NUMO
原子力発電環境整備機構

NUMO-TR-09-03

Development of Methodologies for the Identification of Volcanic and Tectonic Hazards to Potential HLW Repository Sites in Japan

- Summary Report -

Neil Chapman[1], Mick Apted[2], John Beavan[3], Kelvin Berryman[3], Mark Cloos[4], Charles Connor[5], Laura Connor[5], Susan Ellis[3], Olivier Jaquet[6], Koji Kiyosugi[5], Nicola Litchfield[3], Sue Mahony[7], Warwick Smith[3], Steve Sparks[7], Mark Stirling[3], Pilar Villamor[3], Laura Wallace[3], Junichi Goto[9], Tadashi Miwa[9], Hiroyuki Tsuchi[9], Kazumi Kitayama[9]

[1] MCM Consulting, Switzerland
[2] Monitor Scientific LLC, USA
[3] GNS Sciences, New Zealand
[4] University of Texas, USA
[5] University of South Florida, USA
[6] In2Earth Modelling Ltd, Switzerland
[7] University of Bristol, UK
[9] NUMO, Japan

November 2009

Nuclear Waste Management Organization of Japan (NUMO)

Contents

1 Introduction

The potential for volcanic and rock deformation impacts on a repository site needs to be considered at each stage of NUMO's siting programme. Whilst the nationwide evaluation factors for qualification (EFQs) for PIA acceptance are designed to remove clearly unsuitable sites from consideration, they cannot guarantee that, over the next tens of thousands of years, the risks of tectonic hazard for a chosen PIA will be acceptable. This is because large parts of Japan that are potentially suitable for siting are directly affected to varying extents by rock deformation, the peripheral impacts of volcanic activity or the possibility of new magma intrusion or volcanic activity. The EFQs were only intended as preliminary screening guidleines to prevent obviously poor candidates entering the siting process.

Consequently, an integration of additional and more refined techniques is required to evaluate sites that pass the EFQ test, so that NUMO can have a clear idea of the likelihood and potential impacts of tectonic events and processes at each PIA. The ITM project was initiated in 2005 to provide NUMO with such a methodology, based upon state-of-the-art approaches used internationally, developed and extended for the specific purposes of NUMO and the specific conditions of Japan: hereafter, we refer to it as the **'ITM Methodology'**.

The ITM Project developed out of the considerations and discussions that took place at a series of previous International Tectonics Meetings (ITM) organised by NUMO over a period of 7 years, from 2002 to 2009. The ITM Project was completed in March 2009 and this report provides both an overview of the whole project and the final update of the methodology developed, based upon progress during the final year of the project (April 2008 to March 2009). In addition, a brief outline is provided of the ITM activities that preceded the ITM Project itself.

1.1 Probability: the likelihood of future tectonic impacts on a repository

During the course of the project, both NUMO and the Japanese regulatory agencies were considering how best to handle the evaluation of low probability, disruptive events (e.g. volcanic intrusion, fault rupture) and deformation processes that are discontinuous in time and magnitude in response to continuous regional strain, when carrying out safety assessments of geological repositories for radioactive wastes. Essentially, two approaches have been adopted internationally to address this situation:

- To calculate the health risk[1] to people in the future by combining the probability of a disruptive event occurring with its radiological consequences in terms of releases from a repository: simply, risk = probability x consequence. With this approach, regulatory standards or targets can be defined in terms of risk to an individual.

- To consider the impacts of a disruptive event and calculate the radiological doses[2] to people in the future and then, separately, to discuss the likelihood that this might happen (the so-called 'disaggregated' approach). With this approach, separate regulatory targets for radiation doses might be set for events (or scenarios) with different degrees of likelihood (often expressed qualitatively; e.g. 'likely', 'less likely', 'highly unlikely').

In either approach, an appreciation of probability is essential: in the first 'risk approach' a sound quantitative estimate will provide more confident estimation of risk; in the second, some form of quantification of 'likelihood' is needed to decide which category to place an event or scenario into.

