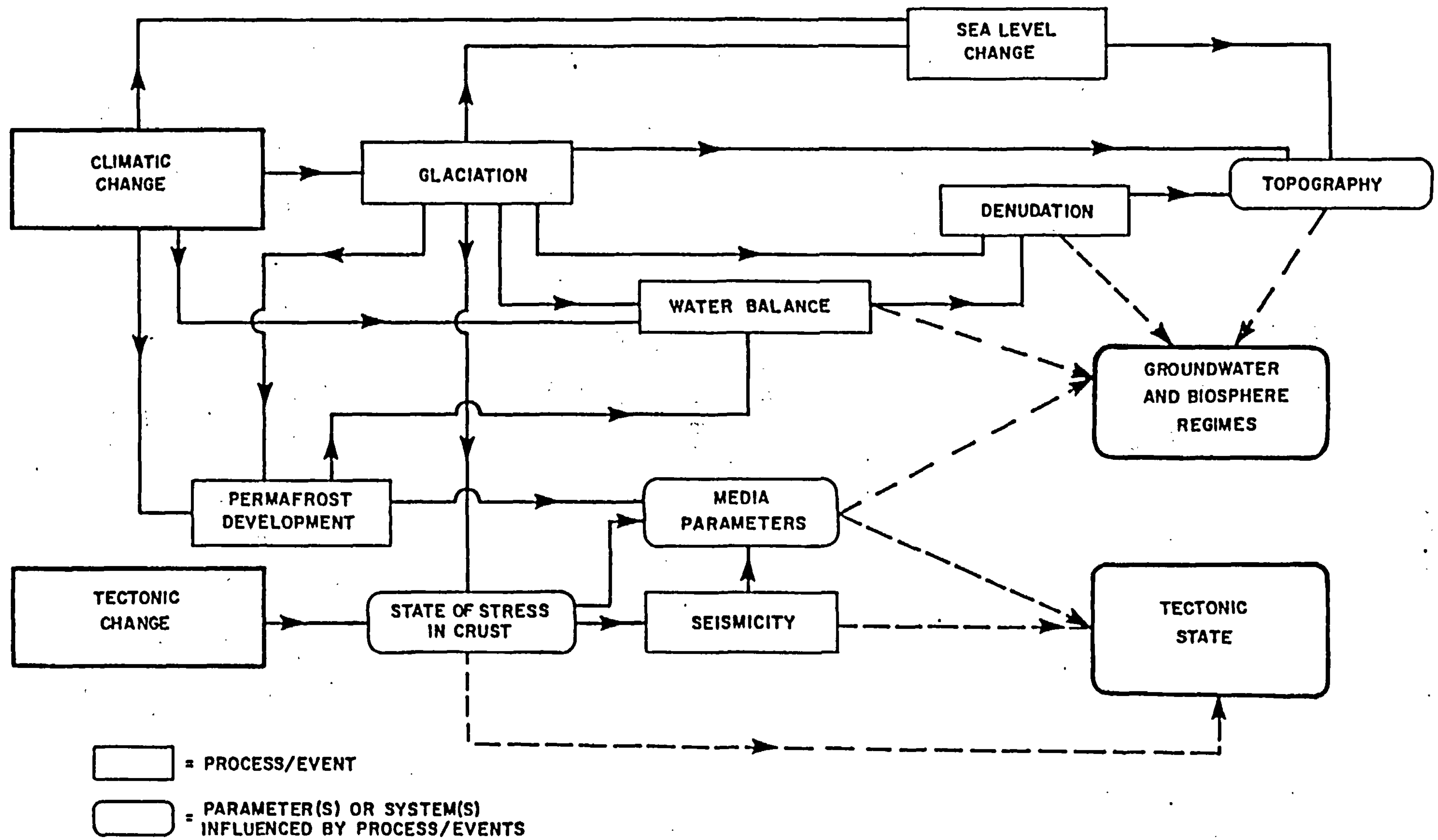

PLATE 2 SCHEMATIC OF THE ENVIRONMENTAL SYSTEM

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The schematic system outlined in Plate 2 terminates with two facets of the state of a repository's environment. These are:

- o Groundwater (and biosphere) regime;
- o Tectonic state.

These two facets of the deep disposal environment are illustrated in Plate 3. Essentially the groundwater regime depicts all the aspects which determine groundwater flow and the tectonic state describes the media in which the groundwater flows. These two facets are not of course independent, but exist in a dynamic interrelation which ultimately determines the deep disposal environment.

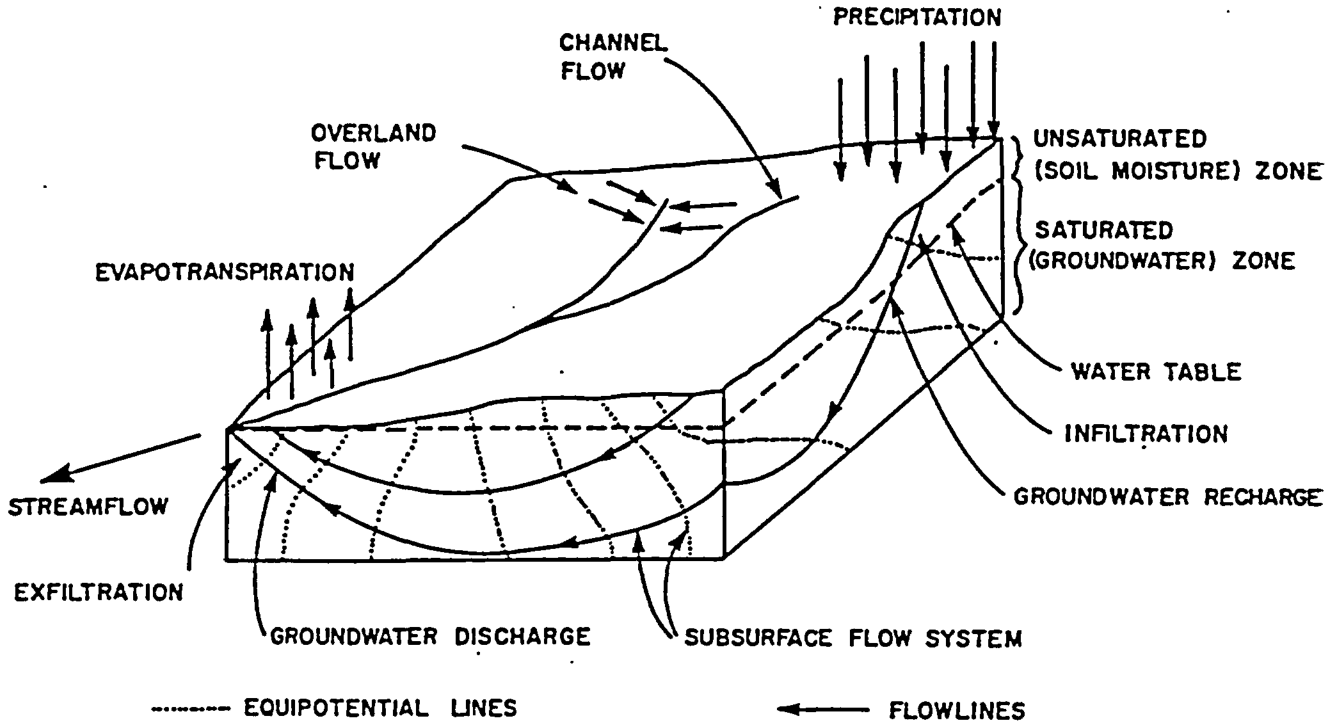
2.4 SIGNIFICANT PROCESSES IN THE DEEP-DISPOSAL ENVIRONMENT

2.4.1 Introduction

Several aspects of the deep-disposal environment are outlined below. The first three sections concern aspects of the 'groundwater regime' and these are followed by four sections which relate to the 'tectonic state'. In each case detailed discussion of the processes involved is not included, instead discussion focusses on aspects related to long-term change. Specifically we address the question "What factors can cause significant environmental change over a period of one million years (viz. significant for performance assessment)?"

2.4.2 Climate and Groundwater

The groundwater regime shown in Plate 3 indicates how climate plays a fundamental role in determining groundwater flow. Precipitation, overland flow and evapotranspiration largely determine the surface water budget, which in turn directly affects groundwater flow. That is, the climatically-derived surface-water budget is the major driving force of the groundwater system. Other factors, such as sea level and vertical crustal movement, will play a role, but it is ultimately climatic change which will cause changes in the groundwater system.



THE GROUNDWATER REGIME
(REDRAWN FROM FREEZE & CHERRY 1979)

THE DEEP-DISPOSAL ENVIRONMENT

THE TECTONIC STATE
(ADAPTED FROM RAMSAY 1967)

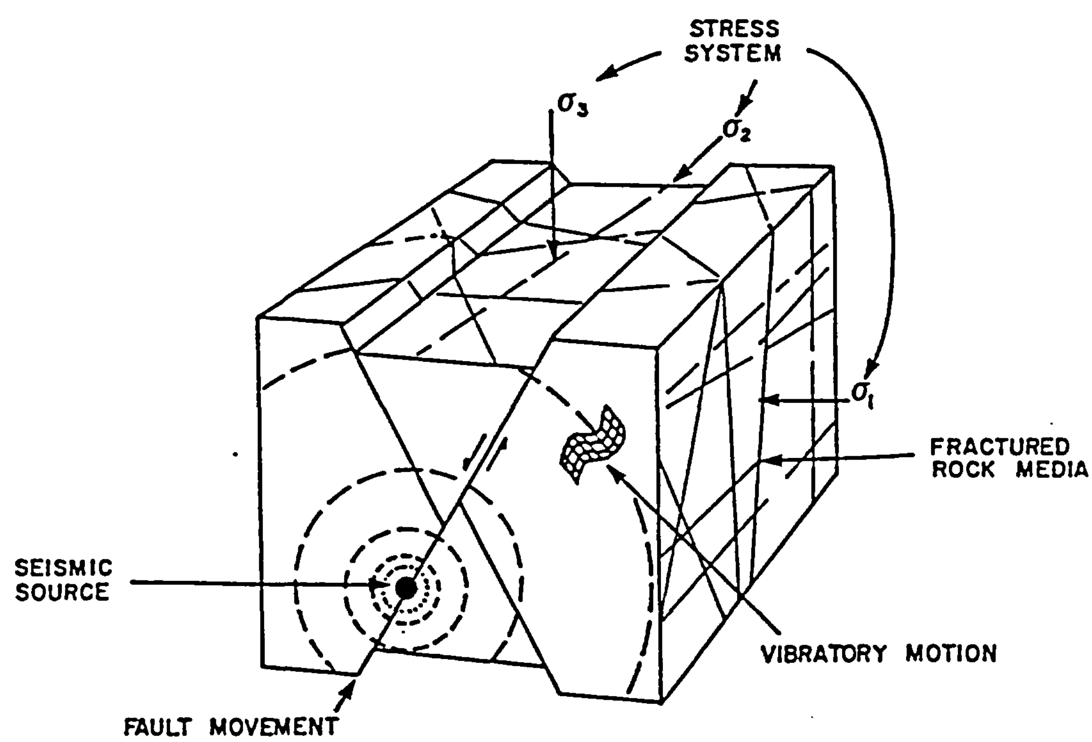


PLATE 3 THE DEEP-DISPOSAL ENVIRONMENT

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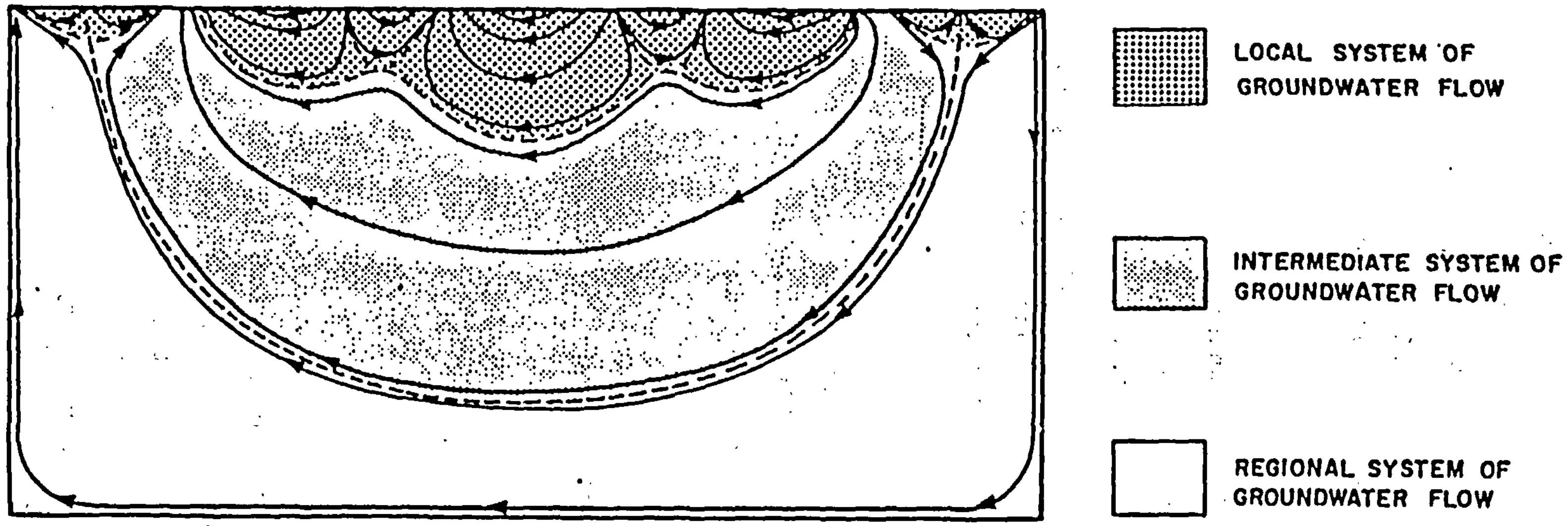
However, this fundamental link may involve a significantly delayed response, whose time-dependent nature is difficult to quantify. Groundwaters of considerable age (10^5 to 10^6 years) are frequently observed to be involved in present-day groundwater circulation. The aquifers of much of North Africa and Arabia, for example, are known to involve waters of Pleistocene age (pre- 10,000 years before present) from recharge zones in upland areas where present precipitation is wholly insufficient to account for the observed groundwater flow (Lloyd & Farag 1978). Study of groundwater in the north-east of England has likewise shown the presence of Pleistocene (9,000 to 25,000 year old) waters in deep limestone aquifers (Downing et alia 1977). Typical response times for aquifers (ie the time for a system in equilibrium to decay to a new equilibrium) range from 100's to 1000's of years, and can be longer. The response time is dependent on several factors including porosity, compressibility and length of flow paths. In general, circulation in near-surface, local groundwater flow systems will respond relatively quickly (1 to 100 years) to changes in recharge and discharge, whereas deeper, regional groundwater flow systems will respond much more slowly (10^3 to 10^5 years). Local groundwater systems typically penetrate to a few hundred metres and regional groundwater systems may circulate to depths of several kilometres (Plate 4). This is usually the case in Britain, where local systems relate closely to the surface topography and river basin morphology, but deeper regional systems may relate to former climatic or tectonic conditions (such as the Pleistocene ice sheet distribution).

Thus, although climate has a fundamental role in determining groundwater flow, its effect is not necessarily simply determined.

2.4.3 Land Elevation, Sea Level and Groundwater

Whereas climate mainly affects the water budget of a groundwater system, land elevation and sea level act as major boundary conditions to a groundwater system. Changes in both land and sea level result in changes in hydraulic gradient by affecting the locations of recharge and discharge points and by changing the flow paths employed. Changes in these boundary conditions are likely to lead to delayed-response effects in the groundwater in a similar manner to that described for climatic changes (above). However, changes in



(REDRAWN FROM FREEZE & CHERRY 1979, AFTER TÓTH 1963).

PLATE 4 LOCAL, INTERMEDIATE, AND REGIONAL SYSTEMS OF GROUNDWATER FLOW

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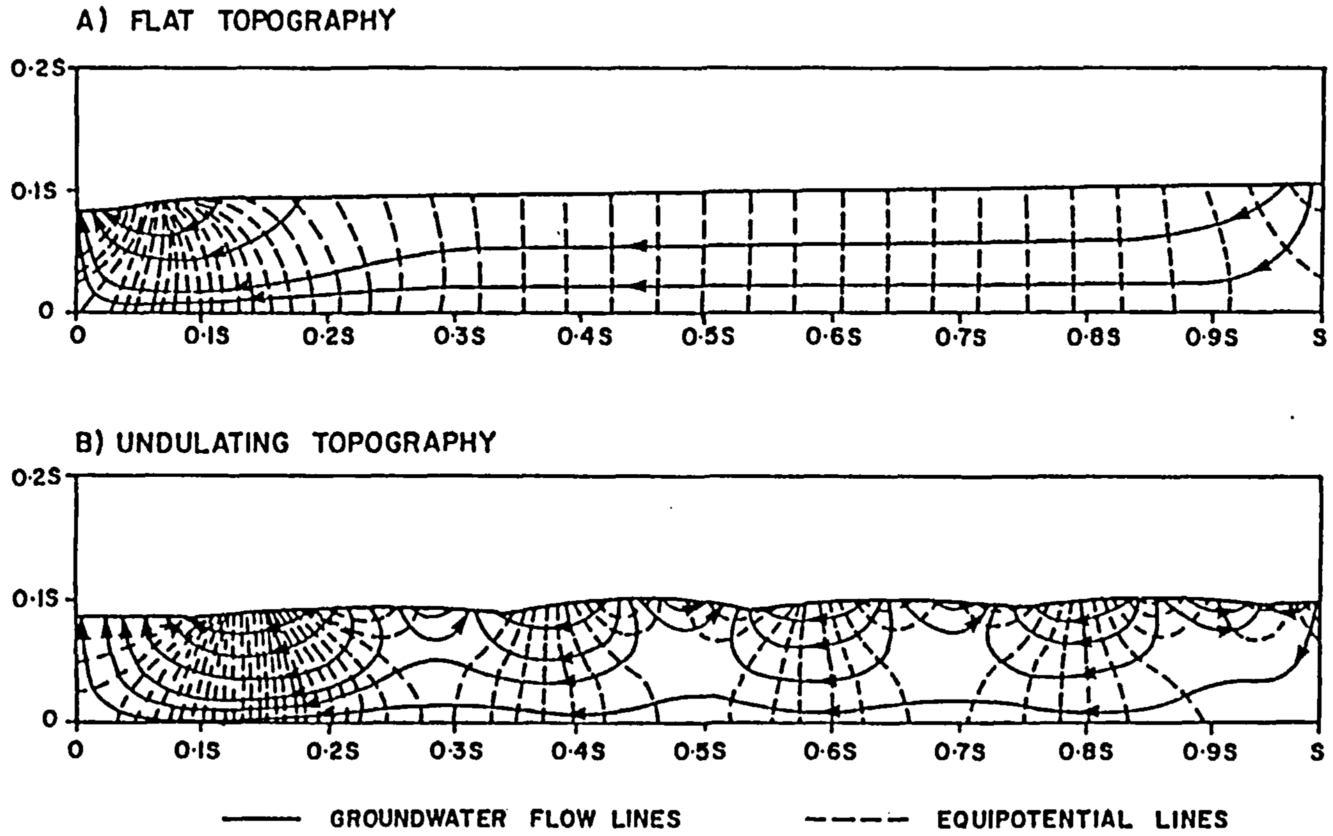
land elevation are generally much slower than sea level or climatic changes so that delayed-response effects are likely to be less significant. Plate 5 shows the effect of even minor topographic changes on a groundwater system. Essentially, varied topography tends to lead to more complex groundwater flow, whereas uniform topography results in simpler systems. The illustration in Plate 5 assumes uniform geology. In reality geological variation in permeability and conductivity will add further complexity to the effects of topography.

The evolution of a landscape with time is therefore likely to be accompanied by substantial changes in groundwater flow. On the whole the response of a groundwater system to such changes is likely to be closely coupled, since the rates of change are not rapid enough for delayed response effects in the groundwater to be important. This may not be the case for sea level changes which can be rapid: rates of 10-100m per 1000 years can occur in association with glaciations.

This illustrates one of the ways in which erosion and denudation processes, although not directly affecting a deep repository, can have a secondary role in affecting the groundwater flow around a repository.

2.4.4 Glaciation and Groundwater Flow

The occurrence of a period of glaciation involves such a severe climatic change that its effects are best considered separately. At the latitude of Northern Europe glaciation is perceived as an important and highly probable development in future environmental change. In association with glaciation, periglacial conditions occur in the areas peripheral to the ice masses. Periglacial conditions involve a severe environment characterized by the effects of freeze-thaw action, which have significant effects on groundwater flow. Essentially, in both glacial and periglacial conditions the physics and hydraulics of ice melting and freezing processes provide an additional component to groundwater flow which greatly modifies the flow system. The effect of these processes is currently the subject of background research being carried out under this contract by Dames & Moore and the University of Edinburgh. The nature of this work will be summarized in Section 4.4.2, below; here we outline the general principle involved.



(REDRAWN FROM FREEZE & CHERRY 1979, AFTER FREEZE & WITHERSPOON 1967)

PLATE 5 EFFECT OF TOPOGRAPHY ON REGIONAL GROUNDWATER FLOW PATTERNS

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In some respects the effect of covering the ground surface with an ice mass is analogous to the removal of topographic effects on the groundwater system. This occurs, not because topography is removed (although it may be altered by glacial processes), but because ice-cover interrupts the pattern of meteoric (ie from precipitation) groundwater recharge, on topographic highs, and discharge to surface waters, at topographic lows. The gross effect of glaciation is thus to break up smaller circulation cells (similar to Plate 5b) and to replace them with larger systems (similar to Plate 5a). Meteoric recharge is replaced by glacial recharge in a manner illustrated in Plate 6.

During glaciation, then, it is primarily the ice distribution which determines groundwater flow, in contrast to more temperate climatic conditions where topography plays the key role.

2.4.5 Tectonic Stress

The word 'tectonic' comes from the Greek for 'craftsman' (Tekton) and is used in geology to refer to the earth's structure and form as a whole. Usually this is restricted to the outer, brittle shell of the earth, the crust. Tectonics thus includes structural composition, deformation processes and the forces at play within the crust. Plate 3 illustrates the many aspects which contribute to the tectonic state of a body of rock. In this section we focus on tectonic stress - the forces which can develop in the crust.

The main sources and causes of tectonic stress are:

- Plate Tectonic stress: stresses caused by the movement and interaction of the crustal plates around the earth;
- Lithostatic stress: the weight of overlying rock;
- Hydrostatic stress: the pressure caused by the weight of water in and overlying a rock-mass;
- Thermal stress: expansion and contraction due to temperature changes in the crust;
- Bending stresses: caused by flexure of the crust;
- Loading stresses: caused by the addition or removal of masses on the surface of the crust (such as glaciers and volcanic material as well as erosion of mountains).

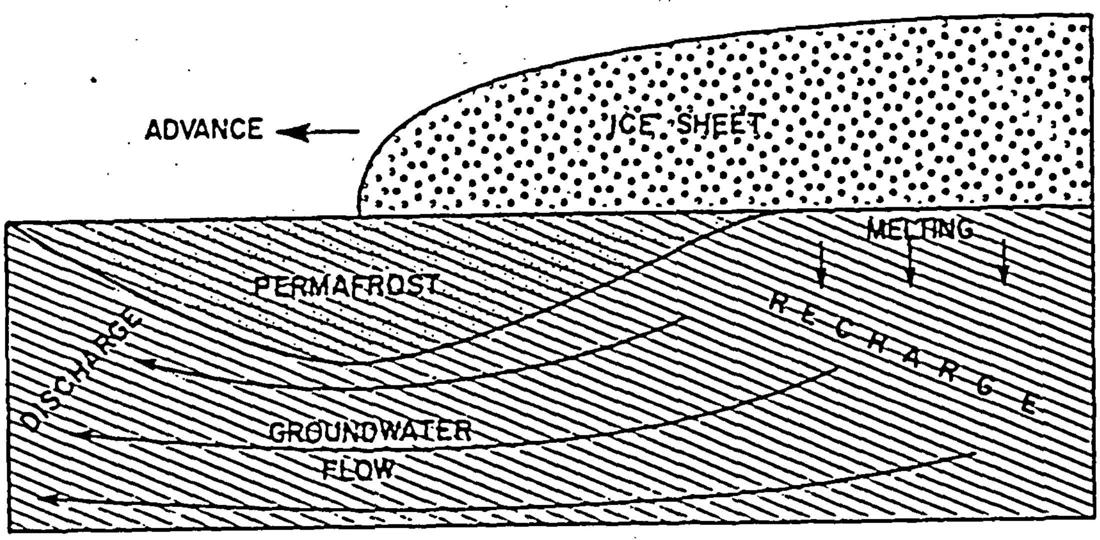


PLATE 6

GLACIAL RECHARGE AND
GROUNDWATER FLOW

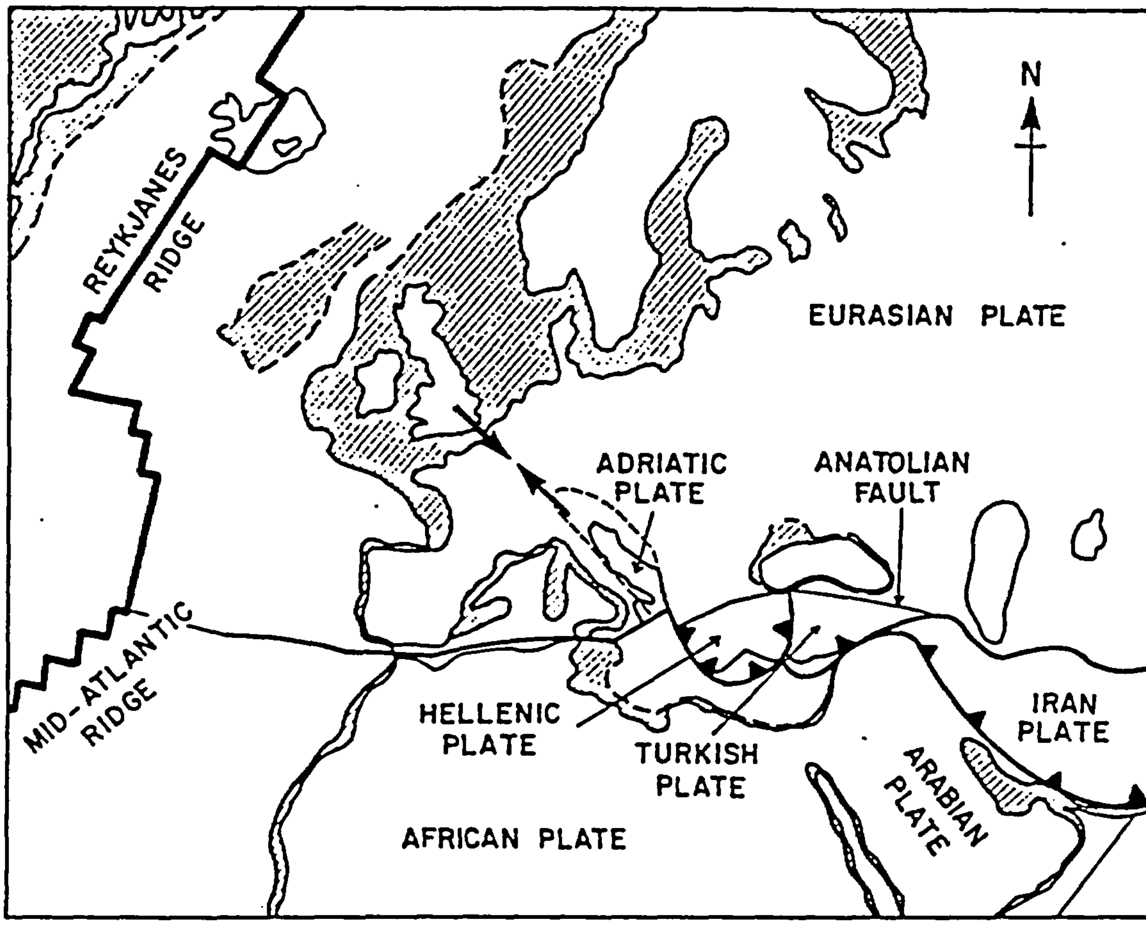
Of these, plate tectonic stress is the dominant source of stress; the others occur essentially in terms of spatial and temporal departures from the ambient plate tectonic stress. The plate tectonics of the European area are illustrated in Plate 7. Northern Europe comprises a plate interior subject to north-west / south-east trending compressive stress. In the south of Europe more complex, active tectonics occur, associated with the compression of the African Plate against the Eurasian Plate.