---

[1] Health risk is normally defined as the risk of death or serious genetic effects.

[2] Of course, a radiological dose can also be expressed in terms of health risk, by applying accepted dose-to-risk conversion factors.

The ITM methodology that has been developed in this Project is centred on a probabilistic approach. A probabilistic approach is seen by the ITM group as the only realistic means of quantitatively addressing the uncertainties in assessing possible hazards when there is marked variability in the spatial distribution, the timing, the intensity and the style of the volcanic and deformational events and processes being evaluated (for convenience, in this report, we frequently group these together within the general term 'tectonic events and processes'). The probabilistic approach being developed is based upon and strongly supported by deterministic models of the underlying tectonic processes that lead to magma intrusion, volcanism and rock deformation.

NUMO is developing both the probabilistic ITM methodology and other, independent, deterministic approaches, in parallel projects that will eventually be deployed at volunteer sites when they arise. The weight that will be given to deterministic and probabilistic evaluation results will depend, to some extent, on the nature and the geographical location of these sites. It will also be influenced by the direction in which regulatory development move over the next few years. As noted above, however, some quantification or estimation of probabilities is required in any reasonable approach to safety evaluation and regulation. For the specific tectonic circumstances of Japan, this is especially relevant and important.

The aim of the current project reported here is to use the probabilistic ITM methodology at three important stages of NUMO's siting programme:

- SITING STAGE 1: during the literature survey (LS) stage when potential PIAs are being assessed. The ITM methodology will use currently available information to allow comparison of sites in terms of confidence that they are likely to prove acceptable with respect to tectonic impacts.

- SITING STAGE 2: during the planning of the PIA site investigations, to identify geoscientific information requirements that will be needed to refine the Stage 1 analysis.

- SITING STAGE 3: at the point where PIAs are being evaluated and compared in order to select a preferred site (or sites) for detailed investigation (as DIAs).

The ITM project is mainly concerned with Stages 1 and 2. Application of the methodology in Siting Stage 3 is several years into the future and it is expected that it will be most efficient to carry out any necessary updates/refinements on a region-specific basis during the PIA investigations when NUMO has narrowed down to a group of sites. The ITM project involves methodology development and testing only and does not include actual deployment for volunteer sites/regions. The methodology can be used to:

- produce regional maps of relative probability of volcanic events within 5 x 5 km areas (the approximate repository footprint, plus immediately surrounding rock volume);
- produce regional maps of probability of exceeding specified strain rates (rock deformation) within 5 x 5 km blocks;
- identify possible impacts of such events and the information that needs to be fed into safety assessment scenarios to comply with risk-based or disaggregated dose-probability regulatory requirements;
- identify the information that can be obtained during PIA investigations to refine and provide confidence in the regional probability analyses.

The way in which the methodology could be applied at any of these stages could be at different levels:

- simple hazard evaluation using probabilities: estimation of susceptibility to tectonic and volcanic events and processes:
    - of a single site;

    - comparison among a group of sites.
- full safety evaluation combining probabilities with consequences: safety assessments for tectonic scenarios, evaluating in detail how an event might impact a repository at a site and what the radiological health effects would be:
    - risk based;
    - disaggregated, dose-based consequence analyses.

1.2 Participants in the ITM Project

The Project involved the close interaction of Japanese and international experts to gain the necessary understanding to carry out the methodology development and testing. The international project team would like to thank in particular all those Japanese experts who provided information and advice and led the team on field visits, sometimes over several weeks, to the Case Study areas and other localities where data could be gathered and observations made on features and processes of interest.

The international experts came from the following organisations (the acronyms used in this report are indicated):

MCM	MCM Consulting, Switzerland
UBR	University of Bristol, UK
USF	University of South Florida, USA
UTX	University of Texas, USA
GNS	Geological and Nuclear Sciences, New Zealand
MSL	Monitor Scientific LLC, USA
CPE	Colenco Power Engineering, Switzerland[3]

ITM International Project Team Members		
Rock Deformation	Dr Kelvin Berryman Dr Nicola Litchfield Dr Mark Stirling Dr Laura Wallace Dr Pilar Villamor Dr John Beavan Dr Susan Ellis Dr Warwick Smith	GNS Sciences, New Zealand
	Professor Mark Cloos	University of Texas, USA
Volcanics	Professor Charles Connor Laura Connor Koji Kiyosugi	University of South Florida, USA
	Professor Steve Sparks Susan Mahony	University of Bristol, UK
	Dr Olivier Jaquet	CPE Power Engineering, Switzerland (now at In2Earth Modelling, Switzerland)
Interface with PA	Dr Mick Apted	Monitor Scientific, USA
Project Co-ordination	Professor Neil Chapman	MCM Consulting, Switzerland

---

[3] Work was transferred to In2Earth Modelling Ltd, Switzerland in early 2008, following movement of the key expert.

1.3 Report content and associated reports

This report provides both an overview of the whole project and the final update of the methodology developed, based upon progress during the final year of the project (April 2008 to March 2009). To begin, Section 2 provides a short outline of the ITM activities that preceded the ITM Project itself, as well as the development of the Project over the last few years. Section 4 reports on the conclusions of the evaluation of how to transfer the results of the ITM methodology to NUMO's safety assessors (Step 6 of the ITM methodology, described in Section 3).

Two other reports comprise the main output of the Project. These describe the development, application and testing of the methodology in two Case Study areas, in northern Honshu and Kyushu:

- **The Tohoku Case Study Report** was completed in the previous financial year and finalised for publishing as a NUMO Technical Report in 2009 (NUMO-TR-08-03).

- **The Kyushu Case Study Report** was completed this year and will be finalised for publishing as a further NUMO Technical Report in mid-2009.

This report and the Case Study reports are compilations of material provided by all of the research groups listed above.

2 The ITM Project and Precursor ITM activities

The earliest work of the International Tectonics Meeting (ITM) dates back to 2002. At this time, NUMO issued its call for volunteers and was beginning to develop its siting programme. NUMO acknowledged at the outset that a comprehensive and scientifically defensible approach would need to be taken to evaluating tectonic risks to a HLW repository.

The first two years of ITM were intended to familiarise key international scientists with the nature of the problem, initiate discussions between those scientists and Japanese specialists in tectonics and to begin to identify possible approaches that could be used to assess tectonic risks and manage them by an appropriate siting programme.

2.1 ITM-1

The initial, pilot ITM meeting took place in Tokyo in January 2002 and involved Neil Chapman, Nagra, Switzerland (Chairman), Clarence Allen, CalTech, USA, Mick Apted, Monitor Scientific, USA, David Jackson, UCLA, USA and Stephen Sparks, University of Bristol, UK.

The main aim of the meeting was to look at the tectonic information available to NUMO, specifically the recently produced report by JSCE[4] on geological factors in site selection, and to provide suggestions and advice on how best to deploy this in the development of tectonic Siting Factors.

A key consideration was the need for NUMO to take geologically and tectonically informed siting decisions that would achieve a reasonable consensus of support amongst the national and international Earth Sciences and engineering communities. Consequently, one aim was to advise NUMO of issues where it would potentially be exposing itself to contentious debate if it were to adopt a particular position or approach. The meeting focussed on five main topics:

- the 'predictability of stability' of the tectonic framework of Japan;
- volcanic activity;
- seismic activity;
- active faults;
- uplift and erosion.

For each topic, a preliminary statement of a possible NUMO position was set up to catalyse debate. These statements were based on possible interpretations of the recommendations of the JSCE report in particular (although some could be traced back to the H-12, 2nd JNC Progress Report, or earlier, AEC guidelines, and some simply reflected the requirements of the nuclear law). The main findings of the discussion on each topic were recorded, with points of agreement being highlighted. The position statements were then revised to reflect the agreed views. These revisions were advanced for NUMO to consider as more developed or more appropriate bases from which to develop tectonic Siting Factors.