We are principally concerned with significant changes in stress over periods of less than one million years (ie over geologically short time-scales). In geologically stable areas (such as northern Europe), plate tectonic stresses can be assumed to be relatively constant over a period of a million years and attention can be focussed on other causes of stress change. This is not so for the more tectonically active areas of southern and central Europe, where significant changes in plate tectonic stress are likely to occur within a million years.

Lithostatic and hydrostatic stresses are certainly variable over periods of less than one million years. This is especially the case in the shallow crust (less than 1 km depth) where the effects of local erosion and changes in surface water distribution (eg the formation of large lakes) can have a marked effect on the stress field.

On a global scale thermal stresses in the crust are linked to plate tectonic movements so that changes occur at similar rates to plate tectonic rates. However, locally and at shallow depths more rapid changes do occur. For example, glaciation is known to have a marked effect on the geothermal gradient (the profile of temperature against depth). At depths of less than a few hundred metres, glaciation causes changes in rock temperature of between 2°C and 6°C (Kukkonen 1987). Changes of this order will result in significant thermal contraction and expansion stresses in rock.

Bending stresses, significant for periods of less than one million years, are usually associated with the imposition of surface loads. The best attested such condition is the crustal warping associated with loading of the crust by a major ice sheet. Depression of the land surface by several hundred metres is evident in the areas formally covered by the Laurentian and



(AFTER DEWEY 1972)

PLATE TECTONIC BOUNDARIES

SPREADING RIDGE AXIS

TRANSFORM FAULT

ZONE OF COMPRESSION OR SUBDUCTION

UNCERTAIN PLATE BOUNDARY

CONTINENTAL SHELF

DOMINANT DIRECTION OF MAXIMUM HORIZONTAL COMPRESSIVE STRESS IN NORTHERN EUROPE

PLATE 7

THE PLATE TECTONICS OF EUROPE

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Fennoscandian ice sheets, in North America and Scandinavia respectively, during the last Ice Age (Andrews 1970, Morner 1980). In Britain the last major glaciation resulted in a crustal depression of over 200 metres. These differential vertical displacements result in flexure of the crust and produce associated bending stresses. The imposition and removal of the ice mass also results in an additional component of loading stress.

Given appropriate data, most of these stresses can be modelled for the crust by assuming elastic or visco-elastic behaviour. Reasonable approximations to observed data are generally achieved with such calculations, especially where timescales are geologically short (Turcotte & Schubert 1982).

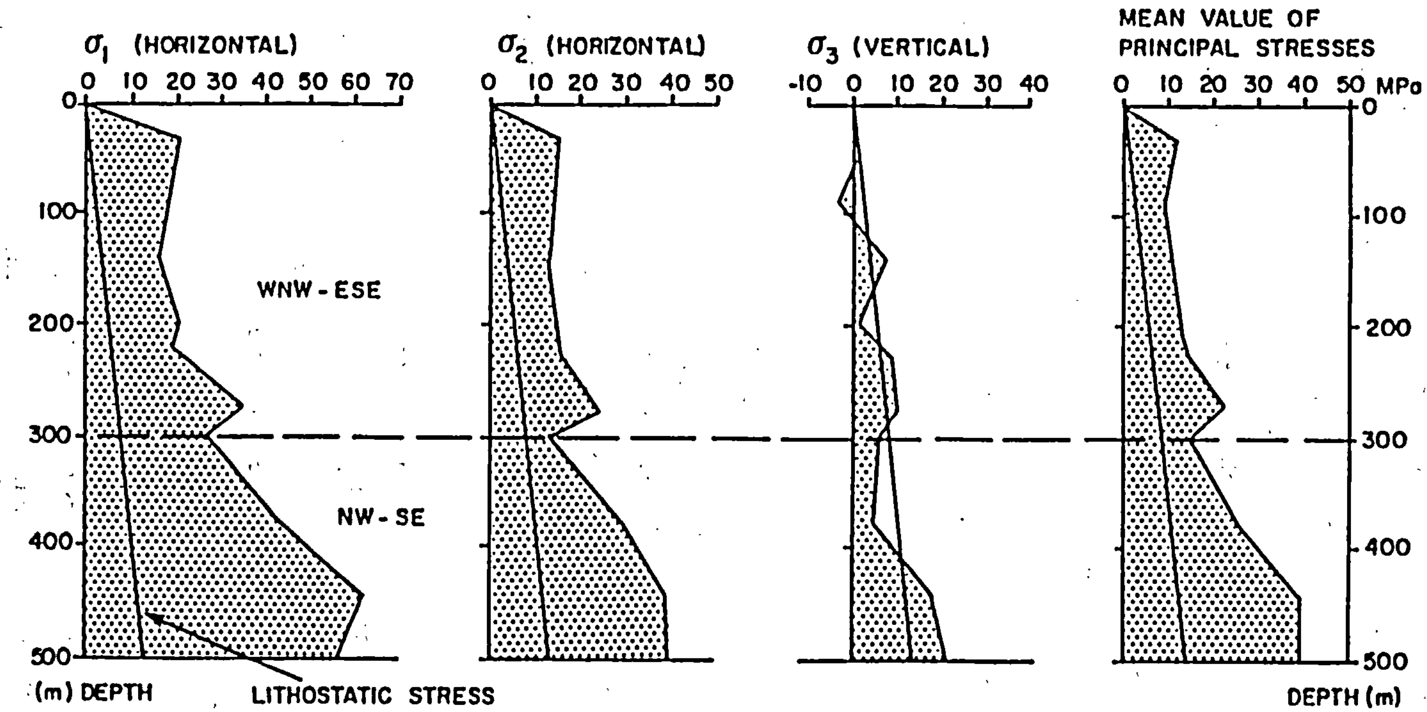
2.4.6 Glacial Stress

Glacial loading stresses are particularly important for modelling the deep-disposal environment in high latitudes. This is because glacial stress levels are high and are applied at relatively rapid rates (10^3 to 10^4 years). Glaciation is perceived as a major probable development in future environmental change in most of northern Europe.

A detailed set of measurements of stress at various depths down to 500m in Sweden indicates the scale and nature of glacial stress (Plate 8). In their report of these measurements, Carlsson and Olsson (1982) (also Carlsson & Christiansson, 1987) point to several features which attest the contribution of the former (Fennoscandian) glacial load to present-day stress conditions. They note:

- o Horizontal stresses are considerably higher than the calculated lithostatic stress (weight of overburden). That is, marked horizontal compression is observed.

- o A decoupling is observed in the profile, in that the orientation of the maximum principal horizontal compressive stress changes from WNW-ESE above 300m depth to NW-SE below 300m. A marked increase in magnitude coincides with this shift in direction.



(REDRAWN FROM CARLSSON AND OLSSON 1982)

PLATE 8 PRINCIPAL STRESSES ($\sigma_1, \sigma_2, \sigma_3$) VERSUS DEPTH OBTAINED FROM A BOREHOLE AT FOSMARK, SOUTHERN CENTRAL SWEDEN, BY THE SWEDISH STATE POWER BOARD.

Carlsson and Olsson show that much of this stress, in excess of calculated lithostatic stress, can be explained by residual stress resulting from a 2 km thick layer of ice over the site (ie the Fennoscandian ice thickness at the site). The very high stress values below 300m require some additional component to explain them, such as regional tectonic stress. The sudden change in stress at 300m is not understood but may relate to features of glacial rebound. It certainly suggests that shallow stress measurements made in deglaciated areas may not be reliably extrapolated to depth.

Thus from this site study (the most detailed available in Europe) it appears that major glaciation causes major changes in stress at the depths of concern for a deep radioactive waste repository. Between 100m and 300m an increase in stress by a factor of two to three is evident in the Swedish data.

2.4.7 Seismicity

Seismic energy release and deformation processes can be seen as two complementary products of tectonic change. Tectonically active areas are seismically active areas. Most of northern Europe has relatively low levels of seismicity, the main exceptions being the Alpine belt and the Rhine graben. Much of Mediterranean Europe is seismically active, being a plate collision zone (Plate 7).

The effects of the passage of seismic waves on underground rock-mass behaviour are complex. Several recent reviews of the subject (eg Pratt et alia 1978, Carpenter & Chung 1985) reflect the importance of this issue for deep disposal. Here, however, we focus only on aspects that could result in changes in the level of seismicity.

Changes in seismicity rates which accompany major changes in plate tectonic configuration will not be considered, their being generally too long-term to be of relevance. Short-term changes can however occur in terms of the following phenomena:

a) <u>Temporal fluctuations in seismicity rate:</u>

In many instrumental and historical records changes in the rate of seismic energy release have been observed on the scale of 10's to 1000's of years. For example, Bath (1978) provides evidence for an abrupt change in seismic energy release in Scandinavia at round 1910 AD. Before 1910 much higher rates than the presently observed rate occurred. In terms of historical evidence, Ambraseys and Melville (1982) show that similar changes in seismicity rates have occurred during the last 13 centuries of the Persian/Iran record. Such phenomena are probably related to minor changes in tectonic deformation rates (ie periodicity of strain release). Although poorly understood, such changes indicate the need for caution when attempting to extrapolate present-day seismic hazard into the long-term future.

b) <u>Migration of seismic zones:</u>

Spatial variations in seismicity have been noted in association with temporal changes; however, they are generally less frequently observed. On the whole seismically active zones have remained so throughout historical time (1000 years). Some spatial variations are evident in the eastern United States during the last 300 years (Mitronovas 1981) and geological evidence indicates recent movement on faults in the area, which are presently seismically inactive (Kerr 1985). It is likely that some apparent spatial variations are simply the result of long-term temporal variations, in that fault zones become 'locked-up' for lengths of time before developing spates of activity. The increasing geological evidence for pre-historic seismicity (Sieh 1978, Thorson et alia 1986, Ringrose 1988) does nevertheless indicate that over periods of thousands of years the locations of seismic zones do change. Again this must be borne in mind in performance assessments extrapolated to the long-term future.

c) <u>Climate-induced seismicity:</u>

Recent studies in the eastern United States (Costain et alia 1987) suggests some link between groundwater hydraulics and seismicity rates. This phenomenon of 'hydroseismicity' is as yet poorly established, but suggests that climatic/water balance changes could significantly change patterns of seismicity. A more severe form of climate-induced seismicity is that which results from glaciation. The period immediately following deglaciation is known to result in dramatically enhanced fault-movement and seismicity. To what extent this is due to glacial stress factors or glacial hydraulic factors is not yet known. The evidence that such changes do occur is now overwhelming. Broadly speaking it seems that seismicity is much reduced or absent beneath an ice cap (such as presently beneath the Antarctic and Greenland ice sheets, Johnston 1987) but that as soon as deglaciation and isotatic rebound occur a dramatic rise in seismicity results, which then decays over several thousands of years to return to 'normal' rates (Morner 1978).

d) <u>Man-induced seismicity:</u>

Reservoir-induced earthquakes have been commonly observed. The largest of these occurred at Koyna, India, in 1967, where a magnitude 6.5 event, causing more than 200 deaths, occurred after the filling of a large reservoir (Adams 1983). The explanation for this phenomenon is not clear, but it is thought to be due to a combination of the reduction in shear strength due to seepage of water under pressure into fault zones and the increase in vertical stress due to the water load. Reservoirs more than 100m deep are found to be much more prone to producing a seismic event. Seismicity can also be induced by mining activities, where earthquakes as large as Magnitude 4 to 5 have been known (Kusznir et alia 1985). Generally such events are much smaller. Activity is usually very localized around the mine.

2.4.8 Fault Movement

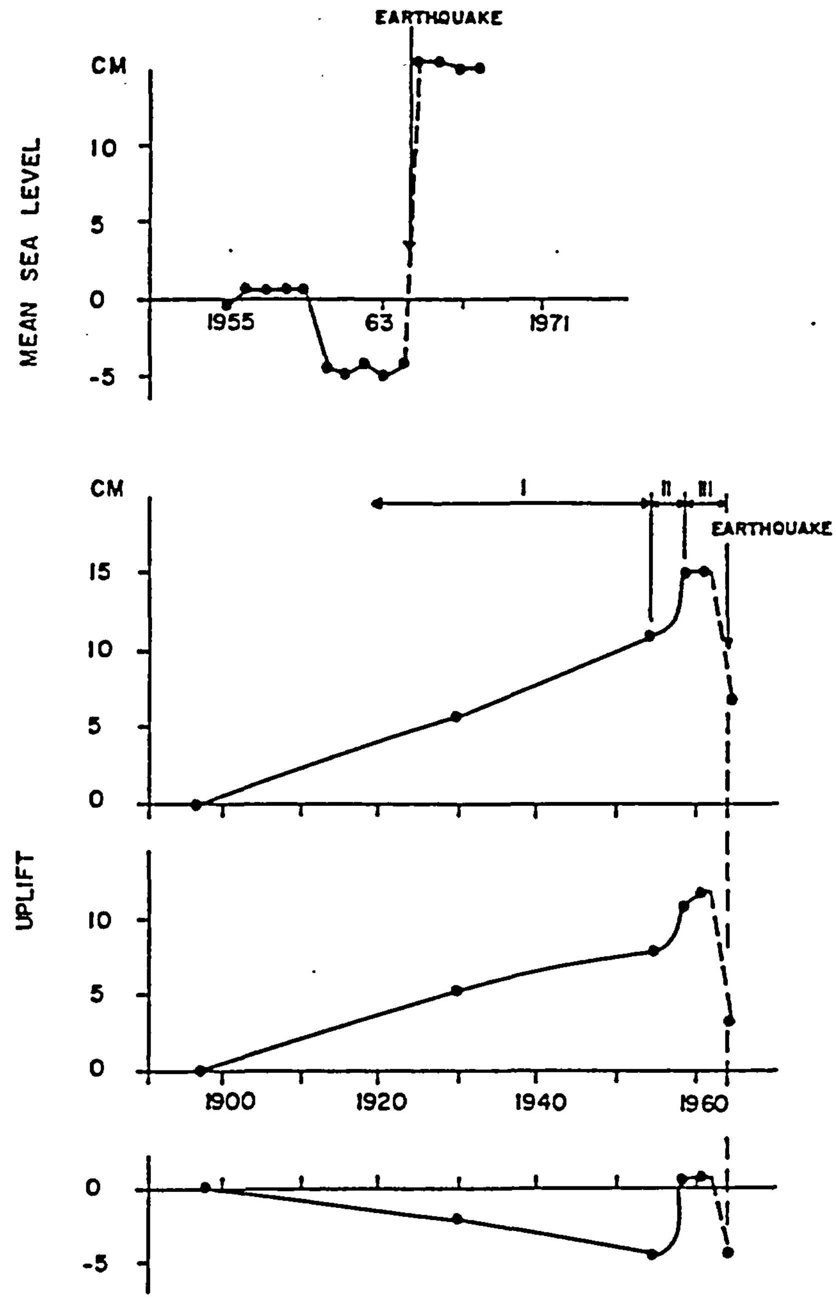
The most significant form of crustal deformation at shallow depths is fault movement. Gradual aseismic, strains do occur in the crust but fault rupture is by far the dominant means of strain release. The basic theory of seismology proposes that rocks undergo gradual, elastic, strain build-up (phase I) before beginning to fail, firstly by microcracking (phases II and III) before the eventual rapid rupture (on large discontinuities) which results in seismic energy release. This is illustrated in Plate 9.

Faults are of critical importance in deep disposal performance assessment since fault movement is a serious potential means of damage to a repository and since discontinuities can be important pathways for groundwater flow. It is not appropriate, here, to discuss the contribution of faults to performance assessment; we shall consider only long-term changes in fault behaviour. Such changes generally relate directly to changes in stress and seismicity: the tectonic state (considered in the three previous sections). However, there is some difficulty in extrapolating future stress and seismicity levels to future degrees of fault displacement, since our knowledge of underground displacement is limited.

It is generally assumed that a repository will be situated in a tectonically stable rock-mass away from the influence of significant faults. That is, the direct effects of faults on a repository can be mitigated by avoiding fault zones. This basic assumption requires careful evaluation when considering long-term environmental change, since the maintenance of an 'unfaulted' state in the long-term needs to be demonstrated. Two examples serve to illustrate that unpredictable locations of fault rupture can occur:

a) The Meckering earthquake in western Australia, 1968, occurred in an area of no previously recorded seismicity and resulted in a fresh surface break in alluvial deposits above basement rock where no fault was previously suspected (Everingham et alia, 1969).

b) Studies of post-glacial faults in areas of glacial rebound indicate that, although most such fault movement is manifested as re-activation of old faults, some major displacements have occurred where no distinct, pre-existing, fracture zones are evident (Kukkonen & Kuivamaki 1986, Ringrose 1988).



The top curve shows relative sea level near Niigata, Japan. The other three curves show elevation differences for three bench marks resurveyed repeatedly before the 1964 earthquake (M = 7.5). Note the correspondance with premonitory stages postulated by the dilatency model, viz (I) elastic strain accumulation, (II) dilatency dominant, (III) influx of water dominant.

(AFTER SCHOLZ ET AL. 1973)

PLATE 9

BUILD-UP OF STRAIN BEFORE AN EARTHQUAKE

These two examples illustrate that, especially where long-term change is to be evaluated, future fault displacement cannot be liberally ignored. The effect of glaciation in particular is likely to result in movement on 'new' faults as well as resulting in the reactivation of existing faults.

3.0 CURRENT RESEARCH STATUS

3.1 INTRODUCTION

This section presents a review of worldwide research on the effects of long-term environmental change on radioactive waste disposal. The review is not comprehensive but summarises the status of work in each country involved. We have concentrated on discussion of aspects which we consider to be of special relevance, being significant advances in this field of knowledge. There are gaps in this review: in particular, we encountered difficulty in obtaining recent information from the United States, Japan and West Germany.

Before discussing research in countries outside the EEC (Section 3.3) and then within the EEC (Section 3.4) we summarise the various approaches adopted in the prediction of environmental change.

3.2 APPROACHES TO THE PREDICTION OF ENVIRONMENTAL CHANGE

3.2.1 Introduction

The issue of long-term environmental change at radioactive waste disposal sites is essentially one of prediction. The question at hand is: 'to what extent can future processes at the site of interest be predicted in order to be sure of adequate long-term safety?' The methods of approach to this problem are diverse and are worth some consideration before outlining the current research strategies in the various countries and organisations.

3.2.2 Determinism and Probabilism

Predictive approaches are often divided into deterministic and probabilistic methods. Deterministic methods place an emphasis on what is known, whereas probabilistic methods attempt to account for uncertainty. Prediction always involves some uncertainty and so 'probability' is always involved (even if not explicitly stated). Conversely, since prediction must be made on the basis of what is known a degree of determinism must also always be employed; that is to say, determinism and probabilism are two ends of a spectrum in predictive science.

An example of highly deterministic prediction is the assumption that present conditions will remain unchanged and that measurements made at a repository site can be extrapolated indefinitely for the purposes of performance assessment. As the reality of a changing environment is included in performance assessment, increasingly probabilistic methods must be employed in order to account for variability and uncertainty.

In the following sections various approaches adopted in safety analyses are outlined, broadly in the order of more deterministic to more probabilistic methods.

3.2.3 Deterministic Geological Argument

The first stage in repository site selection is usually the demonstration of a geologically safe environment. Geological processes and history are analysed in order to be able to state that a site is geologically 'safe' (implicity, that the site has been 'safe' up to the present). The argument for safety may rest with such analyses or proceed to more quantitative and probabilistic arguments. Countries in which a requirement to demonstrate safety has been imposed, in terms of an ultimatum, have generally had to rely on deterministic geological arguments for safety. Two projects in Sweden and Switzerland are largely of this nature (KBS Safety Studies and Project Gewahr). Large databases were assembled in order to demonstrate or 'guarantee' that safe disposal of radioactive waste was indeed feasible. Essential as such studies are in the first stages of disposal programmes, it must be appreciated that they represent fairly subjective argument based on past geological processes.

3.2.4 Disruptive Event Analysis

The next logical step in safety analysis is often the 'what if' approach. That is to say, given a deterministically argued geologically safe environment, what are the consequences of an unpredictable damaging occurrence (such as a fault intersecting the repository or a hole being accidentally drilled through it)? Such 'what if' problems have been addressed by two main approaches:

- o Worst-case analysis: the calculation of the consequences of the most disruptive sequence of events which can be expected to occur;

- o Fault-tree analysis: a method for accounting for many different types of disruption by means of an organised probabilistic scheme.

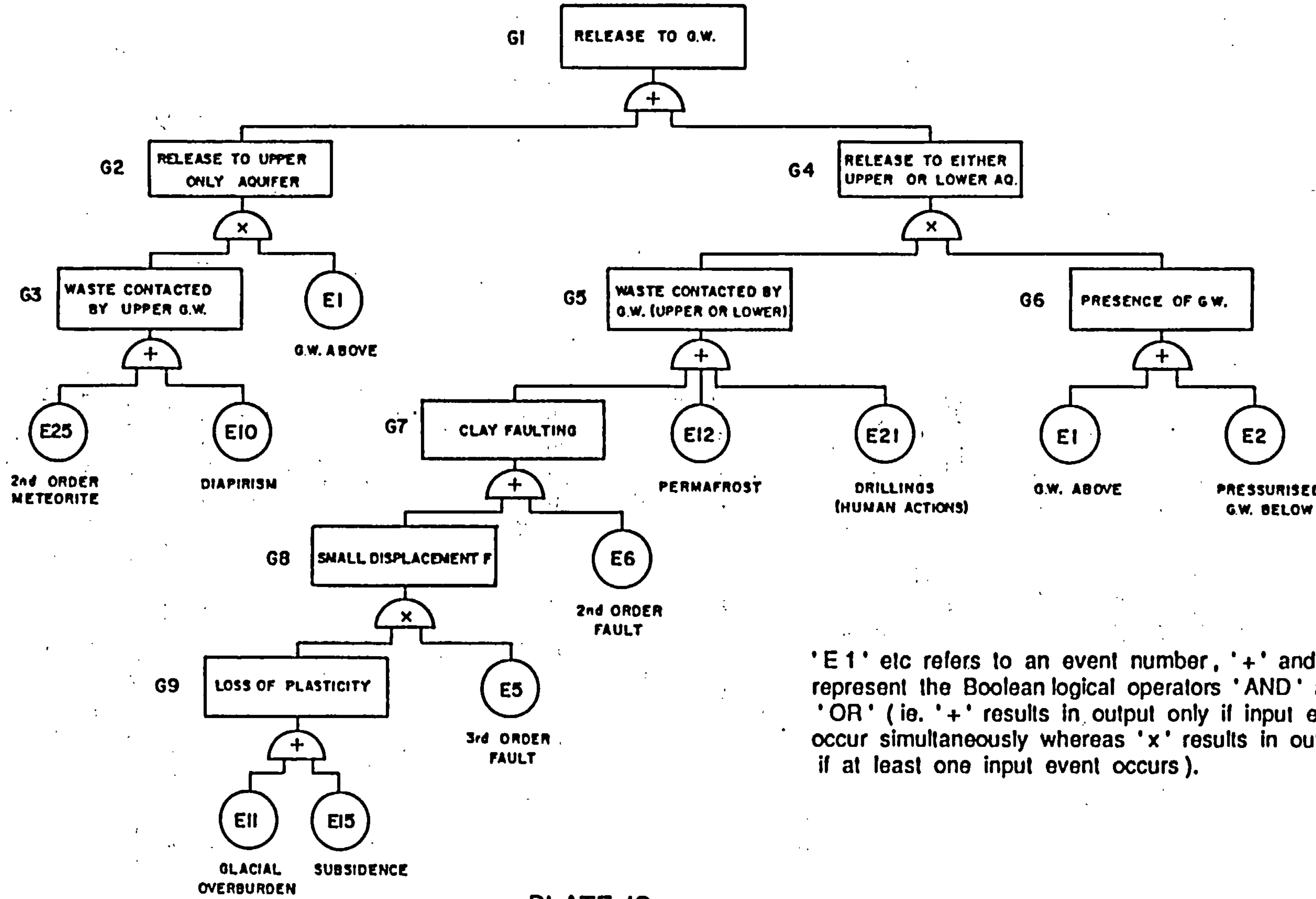
The first of these has the advantage that if the worst case is found to be acceptable then a high degree of confidence in future safety can be retained. However one cannot be sure that the worst case has been evaluated, and very often 'worst-cases' are found to be unacceptable in terms of risk so that more likely, less extreme, conditions have to be considered.