2.2 ITM-2

The second ITM meeting took place in March 2003, again in Tokyo and the international participants (the ITM Core Group) for this meeting were the team that eventually took the ITM programme through to completion six years later: Neil Chapman, Switzerland (Chairman), ,

---

[4] *'Geological Factors to be Considered in the Selection of Preliminary Investigation Areas for HLW Disposal.'* Sub-Committee of the Underground Environment, Civil Engineering Committee of the Nuclear Power Facilities, Japan Society of Civil Engineers. August 2001 (in Japanese): Draft English translation: December 2001.

Mick Apted, USA, Stephen Sparks, UK, Kelvin Berryman, New Zealand, Mark Cloos, USA and Charles Connor, USA. Bill Arnold, Sandia Laboratories, USA, also joined this meeting as an observer and to describe the work he had been carrying out in a joint NUMO-USDOE collaboration project on vocanism.

ITM 2 was convened with the objective of considering two issues of importance at the then current stage of the NUMO siting programme:

1. How NUMO can conduct technically and scientifically defensible assessments of initial volunteer sites on the basis of literature data only.
2. How surface-based investigations can be designed to collect the necessary information during the PIA phase to support the future decision on DIA selection.

As noted by many ITM 2 participants, geological issues are among those that are of greatest concern to both technical and non-technical stakeholders. It was felt that NUMO needed to be confident that it understands the tectonic regime in a volunteer area sufficiently that it could make a properly considered decision on whether to advance a volunteer location as a PIA. The issues that NUMO needed to be aware of at this stage were considered to be:

- the likelihood that the area could be prone to disruptive tectonic processes and events over the lifetime of a repository, which would need to be taken into account when assessing long-term safety of a site;

- whether this likelihood can be adequately judged on the basis of current theory and knowledge about the time and space distribution of these disruptive mechanisms;

- whether there is enough regional and site-specific information available now to apply current conceptual models at the volunteer sites, before it is possible for NUMO to begin collecting its own data in the field;

- whether current conceptual models (at the time of this meeting) were sufficiently credible and robust to withstand peer evaluation by the broader earth science community when PIAs are being selected;

- whether gathering more data in the PIA field investigation stage can significantly reduce and quantify uncertainties in predicting tectonic impacts and their likelihood of occurrence.

Each of these issues was considered to represent a potential risk to NUMO's programme, and the aim of the ITM was proposed as being to help ensure that these risks are properly discussed and understood. Hence, the information needed to explain and resolve such concerns is of extremely high priority to NUMO. With these objectives in mind, the presentations by Japanese and international experts at ITM 2 and the subsequent discussions were focussed onto two key areas (which subsequently became the main strands for the rest of the ITM Project):

- igneous activity;
- rock deformation (faulting, folding and uplift).

At the end of the workshop, the participants summarised by expressing their belief that NUMO's mission to identify and confidently characterise a geologically stable site for long-term geological isolation of nuclear waste was tractable. There are many world-class geological experts, expertise and facilities in Japan that are providing enormous amounts of high-quality information and understanding on the dynamic character of Japanese geology. It is not NUMO alone that is gathering and analysing such information. There is a large resource available and NUMO needs to involve the best sources and use the best data available.

ITM members noted that it would be important for NUMO to develop and publish general methodologies showing how it plans to link these capabilities into a multi-disciplinary programme that evolves in a continuous manner with the planned steps in its site selection process. The importance of documenting these methodologies is not only to provide the technical and scientific basis for site selection, but also to communicate to Japanese policy and public stakeholders that NUMO fully recognises and is addressing their key concerns regarding long-term geological stability, especially over the 100 ka period of principal concern in their safety assessment studies (at the time of this meeting: there is now interest in looking out to 1 Ma in safety assessment work).