Fault-tree analysis represents a more acceptable assessment of disruptive events, and has been relatively successfully applied in a study of the Belgian research site at Mol (d'Alessandro and Bonne 1981). In this study a set of disruptive events, arranged in a hierarchy, are given probabilities of occurrence (Plate 10). The consequences of each path through this hierarchy are then evaluated as a set of hazards associated with their probability of occurrence. The method thus allows the presentation of a logically understandable set of probabilities for a number of disruptive event sequences. It is limited in that it cannot accommodate superimposition of many different events and does not model changes in processes.

3.2.5 Environmental Simulation

In rigorous safety analyses it is not sufficient to merely consider possible disruptive events on the presently stable situation chosen for a radioactive waste repository. Rather, it becomes necessary to accommodate future environmental change (gradual) as well as disruptive events (catastrophic). A possible danger with such analysis is that attention to environmental change may cause the significance of disruptive events to be overlooked. Three main approaches to environmental simulation are evident:

a) <u>Alternative Scenarios:</u> This is the representation of future change as a set of discrete scenarios (each time-independent). Most studies, being conducted in high latitudes, have to some extent employed this



'E 1' etc refers to an event number, '+' and 'x' represent the Boolean logical operators 'AND' and 'OR' (ie. '+' results in output only if input events occur simultaneously whereas 'x' results in output if at least one input event occurs).

PLATE 10

FAULT TREE FOR RELEASE TO GROUNDWATER AT THE MOL SITE, BELGIUM

(AFTER ALESSANDRO & BONNE, 1981)

Dames & Moore

concept by considering the consequences of future, cold-climate, conditions. Different tectonic scenarios may also be considered. This is the method adopted in the European PAGIS study (discussed below, Section 3.4.2) where normal, altered and disruptive evolution scenarios are considered. At this level such studies essentially comprise a 'what if' question applied to different scenarios. For example, the rate of radionuclide dispersal under normal (present) conditions might be compared with that under glacial conditions. This method is largely deterministic and does not consider the consequences of gradual environmental change.

b) <u>Time-dependent path switching:</u> A first approximation of time-dependent modelling is to perform simulations of time-dependent processes within the context of a 'scenario' and then, at some point in simulated time, switch to a different scenario. This method has been used by AECL (Canada) in adapting their SYVAC model to incorporate some degree of time-dependency. The method has the advantage of being relatively easily performed but it still carries the awkwardness of sudden environmental change (switching) and does not fully address the behaviour of time-dependent processes.

c) <u>Probabilistic time-dependent modelling:</u> One method of simulating environmental change, without imposing artificial scenario changes, is the Monte Carlo simulation technique. This involves the use of a set of deterministic sub-models, idealy modelling individual processes rather than using empirical relationships, which operate over a series of time steps. For each complete sequence of timesteps (a run), selected sub-model parameters are sampled from probability density functions (pdf's). The uncertainty in each process (temporal, spatial, and modelling) is thus accounted for, when a significant number of runs are carried out. The output of this kind of analysis is usually in terms of probability distributions of environmental parameters against time (eg sea-level or erosion rates with time). This method provides a quantitative representation of variability in future environmental change. The results can produce a highly credible picture of future evolution. The main drawback is the large amount of data required and the technical difficulties involved in performing such simulations. This method is presently being developed in Britain and the USA.

The use of these three approaches to environmental modelling depends somewhat on the ability and capability at hand. It is relatively easy to conceive various alternative scenarios for a repository environment but relatively difficult to construct 'realistic', predictive models. A developing performance assessment methodology would therfore be expected to follow a route from more deterministic to more probabilistic strategies and from simple scenarios to more complex simulation of the environment.

3.3 NON-EEC COUNTRIES

3.3.1 Introduction

The non-EEC countries actively involved in performance assessment of radioactive waste disposal are the two North American countries (USA and Canada), the Scandinavian countries (Sweden and Finland), Switzerland, and Japan. The USA and Canada are both characterised by advanced disposal strategies and research programmes with large budgets and correspondingly large organisations. Sweden and Switzerland have both recently completed comprehensive demonstrations of the safety and feasibility of disposal in response to requirements imposed by their regulatory authorities. Much of the research in these countries is therefore conveniently summarized in documents produced to justify disposal strategies. The research programmes in Finland and Sweden have also resulted in some particularly useful field data on the potential effects on repositories of processes associated with glaciation. Japan is probably the least advanced of these countries in its disposal programme. Eastern block countries are not considered.

3.3.2 USA

Candidate sites for the construction of the first deep disposal radioactive waste repository in the United States have been selected (in 1986) and construction is scheduled to commence in the late 1990's. The background research which has led up to this state of progress has been extensive and the USA has pioneered the development of may aspects of geological disposal and isolation of radioactive waste.

We have, however, been unsuccessful in obtaining recent statements on the status of research into long-term aspects of environmental change in the

USA. Thus, as far as we are aware, no major studies on long-term environmental change have been completed since the studies done under the Waste Isolation Performance Assessment Programme (WIPAP) of the early 1980's. Under this programme two detailed computer simulations of geological processes were produced, namely:

- o Geologic Simulation Model (GSM);
- o Far Field State Model (FFSM).

In this section we summarize and assess this work which has been of considerable value to the development of geological/environmental simulations elsewhere.

GSM is a site-specific model which was developed for the Basalt Waste Isolation Project in Hanford, Washington. It was designed to model the long-term effects of geological processes and events on the travel time of radionuclides from the proposed repository to the biosphere. This model does not predict the timing and frequency of events and processes which affect environmental change, but instead allows such features to be input as pdf's or polynomial relationships. That is, environmental change is accommodated by allowing variability in the input parameters. This is done using the Monte Carlo simulation technique to sample the range of input pdf's. Modelling of different processes is carried out sequentially, but a different random order of processes is used at each time step. The model is essentially driven by aspects of climatic change. Plate 11 illustrates the processes modelled and the methodology used.

The approach used in the GSM model is the 'breach scenario' concept. Two basic logical steps are made:

- o Breach scenarios are defined and analysed in terms of the processes and events which cause them (Plate 11);

- o The consequences of these scenarios for radionuclide transport from the repository to the biosphere are then identified and analysed.

This approach does not involve strict environmental simulation, but is geared towards the identification of environmental factors which could potentially cause or enhance radionuclide release. Consequently, GSM was successful in demonstrating various plausible radionuclide release scenarios, but was limited

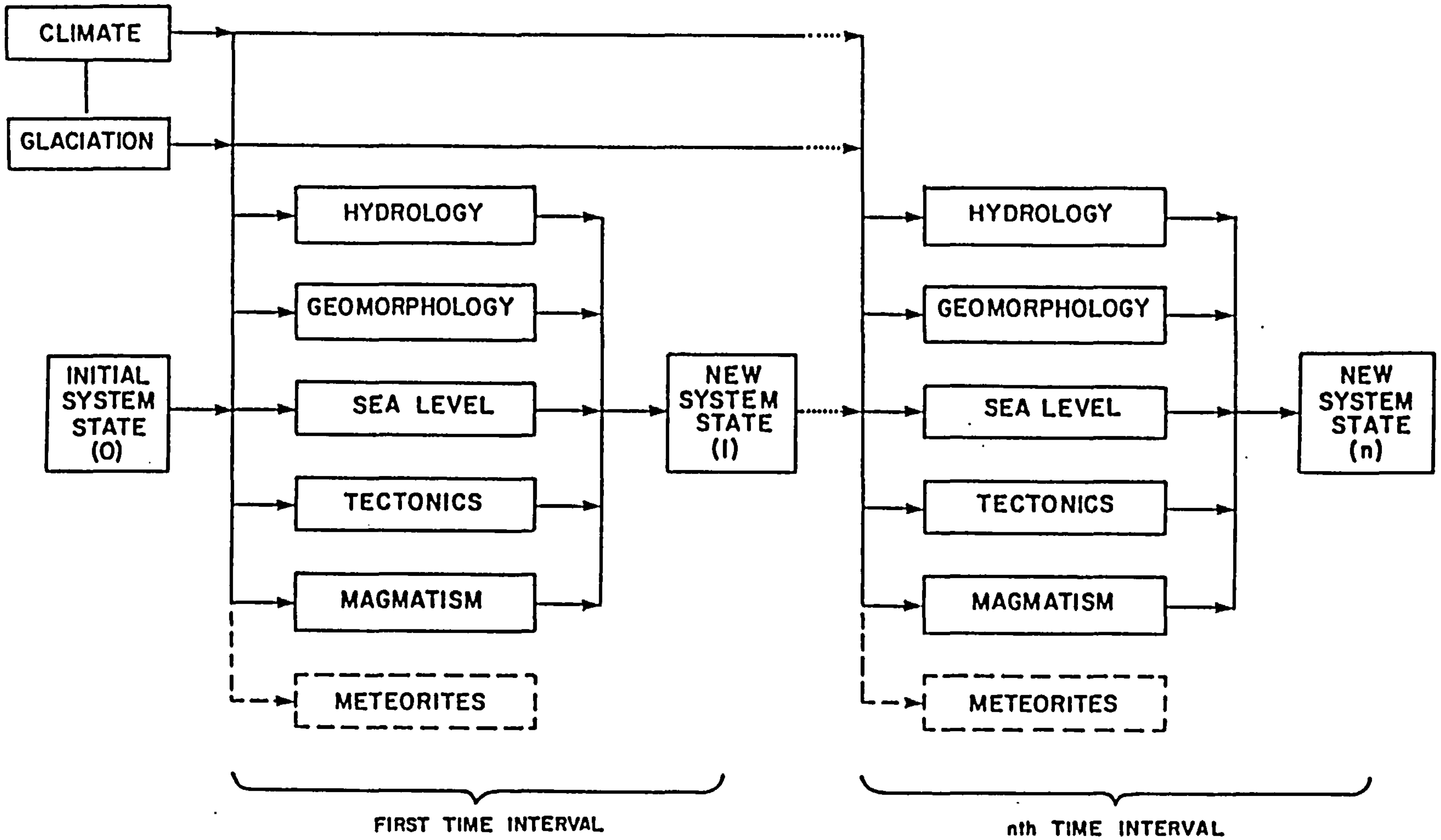


PLATE II SCHEMATIC DIAGRAM OF THE OPERATION OF THE GEOLOGIC SIMULATION MODEL (GSM) (REDRAWN FROM FOLEY ET ALIA 1982)

Dames & Moore

in providing more general performance assessment. In particular, GSM was not linked to groundwater/radionuclide transport models, did not model time-dependent evolution of the environment and was only applicable to the Hanford (basalt) site.

FFSM is an extension of the GSM methodology and is generic, being capable of treating processes at a variety of sites of potential interest for a repository location. Many natural and human-induced effects are modelled, including:

- o Undetected features (such as unknown faults);
- o Climate;
- o Glaciation;
- o Folding;
- o Faulting;
- o Volcanism;
- o Salt diapirism;
- o Biosphere state;
- o Regional deformation;
- o Geomorphological processes;
- o Sub-surface dissolution;
- o Solution mining;
- o Drilling.

The FFSM code can be used in both a deterministic mode (to evaluate interactions or to calculate point values) and a probabilistic mode (to make statistic estimation of future changes). In the probabilistic mode, the technique of Monte Carlo simulation is used to generate output probabilities, based on user-supplied input data that is largely in the form of pdf's of variable or uncertain parameters.

FFSM is an improvement of GSM in that it is generic and can provide some input data for groundwater flow, radionuclide transport and consequence models. However, the basic modelling methodology remains unchanged:

- o Breach scenarios are evaluated;
- o Environmental change is accommodated mainly in terms of parameter variablity.

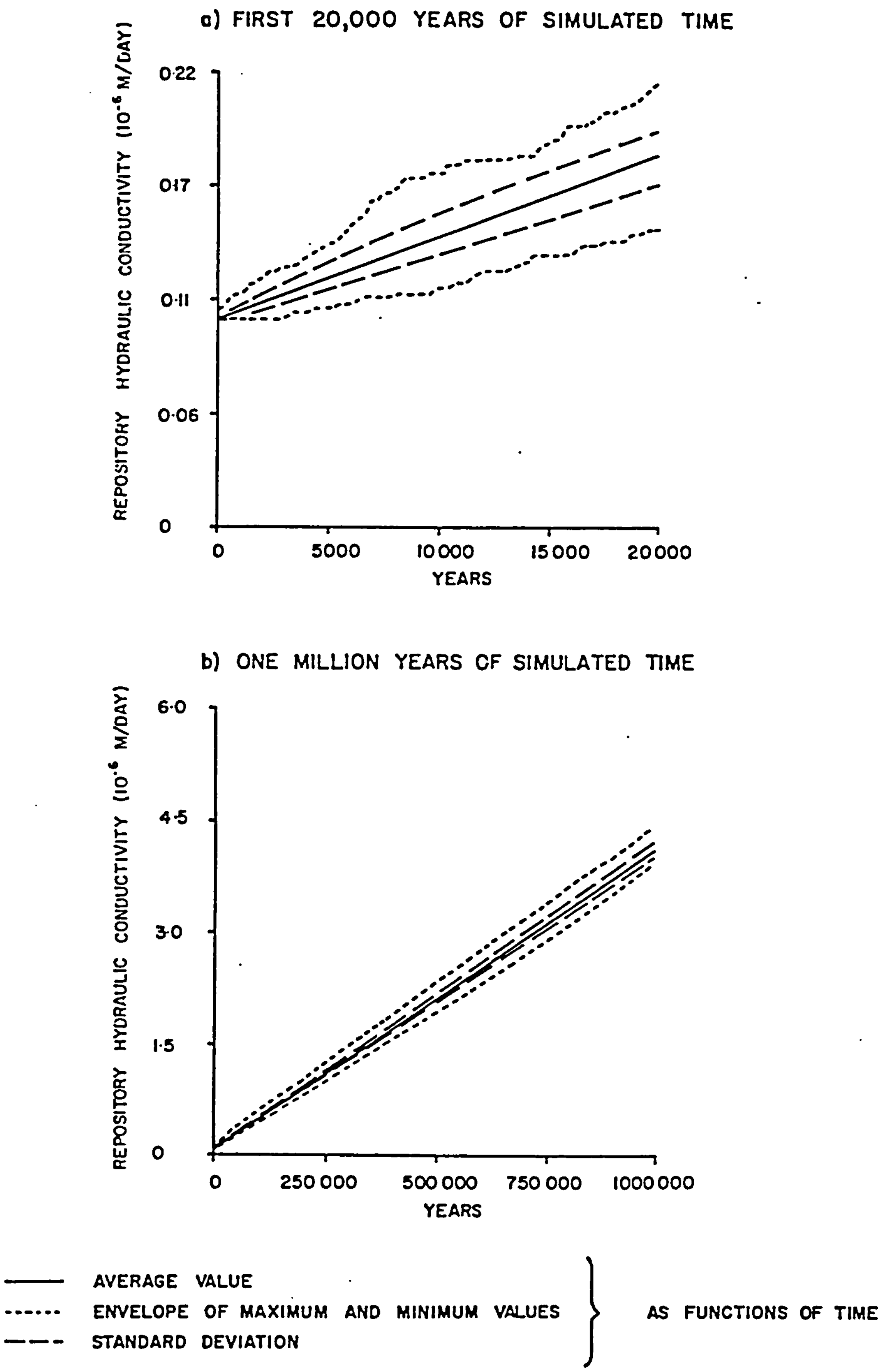
As far as we are aware subsequent work on other similar models of environmental change has not been done. In particular, the problem of coupled groundwater/geosphere models has not been tackled. Some recent work on multi-phase transport and variably saturated flow characteristics is being done at Sandia National Laboratories (Thompson, personal communication; 6th PSAC User Group Meeting, Dec., 1987).

The extensive studies performed in support of the GSM and FFSM programmes stand in their own right as contributions to radioactive waste disposal research. These comprise several state-of-the-art reviews (mostly consultant's reports; Scott et alia, 1979) including reports on:

- o Climatology;
- o Geomorphology;
- o Glaciology;
- o Hydrology;
- o Meteorites;
- o Sea level;
- o Seismology;
- o Structural geology;
- o Vulcanology.

Most of this work is specific to the USA and not generally relevant to studies elsewhere. However, we consider it pertinent to describe one piece of work on the relationship between seismicity and permeability, as it is one of the few attempts to address this problem.

In their report on earthquake engineering aspects, Tera Corporation (1980) reviewed the subject of seismicity/hydraulic conductivity relationships and then developed a polynomial for calculating the change in hydaulic conductivity which results from an earthquake event. It was realised that present data was insufficient for firm conclusions to be drawn and so 'intelligent speculation' was used to generate a workable relationship (for the purposes of release-scenario evaluation). It was concluded that changes in hydraulic conductivity would not occur below 950m (at the Hanford, basalt, site) because below this depth in situ stresses tend to close fractures that open during seismic shaking (this assumed a simple lithostatic stress distribution). Above this depth, increases in hydraulic conductivity were calculated to occur as a result of the cumulative effect of minor earthquake swarm activity in the basalt around the repository (Plate 12). In these



(REDRAWN FROM FOLEY ET ALIA 1982)

PLATE 12 CHANGES IN HYDRAULIC CONDUCTIVITY OF THE HANFORD BASALT REPOSITORY (GSM) CAUSED BY SWARMS OF MINOR EARTHQUAKES

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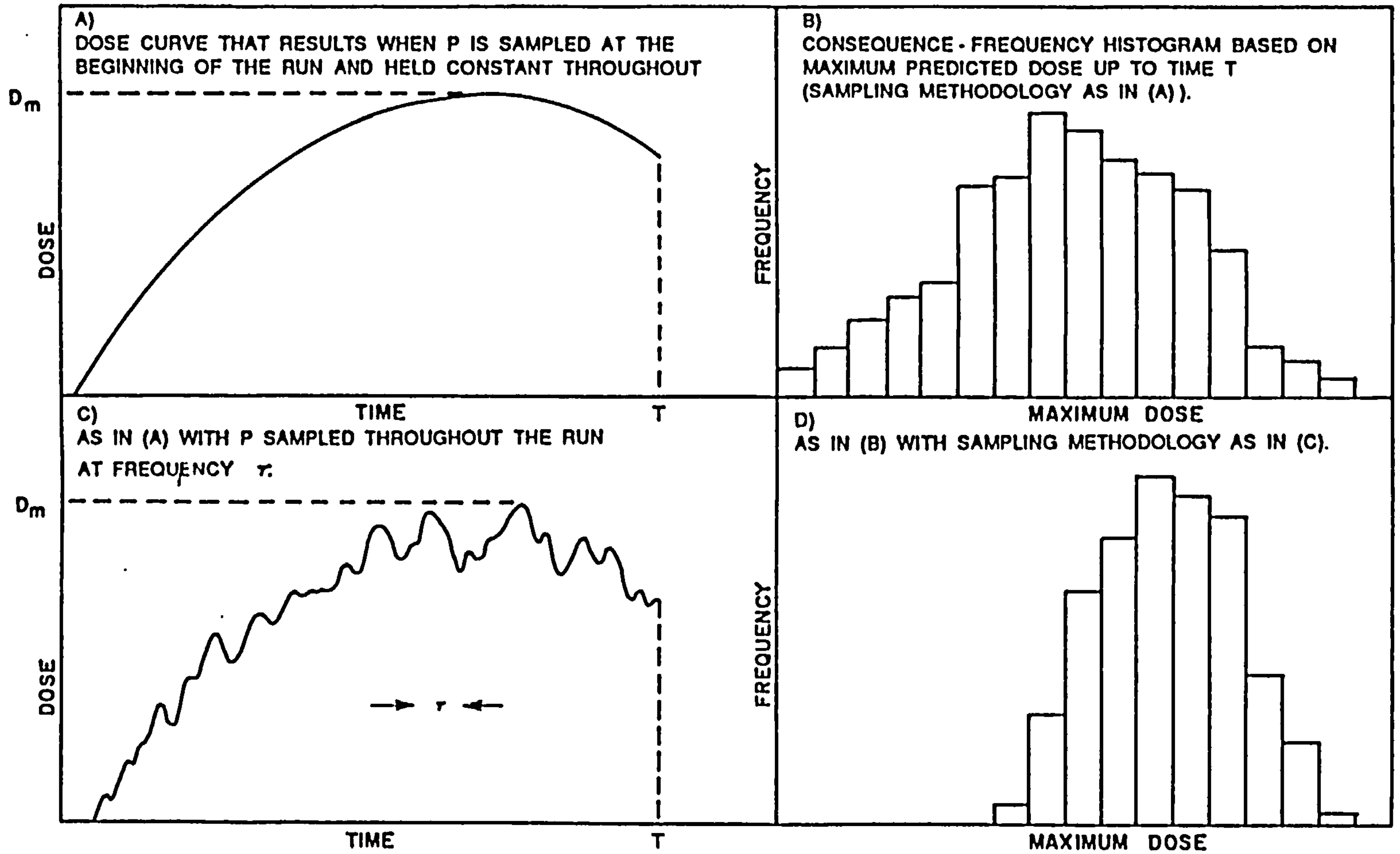
calculations, a fractional increase in hydraulic conductivity (fractions of an inferred maximum of 10%) was assumed to result from each seismic event (the actual effect being unknown). In contrast to the effect of minor earthquake activity, the calculations indicated that major deep faults, beneath the basalt, did not result in significant increases in hydraulic conductivity, except in the case of a very large earthquake (greater than Magnitude 7.5) directly beneath the site. That is to say, hydraulic conductivity around the repository was found to be more strongly influenced by frequent minor earthquake activity than by the generation of large faults.

These calculations are conjectural, and the subject of earthquake/ hydraulic conductivity relationships is undoubtably one requiring substantial further work. Nevertheless the conclusion is interesting and worthy of more critical analysis.

3.3.3 Canada

The concept for radioactive waste disposal in Canada involves disposal in a vault within the stable rocks of the Precambrian shield, at a depth of 500 to 1000 metres. The vault will be sealed and isolated. A large body experimental and theoretical work on the modelling of the transport of radionuclides through the engineered and natural barriers has been carried out (by the Atomic Energy of Canada Limited, AECL). These transport models are linked into the risk assessment code SYVAC, which estimates the dose consequence to man. Initially these estimates were time-independent, but the importance of time-dependent aspects was realised. At first a simplified method of 'path-switching' was investigated (ie discrete future scenarios were engaged as a function of modelling time). However, the need for more sophisticated incorporation of time-dependence into risk assessment became evident, as outlined by Davis (1986).

Plate 13 illustrates how a parameter affecting radionuclide release leads to under-estimation of the maximum dose if it is assumed constant rather than variable with time. Accordingly, the characteristies of a large number of time-dependent processes and their effect on the Canadian shield have been assessed (Plate 14). Following this preliminary assessment of time-dependent effects it was decided that the dominant effect of glaciation in the future Canadian environment made it the only factor for which detailed time-dependent modelling was necessary. This is partly because other effects are small in



(AFTER DAVIS 1986)

PLATE 13

SCHEMATIC REPRESENTATION OF THE EFFECT OF A VARIABLE PARAMETER (P) ON MAXIMUM PREDICTED DOSE

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Process	Duration (Ma*)	Time Between Events (Ma*)	Time Since Last Occurrence (Ma*)	Remarks
Tectonism (intrusion volcanism, epeirogenesis)	100-200	500-700	100	Ottava-Bonnechere graben may still be volcanically active
Erosion	Continuous but rate is irregular		Present rate (10^{-5}m/a) constant for 10 ma	
Inundation and sedimentation	50-100	100-150	150	
Tectonic drift	Continuous but rate is irregular		Present behaviour (a westward drift at 1-2 cm/a) began ca. 100 Ma ago	
Global glaciation	50-200	300-400	Presently occurring. Present glacial age began 3 ma ago	The next glacial maximum is expected within 20 000 years.
Seismic activity and earthquakes	Discrete events that occur continually		Presently occurring	Activity of significant magnitude occurs on the Shield only in association with glaciation and major tectonic events.
Faulting	Discrete events that occur occasionally		Minor faults induced by the last glaciation	No new major faults created on the Shield for 100 Ma
Magnetic reversals	Periods of stability alternate with periods of frequent change every 150 Ma. Reversals occur every 0.5 Ma during unstable epochs		0.02	3 brief reversals in the last 0.4 Ma
Meteorite impact	Continuous		Presently occurring	Probability of an impact creating a crater > 20 km in diameter is $5x10^{-15}$ $km^{-2}a^{-1}$. Probability that an impact will damage the vault is $2x10^{-11}a^{-1}$
Genetic evolution	Continuous, but rate is irregular		Presently occurring Mammals emerged 160 Ma ago, man 3 Ma ago	
Changes in earth's orbital parameters	Three parameters vary with periods of 21 000, 41 000 and 92 000 years		Presently occurring	Force glaciations in a susceptible climate regime
Climatic variations	Hours to tens of years		Presently occurring	Force variations of simalar scale in other bio-sphere parameters
Anthropological effects	Unknown		Major effects began to be seen 200 a ago	Effects can be expected to increase rapidly

*Ma = million years

(IN CANADA; FROM DAVIS 1986)

PLATE 14

CHARACTERISTICS OF TIME-DEPENDENT PROCESSES THAT HAVE AFFECTED THE SHIELD BIOSPHERE IN THE PAST

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comparison to glaciation but also because the complications of incorporating a large number of factors tends to count against the ability to make meaningful risk assessment calculations. This approach reflects the philosophy that as little time-dependent modelling as possible should be done, especially in the face of poorly known and unpredictable time-dependent parameters.

The present work in Canada involves tackling a fully time-dependent model for glaciation only. This is then coupled to biosphere models comprising a sequence of discrete climatic states. This approach is viewed as a 'manageable first approach' to time-dependent modelling.

Background studies on aspects of glacial evolution are presently being conducted at various universities and government institutions. These include a study of the migration pathways and parameter values characteristic of a number of discrete stages in a glacial cycle (Elson & Webber 1987) and an evaluation of the amount of glacial erosion in a specific location in North America (Shilts & Kaszycki 1987).

3.3.4 Sweden

Sweden has recently decided to phase out nuclear power generation by the year 2010. This decision followed a period of intense debate during which a requirement to demonstrate safe disposal of radioactive waste was imposed by the Government. As a result, the disposal programme in Sweden is one of the most advanced, with an underground facility for low and intermediate level waste already under construction and detailed plans for a repository for high level waste (HLW) submitted. The facility under construction lies 50 metres below the seabed, in rock, about 1km offshore at Forsmark on the east coast of Sweden. The proposed repository (for HLW) involves disposal 500m below surface, onland, in crystalline bedrock.

The Swedish Nuclear Fuel and Waste Management Company (SKB), set up to manage this disposal programme, has produced three main reports on their extensive feasibility study (for HLW):

- o Handling of Spent Nuclear Fuel and Final Storage of Vitrified High Level Reprocessing Waste (KBS-1), 1977;

- Handling and Final Storage of Unreprocessed Spent Nuclear Fuel (KBS-2), 1978;

- Final Storage of Spent Nuclear Fuel (KBS-3), 1983.

These three KBS reports included a comprehensive study of possible future effects on the proposed repositories. The processes and events considered included:

- Bedrock movements;
- Orogenesis and tectonic changes;
- Uplift;
- Faulting and fracture development;
- Earthquakes;
- Glaciation;
- Climatic change;
- Ecosystem change;
- Meteorite impact;
- Human-induced effects.

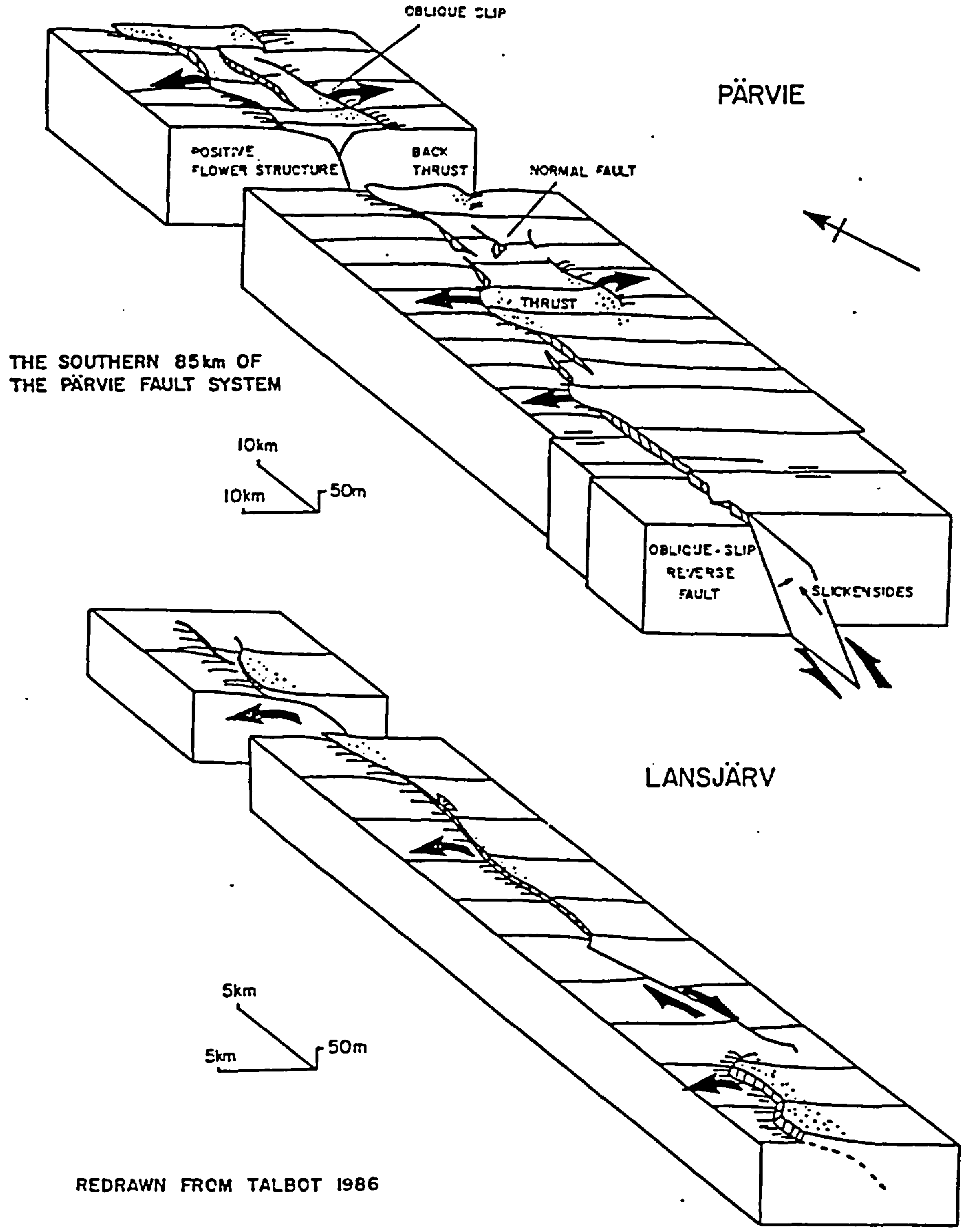
In many cases the depth of the proposed repository (500m) and the nature of the host rock (crystalline) were taken as the basis for neglecting potentially significant factors (such as glacial erosion). No attempt was made to model long-term changes in safety analysis but rather long-term safety was argued in terms of the available information.

Several criticisms of these arguments, used in justification of the safety analysis, were voiced in response to the KBS study. These principally focused on the 'geological stability' of rock formations in Sweden. One of the issues to receive most attention was the nature and degree of fault movement in the Swedish bedrock. Although considerable attention had been focused on this in the KBS Reports, it was concluded that the main source of fault movement (glacially-induced fracturing) was relatively minor, generally near-surface, and occurred only on existing fracture zones. It was therefore not considered to be a problem for repository safety, particularly since any proposed repository would be situated in a stable, unfaulted block. This view was, and is, considered to be over-complacent and further work at SKB has included more detailed evaluation of the nature of post-glacial faulting.

This recent work has included detailed field analysis of the most prominent postglacial faults in Sweden (Talbot 1986). Plate 15 shows a reconstruction of the tectonics of two of these faults. There is now general agreement that these spectacular faults and associated landslides, which followed ice retreat, resulted from a comparatively sudden release of stored plate tectonic forces as a result of the process of glacial downwarping and rebound of the crust. The burst of tectonic activity is demonstrably short-lived and similar movement is not considered likely under present conditions. Faulting of this nature is, however, to be expected in future glacial cycles, and the former view of an essentially stable crust in Sweden has given way to a more dynamic picture of the recent tectonics of Sweden. The dynamics of recent tectonics in Sweden have been most notably championed by Morner (1978, 1985) who strongly contests the view that the Swedish bedrock can be judged safe for long-term radioactive waste disposal.

The consideration of faulting appears to be the only work done on aspects of long-term change since the KBS feasibility studies. The issue of future fault movement has yet to be resolved.

Some interesting data has, however, come to light as a result of the site investigation studies at Forsmark (Swedish State Power Board; Carlsson & Christiansson, 1987). The high levels of horizontal compressive stress at the site have already been referred to (section 2.4.6; Plate 8), and we discuss here some possible implications for the long-term behaviour of the geosphere. Excavation and drilling at the site revealed the presence of large, extensive, near-horizontal fractures in the crystalline rock. These fractures display a relationship to the stress distribution which suggests that their presence is, at least in part, due to the the high horizontal stress developed during glacial times (Carlsson & Christiansson, 1987). The horizontal fractures are mostly open and infilled with sand and clay deposits, which indicates that they must have opened fairly recently. This is in contrast to the (more abundant) near-vertical fractures which are typically tight or closed. These observations point to the potential for the development of horizontal fractures in bedrock (down to depths of 500m at Forsmark) during future ice cap growth and decay over a potential repository site.



REDRAWN FROM TALBOT 1986

The post-glacial displacements along local thrust and back thrust flakes or nappes (stippled) integrate on a regional-scale into a positive flower structure rooted in en-echelon steep oblique-slip reverse faults. The regional picture is of transpression along a subhorizontal WNW shortening axis with surficial relief by thrusting.

PLATE 15

SCHEMATIC BLOCK DIAGRAMS OF THE SOUTHERNMOST 85km OF THE 160km LONG PÄRVIE FAULT SYSTEM AND THE LÄNSJARV FAULT SYSTEM IN NORTHERN SWEDEN

Dames & Moore

3.3.5 Switzerland

A major study on nuclear waste management, feasibility and safety, entitled 'Project Gewahr' (in English: "Guarantee"), was completed in 1985. The study was conducted in response to the Swiss Government's demand that the safety and feasibility of radioactive waste disposal should be demonstrated before operational licences for nuclear power plants could be renewed. The results of this project which relate to long-term safety are summarised here.

Two types of repository were considered in Project Gewahr: a 1200m deep cavern, with vertical assess, in a stable granite formation (type C) and a 750m deep cavern in clay (Marl) in a mountainside, with horizontal access (type B). Long-term safety in terms of Geosphere and Biosphere performance was assessed for periods of up to 10^6 to 10^7 years. These assessments considered both types of repository but concentrated on the deep type C cavern.

The basic approach used was to consider various possible future scenarios, make qualitative and semi-quantitative assessments where possible, and then either assess associated risk or discount scenarios as insignificant. A large number of factors were considered, including:

- o Tectonic and Neotectonic rates;
- o Glaciation;
- o Permafrost and Tundra environment;
- o CO_2 warming of the atmosphere;
- o Erosion;
- o Magma intrusion;
- o Volcanism;
- o Meteorite impact;
- o Earthquakes;
- o Drilling activities.

In terms of geosphere behaviour, magma activity, volcanism and meteor impact were considered of negligible importance within a period of 10^6 years. The effects of permafrost on hydrology, and glacial and fluvial erosion were not considered significant for a repository at a depth of 1200m. The effects of earthquakes were considered manageable with existing seismic hazard assessment methods, since acceleration effects for even large earthquakes are much reduced at depth.

The factors which were considered important by the project team included the following:

- o Changing tectonic rates (effects of a continuing Alpine orogeny were considered);
- o Glacial erosion and hydrology (where effects were largely unknown);
- o Groundwater extraction drilling (especially during a drier, warmer climatic phase).

A hydrological model was developed in order to assess some of these effects, but did not fully address the consequences of long-term changes in hydrogeological parameters.

In terms of Biosphere modelling, climatic changes were considered the most significant. Two scenarios were considered, a tundra climate and a climatic warming (greenhouse effect). The tundra scenarios did not result in doses greater than the biosphere base case (present conditions), but the effect of climatic warming was found to cause increases in expected dose (especially under the affects of increased groundwater extraction drilling for irrigation).

It should be remembered that the purpose of Project Gewahr was to demonstrate feasibility and safety of disposal, rather than critically assess long-term safety and risk. The tendency in the study to discount or minimize a large number of factors should be noted with this in mind. As studies in Switzerland develop on a more site-specific level, more rigorous analysis of the effects of long-term environmental change is to be expected.

Present studies are focusing on erosion, transport processes in the biosphere, and human-induced effects. The work is generally conducted in terms of different climatic states rather than long-term time-dependent modelling of parameters.

3.3.6 Finland

Research on the geological and environmental aspects of radioactive waste disposal in Finland is conducted by the Geological Survey of Finland. Following geological investigations carried out in the early 1980's, they concluded that the Finnish crystalline bedrock was generally suitable for radioactive waste disposal, since it has both low porosity and low hydraulic conductivity. The main problem area identified was the role of fractures in repository behaviour and radionuclide dispersal. Background studies by the Geological Survey have therefore been focussed on this aspect. The main factors in determining long-term environmental change are considered to be vertical crustal movement and climatic evolution.

The Finnish approach has been to identify homogeneous, stable bedrock blocks, bordered by fracture zones, as potential repository locations and focus background studies on such areas. Research has developed in two main areas:

(a) Long-term behaviour of groundwater systems: Heat-flow and groundwater measurements in about 20 exploratory boreholes in crystalline bedrock (to depths of up to 1000 metres) indicate the following:

- Past climatic changes have had a considerable effect on bedrock temperature gradients. Undisturbed temperatures can only be measured at depths below 1400-1600m.

- Sharp, vertical changes in heat flow density suggest disturbance by rapidly circulating groundwater at depths of less than 500m.

- Negative temperature gradients with temperature minima at depths of 45-80m occur, and are partly due to climatic rises in temperature during this century.

- Dense saline groundwaters were encountered at depths below 200m and indicate that layered groundwater structures are common in the Precambrian bedrock in Finland.

- Layers of saline groundwater are thought to develop beneath permafrost layers and may promote the penetration of permafrost into bedrock by up to 100 per cent.

(b) Postglacial fault movement: Field investigations of several postglacial faults in northern Finland indicate that:

- o The faults are up to 48 km long and are mostly reverse faults, with vertical displacements of up to 12 metres.

- o The faults mostly follow pre-existing fault lines, but in places their occurrence is not simply determined by pre-existing structures.

- o Landslides, associated with some of the faults, indicate that significant seismic activity accompanied the postglacial fault movements.

These studies have identified important aspects for long-term risk assessment. In particular, rapid groundwater circulation, anomalous salinity, disturbed temperature gradients and fault movement have been identified in the evolution of the environment since the last glaciation. As well as providing relevant data for Finnish siting studies, much of this information could be usefully applied to long-term assessments elsewhere. The high latitude of Finland makes it a useful laboratory for the study of future glacial and periglacial conditions at the lower latitudes of Northwest Europe.

3.3.7 Japan

The radioactive waste disposal programme for HLW in Japan has reached the stage of site selection. Favourable geological formations have been identified, but no site has yet been specified. The formations identified are diverse and include intrusive and extrusive volcanics and bedded metamorphic rocks (eg schists). Site selection studies focus on hydrological and physical properties of the site geology (often varied) rather than on identification of a single suitable formation.

We are not aware of any studies of long-term effects on safety. Seismic and tectonic considerations are of major importance in the tectonically active setting of Japan, such that the hurdle of present safety is large compared with the issues of long-term change. Probabilistic risk assessments have been carried out by the Japan Atomic Energy Research Institute. This has included the use of the SYVAC A/C code but does not yet include any consideration of time-dependent effects.

3.4 EEC COUNTRIES

3.4.1 Introduction

The work on radioactive waste disposal in the EEC countries is co-ordinated at the generic level and the various independent research programmes are linked. We describe first the two joint European studies, PAGIS and PACOMA, and then consider the work in four member countires where national programmes are large and have resulted in studies of particular note. Discussion of studies in Britain is expanded further in section 4.0, which describes the work on environmental change modelling at Dames & Moore.

3.4.2 Joint European Studies

The PAGIS Project

PAGIS is a joint European study on the disposal of HLW (Performance Assessment of Geological Isolation Systems) and is essentially a pre-site-selection evaluation of the capability of suitable geological formations for containment. Although PAGIS is specifically directed to high level waste disposal, it outlines many of the principles and approaches adopted in the EEC on all forms of radioactive waste disposal.

Phase one of PAGIS proposed the reduction of the many aspects of long-term geological performance of waste repositories to a number of convenient scenarios. For each type of repository environment (clay, granite, salt and sub-seabed) a set of 'normal', 'altered' and 'disruptive evolution' scenarios are considered in order to make the preliminary performance assessments. These scenarios are considered with reference to several hypothetical disposal sites chosen to represent the range and variability in environmental and design parameters within the EEC. The scenarios selected are shown in Plate 16. Two basic concepts have been used in the construction of these scenarios. Firstly, modelling has been divided into three fields:

- o Near-field (corrosion, degradation and radionuclide migration in the repository);
- o Far-field (radionuclide migration in the geosphere);
- o Biosphere (pathways to man and dose calculation).

Secondly, the altered evolution scenarios have been classified according to timescale:

- o Short-term (during the thermal period when decay heat may be the source of perturbations);
- o Medium-term (when no major geological changes occur but human intrusion becomes a possibility);
- o Long-term (events occurring on a 'geological' timescale).

Within this framework, the main factors of long-term and medium-term change which have been considered are (see also Plate 16):

- o Tectonic effects - fault displacement, magmatic activity;
- o Climatic effects - glacial erosion, fluvial erosion, sea level change;
- o Human effects - drilling, mining.

These factors are generally only assessed for their regional significance, and many other potential factors are assumed to remain unchanged. For example, for clay sites small-scale faulting is considered as the main altered evolution scenario and "other properties of the rock and groundwater are assumed to remain unchanged". Thus the simplification which this approach necessarily introduces tends to reduce the effects of long-term change, since the interplay of multiple factors on the long-term evolution of a site is specifically avoided. Although valuable for Europe-wide, generic studies, this methodology largely bypasses the issue of long-term environmental change because the effects of gradual long-term change are neglected in the adoption of discrete scenarios.

The prescription of this methodology in the PAGIS programme was made in the face of highly varied approaches in the countries of the Community, and worldwide. As a synthesis of this variety it does provide a useful common

OPTION	NORMAL EVOLUTION	ALTERED EVOLUTION		
		SHORT TERM	MEDIUM TERM	LONG TERM
CLAY	- WASTE DEGRADATION AND DIFFUSION - THERMAL EFFECTS	- UNEXPECTED EFFECTS IN THE NEAR-FIELD	- HUMAN INTRUSION (WATER WELLS)	- TECTONIC DISPLACEMENT - CLIMATIC CHANGES
GRANITE	- WASTE DEGRADATION, DIFFUSION IN NEAR-FIELD AND TRANSPORT IN FISSURED ROCK - THERMAL EFFECTS	- CONVECTION IN NEAR-FIELD - CONVECTION IN THE SHAFT	- CHANGE OF FRACTURE PATTERN (FAR-FIELD) - HUMAN INTRUSION	- TECTONIC DISPLACEMENT - CLIMATIC CHANGES
SALT	- THERMAL AND CONVERGENCE EFFECTS - RESIDUAL UPLIFT - SUBROSION	- WATER INTRUSION - THERMAL AND CONVERGENCE EFFECTS	- HUMAN INTRUSION (SOLUTION MINING, DRILLING)	- CLIMATIC CHANGES
SUB-SEABED	- WASTE DEGRADATION AND DIFFUSION - THERMAL EFFECTS	- INCOMPLETE HOLE CLOSURE - THERMAL TRANSIENTS	- HUMAN INTRUSION	- TECTONIC DISPLACEMENT - HUMAN INTRUSION - CLIMATIC CHANGES

PLATE 16

SCENARIOS SELECTED FOR THE FOUR OPTIONS IN THE JOINT EUROPEAN STUDY, PAGIS

Dames & Moore

denominator. The scenarios approach can, therefore, be regarded as a background from which the many aspects of long term environmental change can be considered. As studies in the Community develop, more specific and rigorous methodologies are likely to emerge and should be sought after.

The PACOMA Project

As an extension of the PAGIS programme on HLW, a second programme of work has been set up to consider the 'Performance Assessment of Confinements for MLW and Alpha waste' (PACOMA). This programme adopts essentially the same methodology as PAGIS and considers normal, altered and disruptive evolution scenarios on three types of (onland) geological formation (clay, granite and salt). The sites to be considered will be chosen from among those selected for PAGIS.

Results from this study are not yet available; it having commenced only in 1986. Publication of the final results is scheduled for 1989.

3.4.3 Belgium

Work in Belgium is focussed on the research site at Mol and has been conducted by SCK/CEN, set up in 1975. The geological formation of interest is the Boom clay, which is part of a sequence of alternating clays and sands of Tertiary age (deposited in the last 60 million years). The Boom clay and surrounding formations have been extensively studied, especially with regard to their hydrogeological properties. An underground laboratory in the Boom clay has been constructed at a depth of 225m.

Long-term safety studies have been based on the probabilistic, fault-tree analysis method (d'Alessandro and Bonne 1981). This concept was outlined in Section 3.2.4 (see also Plate 10). We summarise, here, the main conclusions of this study. The fault tree method applied to the Mol site demonstrated the overiding importance of 'human activities'. In the first 2000 years after repository closure, human activity is the only event able to provoke a release of radionuclides to the land surface. After this time, natural groundwater release begins to be important, but human aspects continue to dominate. Soil retention capability was found to play a major role in governing the release probability to the land surface. Phenomena related to future glaciation were found to be of some importance, but more detailed analysis of the glacial environment was considered necessary before firm conclusions could be drawn.

Since this study, research at SCK/CEN has focussed on two aspects:

- o A hydrogeological study of the present deep groundwater system.
- o Analysis of human-induced effects.

The report on human-induced effects has not yet been released, so we can consider only the hydrogeological study. This mainly addressed the present situation and only partially considered long-term effects. Patijn (1987) identifies two main conclusions from this study:

- o Cross-layer flow between aquifers through semi-permeable layers (aquitards) does occur. Such flow typically takes of the order of 10,000 years.

- o Siting of a repository should avoid areas where groundwater migrates down through the Boom clay.

The first conclusion arose initially from field data which demonstrated that simple, aquifer-parallel flow does not occur. Flow from confined aquifer layers was observed to occur across clay layers hundreds of metres thick. This observed phenomenon was then modelled with a numerical code, NEWSAM, which prescribes a 2-dimensional Darcian flow within aquifer layers and 1-dimensional orthogonal flow across aquitards. The modelling indicated that circulation of groundwater through the Boom clay takes a period of 6.3×10^5 years. However, actual flow across the Boom clay was considered to occur much faster (10^4 years) since only 1 to 3% of clay-water is thought to participate in 'mobile' flow within the clay. This conclusion was supported by the result of radiocarbon dating of the ground waters beneath the Boom clay, in the Rupeliens sand, where ages of the order of 10^4 years were measured.

Preliminary assessment of the influence of long-term changes on this hydrogeological model has been made by employing different scenarios and judging their effect on the flow regime. This involved an essentially deterministic allocation of parameters and boundary conditions in the model, for each scenario, and then assessment of their influence case by case. General probabilities of occurrence for each scenario over the next 250,000 years were determined. The factors considered were:

- Climatic change;
- Sea level;
- Denudation and (localized) fluvial erosion;
- Sub-marine erosion;
- Glacial erosion;
- Diapirism;
- Epeirogenesis (regional vertical crustal movement).

Of these factors, denudation/fluvial erosion was considered to have the greatest influence. The envisaged sea level and marine erosion scenarios did not greatly effect the form of the model, although minor changes in flow could occur. The effect of salt diapirs was found to be a major influence in increasing clay permeability, locally (ie where salt diapirs are likely to occur), but did not appear to significantly change the regional model. The model ceases to be valid for climatic scenarios involving low precipitation since infiltration rate begins to play a more important role than drainage (infiltration not being specifically modelled). Sedimentation, glacial erosion and glacial hydrology were not modelled, being beyond the scope of the study.

Thus long-term change has mostly been deterministically considered by calculating the effects of altered scenarios on the hydrological model. The study has not specifically addressed the issue of environmental change modelling. The hydrogeological model does, however, constitute a highly valuable study in the flow characteristics of a clay/sand multi-layered system, and provides a sound basis for on-going evaluation of risk assessment in a changeable environment.

3.4.4 France

A shallow land burial facility for low level waste is already in operation in France (at Centre de la Manche, near Cherbourg) and a second site has been selected (at Soulaines, 200km east of Paris). Site-selection studies for a suitable location for deep disposal of high and intermediate level wastes are in progress. An underground laboratory is planned. Several forms of geological media are being investigated, namely, salt, clay, granite and schist.

The chief method adopted in France for long-term safety studies is the "prospective" approach: the examination of possible future scenarios and their bearing on safety assessments (Masure et alia, 1983). The principle employed is the projection of known geological history, and recent trends within it, into the future in order to construct 'plausible scenarios'. In presenting this approach, Masure et alia (1983) outline four basic types of scenario:

- "Stable-environment" (strict determinism): this supposes that the present natural conditions are constant and that the environment evolves only under the effect of the repository (heat, physical disturbance etc.). This hypothesis is plausible if limited to a timescale of a few centuries.

- Retrospective scenario (historical determinism): this pre-supposes the construction of an underground repository for long-lived wastes at times of 10,000 years, 100,000 years or 1,000,000 years before present at a site selected with the characteristics of that time. The context and natural evolution of the "paleosite" are known by the study of recent geological history. Only the effect of disposal on the geosphere must be integrated within the context of these exercises which are, as in the previous case, purely deterministic.

- Tendency scenario (non-quantitative, subjective extrapolation of known processes): this takes account of the typical trends of natural evolution, as determined by a historical analysis of the environment. It is possible to identify two levels of complexity in these scenarios. Either one can adopt natural linear tendencies (simple tendency scenarios) or, pessimistically, one can bring into effect trend convergencies (complex tendency scenarios). These hypotheses are plausible within timescales of up to tens of millennia.

- "Disaster" scenarios (strict probability): these involve complication of the preceding scenarios by taking into account rapidly occurring disasters (major earthquakes, meteorite impacts, man-made accidents, etc.). They can be used to substitute the other scenarios entirely for the purpose of safety analyses in relation to the operational phase of construction and disposal of wastes (accidental flooding of repository, collapsing of a tunnel, etc.).

This set of scenarios comprises mostly deterministic study but incorporates some probabilistic evaluation, namely for disruptive events (disaster scenarios) which are unpredictable and sporadic. A purely probabilistic approach has been rejected on the grounds that most geological processes are not random. Confidence is placed in known geological history which is extrapolated to several plausible scenarios which are then compared case by case.

A series of reports, published in 1985, outline the background studies made for this 'geoprospective study': "Etude geoprospective des sites de stockage" (see Appendix). These reports comprise mostly review studies which are then used as the basis for a computer model, CASTOR, which simulates the evolution of a site in terms of a large number of deterministically derived variables.

These review documents are mostly comprehensive and cannot realistically be summarised here. They include particularly useful tabulated data-sets on worldwide measurements of erosion rates, vertical crustal movements and seismic parameters. Some more significant conclusions for long-term safety analysis are, however, selected and listed below.

- <u>Erosion:</u> During non-periglacial climates local erosion rates are usually in the range of 50-500 mm/10^3 years; during periglacial conditions rates of ten times this amount can occur.

- <u>Seismicity:</u> Micro-crack formation is considered an important phenomenon. Micro-crack dilatancy can cause expansion of rock up to 2 times that which would be expected by unfractured elastic expansion, and can occur a considerable distance from the fault zone. Ground-shaking is less significant for disposal at depth than is fault movement.

- <u>Tectonic change:</u> Rapid changes in stress are unlikely within a period of 100,000 years. The most likely future change in France is considered to be an increase in the principal horizontal stress.

- <u>Permeability:</u> Glacial loading and rock temperature increases are found to be the most significant influences on changes in permeability. Effective permeability of fractured granite is calculated as decreasing by 50% with glacial loads of 1km of ice, and by 30% for rock temperature increases of 9°C (data considered appropriate for conditions 100,000 years after present).