Both topical areas, volcanism and active rock deformation, reduced to a matter of estimating reliable probabilities of disruption to a repository. Fully supported probabilities are not needed until the time of justification of the choice of a repository site and its associated safety case. Until that time, proceeding with a site where there may be uncertainty about the likelihood and impacts of disruptive tectonics is NUMO's own 'developer risk' – it could eventually prove to be too difficult to make the safety case for such a site.

It was considered that volcanism could be addressed at that time, using available information and it is thought unlikely that NUMO will encounter any major surprises when it evaluates volunteer areas. The probability of proceeding with a volcanically 'risky' site into DIA and beyond should be easy to establish early on. Instead, NUMO is likely to see a progressive increase in understanding of the inevitable uncertainties involved as it moves through the PIA and DIA stages, which will lead to increasing confidence in risk estimates. The level of confidence to attach to probability estimates made during the next few years, before site - specific information is of sufficient quality and quantity, will be relatively low. It was recommended that NUMO carries out scoping PA studies of volcanic impacts to see what level of likelihood of different volcanic impacts is tolerable in terms of consequent radiological risk. The underlying models used to estimate probabilities and the approach to applying them could be tested best by establishing some **case studies** in regions of polygenetic and monogenetic volcanism over the coming 2-3 years, in consultation with the groups responsible for the conceptual models and the data gathering.

For active rock deformation, the picture was not considered to be quite as simple. While it is possible to avoid known features, there may be surprises in the DIA stage when new features, especially at depth, are discovered. NUMO's best approach in the meantime was to develop an approach to identifying stable rock blocks (volumes of rock with little internal deformation, where strain is largely taken up on well-defined boundaries) using the full range of geological, geodetic and geophysical data that are coming available, particularly seismic, GPS and radar imagery data. Again, this approach could usefully be tested using a case study region of Japan.

The literature survey stage involves uncertainties for NUMO, and it was thought important that NUMO states clearly that it recognises these uncertainties and that it has, and is continuing to develop, approaches to address them. Initial geological analysis of specific volunteer sites will, of course, be qualitative in assigning probabilities of hazards because of limited and variable literature data that will undoubtedly contain some gaps of information. A potential risk in reliance on literature data is in understanding the limitations, uncertainties and deficiencies that are inherent in any set of collected data. This risk is further compounded by the fact that interpretations published with these data are typically not addressing repository-specific situations and issues, and credible alternative interpretations may not be fully explored.

The participants felt that, as early as possible, NUMO should assess what types and levels of information it is likely to have at each step of the site-selection process, and compare this assessment to what information is needed to support a decision to proceed to the siting step. This comparison by NUMO is necessary so that that potential information gaps and insufficiencies can be identified and addressed well in advance of the time when siting decisions must be made and defended. ITM members themselves expressed interest in perhaps assisting NUMO and its contractors in this effort of integrating data and information in the areas of credible predictions of long-term igneous activity and rock deformation.

A major challenge facing NUMO would be its ability to integrate and interpret all of this diverse information, and to keep pace with the steady generation of new seismic and geodetic data, the latest developments in techniques and evolving conceptual models. Although site - specific data will always be necessary for basing siting decisions, NUMO was sensibly planning to supplement such site-specific perspectives with analogue information that is being developed in two underground research laboratories in Japan. In exactly the same manner, ITM members recommended that NUMO also consider studies from other analogue sites outside of Japan (e.g. New Zealand and California have analogous deformation environments and features, the circum-Pacific region is characterised by pervasive polygenetic and monogenetic volcanism that is contemporaneous and mechanically related to similar volcanism in Japan). Supplemental data and interpretations from such studies were thought to be equally useful to NUMO in providing the highest level of scientific confidence to concerned policy makers and public stakeholders regarding their future siting recommendations. This was also an area where the international members of ITM might be able to assist NUMO.