In the construction of the CASTOR computer model, the geological and environmental processes reviewed were synthesized and rationalised into a logical framework. The 'system-state' of the site is described in terms of 48 variables (Plate 17), and the simulation is performed by determining the interaction of these variables, as they change, by repeatedly calculating the known empirical relationships between them. Calculations are repeated at each time step, the duration of which can be varied between 500 and 20,000 years. The total length of time simulated is between 100,000 and 1,000,000 years, involving up to 2000 time steps. Thirteen processes are modelled and these are classified into two groups:

- User-independent processes whose behaviour is known and determined by established relationships. These are:

  Sedimentation;
  Fluvial erosion;
  Isostatic vertical crustal movement;
  Morphological effects on hydrogeology;
  Stress;
  Permeability variations;
  Surface water flow at the site.

- User-dependent processes which being sporadic or unpredictable are modelled at the user's discretion. These are:

VARIABLE NUMBER	VARIABLE NAME	DESCRIPTION	UNITS
1	VITGLA	RATE OF FORMATION OF ICE CAP	m/yr
2	VITDES	RATE OF GLACIAL DESCENT TO THE SEA	m/yr
3	VITISO	RATE OF ISOSTATIC MOVEMENTS	m/yr
4	VITERO	EROSION RATE	m/yr
5	EPAGLA	THICKNESS OF ICE	m
6	VITEPI	RATE OF EPEIROGENIC MOVEMENTS	m/yr
7	PRODIA	DEPTH OF DIAPIR	m
8	HALT	ALTITUDE	m
9	PROF	DEPTH	m
10	HMER	SEA LEVEL	m
11	FMORFO	MORPHOLOGY (0=SEA; 1=PLAINS AND HILLS; 2=MOUNTAINS)	
12	EPAALT	THICKNESS OF ALTERATION	m
13	VITSED	SEDIMENTATION RATE	m/yr
14	DENROC	MEAN DENSITY OF ROCK	kg/m^3
15	YOUNG	YOUNG'S MODULUS	bar
16	POISS	POISSON'S COEFFICIENT	
17	CHAISO	ISOSTATIC LOAD	bar
18	VITERG	RATE OF SUBGLACIAL EROSION	m/yr
19	PERM1	PERMEABILITY TENSOR (1st COMPONENT)	m/s
20	PERM2	PERMEABILITY TENSOR (2nd COMPONENT)	m/s
21	POROS	POROSITY	
22	HAMON	BASE LEVEL, UPSTREAM	m
23	HAVAL	BASE LEVEL, DOWNSTREAM	m
24	XLIGAM	LENGTH OF FLOW PATH, UPSTREAM	m
25	XLIGAV	LENGTH OF FLOW PATH, DOWNSTREAM	m
26	VITFON	RATE OF ICE FRONT ADVANCE	m/yr
27	SIGVER	VERTICAL STRESS	
28	SIGMIN	MAXIMUM HORIZONTAL STRESS	
29	SIGMAX	MINIMUM HORIZONTAL STRESS	
30	THETA	ANGLE OF SURVEY PLANE WITH SIGMAX	
31	RECSIG	STRESS CONDITION	
32	COSTHE	COSINE THETA	
33	SINTHE	SINE THETA	
34	VITEAU	TRANSPORT VELOCITY	m/yr
35	TEMEAU	TRANSIT TIME	yr
36	XMAX	SIZE OF HYDROGEOLOGICAL DOMAIN	m
37	DALT	CHANGE IN ALTITUDE	m
38	DNIV	CHANGE IN LEVEL	m
39	CAVAL	HYDRAULIC HEAD, DOWNSTREAM	m
40	PAMON	DEPTH OF HYDRAULIC HEAD, UPSTREAM	m
41	VITMON	RATE OF POSTGLACIAL SEA-LEVEL RISE	m/yr
42	ALTGLA	ALTITUDE OF ICE CAP	m
43	VITBAS	RATE OF RIVER FLOW AT BASE	m/yr
44	HFLUMI	ELEVATION OF RIVER IN EQUILIBRIUM	m
45	FACERF	FLUVIAL EROSION FACTOR	yr^{-1}
46	HSEINE	RELATIVE LEVEL OF THE RIVER SEINE	m
47	HMERRE	RELATIVE SEA LEVEL	m
48	HALTRE	RELATIVE HEIGHT OF SOIL LEVEL	m

TRANSLATED FROM FILIPPI ET AL 1987

PLATE 17

LIST OF VARIABLES IN THE FRENCH COMPUTER MODEL OF ENVIRONMENTAL CHANGE: CASTOR

Dames & Moore

Glaciation;
Ice front movement;
Rising of salt diapirs;
Regional vertical crustal movements (epeirogenesis);
Modifications to fracturing.

In order to test the CASTOR model a trial run on simulating known history was performed (ie a retrospective scenario). This study was made for a site in Normandie, to the north-east of the river Seine, where existing oil-company borehole data gave detailed documentation of the geology (Jurassic, calcareous marls in a fault bounded block). The simulated history was then compared to the known, Quaternary (last 2 million years), history of the area. A fairly close match was claimed between most modelled and real data. For example, sea level and the level of the river Seine were reasonably similar back to 60,000 years BP. It was found that erosion rate was an important influencing factor and was poorly known. A rate set at $80mm/10^3$ years was found to give the closest match between modelled and real evolution. Factors affecting base-level/erosion were considered important (eg. fault movement and epeirogenesis). The 'time lag' of the hydrogeological system was also considered to be a crucial, largely unknown, effect on site evolution.

Thus the CASTOR deterministic model has been shown to have some success in modelling site evolution. Its use enables critical factors in site evolution to be identified. Its credibility depends largely on the ability to set realistic variables into the model, and this is based on professional judgement of observed data. This may be possible for past history but is an ambitious task for predictive modelling. In justification of this approach the authors (volume 9) state the following:

- Simple linear calculations can be an advantage;
- The aim is to understand maximum effects (ie worst-cases) and consider their superimposed effect;
- The approach is flexible, calculations can be rapidly adjusted with new data;
- Simulations are reproducible;
- Neutrality: it avoids the adoption of a particular scientific philosophy or view of site evolution.

In conclusion, the CASTOR simulation is essentially an elaborate 'what-if' analysis, which compares multiple evolutionary scenarios and assesses their effect on safety. The consequences of worst-cases and plausible scenarios can be compared. Its potential value is in the deterministic impressions it can give of different future scenarios. However, its use in the prediction of future (as opposed to paleosite) evolution has yet to be demonstrated and its purely deterministic nature makes it inherently subjective.

3.4.5 West Germany

The waste management policy for HLW in the Federal Republic of Germany (FRG) follows a 'reprocess and dispose' philosophy. A large amount of FRG activity has therefore focussed on reprocessing/encapsulation/disposal technology rather than safety assessment. Two disposal sites are currently under investigation: one in salt at Gorleben (presently an underground laboratory) and a second in an abandoned iron mine at Konrad.

Only qualitative assessments of long-term and time-dependent effects on disposal sites have been made to date. The German Geological Survey has investigated various geological phenomena including glaciation, earthquakes, tectonic movement and subsurface erosion and their bearing on a potential underground repository in salt.

Human-induced effects have also been investigated in relation to disposal in salt. Solution mining activities are considered to present the scenario of greatest potential hazard for a salt repository and have been quantitatively evaluated.

Safety studies do involve probabilistic risk analysis, however, we are not aware of any present or planned incorporation of environmental change into these analyses in Germany.

3.4.6 Britain

Work on radioactive waste disposal in Britain is divided between two main organisations:

- o NIREX is the company charged with the task of disposal of low and intermediate level radioactive waste and is responsible for site selection, assessment, design and related research.

- o THE DEPARTMENT OF THE ENVIRONMENT (DOE) acts as the principal regulatory body and is primarily involved in the development of risk assessment methodologies for performance assessment, as well as associated long-term research.

Other organisations involved include the Central Electricity Generating Board (CEGB), British Nuclear Fuels plc (BNF) and the Ministry of Defence (MOD), who are the principal producers of radioactive materials, and the National Radiological Protection Board (NRPB) who are an independent, government-funded, advisory body concerned with radiological safety.

The present status of radioactive waste disposal in Britain is that low level waste is mostly disposed to shallow trenches at the BNF site at Drigg, Cumbria. Some other sites also take small quantities of low or very low level waste. All other wastes are stored pending the development of one or more deep repositories for low and intermediate level wastes (underground cavern 200m to 1000m in depth). No decision has yet been reached on the future handling of high level waste. Current research is concentrated on developing performance assessment methodologies for such facilities and the optimisation of site selection. The study of long-term effects is conducted both by NIREX and the DOE.

NIREX

Research related to biosphere modelling was introduced into the NIREX programme in 1987, and is managed by Electrowatt Engineering Services (UK) Ltd. This programme draws on a large body of previous research on radionuclide distribution and transport but also involves a programme of current research at universities and professional organisations. At present these studies are focusing on the following areas (M. Thorne, personal communication):

- Climate and sea level changes (at the Climatic Research unit and School of Environmental Sciences, University of East Anglia UEA); this includes assessment of the greenhouse effect and the mechanisms and causes of long-term climatic changes.

- Geomorphology and denudation (also at UEA), with the principal aim of producing a map of the geomorphology of Britain and developing the capability for modelling the surface around a future disposal site.

- Land management and radionuclide migration in natural systems (Associated Nuclear Services).

- Near-surface hydrology, soil uptake of radionuclides, and lysimeter studies (Institute of Hydrology, University of Newcastle and University of Lancaster).

These studies are at an early stage, but due to a large body of existing data some preliminary results may be available in 1988. The work which relates most directly to long-term change is the research programme on climate, sea level and geomorphology.

Department of the Environment

The development of a methodology for post-closure probabilistic analysis of radiological risk is a major activity within the DOE radioactive waste disposal programme (Thompson 1987). Probabilistic risk analysis (pra) is to be used as the performance assessment approach at all stages of the disposal programme. Individual risk must be demonstrated to be less than 10^{-6} per annum during the post-closure period (HMSO, 1984). Fully probabilistic risk analysis has been selected as being preferable to deterministic or 'worst case' estimates since it provides the most realistic long term performance assessment.

During 1985 a trial assessment of a hypothetical ILW repository at a depth of 150m in clay at Harwell, England, was conducted as the first in a series of tests for the development of pra assessment. The first test (DRY RUN 1) involved a single groundwater transport pathway with parameters invariant with time. An adaptation of the Canadian SYVAC code was employed. This Dry Run was preliminary and many refinements and adaptations were identified as necessary for the development of an effective assessment methodology. These fall into two main categories:

- Verification of the methodology, including consideration of factors such as correlation between parameters, statistical justification, systematic bias and sensitivity analysis;

- The incorporation of time-dependency of parameters into the pra code.

The first of these, relating to the on-going refinement of the model, is part of the overall research programme at the DOE. The second, however, comprises an added dimension to the analysis and had led to a new programme of work on environmental change at Dames & Moore, commissioned by the DOE. This work hinges on the development of computer models (eg. TIME2) which simulate future long-term environmental change (Frizelle 1986, Frizelle et alia 1986). It is discussed more fully in Section 4.0. The results of such modelling of time-dependent aspects will be fed into a new pra code, called VANDAL, specifically designed to handle parameter variability in an environment changing with time. VANDAL will replace the use of the (time-independent) SYVAC code in performance assessments so as to result in a capability for time-dependent pra assessment for periods of up to one million years. The first version was completed in 1987 (Scicon, 1987) and is currently being tested.

British Geological Survey

Part of the DOE radioactive waste programme involves the commissioning of background research, some of which is performed by the British Geological Survey (BGS). The BGS research programme is managed by the Fluid Processes Research Group and has resulted in three reports specifically on long-term aspects (see Appendix) including a general review of climatic and geomorphological changes and their effects on potential repository locations. The BGS also compiles primary data on directly relevant aspects, such as Quaternary geology and the categorisation of faults. BGS have also carried out studies on behalf of NIREX.

4.0 ENVIRONMENTAL CHANGE MODELLING AT DAMES & MOORE

4.1 INTRODUCTION

Having identified the need to incorporate time-dependent effects into performance assessment, the Department of the Environment commissioned Dames & Moore to construct a model of environmental change which could link into the on-going radioactive waste pra programme. After performing background and feasibility studies a Monte Carlo simulation approach was selected. The first model developed in this programme of work is called TIME2 and simulates environmental change at shallow engineered repositories. Version 1.0 of TIME2 was completed in 1986. This version was then demonstrated for a hypothetical site in Bedfordshire, England (Dames & Moore, 1988a).

Since the development of this first version of TIME2, shallow disposal has been rejected in favour of deep disposal. As a result of this proposals are now in progress to develop a similar model for deep repositories, to be called TIME4. In this section we describe TIME2, as an example of probabilistic modelling of environmental change, outline the background studies which accompanied this work and then consider the proposed development of TIME4.

4.2 BACKGROUND STUDIES

4.2.1 Introduction

This section outlines the background studies carried out in support of the programme of environmental change modelling for radioactive waste disposal, at Dames & Moore. Most of this work was done with TIME2 (shallow disposal) specifically in mind, but nevertheless comprises important background material to the on-going work, now focussing on deep disposal.

4.2.2 Time-Dependent Effects

A review of time-dependent effects on radioactive waste disposal was carried out by Dames & Moore in the early stages of the research programme. This review (Dames & Moore, 1984) outlined potential time-dependent effects, reviewed previous studies and proposed methods for modelling the effects in Britain. The events and processes considered were:

- Intraplate crustal processes (seismicity and vertical crustal movements);
- Diapirism (the movement of salt domes);
- Climate Change;
- Geomorphological and surface processes;
- Meteorite impact;
- Human-induced effects.

Of these, diapirism and meteorite impact were considered insignificant for the timescales to be modelled (c. 25,000 years, up to the next glaciation) and the setting (Britain). Further detailed background studies were then focussed on three main areas: climate and geomorphology, seismicity and human-induced effects.

4.2.3 Climate and Geomorphology

The principal element in time-dependent modelling (over timescales of tens of thousands of years) is adequate representation of climatic change. Consequently, a major assessment of climatic and geomorphological aspects of environmental change was made (Dames & Moore, 1987a) in consultation with specialists from the University of East Anglia (School of Environmental Sciences and Climatic Research Unit). This study outlined and described the following phenomena:

a) Climate Sequence: A statistical approach to the modelling of future climatic change was selected, and a fixed sequence of climates up to the glacial maximum was determined. A set of probability density functions based on the past record of climatic change (over the last two million years) was defined, from which durations of each climatic phase could be selected.

b) Greenhouse effects, sea-level rise: A probability distribution of possible sea level rise resulting from atmospheric warming due to increase CO_2 and trace gases was determined from various assessments given in the published literature. A temperature rise of 10°C (savannah climate) and a corresponding sea level rise of 0.2m/°C was proposed as the maximum likely effect of this phenomena, for the purposes of modelling (in terms of the pdf).

c) Ice sheet model: An approach to modelling future ice sheet growth and decay and consequent crustal depression and sea level effects was presented. This was based on a deterministic model developed at the University of East Anglia (Boulton et alia, 1985). The model describes the advance and retreat of an ice sheet in Britain and its effects on sea and land elevation. The ice sheet is modelled in terms of non-linear viscous flow and the crustal response in terms of visco-elastic behaviour. The model is illustrated in Plate 18, which shows the growth of an ice sheet with time in eastern Britain and the consequent effects on sea level (isostatic and eustatic).

d) Ice-dammed lakes: The consequences of the formation of ice-dammed lakes over potential repository sites were discussed in terms of depth of water, duration of lake and effects on groundwater recharge. A methodology for modelling these effects was outlined in which pdf's of lake duration in front of an advancing ice sheet site were constructed. The presence of a lake tends to temporarily halt groundwater flow around the repository.

e) Water balance: Data and methods were presented for modelling a surface water balance (for the model domain), varying with time under different climatic conditions. A methodology involving stochastic estimates of average annual recharge and infiltration per unit area for each climatic type was proposed. In this method, modelling is done by calculating successive monthly balances of water movements into and out of the drainage basin in which the repository is located.

f) Periglacial effects: A brief review of the potential effects of periglacial processes on shallow repositories and groundwater systems was given. Information was considered insufficient for modelling these effects at that time. Research on periglacial effects is continuing.

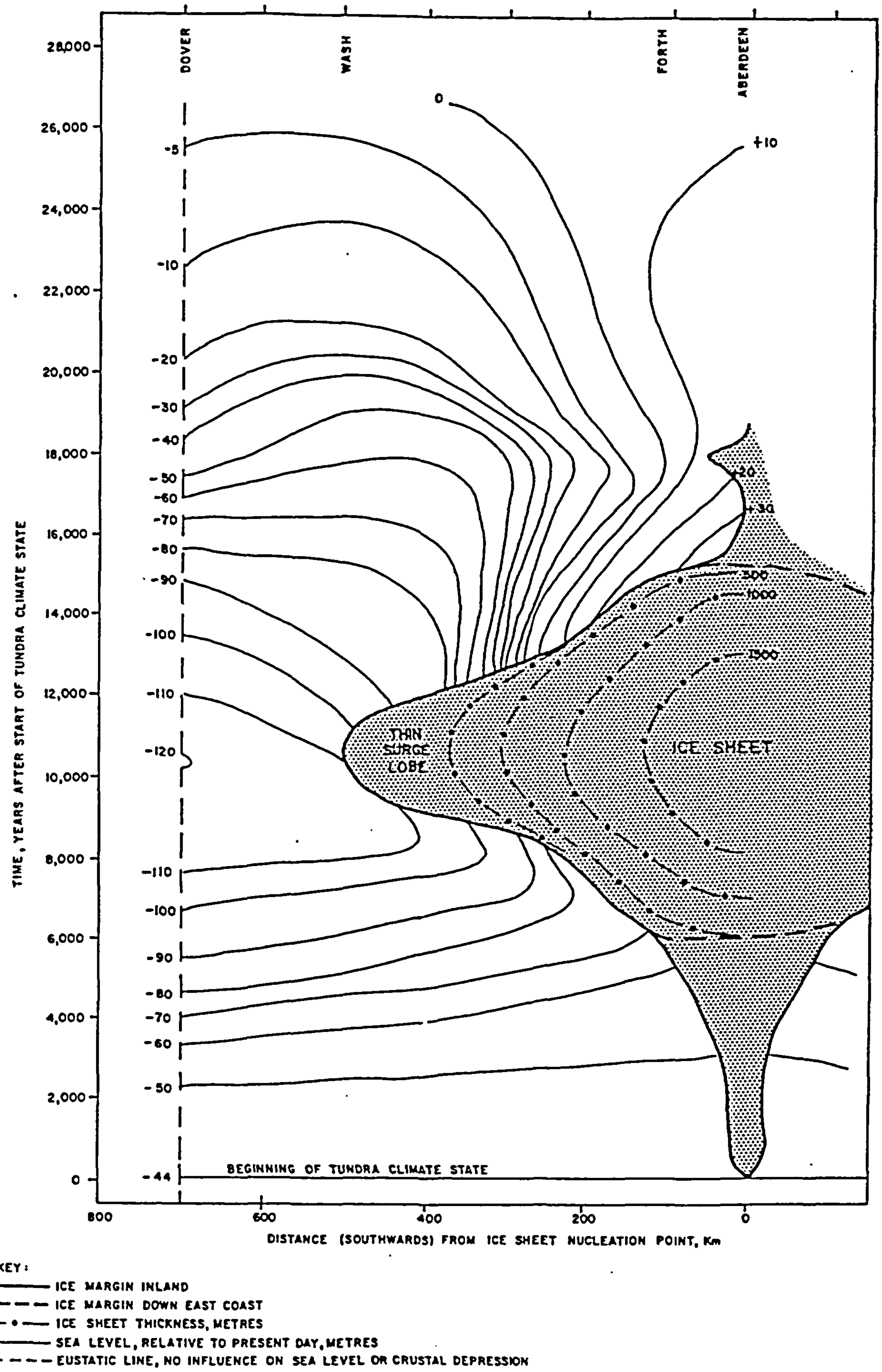


PLATE 18 GRAPHICAL CHARACTERISATION OF ICE SHEET ADVANCE / RETREAT, CRUSTAL RESPONSE AND SEA LEVEL EFFECTS FOR EASTERN BRITAIN, FOR A GLACIAL EPISODE LASTING 18,000 YEARS FROM INCEPTION TO DECAY

Dames & Moore

g) <u>Denudation</u>: Processes of river erosion, migration of meanders, slope retreat and basin evolution were described and an approach for modelling these effects under different climatic conditions was outlined. This involved different denudation factors for slopes, flood-plains and river channels under changing climatic and water budget conditions. The potential erosion of shallow repositories by the migration of river meanders was also modelled.

In these studies emphasis was placed on modelling and understanding the processes involved in environmental evolution in an attempt to model the environment as realistically as possible. Where ignorance in the understanding of any process has been encountered, simplifying assumptions have been made (for example, a pessimistic sea-level and temperature rise due to the greenhouse effect was assumed in the face of widely differing expert opinion on the likely severity of this effect).

This approach is in contrast to most other studies (eg GSM, FFSM, CASTOR) which tend either to oversimplify processes by considering them independently, or which, although describing many processes together, do so only in terms of a climatic scenario (invariant with time).

4.2.4 Seismicity

The incorporation of seismic effects into models of environmental change in Britain presents a difficult task on at least two accounts:

- The effects of earthquakes on underground media are poorly understood;
- There is relatively little information on seismicity in Britain because of the low level of present-day seismic activity.

These difficulties should not preclude attempts to address the task, particularly in view of the changeable nature of tectonic and seismic behaviour (section 2.4) and the long time scales to be considered (10^5 to 10^6 years). Consequently, work at Dames & Moore has concentrated on developing a strategy and capability for modelling earthquake effects in Britain as components of environmental change. The need for background research is recognised.

Two reports have been completed to date:

- Background studies: earthquake effects on underground waste repositories (Dames & Moore, 1986a);
- Earthquake effects on groundwater systems: an introductory review (Dames & Moore, 1987b).

We outline here the important conclusions of these reports, emphasizing the further work which is considered necessary before earthquake effects can be realistically included in probabilistic, time-dependent environmental models.

The first report (Dames & Moore, 1986a) outlined the tectonic and seismic history of Britain and presented a methodology for probabilistic estimation of fault rupture and ground shaking (seismic hazard assessment). The principal conclusions were as follows:

- Seismicity in Britain: The historical record reveals that Britsh earthquakes are of relatively low magnitude and shallow depth; earthquakes approaching Magnitude 6.0 have occurred offshore;

- Seismotectonics: A clear seismotectonic model for Brtain is not tenable at present; however, large events are most common in some discrete zones;

- Glacial effects: Glacial loading has been shown to be a substantial factor in changing seismicity rates; higher rates of seismicity in Britain following deglaciation are evident in the past and would be expected after future glacial episodes;

- Seismic hazard evaluation: Workable methods for probabilistic evaluation of fault-rupture, ground-shaking and associated effects are available (and were outline in the report); both time-dependent and time-independent methods were considered;

- Seismic effects on rock and soil properties: These were reviewed (fracturing, micro-fracturing, liquefaction, etc.), but available information was found to be lacking; further study was prescribed.

These principal conclusions can be conveniently reduced to two main issues: seismic hazard potential (for the repository) and seismic effects on the properties of the geosphere. Seismic hazard in Britain is undoubtably low, at present, and thus long-term evaluations are likely to focus on enhanced seismicity in future glacial periods. This issue will, in part, be addressed by background research studies on glacial modelling (Section 4.4.2, below).

The second issue, seismic effects on the properties of the geosphere, is addressed in the second report (Dames & Moore, 1987b). It is shown that even low levels of seismicity can affect the properties of the geosphere. That is, even where direct hazard to a repository (as a result of small earthquakes) can be neglected, the effects on the groundwater flow and stress distribution can still be of concern. The report on earthquake effects on groundwater systems thus addresses an issue of particular importance to performance assessment of radioactive waste repositories. This report outlines an approach for modelling the effects of earthquakes on media parameters (the properties of the geosphere) and then reviews the available data relating seismicity to media parameters. Considerable gaps in the state of knowledge were uncovered. Most critically, the relationship between seismicity and fracture behaviour is poorly understood. The areas requiring further work were identified and a strategy for developing a seismicity sub-model was outlined.

4.2.5 Human-Induced Effects

Human influences on repositories and their surroundings, in the context of climate and environmental changes, have been assessed by Dames & Moore in consultation with specialists from University College, London, and the University of East Anglia (Dames & Moore, 1988b). Three aspects of human influence were addressed:

- Planning and legislative controls over site usage;
- Changes in land use;
- Human intrusion into a repository.

This study identified the very significant role that human influence plays in determining repository performance. In particular, it was concluded that:

- The nature and effectiveness of the planning and legislative framework in the post-closure period fundamentally controls many aspects of human influence on a repository, especially intrusion;

- It is virtually impossible to make sensible predictions of change in the human environment, even over timescales of tens of years.

Consequently, a modelling strategy was developed which involved estimation of human-induced effects based on the assumption of present-day technology, policy and priority. Thus, even where different future land-use is modelled for different climatic conditions, present-day technology and human behaviour is assumed. This approach allows an achievable assessment of human-induced effects. It cannot be regarded as prediction, merely a simulation based on present human activity patterns. The types of human activity which have been identified as causing possible intrusion of potential repository sites are as follows:

- Drilling:
  - -Site investigation;
  - -Groundwater extraction;
  - -Mineral/groundwater exploration;
  - -Hydrocarbon exploration/production.

- Surface Excavation:
  - -Housing construction;
  - -Light industry construction;
  - -High rise/heavy industry construction;
  - -Road or rail construction;
  - -Trenching for services;
  - -Archaeological excavation;
  - -Shaft construction.

- Underground Excavation:
  - -Tunnelling for services.

For each of these activities the amount of repository material removed in each occurrence of the activity and the probability of occurence of each activity in Britain were assessed. An example of this data, as calculated for an hypothetical site at Elstow in Bedfordshire, is shown in Plate 19.