Nevertheless, the main recommendation of ITM 2 for the next step was for NUMO to develop volcanic and active deformation **case studies** in selected regions of Japan, involving the resources that NUMO already has to hand, plus other organisations that hold data and concepts that could be useful.

Prior to the ITM 2 Meeting, NUMO arranged an extremely useful 2-day field trip to the Kiso-Mino area of Central Japan. Of particular interest to ITM experts was examining field relationship associated with active faults, including the Atera and Neodani Faults, as well as accompanying subsidiary faults within several hundred metres of these principal faults. In addition, field relationships of wider-scale deformations arising from geological and tectonic processes were examined and discussed with respect to implications for geological disposal. Remnants of earlier igneous activity in the Japanese islands were also inspected as analogues of current and future igneous activity that may develop in Japan. These field trips provided invaluable opportunities for Japanese and international ITM experts to examine the actual field relationships of Japan geology, to compare alternative interpretative models based on such evidence, and therefore begin to establish scientific consensus on key geological issues related to long-term safety of nuclear waste repositories. Discussions in the field helped expand perspective and build mutual understanding among Japanese and international ITM experts. For future ITM workshops, it was considered useful to link field visits to case study regions, if case studies were being undertaken.

2.3 ITM-3

The ITM activities during FY 2003-4 were more diverse than in previous years, as two topical 'mini-workshops' were organised in the UK and USA as well as the full ITM-3 Workshop in Tokyo in March 2004. The main focus remained on how NUMO would address the two key areas of future volcanism and rock deformation (active faulting, flexuring and uplift-subsidence). Both topical areas, volcanism and active rock deformation, reduce to a matter of estimating reliable probabilities of disruption to a repository. It was felt that fully supported probabilities are not needed until the time of justification of the choice of a repository site and its associated safety case, but NUMO needed to have an established methodology to dealing with these issues during each stage of its programme: PIA selection, PIA studies and DIA selection and site characterisation. It is expected that this methodology will grow and develop in parallel with the developing requirements of the siting programme, so that it is 'fit-for-purpose' at each stage.

In March 2003 it was suggested that NUMO developed and tested the underlying models used to estimate probabilities of future volcanism and the approach to applying them by establishing some **case studies** in regions of polygenetic and monogenetic volcanism over the coming 2-3 years, in consultation with the groups responsible for the conceptual models and the data gathering. For active rock deformation, it was suggested that an approach to identifying stable rock blocks using the full range of geological, geodetic and geophysical data that are coming available, particularly seismic, GPS, active faulting and folding data should be developed. This approach could usefully be tested using a case study region of Japan, and the advantages of looking at the same area as the volcanism study were apparent.

The 2003-4 activities were planned against this background. Two ‘mini-workshops’ were organised to develop the suggested case studies for volcanism and rock deformation and to evaluate the information held on NUMO’s database for suitability. Following these workshops, suggestions were developed for projects for the next FY to begin building the approaches to assessing the likelihood of future tectonic impacts at potential PIAs. The two outlines formed the core of the discussions among the wider group of ITM members at the March 2004 meeting.

In addition to these workshop activities, a review was made of the report by the Sub-Committee for Safety of Radioactive Waste on *“For securing the basis related to the safety regulation of HLW Disposal”*, which contains many comments and suggestions on how to deal with tectonic issues in the regulatory research programme.

The two mini-workshops were focussed on applying expert knowledge to a 'type' region of Japan that displays volcanic and deformational characteristics similar to those that may occur in some areas where volunteer communities might come forward. The proposed region was in the Sengan area of north-central Honshu and was suitable for independent evaluation by both the 'volcanics' and the 'deformation' groups, from their own perspectives. The two groups could then integrate their evaluations and look at factors of overlapping concern. The intention of the two mini-workshops was to begin to evaluate the data from the Sengan ‘type region’ as a test bed to develop ideas and approaches. The data from this area were considered to be typical (to good) and thus fairly representative of what NUMO would have to hand when volunteers come forward.

The first mini-workshop (on volcanism) was held in December 2003, hosted by Professor Stephen Sparks at the University of Bristol, UK. The group heard presentations on the use of probabilistic and deterministic approaches to predicting future volcanism (CRIEPI-NUMO studies and University of South Florida) and worked on-line with the NUMO GIS database to evaluate the scope and quality of data from the Sengan area. The way forward and the data needs identified in the discussions are summarised in the following slides.

The second mini workshop (on rock deformation) was held in January 2004 in California, USA, jointly hosted by Dr Mick Apted and Professor Mark Cloos (University of Texas at Austin) in coordination with Dr Kelvin Berryman (GNS, New Zealand). The workshop was spanned by a field visit to tectonic accretionary rocks analogous to those in SW Japan. The field visit examined mélange-style deformation in the Franciscan Formation, Quaternary and more recent coastal deformation associated with plate subduction, and also strike-slip deformation (locked, as well as creeping motion) associated with the San Andreas system. The mini-workshop considered the same issues as that held the previous month in the UK, but from the viewpoint of rock deformation. The main points that came out were:

- Evaluating long-term rock deformation will be a key issue for any conceivable repository site in Japan. Slow deformation/ folding, as well as faulting, has the potential to compromise the isolation capability of both engineered and natural barrier systems over the relevant time scale.
- It was suggested developing and adopting a ‘deformation index’ or ‘strain budget’ as a fundamental framework to integrate the wide array of information that can be used assess rock deformation. This includes aerial photography, trenching, geological mapping, GPS data, geodesy, multiple geophysical measurements, relevant natural analogues from other sites both within and outside of Japan, local historical and stakeholder information, etc.
- The ‘strain budget’ framework would help support NUMO's mission and decision-making at each stage of its step-wise siting process, starting with the literature-only survey of volunteer sites through the final ranking and selection of a candidate site. It would also serve as an important guide to NUMO when it must set up site characterization programs, providing a basis for (1) comparing different sources of

site-specific data on rock deformation from existing different techniques, (2) identifying additional site characterization data that may be obtained to help resolve any discrepancies, and finally (3) identifying credible alternative conceptual models for local, long-term rock deformation.

Based on the discussions at the two mini-workshops, the two groups ('volcanism' and 'rock deformation') went on to develop project outlines to provide NUMO with the first elements of an approach to be used in the first (PIA selection) stage of its siting work. As the outlines were prepared by small sub-sets of the regular ITM expert group, a key objective was to have these suggestions presented and discussed at the March 2004 main workshop so that a broader consensus could be reached on the best approach to each issue.

The main ITM-3 workshop was held in Tokyo from 15 – 16th March 2004 and was preceded by a field visit on 13th and 14th March to examine active faults in the Kobe area and rocks of the Cretaceous and Tertiary Shimanto Belt in Honshu. The two top-level topics that were considered at this meeting were:

- TOPIC 1: How to make best use of desk information during the pre-PIA definition stage (i.e. as volunteers come forward) to evaluate whether the areas would make suitable PIAs. This means using the data to evaluate the controls on the distribution of volcanic activity and on the nature of future rock deformation (fault and flexure behaviour).
- TOPIC 2: How to define a preliminary programme of fieldwork at the PIAs selected so as to improve the database on these issues, leading eventually to a decision on whether the areas would make suitable DIAs.

The two suggestions being developed as a result of the two mini-workshops were introduced for discussion in Working Group sessions within the full ITM group. The principal aspects of the proposals were outlined as comprising:

- **Rock Deformation:** Establishment of a probabilistic 'deformation index' or 'strain budget' as a fundamental framework to integrate the wide array of information that can be used assess rock deformation. This includes aerial photography, trenching, geological mapping, GPS data, geodesy, multiple geophysical measurements, relevant natural analogues from other sites both within and outside of Japan, local historical and stakeholder information, etc. This will help support NUMO's decision-making at each stage of its step-wise siting process, starting with the literature survey of volunteer sites through the final ranking and selection of a candidate site. It will also serve as an important guide to NUMO when it must set up site characterization programmes, providing a basis for (1) comparing different sources of site-specific data on rock deformation from existing different techniques, (2) identifying additional site characterisation data that may be obtained to help resolve any discrepancies, and finally (3) identifying credible alternative conceptual models for local, long-term rock deformation.