ATTRIBUTE NUMBER	1	2	3	4	5	6	7	8
INTRUSION TYPE								
SITE INVESTIGATION DRILLING	0	50	135	45	1	2	2	0.0190
GROUNDWATER EXTRACTION DRILLING	0	1000	4	100	1	2	2	0.0045
MINERAL/GROUNDWATER EXPLORATION DRILLING	0	1000	72	90	1	1	2	0.0062
HYDROCARBON EXPLORATION/PRODUCTION DRILLING	0	5000	8	2000	1	1	2	0.0001
HOUSING CONSTRUCTION: FOUNDATION EXCAVATION	31500	7	63000	90	2	2	1	0.0100
LIGHT INDUSTRY CONSTRUCTION: FOUNDATION EXCAVATION	36000	7	72000	90	2	2	1	0.0077
HIGH RISE/HEAVY INDUSTRY CONSTRUCTION: FOUNDATION EXCAVATION	90000	20	900000	360	2	2	1	0.0009
ROAD/RAIL CONSTRUCTION	18000	7	36000	90	2	2	2	0.0029
TRENCHING FOR SERVICES	22500	7	45000	90	2	2	1	0.0055
ARCHAEOLOGICAL EXCAVATION	180	6	180	430	2	1	2	0.0033
SHAFT CONSTRUCTION	650	50	6500	100	2	1	2	0.0001
TUNNELLING FOR SERVICES	0	20	40000	1500	2	2	2	0.0006

ATTRIBUTE	DESCRIPTION
1	Surface area of waste exposed during activity, m^2.
2	Depth of termination of activity, m.
3	Volume of repository material (waste plus structure). permanently removed, m^3
4	Duration of activity, hours.
5	Flag determining whether control over site use is re-instituted after the activity has occurred; 2 specifies re-institution, 1 prevents it.
6	Flag determining whether the activity is allowed if the repository is located in a built land area; 2 specifies "yes", 1 specifies "no"
7	Flag determining whether the activity is allowed if the repository is not located in a built land area; 2 specifies "yes" 1 specifies "no".
8	Occurrence rate (per year for a site area of 0.45 km^2)

Note that attributes 1 and 2 are for a site area of 0.45 km^2

PLATE 19 HUMAN INTRUSION DATA (FOR ELSTOW, BEDFORDSHIRE)

Dames & Moore

These activities were then categorised in terms of their occurrence under different land use conditions. At a specified site and point in time, land use is determined to be either 'built-up land' or 'not built-up land' depending on climatic conditions and geographical location. The human activities listed above were then judged to occur:

- Only under 'built-up' conditions (eg. housing construction);
- Only under 'not built-up' conditions (eg. hydrocarbon exploration);
- Under both land use condition (eg. road/rail construction).

This framework then allows probabilistic, time-dependent modelling of human-induced effects on a repository, and as such has been incorporated as a submodel in TIME 2.

4.3 TIME2

4.3.1 Introduction

This section describes the environmental simulation model TIME2 developed at Dames & Moore. The model is first described and then its use at a hypothetical site is discussed. More detailed accounts of the model are given in Dames & Moore (1986b, 1988a).

4.3.2 Description of TIME2

TIME2 is a Monte Carlo simulation code for modelling environmental change at shallow radioactive waste disposal sites. The core of the model is a series of six sub-models which simulate natural and human events and processes in a defined sequence (Plate 20). These submodels are operated within a climatic sequence which is deterministically set (on the basis of our understanding of the past climatic record and the cyclic nature of climatic change), but which consists of probabilistically selected durations (in order to account for variability in the past record). The climatic sequence is as follows:

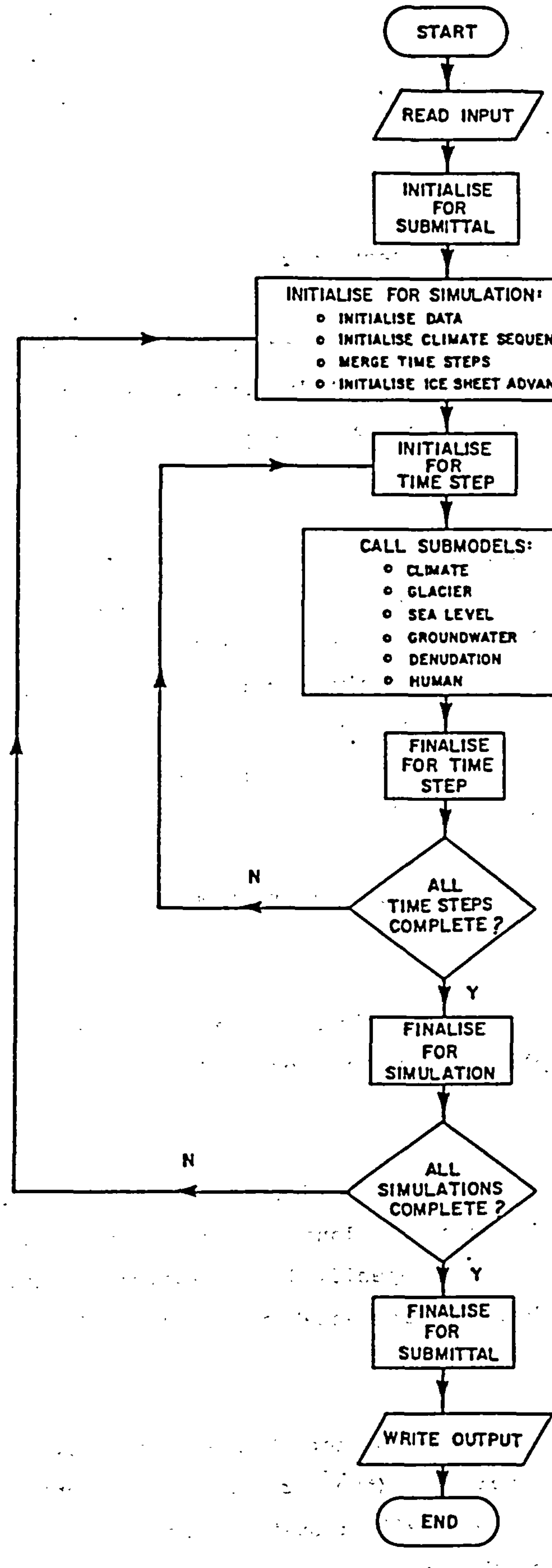


PLATE 20

TIME2 OPERATION

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Temperate;
Savannah (optional);
Temperate;
Boreal;
Tundra;
Glacial (ie. ice sheet over the site).

The 'Savannah' climatic type is not based on the past record and is inserted to account (pessimistically) for the likely rise in temperature in the near-future due to the increase in atmospheric CO_2 and trace gases (the 'greenhouse' effect).

Modelling is carried out over a series of time steps. One complete sequence of time steps (covering the complete climatic sequence) comprises one simulation. One simulation provides a complete set of deterministic data; the operation of a large number of simulations (each randomly sampling the input data) provides a probabilistic output of data. Typically, between 1000 and 3000 simulations are run in order to produce an adequate evaluation of parameter variability through time.

The six submodels (Plate 20) which simulate time-dependent processes function as follows:

- CLIMATE: Determines precipitation and temperature data for each time step, by sampling from input pdf's according to the climate state in existence.

- GLACIAL: Calculates the effects of an advancing ice sheet on the study area: tilting of the land surface, tilting of riverbeds, changes in elevation of each specified geographical point, and estimation of the time at which the ice sheet's advance will cause the formation of a glacial lake.

- SEA LEVEL: Calculates the net change in sea level for each time step due to global warming (the greenhouse effect) or global cooling (eustatic sea level fall resulting from the retention of water in growing world ice sheets).

- **GROUNDWATER:** Performs two functions: it provides data on estimated land use for each climate type and performs a water balance for the site area for each time step. The water balance element calculates runoff, infiltration and recharge at each geographic point, based on the sampled temperature and precipitation and data on land use, etc. A separate calculation estimates infiltration and recharge under a glacial (ice-dammed) lake, due to the head of water in the lake.

- **DENUDATION:** Based on a calculation of the sediment flux in the river system in the study area, this sub-model calculates denudation (surface lowering) at each geographic point, thus updating the elevation of each point. Also, the migration of meanders on river channels close to the repository is simulated, including the intersection of meanders with the repository and the consequent removal of repository materials. Lastly, if a glacial lake is simulated to exist at the time step, the elevation of the lake surface is calculated.

- **HUMAN INTRUSION:** This final sub-model simulates the occurrence and effects of human intrusion into the repository. The timing and type of intrusive activities depends on the status of institutional controls and the surrounding land use. A total of twelve types of intrusion are simulated, comprising drilling, surface and underground excavation.

The output of the model is a series of data arrays which comprise the 'system state parameters'. The parameters describe the system state at each time step and thus comprise a space-time description of the repository environment. Up to 600 items of data are generated at each time step and these may be written into an external file or erased and updated at each time step. A graphics plotting routine is used to present this data as a series of pictures of time-dependent parameter space in the repository environment. Examples of this output will be given in the following section (4.3.3).

Several assumptions underlie the construction of this model. The overall premise in these studies is the importance of modelling time-dependent processes and the conviction that this is best done probabilistically with a Monte Carlo type simulation. The basic assumptions employed in the TIME2 model are:

- Climatic change is the primary driving force in environmental evolution; other processes tend to follow climatic change;

- Models of future climate (and glaciation) are based on our understanding of the past record of climate; past climatic trends are assumed to continue into the future;

- Surface and near-surface processes are of primary concern for the environment of a shallow repository;

- Modelling beyond the first future glaciation is unnecessary; ice cover is assumed to remove a near-surface repository.

The above description demonstrates how TIME2 simulates the environment in an attempt to produce a realistic description of a changeable environment. This is in contrast to the 'scenario' pictures produced by other models.

4.3.3 Demonstration of TIME2 - Elstow, Bedfordshire

Version 1.0 of TIME2 has been demonstrated for a hypothetical disposal facility at Elstow, Bedfordshire (Dames & Moore 1988a). The TIME2 code was used to investigate the evolution of the Elstow site and its environment over the period up to the next glacial maximum (30,000 to 50,000 years after present). This was done using available geological, geomorphological and climatic data. The demonstration was successful and it was shown that long-term changes in the environment could substantially affect a disposal facility. Preliminary risk evaluations were performed, for different environmental states, using a Dames & Moore groundwater flow model (TARGET) and the time-independent DOE/SYVAC risk analysis code. Biosphere modelling (using the ECOS code) was also done by Associated Nuclear Services (under subcontract to Dames & Moore). We illustrate, here, some principal features of the TIME2 demonstration at Elstow. TIME2 has also been used to evaluate environmental change at the shallow disposal site for low level waste, operated by British Nuclear Fuels plc, at Drigg in Cumbria.

In order to assess the contribution of different environmental phenomena, five different 'cases' of TIME2 environmental simulation were performed at Elstow as follows:

- o BASE CASE: with the savannah climate included and an ice-dammed lake allowed, but no meandering or human intrusion (Case 01);

- o INFLUENCE OF MEANDERING: As for the base case, but excluding the savannah climate from the climate state sequence (Case 02);

- o INFLUENCE OF GREENHOUSE EFFECT: As for the base case, but excluding the savannah climate from the climate state sequence (Case 03);

- o HUMAN INTRUSION: Two cases were run with the human intrusion sub-mobel of TIME2 switched on, one as for the base case (Case 01) and one as for the meandering case (Case 02); these were Case 04 and Case 05 respectively.

The primary 'driver' of TIME2 environmental change is the climatic sequence (Plate 21). This was the same for each case, except case 03 where the 'Savannah' phase was omitted. With the exception of the Savannah phase, the onset of each climatic phase is sampled probabilistically in order to account for variability in possible future evolution. Thus, the earliest that glaciation is simulated to occur at the site is 15,000 years after present. However, at this time only 0.1% of the runs simulate an ice sheet at the site; by 20,000 years, 5.3% of the runs simulate glaciation. Thus the curves in Plate 21 depict the probable range of times of onset of a climatic type, the centre of the range being the most probable. The only exception to this is the Savannah phase which is modelled without variability. This is because there is no historical analogue from which its variability can be determined.

Examples of 'system state' parameter output diagrams for Elstow are shown in Plates 22 and 23. These show the variation in the cumulative distributions (cdf's), with time, of mean annual temperature (Plate 22A), sea level (Plate 22B) and denudation (Plate 23A), each under base case conditions. Plate 23B shows the pdf and cdf of material removed by human intrusion at 5000 years after present. It will be seen that the 'stepped' nature of most of the curves relates to the input climatic changes. This is most pronounced for the Savannah climate where no temporal variability was modelled. Variability in each parameter is shown by the 'quartiles' and deciles' of the cdf's. 3000 simulations were performed, for each case, in order to generate these distributions.

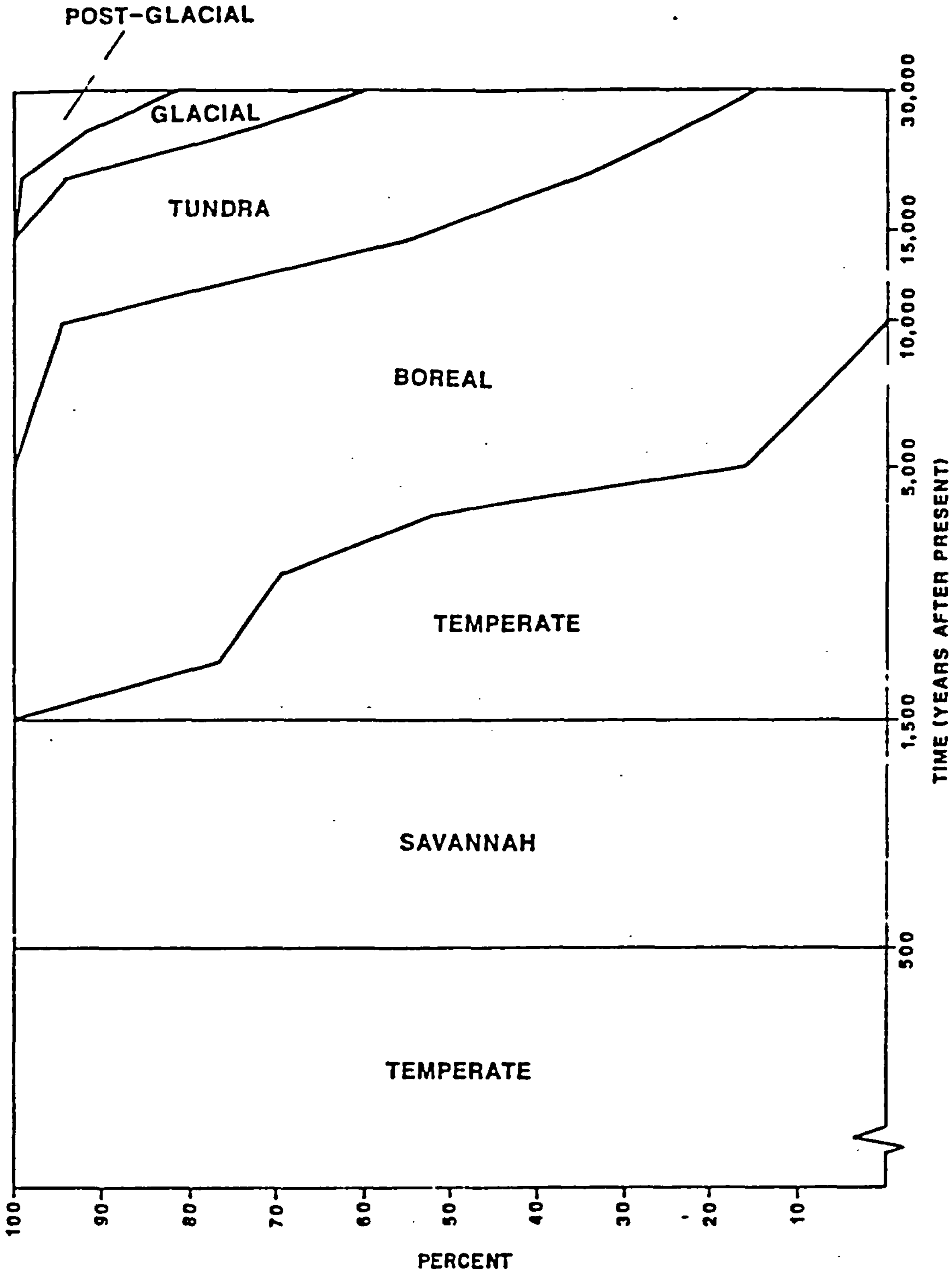

PLATE 21

SIMULATED PATTERN OF CLIMATIC CHANGE (BASE CASE) AT ELSTOW

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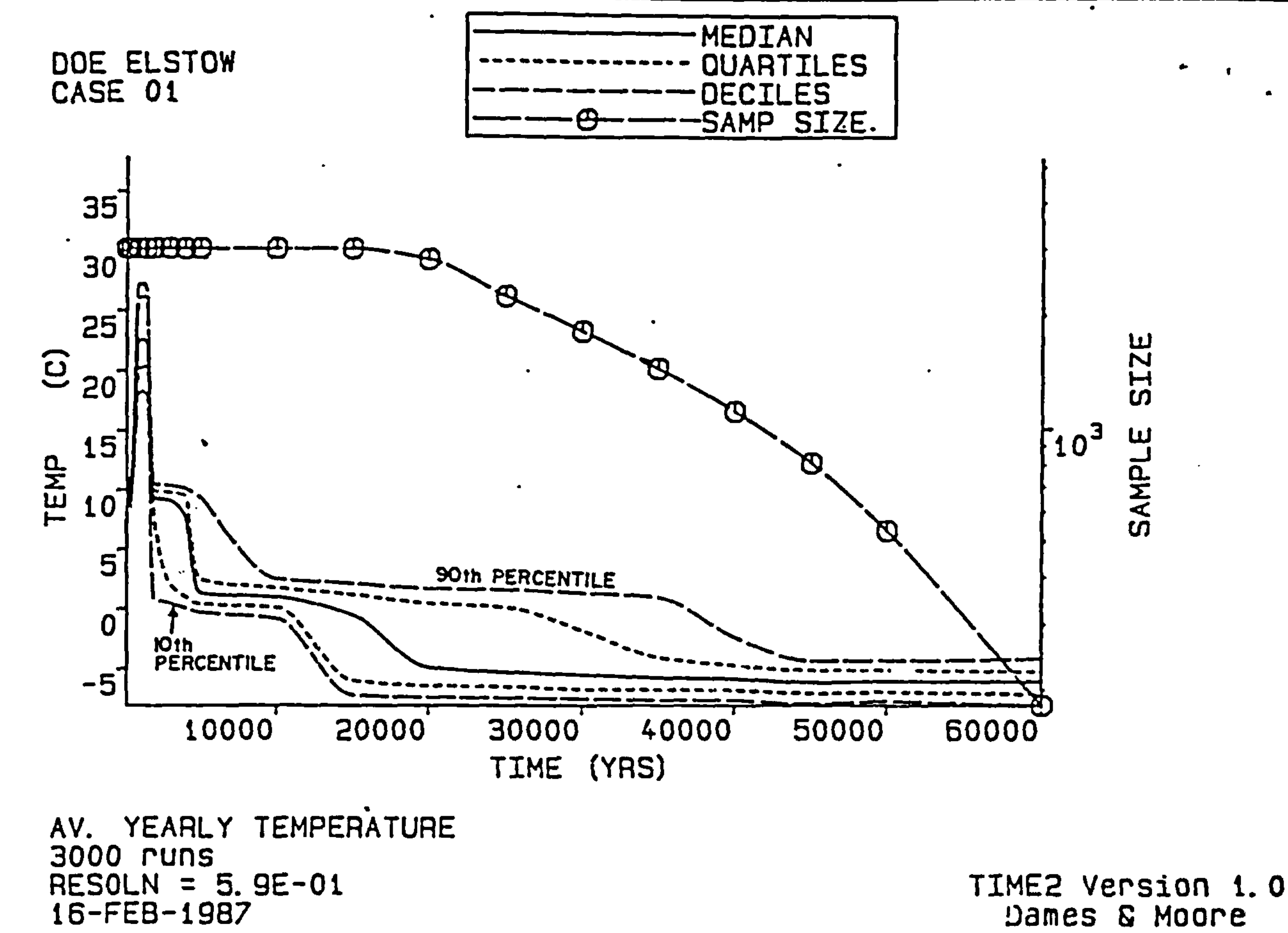
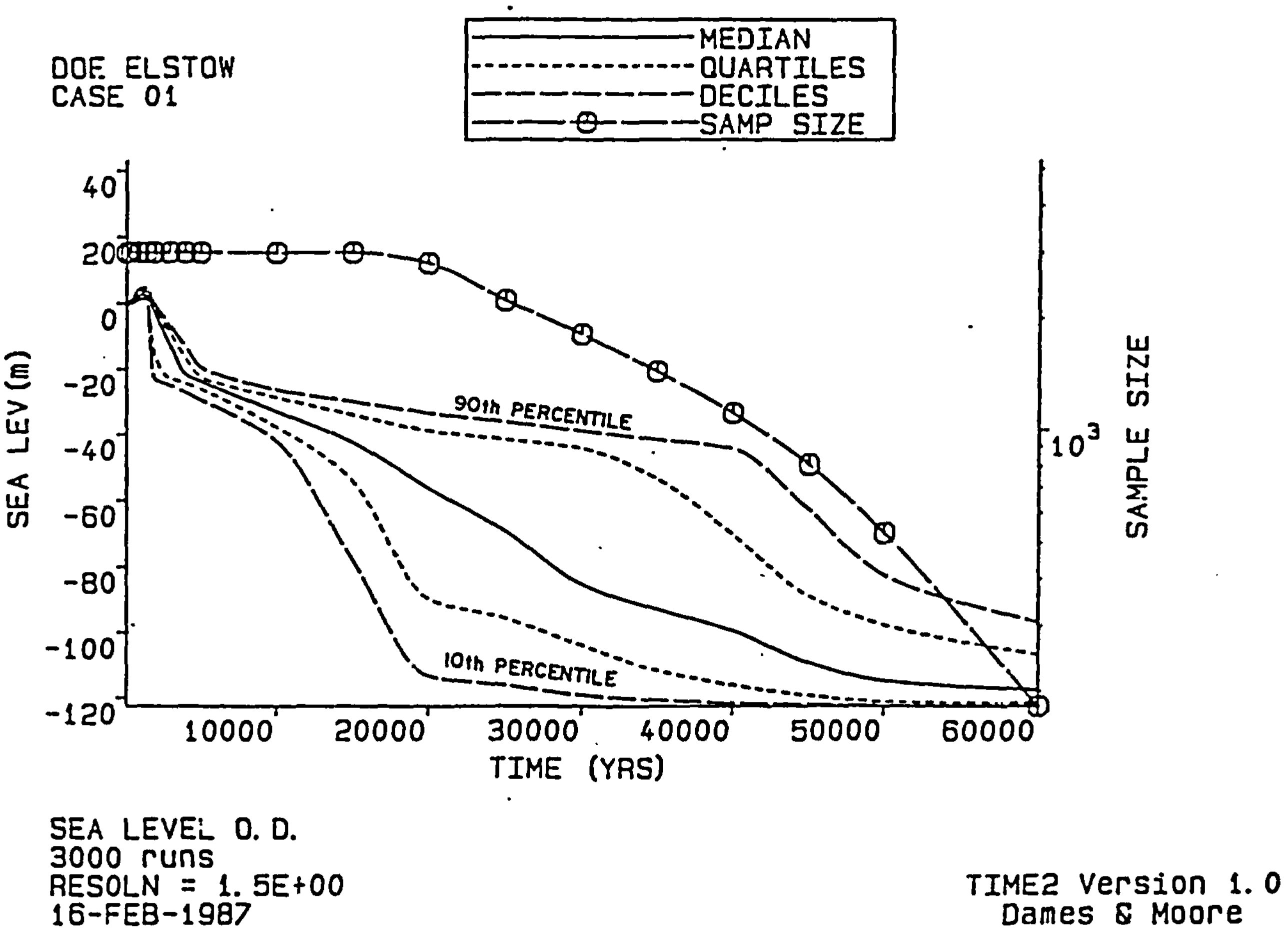


A. MEAN ANNUAL TEMPERATURE VARIATION, BASE CASE



B. SIMULATED SEA LEVEL CHANGE, BASE CASE

PLATE 22 EXAMPLES OF TIME2 OUTPUT

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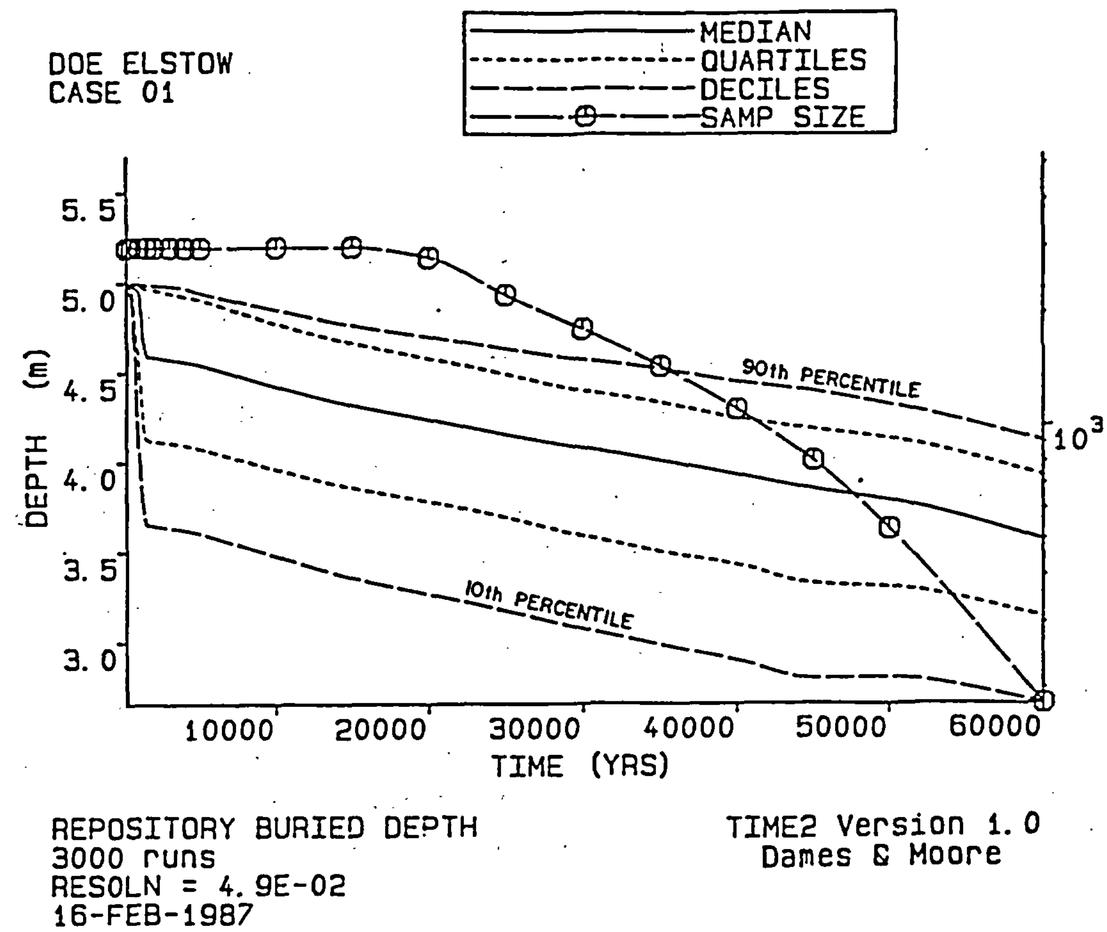
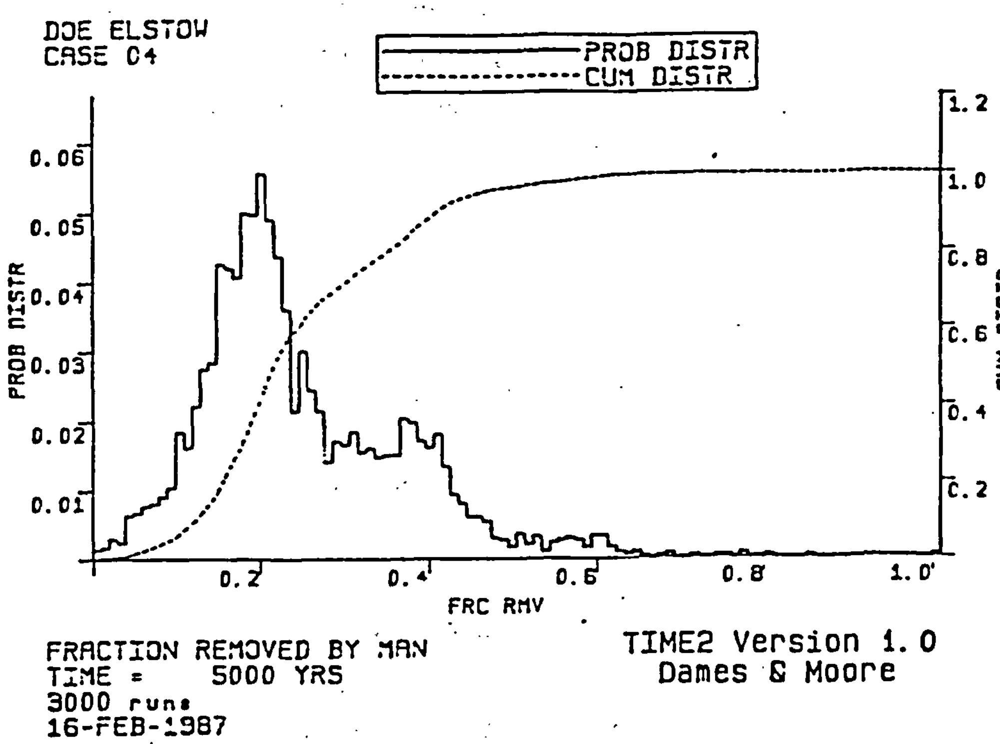


A. REDUCTION OF COVER OVER WASTE DUE TO DENUDATION, BASE CASE



B. PDF AND CDF OF FRACTION OF REPOSITORY MATERIAL REMOVED BY HUMAN INTRUSION AT 5,000 YEARS

PLATE 23 EXAMPLES OF TIME2 OUTPUT

Dames & Moore

Denudation at the site (Plate 23A) is represented in terms of erosion of the repository cover, initially at 5 metres thickness. The simulation indicates that the repository is likely to be preserved from general denudation up to the glaciation (which is assumed to completely remove the repository). Two specific forms of disruption to the repository were modelled in addition to general denudation processes. River meander erosion (case 02) by migration of a major nearby river was modelled and found to present some hazard in removing small fractions of the repository at various times in the future. Much greater damage was found to occur with processes associated with human intrusion (cases 04 and 05), as illustrated in Plate 23B. Large fractions of the repository were removed, in the simulation, well before the onset of glaciation. Human intrusion was consequently highlighted as an issue needing special attention. The large influence of human intrusion arises from the close proximity of the proposed site to the town of Bedford (6km) and the consequent high potential for development at the site. Periglacial effects were not specifically modelled in this simulation at Elstow, but were considered to have a significant effect on disruption of the repository during the tundra phase (on the basis of information available in the literature).

Evaluations of the influence of these environmental changes on radiological risk were also made. This was done using the time-independent DOE SYVAC A/C code applied to different climatic states. At the time of this demonstration at Elstow, linkage of TIME2 with a time-dependent pra code had not been achieved, such that this evaluation was very much a 'first-look'. It was, nevertheless, demonstrated that environmental change significantly influences radiological risk, by:

- Bringing transport pathways into and out of operation;
- Raising and lowering overall risk levels;
- Altering the timing of risks arising from changing groundwater pathways.

The main conclusion of the study was that human intrusion at the site would be the major contributor to the loss of physical containment up to the time of arrival of an advancing ice sheet. After intrusion, periglacial activity was considered as the most likely to influence the repository.

4.3.4 Assessment of TIME2

The development of TIME2 and the demonstration of its use at Elstow have confirmed and supported the view that a time-dependent approach to probabilistic risk asessment of radioactive waste disposal sites is the optimum approach. The TIME2 project has also shown that this approach is both practical and achievable.

The next stage in the work involves the assembly of a time-dependent risk analysis code to link in to the TIME2-type environmental model (only time-independent risk assessment codes had been developed at the time of the Elstow demonstration). The first version of such a code (VANDAL, V1.1) has since been developed under the DOE programme. Future versions of environmental models, like TIME2, will therefore be designed to operate in conjunction with VANDAL in order to provide the capability for fully time-dependent risk assessments.

4.4 CURRENT STUDIES

4.4.1 Introduction

This section outlines work currently in progress at Dames & Moore. Background studies are in progess and are being jointly funded by the CEC and DOE. Much of this is preparatory work for the planned development of TIME4, an environmental change model for deep disposal sites. This proposed work is also briefly discussed.

4.4.2 Background research

As part of the ongoing work on environmental change modelling at Dames & Moore, background research is being conducted. These research efforts are summarised below.

Glacial Modelling

Research in association with the Grant Institute of Geology, University of Edinburgh, under the leadership of Professor G.S. Boulton, is currently in progress. This work is funded jointly by the DOE and CEC.

Initial results are expected towards the end of 1988. Professor Boulton's previous work on glacial modelling was extensively used in the development of TIME2 and further developments in fundamental research are now being sponsored with a view to modelling environmental change over longer periods (c. one million years) and under conditions of repeated glaciation. This work focusses on two main aspects:

- o Ice sheet erosion and deposition;
- o Groundwater flow.

The first of these concerns the development of models of ice sheet erosion and deposition, and the consequent modifications of topography around a disposal site together with the dispersion patterns of eroded materials. This work is intended to support modelling studies of radionuclide migration during successive glaciations over a radioactive waste disposal site.

The second aspect concerns research into the effects of the combined processes of permafrost development/degradation and ice sheet advance/retreat on groundwater flow systems. This involves fundamental theoretical research into groundwater flow under conditions of ground ice development. Groundwater behaves very differently under 'glacial' conditions and as such needs to be understood before time-dependent modelling can progress to include multiple glacial cycles. A schematic illustration of the system being modelled in this research is shown in Plate 24. The research involves the application of the continuum theory of mixtures (Morland 1978, Kelly et alia, 1986) to rock-water-ice media beneath a progressing ice front. Mathematical models of water and ice flow are first being constructed for one dimensional (vertical) profiles in the geosphere. These will then be extended to construct two-dimensional profiles to model flow under glacial and periglacial conditions. The implications of freeze-thaw processes for the expansion and contraction of rock will also be considered.

<u>Geosphere Behaviour</u>

Although the glacial aspects of future change are of primary importance in long-term modelling, the whole spectrum of time-dependent behaviour of the geosphere needs to be addressed. Much of this links in to the work on glacial modelling in that ice loading of the crust and glacial hydrogeology cause changes in geosphere parameters such as permeability,

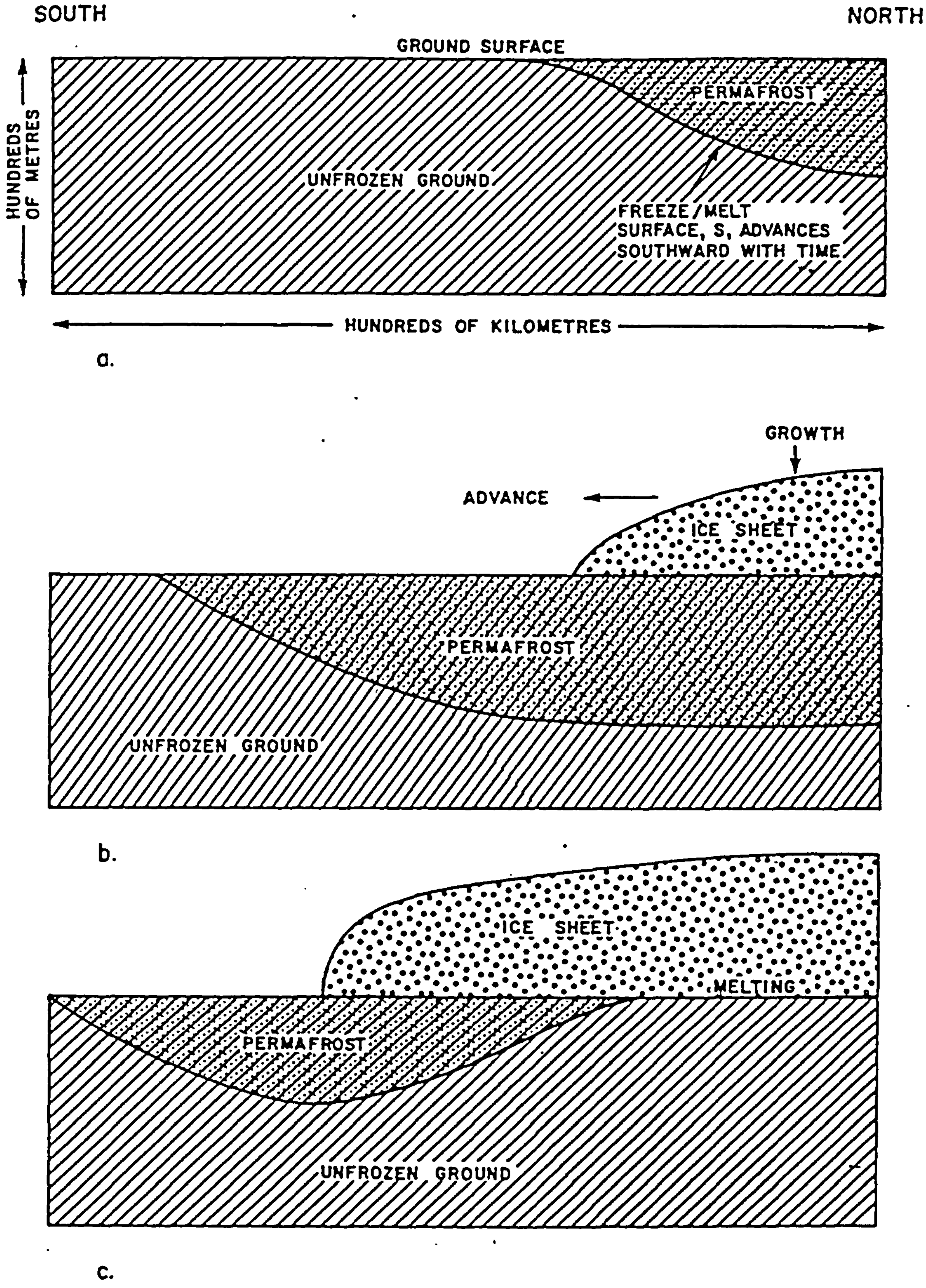


PLATE 24

SCHEMATIC ILLUSTRATION OF PERMAFROST DEVELOPMENT

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fracturing and seismicity. Dames & Moore is doing some preparatory work on these aspects including consideration of long-term seismicity and fracture behaviour. Areas of ignorance have been identified and workable methodologies are being developed with a view to the inclusion of tectonic modelling in the long-term environmental change models. Specialist advise will be sought.

4.4.3 TIME4

A new computer model of environmental change at deep disposal sites is proposed. This new code, TIME4, will be a development of TIME2 on at least four fronts:

- Deep disposal, as opposed to shallow disposal, will be addressed;
- A longer timescale will be considered (c. 1 million years) which will involve the modelling of several successive glacial cycles;
- Existing TIME2 sub-models will be refined and developed, and new sub-models will be devised;
- TIME4 will be specifically designed to interface with a new pra code, VANDAL, which will account for time-dependent changes.

The first three of these essentially represent developments in environmental modelling. These developments will result from ongoing research and development at Dames & Moore on environmental modelling for radioactive waste disposal. The last of these points, however, represents a new step in pra assessment - the creation of a unified, fully time-dependent pra model. TIME4 will be linked to VANDAL in terms of compatible output and input of the two computer codes. TIME4 will act as a "futures generator" for successive time-dependent parameter inputs into VANDAL. Both models, and the linking process, are currently being developed. VANDAL is being developed for the Department of the Environment by a team of independent contractors.

5.0 INCORPORATION OF ENVIRONMENTAL CHANGE EVALUATION INTO PERFORMANCE ASSESSMENT

5.1 INTRODUCTION

Previous sections of this report have discussed the nature of environmental change and the status of research into its effects on radioactive waste disposal. This section attempts to place this within the context of performance assessment of disposal facilities. Performance assessment criteria are defined and the Scenarios and Time Dependent Performance Assessment (deterministic or probabilistic) approaches reviewed. Plate 25 summarises the approaches adopted by various research teams in Europe and North America, against the factors and processes considered.

5.2 PERFORMANCE ASSESSMENT CRITERIA

A variety of criteria exist against which performance assessments of radioactive waste disposal are carried out. These criteria are determined by the relevant regulatory bodies in each country and include:

- Health effects:
  - Radiation dose,
  - Radiological risk;
- Containment:
  - Travel time of radionuclides in groundwater,
  - Time of "guaranteed" engineered containment.

In Europe and Canada health effects have normally been used, whereas the USA has favoured containment criteria. In recent years, there has been a tendency towards adoption of a radiological risk criterion. In Britain, a risk target of 10^{-6} per annum has been adopted (HMSO, 1984).

The use of risk, as opposed to dose, as a performance assessment criterion allows the formal incorporation of uncertainties. These can include spatial, data and modelling uncertainties, as well as temporal uncertainties.

MODEL/ STUDY	METHODOLOGY EMPLOYED	CLIMATE	GLACIATION	GROUNDWATER	SEA LEVEL	VERTICAL MOVEMENT	STRESS/TECTONICS	FAULTING	SEISMICITY	VOLCANISM	DIAPIRISM	EROSION	DEPOSITION	LANDSLIDES	TSUNAMI/SEICHE	DRILLING/MINING	EXPLOSIONS	METEORITES	OTHER MISCELLANEOUS FACTORS
GSM (USA)	SCENARIO MODELS (SITE SPECIFIC)	✓	✓	✓	✓	✓	✓	✓	✓	✓		✓						✓	UNDETECTED FEATURES / FAULTS
FFSM (USA)	SCENARIO MODELS (GENERIC)	✓	✓	✓			✓	✓	X	✓	✓	✓				✓			UNDETECTED FEATURES / FAULTS AND SUBSURFACE DISSOLUTION
SANDIA (USA)	SCENARIO ASSESSMENT	✓	X	✓	X	X	X	✓	X	✓		✓	✓	X	X	X	X	X	TRANSPORT OF GASEOUS RADIONUCLIDES
AECL (CANADA)	TIME-DEPENDENT PATH SWITCHING	✓	✓	✓			X	✓	X	✓		✓				✓		✓	MAGNETIC REVERSALS AND GENETIC EVOLUTION ALSO CONSIDERED
TIME2 (BRITAIN)	TIME-DEPENDENT SIMULATION	✓	✓	✓	✓	✓			X		X	✓	✓			✓		X	(MODEL FOR SHALLOW DISPOSAL ONLY)
CASTOR (FRANCE)	DETERMINISTIC SCENARIOS	✓	✓	✓	✓	✓	✓	✓			✓	✓	✓						
CEN/SCK (BELGIUM)	HYDROGEOLOGICAL MODEL + SCENARIOS	✓	✓	✓	✓	✓					✓	✓							SUBMARINE EROSION. (NOTE THAT ONLY THE LONG-TERM EFFECTS ON A HYDROLOGICAL MODEL WERE CONSIDERED)
KBS-3 (SWEDEN)	DETERMINISTIC STUDY	✓	✓	✓		✓	X	✓	X	X						X	X		(FEASIBILITY/SAFETY STUDY)
GEWAHR (SWITZERLAND)	DETERMINISTIC STUDY	✓	✓	✓		✓	✓	✓	✓	X		X	X			✓		X	(FEASIBILITY/SAFETY STUDY)

✓ = FACTOR CONSIDERED SIGNIFICANT AND MODELLED

X = FACTOR CONSIDERED INSIGNIFICANT AND NOT MODELLED

PLATE 25 FACTORS OF LONG-TERM ENVIRONMENTAL CHANGE CONSIDERED IN RECENT MODELLING/SAFETY STUDIES

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5.3 THE SCENARIOS APPROACH

5.3.1 Introduction

We have, in this report, followed a conviction that the environment behaves as a unified system. Despite the numerous processes involved and the intricacies of the ways processes relate to one another, natural phenomena are inherently interrelated.

We therefore consider that the frequent adoption of 'scenarios' in evaluating the influence of environmental processes on radioactive waste disposal conflicts with the very nature of the environment. The concept of scenario analysis arose initially in the study of operation systems and engineered structures where the performance assessment problem was considered in terms of 'system failure' of various individual components (Burkholder, 1980). When this form of analysis is applied to the environment one is confronted with the fact that the environment does not consist of separate (replaceable) components. 'Component failure' is inappropriate in this context; 'system behaviour' being a more relevant term.

In this section we outline recent developments in scenario methodology and go on to extend the case against the use of scenarios in environmental modelling.

5.3.2 Current Scenario Methodologies

Scenario strategies are currently being developed in the United States (SANDIA) and the EEC (PAGIS/PACOMA). The Nuclear Energy Agency (NEA) of the OECD is also in the process of formulating a cohesive, common methodology for scenario development (NEA Working Group on The Identification and Selection of Scenarios for Performance Assessment of Nuclear Waste Disposal). The CEC PAGIS/PACOMA methodology has already been outlined (section 3.4.2) and we concentrate our attention in this section on the methodology currently being developed and proposed at SANDIA and by the NEA. The NEA working group (INTERA, 1988) has chosen to adopt the approach developed at SANDIA as a basis for development. Thus we outline the SANDIA study and then go on to consider the NEA proposals for scenario development.

The SANDIA approach involves a scenario selection methodology developed by Cranwell et alia (1982), which has been applied to the Yucca Mountain, welded tuff, potential repository site in Nevada (Guzowski, 1987). This scenario selection methodology forms one half of a two-pronged strategy also involving the development of computer simulation codes of radionuclide flow and transport. The scenarios will be used to test the flow and transport codes under a variety of possible future conditions.

The scenario selection methodology involves six steps, as follows:

1. Identification of Events and Processes: a comprehensive set of events and processes is compiled by a panel of experts.

2. Classification of Events and Processes: the comprehensive set of events and processes is organised into various categories (such as natural/human-induced/repository-induced or release/transport phenomena.

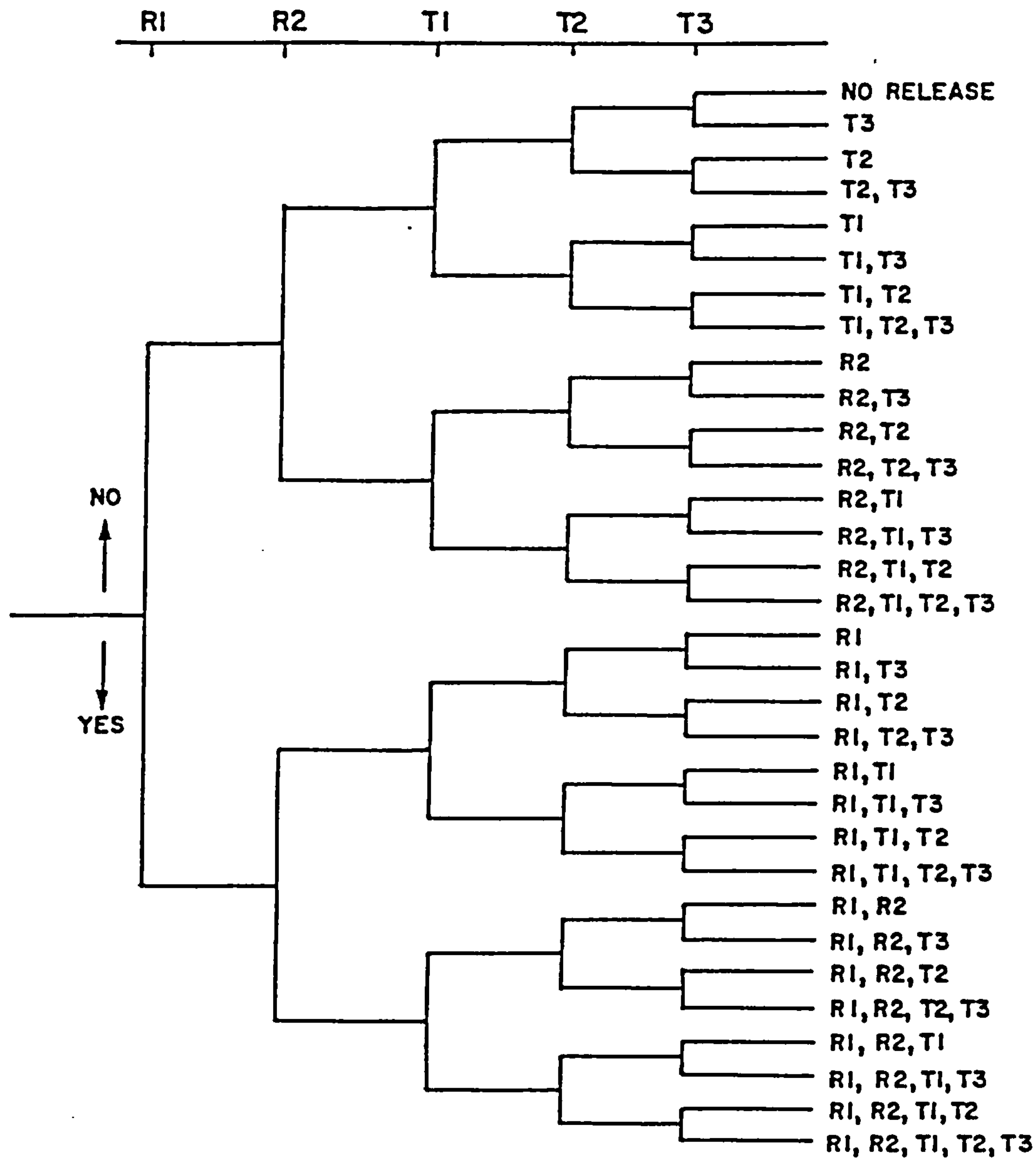
3. Initial Screening of Events and Processes: events and processes are selectively eliminated from consideration on the basis of the following criteria:

   - o Physical reasonableness;
   - o Probability of significant radionuclide release;
   - o Potential consequence to man.

4. Scenario Development: the remaining events and processes are arranged to give all possible combinations of transport and release phenomena and these constitute the scenarios (Plate 26).

5. Initial Screening of Scenarios: these scenarios are then evaluated, firstly with regard to physical reasonableness and secondly in terms of calculations (for each scenario) to determine the discharge of radionuclides. This results in a substantial reduction of the number of scenarios to be considered.

6. Final Screening of Scenarios: the probability of occurrence and the consequence are used as the criteria in a final screening process, before risks resulting from the remaining scenarios are calculated.



R=RELEASE PHENOMENA
T=TRANSPORT PHENOMENA

(CRANWELL ET ALIA, 1982)

PLATE 26

EXAMPLE OF A LOGIC DIAGRAM FOR THE CONSTRUCTION OF SCENARIOS DEVELOPED AT SANDIA

Dames & Moore

In their application of this methodology to the Yucca Mountain Site, SANDIA identified 30 events and processes for consideration. However, their initial screening of these (step 3) led to the retention of only 5 for further consideration (Plate 27). These 5 events/processes resulted in 11 release and transport phenomena which could be combined to form over 2,000 possible scenarios. These scenarios were then screened and reduced to 128 (by initial screening, step 5) and then to 39 (by final screening, step 6). A final stage of 'consolidation' (involving the removal of scenarios which duplicate others in terms of consequences) results in a final set of only 7 scenarios. Of this final set of scenarios the dominant process was found to be the possibility of additional recharge under pluvial (high rainfall) conditions; that is, climatic change effects were found to dominate.

Thus the SANDIA methodology involves a highly efficient reduction and elimination of possible scenarios, in a defined, logical framework, in order to identify important ones. It cannot be denied that this process is a drastic one, the emphasis being on elimination (Plate 27). In justification of this approach, the lack of field data for the site was emphasised. For example, neither the mean nor range of precipitation at Yucca mountain are known. In view of this sparcity of data, environmental change modelling would have been difficult and consequently the scenario methodology was developed as the most suitable means of testing the radionuclide flow and transport models.

The NEA working group on scenarios have chosen to adopt the SANDIA procedure as a basis for development. In their preliminary report (INTERA, 1988) they extend the arguments for scenario development and compare these with other methods of radioactive waste disposal performance assessment. They argue that 'simulation' techniques should not be seen as an alternative to scenario development, but rather in terms of complementing scenario methodologies. A three-stage logical sequence in performance assessment is advocated:

- Scenario development;
- Model development;
- Consequence analysis.

Modelling in this context is seen as the means of addressing the phenomena identified in scenario analysis and tackling the task of consequence analysis.

NATURAL PHENOMENA AND PROCESSES	INITIAL SCREENING OF EVENTS AND PROCESSES			
Celestial Bodies	Physically unreasonable	Low probability	Lack of Consequence	RETAINED AS SCENARIO
Meteorites		x		
Surficial Phenomena and Processes				
Erosion/Sedimentation			x	
Glaciation	x			
Pluvial Periods				✓
Sea Level Variations	x			
Hurricanes			x	
Seiches			x	
Tsunamis			x	
Regional Subsidence or Uplift (also applies to subsurface)	x		x	
Landslides	x			
Subsurface Phenomena and Processes				
Earthquakes			x	
Volcanic Activity				✓
Magmatic Activity		x		
Dissolution Cavities	x			
Interconnected Fracture Systems		x		
Faults				✓
HUMAN INDUCED PHENOMENA AND FEATURES				
Inadvertent Intrusions				
Explosions	x			
Drilling			x	
Mining	x			
Waste Disposal (Injection Wells)		x		
Withdrawal Wells				✓
Undetected Features				
Boreholes		x		
Mines		x		
Hydrologic Stresses				
Irrigation				✓
Dams	x			
WASTE AND REPOSITORY INDUCED PHENOMENA AND PROCESSES				
Subsidence and caving				LACK OF INFORMATION
Shaft and Borehole Seal Degradation			x	
Thermally-Induced Stress/Fracturing in Host Rock			x	
Excavation-Induced Stress/Fracturing in Host Rock			x	

PLATE 27

SCREENING OF EVENTS AND PROCESSES IN THE SANDIA (YUCCA MOUNTAIN) SCENARIO SELECTION METHODOLOGY

Dames & Moore

This preliminary NEA document is intended to be a basis for discussion and no firm conclusions have been reached. The emphasis has been placed on the development of a broad systematic framework capable of encompassing alternative methodologies and models.

5.3.3 The Case Against Scenarios

The case for the use of scenarios in environmental performance assessment has been made on at least two fronts:

- Future (disruptive) evolution scenarios, despite being unrealistic, are useful in identifying potential natural hazards and evaluating the severity of their consequences;

- Our knowledge of the environment is poor such that the use of simplified scenarios is the only justifiable approach.

These points were made in both the SANDIA and NEA documents discussed above. With regard to the first case, one cannot deny that in the early stages of work on performance assessment the consideration of scenarios did greatly help in the identification of important processes and factors and the elimination of unimportant ones. For example, the probability of meteorite impact has been judged as negligible in many studies, whereas the effects of human intrusion have been shown to be of high importance. Thus the first case for the use of scenarios has been justified, but only in the preliminary stage of 'homing-in' on important issues.

The second case (that our knowledge of the system is insufficient for anything more refined than scenarios) is misleading and unjustified on several accounts:

- Scenario methodology is not the only means of simplifying the complicated natural system;

- Though limited, our knowledge of the environment is substantial and comprises a rapidly expanding field of science;

- Scenario methodology does not merely simplify our appreciation of the environment, but actually constrains it to behave in terms of independent processes (in complete contrast to the true behaviour of the environment);

- Although extreme-case scenarios can produce conservative performance assessments, in many cases failure to account for time-dependent evolution of the system actually leads to significant under-estimation of the consequences of containment failure (see Plate 13);

- A false sense of confidence in performance assessment can be arrived at when various scenarios are eliminated as being insignificant (on a one-by-one basis) and yet their combined, cumulative effect (which may be significant) is ignored.

Thus the argument that scenarios comprise a suitable means of describing and simplifying the environmental system, acknowledged to the complicated, is inappropriate. Whatever simplifications need to be made, performance assessment must still recognise the nature of the environmental system as a whole. We propose that this is best done by attempting to simulate the environment (to the best of our ability) accounting for variability, future change and possible disruptive events.

Our rejection of the scenario methodology is qualified by the following reservations:

- This argument only applies to the environment; scenario methodology may still be appropriate for engineered structures (including repository barriers);

- Scenarios may be usefully employed in preliminary studies which seek to home-in on critical factors in the environment (although caution must be maintained in attempts to discount scenarios on a one-by-one basis);

- Some sporadic, disruptive events may still lend themselves to consideration in terms of scenarios which influence the evolving environmental system (ie some 'scenarios' may usefully supplement environmental simulation).

5.4 TIME-DEPENDENT PERFORMANCE ASSESSMENT

5.4.1 Introduction

There are, essentially, two key aspects which must be considered when environmental simulation is attempted:

- o The environment is a system in which processes cannot be considered in isolation;

- o The environment changes, as do the processes involved (ie they are time-dependant).

In our consideration of the 'scenarios approach' we focussed mostly on the first of these issues. Scenarios tend to (artifically) compartmentalise the environment and for that reason environmental simulation is preferred. This issue is thus straightforward: environmental simulation aims to model the environmental system as a whole.

The second issue, which we consider in this section, is less clear-cut. Environmental change (or time-dependence) should be an integral part of 'environmental simulation'; however, its incorporation into 'scenario assessment' may or may not occur and can lead to further misunderstandings of the environment. Even when scenario methodologies do attempt to incorporate time-dependency, short-comings are inevitable, since:

- o Time-dependent aspects of different scenarios do not necessarily relate to one another; for example, climatic change effects on infiltration rate (one possible scenario) would be considered separately from climatic change effects on erosion rate (another possible scenario);

- o Different scenarios often relate to different points in time, for example, a 'glacial erosion scenario' and a 'fluvial erosion scenario' refer to different post-closure times.

Thus, scenario assessment methodologies not only compartmentalise environmental processes, but also compartmentalise time-dependent aspects. Environmental simulation is thus the preferred means of tackling time-dependent performance assessment on both accounts.

5.4.2 The Use of Environmental Simulation in Performance Assessment

The description of TIME2 in Section 4.3 serves as an example of the construction of a Monte Carlo, time-dependent, environmental simulation model. We discuss here the merits of this form of environmental simulation for time-dependent performance assessment.

An environmental simulation model should be seen as producing a series of "environmental system states" which change with time. The environmental system state can be defined as the total characterization of the environment (natural, human and engineered systems) at any single moment in time. This characterisation will be in terms of a family of parameters chosen to represent the environment. This family of parameters will be limited by the assumptions and limitations of the model: the size and density of the parameter space will be a measure of how 'realistic' the simulation is. Environmental simulation can be deterministic (as in the CASTOR model) or probabilistic (as in TIME2, where many deterministic runs are used to produce a probabilistic output). When used in time-dependent performance assessment, the series of environmental system states produced for a site over a specified length of time are used as input parameters for groundwater flow, radionuclide transport and dose calculation models (designed to handle time-dependency).

The environmental system states produced in an environmental simulation should not be confused with the term 'scenario'. The definition of a scenario is varied but usually refers to a "possible future set of conditions". Thus a scenario is different from the system states produced in an environmental simulation on two fronts:

- A scenario comprises a limited portion of the environmental parameter space (often involving only one or two parameters, eg precipitation changes);

- A scenario may encompass a significant span of time or even the complete timescale of a performance assessment (eg if an alternative tectonic state comprises a scenario).

Furthermore, it has been suggested that environmental simulation itself should be viewed as one type of scenario; albeit a very comprehensive one (INTERA, 1988). Such a suggestion is confusing because it further obscures the definition of a scenario (already variably defined) and misrepresents the nature of environmental simulation.

The difference in nature between environmental simulation and scenario analysis is most evident when risk or dose calculations are attempted. With the scenarios approach the results can be used for performance assessment in one of two ways:

- Assume that the scenario with the highest risk (or dose) represents the worst case and use this for assessment;

- Combine the results of various scenarios to give an estimation of overall risk (or dose).

The first of these has some merit, as long as the scenario selected is genuinely the worst case and that the results are acceptable in relation to the relevant regulatory criteria. The second approach may be achieved either by arithmetically combining the results of each scenario (difficult to justify statistically) or by incorporating estimates of the probability of occurance of each scenario into the risk calculations. The second of these options (estimation of probabilities) presents considerable difficulties and is necessarily subjective. For example, the NEA working group, INTERA 1988, suggested the use of 'degrees of belief' where firm conclusions cannot be drawn. Even if estimates of probability are made the approach is difficult to justify, since:

- Environmental conditions at any one time depend on the nature of environmental change which has occurred prior to that time;

- The probability of a scenario may change with time (eg. under different climatic conditions);

- Fundamentally, the environment simply does not comprise individual components (scenarios) to which one can assign probabilities.

In contrast, these difficulties and shortcomings do not arise with time-dependent modelling of environmental change (environmental simulation) since the time-dependent performance assessments are derived from environmental parameters which vary with time and which allow for parameter variability and uncertainty.

In practice, the implementation of environmental simulation involves a trade-off of economy (time and budgets) against the achievement of comprehensive, 'realistic' simulations. Ideally, the parameter space which is included in the model should be determined after testing various environmental processes and events for their overall influence. That is, the limitations imposed should be arrived at as part of the model development. This is in contrast to the scenarios approach where scenarios are eliminated at an early stage without first determining their influence on the system (Plate 28).

5.4.3 The Complementary Use of Scenarios and Environmental Simulation

It must be emphasised that our rejection of scenario methodology applies only to environmental change modelling. In itself, scenario methodology has been and will continue to be of great use in safety analysis. However, we consider that the derivation of risk (or dose) calculations directly from an environment described in terms of 'scenarios' leads to inaccurate results and is unjustifiable (except perhaps in rare cases where environmental data is severely lacking). Instead, scenario methodologies should be seen as complementary to environmental change modelling. The three stages of performance assessment advocated by the NEA workshop (INTERA, 1988) provide a good framework for appreciating the appropriate role of scenarios:

1. Scenario development;
2. Environmental modelling;
3. Consequence analysis.

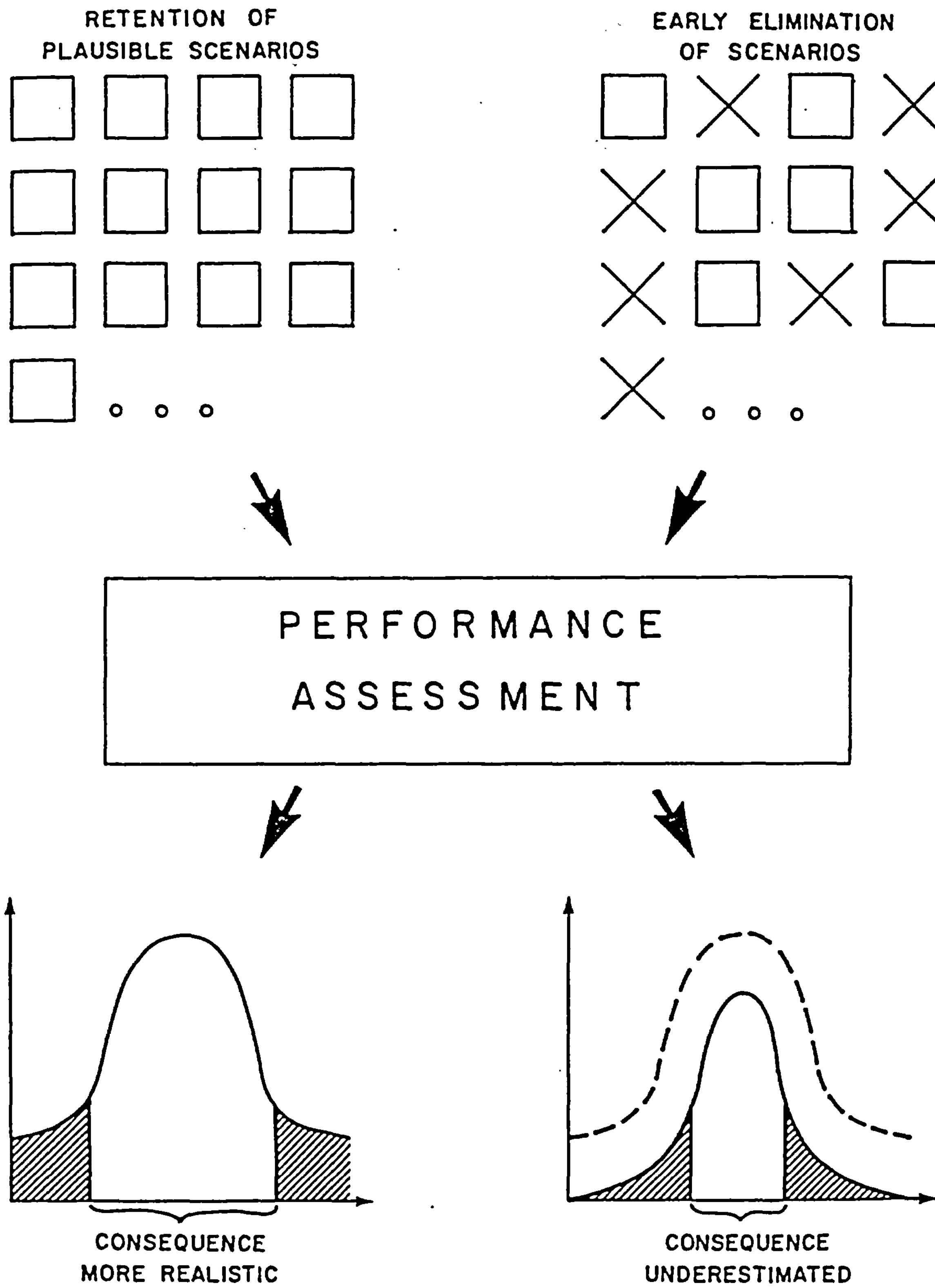


PLATE 28

SCHEMATIC ILLUSTRATION OF THE EFFECT ON
CONSEQUENCE ANALYSIS OF PREMATURE
ELIMINATION OF 'SCENARIOS' IN PERFORMANCE ASSESSMENT

Dames & Moore

Our conviction is that scenario analysis provides a useful foundation for determining relevant and important processes and events during the preliminary stages of performance assessment. This stage should be followed by environmental change modelling, being the best basis for consequence analysis. The environment must be modelled in a manner which accounts for both the unified nature and the time-dependent nature of the environment. Consequence analysis should only be based on such 'realistic' models and not simply on scenarios.

6.0 CONCLUSIONS

This final section of the report presents some conclusions from our review. These are grouped under headings for each of the major sections of the report.

THE NATURE OF ENVIRONMENTAL CHANGE

- The processes and events involved in environmental change act together as a unified system and it is important to model the linkages between processes and events wherever possible. However, our understanding of the environmental system as a whole is limited. The deep disposal environmental system can therefore be considered to be a simplified sub-set of the total environmental system for the practical purposes of performance assessment.

- Two primary drivers afect the deep disposal environmental system: climatic change and tectonic change. For the next one million years climatic change in Northern Europe is expected to be dominated by glacial-interglacial cycles. Ice sheet effects are also likely to dominate tectonic changes (due to changes induced by isostatic depression and rebound of the earth's crust).

- Significant processes in the deep disposal environment include the interplay of climate, land elevation, sea level and glaciation with groundwater flow (and consequent transport of radionuclides from a repository).

- Changes in tectonic and glacial stresses are likely to cause an increase in the overall level of seismicity: the size and frequency of earthquakes. The predominant effect of seismicity is expected to be changes in groundwater flow parameters of geological media as a result of induced fracturing. Faulting may also occur.

- A variety of approaches have been taken to the prediction of environmental changes with respect to radioactive waste disposal. The funadamental distinction is between deterministic and probabilistic approaches. The latter approach recognises and attempts to incorporate our uncertain knowledge of the environmental system.

- Non-EEC countries actively involved in performance assessment of disposal include the USA, Canada, Sweden, Finland, Switzerland and Japan. We have not considered Eastern Block countries in this review.

- Formal simulation of environmental change for performance assessment was pioneered in the USA, with the development of the GSM and FFSM computer models. These models were the first to attempt probabilistic, Monte Carlo, simulation of the environment for the purposes of performance assessment. However, they did not address the issue of time-dependent evolution of the environment, but instead considered the evaluation of "breach scenarios".

- In Canada, the performance assessment approach centres around the SYVAC computer code. The incorporation of environmental change through time-dependent path switching was investigated but not pursued. More recently, some modelling of glacial effects - especially on the biosphere - has been initiated.

- Sweden has completed performance assessments for deep disposal of HLW which included a thorough review of environmental change aspects. Modelling was not attempted. More recent work has focussed on post-glacial tectonics and faulting.

- A major performance assessment study has been recently completed in Switzerland: Project Gewahr. Qualitative and semi-quantitative evaluations of various possible future scenarios were made, covering a wide variety of environmental change events and processes. Presently ongoing studies are aimed at more detailed evaluation of some of these aspects.

- In Finland, research relevant to environmental change has centred on the long term behaviour of groundwater systems and postglacial fault movement. Both areas have been approached by studying recent geological history in some detail, as a pointer to future events.

- Japan has not, to our knowledge undertaken any studies of environmental change with respect to disposal.

- EEC countries have collaborated under the leadership of the CEC in carrying out the PAGIS and PACOMA projects, aimed at defining a unified European approach to performance assessment, as well as pursuing their own independent research.

- PAGIS and PACOMA utilise the "scenarios" approach to incorporation of environmental changes into performance assessment. Sets of "normal", "altered" and "disrupted" evolution scenarios have been constructed, covering a range of environmental events and processes.

- Long term safety studies have been made for the research site at Mol in Belgium, using the fault/event tree analysis approach more commonly associated with reactor safety studies. Subsequent research has investigated human influences and environmental change effects on groundwater flow, by means of applying various "scenarios" to a detailed flow model.

- In France, BRGM has adopted the "prospective" approach to environmental change aspects of performance assessment: the examination of possible future scenarios, drawn from extrapolations of recent geological history, and their implications. A simple deterministic computer model of environmental change has been constructed to assist in this work: CASTOR. The model has been tested on a site in Northern France.

- In West Germany, only qualitative assessments of environmental changes have been made, addressing aspects such as glaciation and seismicity. Human intrusion has also been investigated.

- Work on radioactive waste management in Britain is divided between two main organisations: NIREX (the disposer) and the Department of the Environment (DOE, the licensing body). Nirex has been sponsoring research into environmental change for several years, but has not as yet carried out any modelling studies. The DOE, in contrast, has supported the development of the TIME2 computer code for probabilistic simulation of environmental change (by Dames & Moore) and is committed to a time-dependent probabilistic risk assessment approach to performance assessment of deep disposal.

ENVIRONMENTAL CHANGE MODELLING AT DAMES & MOORE

- The main feature of work at Dames & Moore on environmental change has been the development of the TIME2 computer code. This has been supported by a programme of background studies. The code has also been applied to two sites in Britain.

- Background studies were initiated in 1984 with a review of significant processes and events, previous research worldwide and possible approaches to the modelling of environmental change. Following this, specific research was undertaken in climatic change, geomorphological processes (especially glaciation), seismicity and human intrusion.

- The TIME2 code uses a Monte Carlo simulation method, incorporating the uncertainty in the processes, events and associated data concerned. The model is applicable to shallow disposal sites and simulates environmental change over the period up to the next glacial maximum (30,000 to 50,000 years after present). Submodels in the code include climate, glaciation, sea level change, surface water balance, denudation and human intrusion.

- TIME2 has been used to evaluate environmental change at a hypothetical disposal site at Elstow, Bedfordshire (for DOE) and an operational site at Drigg, Cumbria (for British Nuclear Fuels plc).

- Current studies are continuing basic research in glacial and periglacial effects, under the joint sponsorship of CEC and DOE, in collaboration with the University of Edinburgh. A new simulation model, TIME4, is to be developed for DOE. This code will simulate environmental change at deep disposal sites for a period of up to one million years after present. It will incorporate recent advances in basic research enabling the effective treatment of multiple glacial advance-retreat cycles.

- As well as the specific research and development work described above, Dames & Moore has provided ongoing consultancy to DOE in their development of a fully time-dependent approach to post closure probabilistic risk assessment. This has included assistance during development of the VANDAL time-dependent pra code, which is ultimately to be linked with the TIME4 environmental change simulator. A simpler prototype pra code is also being used to help in defining the logic of time-dependent pra and demonstrate its feasibility.

INCORPORATION OF ENVIRONMENTAL CHANGE EVALUATION INTO PERFORMANCE ASSESSMENT

- Two alternative approaches have been proposed for the incorporation of environmental change evaluation into performance assessment of radioactive waste disposal: the scenarios approach and time-dependent performance assessment.

- We conclude that the frequent adoption of "scenarios" in evaluating the influence of environmental processes on disposal conflicts with the very nature of the environment. We see the environment as a dynamic system, continually changing in response to a wide range of interlinked processes and events.

- The scenario selection methodology, developed at SANDIA Laboratories, is discussed. This kind of approach is considered to lead to mis-representation of the environment, particularly when processes are eliminated from consideration on a one-to-one basis without first assessing their combined effect on performance assessmnet.

- The issue of time-dependency is frequently confused or by-passed in scenario methodologies. Time-dependent simulation is a key issue in developing realistic simulations of environmental change.

- For these reasons, we believe that environmental change should be modelled at the level of individual major processes, ideally probabilistically. Such modelling should be used to drive performance assessment models able to accept continuously changing information about the environment within which they are simulating the release, transport and uptake of radioactivity.

- The scenarios methodology does have value in performance assessment: in the identification and rejection of the least important processes and events contributing to environmental change, as well as in the evaluation of mechanical systems (ie failure of components). A complementary use of scenarios and environmental change simulation is therefore seen as the best way forward.

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GLOSSARY

AQUIFER	Layer of rock sufficiently porous or permeable to be water bearing.
ASEISMIC	Without seismic activity.
BOREAL	Cold climatic conditions (literally 'northern').
DEGLACIATION	The process of melting of ice sheet due to climatic warming.
DENUDATION	Lowering of the land surface by sum total of processes of weathering and erosion.
DETERMINISTIC	That which is derived from logical, reasoned argument.
DIAPIRISM	The rising of bodies of salt (diapirs) within the earth's crust due to density differences.
DISCHARGE	Zone of outflow from a groundwater system.
ECOSYSTEM	The System of living organisms and plants.
EPEIROGENISIS	Regional uplift or depression of the laid surface as a result of widespread adjustments of level.
EROSION	Active lowering of land surface due to mechanical surface processes.
EVAPOTRANSPIRATION	The loss of water into the atmosphere by the process of evaporation and the action of plant life.
EUSTATIC	Changes in sea level due to regional effects (usually temperature and ice/water balance).
FAULT RUPTURE	Displacement of a geological fault which accompanies an earthquake.

GEOTHERMAL GRADIENT	The profile of temperature with depth in the earth's crust.
GLACIATION	The process of ice sheet growth due to a global fall in temperature.
GREEN HOUSE EFFECT	The rise in atmospheric temperature due to the production of carbon dioxide and various trace gases which result in heat retention (in a similar manner to a greenhouse).
HIERARCHY	System in which grades of status rank above one another.
HYDRAULIC CONDUCTIVITY	A measure of the permeability of rock strata (being a function of the rock media and the fluid flowing through it.
HYDRAULIC GRADIENT	The change in level of the hydraulic head with distance within a permeable strata.
HYDROSTATIC STRESS	Pressure due to the weight of overlying water (in the rock).
INFILTRATION	Flow of water from the surface down into rock strata.
INTRAPLATE	Within the interior of a tectonic plate (away from the more active zones at the edges of plates).
ISOSTATIC	Changes in (sea or land) elevation due to vertical crustal movements caused by the bouancy of the earth's crust.
LITHOSTATIC STRESS	Stress due to the weight of overlying rock.
LYSIMETER	A true water balance device which hydrologically isolates a volume of soil and its plant cover.

MAGMATISM — Processes in the crust due to the rising of melted rock (magma).

MARL — Calcareous mudstone/clay.

METEORIC — That (water) which ultimately originates from above (ie rain, snow, rivers, streams).

MICROCRACKS — Miniature pervasive cracks within rock resulting from deviatoric stressing (usually micrometers to millimeters in dimension).

MICROCRACK DILATANCY — Expansion of rock due to the opening of microcracks.

MONTE CARLO METHODS — The simulation of processes by probabilistic means (in this context, the random sampling of probability density functions).

OROGENESIS — The process of mountain building leading to the formation of intensely deformed belts which constitute mountain ranges.

PERIGLACIAL — Conditions in the vicinity of an ice sheet where freeze-thaw actions of ground ice dominate the near-surface environment.

PERMAFROST — The presence of frozen ground (throughout the annual climatic cycle).

PERMEABILITY — (=Intrinsic permeability). A measure of the ability of a (rock) media to allow the passage of fluid (regardless of the properties of the fluid).

PLATE TECTONICS — Theory of the earth in which the crusts consist of separate plates moving over a mobile substratum.

PLEISTOCENE — Subdivision of the Quaternary period of geological time (between 2 million and 10,000 years before present).

PLUVIAL	Wet climatic conditions in lower latitudes which accompany the glaciation in higher latitudes.
POLYNOMIAL	Algebraic expression constituting three or more terms.
POROSITY	Fractional (per cent) of a (rock) material which comprises voids.
POSTGLACIAL	Period of geological time following the last glacial (usually the last 10,000 years).
pra	Probabilistic Risk Analysis.
PRECIPITATION	All forms of water derived from the atmosphere (rain, snow, hail, etc).
PRECAMBRIAN	Period of geological time which preceded the Cambrian (ie before 600 million years before present).
PROBABILISTIC	That which is derived in terms theories of probability.
pdf	Probability Density Function: the distribution of observed or theoretical values of a variable parameter.
QUARTERNARY	Most recent period of geological time (2 million years before present to the present time).
RECHARGE	Zone of inflow into a groundwater system.
SAVANNAH	Warm climatic conditions characteristic of tropical areas.
SEISMIC (SEISMICITY)	Relating to earthquakes (the degree of occurrence of earthquakes).
SEISMOTECTONIC	Tectonic processes which relate to/result in seismicity.

SEISMIC HAZARD	The evaluation of the danger to man and structures caused by the occurrence of earthquakes.
SOLUTION MINING	Method of extracting salt from deep layers by pumping water down into layer and extracting brines. The method results in a subsurface cavity caused by the solution of salt.
STOCHASTIC	A process comprising an ordered (logical) sequence but using probability functions or methods.
TECTONICS	The structure and physical state of the earths crust (tectonic activity refers to the degree of deformation).
TEMPERATE	Moderate climatic conditions like those prevailing in Europe at present.
TERTIARY	Period of geological time since 65 million years before present and including the most recent Quaternary period (last 2 million years).
TIME-DEPENDENCY	Being variable with time.
TUFF	Volcanic deposit derived from ejected volcanic debris (ash, pumice etc).
TUNDRA	Very cold climatic conditions characterised by the presence of ground ice (Permafrost).
VISCO-ELASTIC	A material whose behaviour can be described in terms of an elastic solid or a viscous fluid depending on the rate of strain applied.
VOLCANISM	Processes at or near the surface which result from magmatic activity and associated with volcanoes.

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'CURRENT RESEARCH STATUS' - SOURCE MATERIAL

This appendix lists the source material used in the assessment of research on the effects of long-term environmental change on radioactive waste disposal in the various countries considered in Section 3.0. Sources are listed country by country (in the order treated in the report) and are given in chronological order. Personal communications, by letter, telephone, or in person, are listed in the final section, and all occurred between November 1987 and February 1988. References cited within the body of the text are not given here but are listed under 'references' at the end of the report.

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