- **Volcanism:** Development and testing in parallel of (a) deterministic, (b) empirical, (c) probabilistic and (d) Bayesian methods of establishing likelihood of volcanic activity in an area over various future timeframes, using currently available tools and experience as a basis and the Sengan, Tohoku and Chokai-Kurikoma datasets as raw material. These activities would be tailored to provide NUMO with the scientific and technical support that they will need to develop methodologies for volcanic hazard assessment in the PIA stage that (1) provide a conservative – but not overly conservative – approach to volcanic hazard assessment, (2) start from a generic approach that will have wide support in the scientific and technical communities, (3) explain guidelines for assessment of volcanic hazards, (3) create consistency in the volcanic hazard assessment in the PIA stage and (4) easily transfer to the DIA stage if necessary.

The central section of the workshop looked into detail at the current state of understanding of the distribution of volcanoes and on approaches to active fault identification and GPS strain data evaluation.

NUMO was keen to see the results of the ITM programme published and made more widely available. Consequently, it was proposed that a topical article be prepared for EOS[5] (the American Geophysical Union weekly publication that attracts a huge readership in the earth science community). In addition, those involved in project work were urged to aim for publication in the peer-reviewed literature.

The two Working Groups reached consensus on how to proceed with the proposed projects. Each project would establish an Expert Group to provide scientific and technical input and to help guide the progress of the work. The concept of Case Study areas was retained. The key features of the proposed work was as follows:

- The volcanism project will test and compare a wide range of alternative approaches (within the general headings of probabilistic, empirical and deterministic) and apply them to the same dataset. By the use of ensemble modelling, numerous realisations of possible volcano distribution will be made and compared. This will provide an overall likelihood and degree of confidence for the Case Study area.
- For the Case Study area, the rock deformation group will develop a balanced, probabilistic strain budget model that accounts for all seismic, GPS, fault movement and uplift data and which can be constrained within the overall long-term tectonic (subduction) strain. The objective is to determine whether this approach can account for all the expected strain that has occurred within a region over a time period of hundreds of thousands of years and can thus be extrapolated forward in time.

ITM-3 made considerable advances over the two earlier workshops. It transitioned from being largely an information exchange meeting to being an active discussion group proposing solutions to NUMO’s requirements in its siting programme. In the following year, it was anticipated that ITM would have made the first steps in developing practical approaches that can be applied by NUMO.

2.4 The ITM project

By the end of these initial reviews and explorations, it was thus clear that a specific methodology would need to be developed that incorporated the best available techniques in tectonic hazard assessment worldwide and would be directly applicable to the Japanese environment and the specific issues faced by NUMO. Several possible techniques were already available at this time, but the techniques would need to be imported, further developed and then tested before actual deployment by NUMO.

Exploratory work to develop a specific **‘ITM Methodology’** began in 2004-5 and the first 18 months involved the transfer of existing approaches and technologies from the scientific organisations involved in ITM (from New Zealand, the UK and the USA) to NUMO and testing and consideration of their applicability to the siting programme.

2.4.1 ITM-4

A milestone workshop named *"Development of Strategies for Volcano Hazards Assessment"* was held at Tampa in Florida in January 2005. The main objective of the workshop was to review the progress of work on the Case Study. One of the problems encountered in early development of the methodology was the meaning of the "dots on the map" in the Catalogue of Quaternary Volcanoes of Japan (CQV). There were several ambiguities and inconsistencies in the CQV associated with definitions of age, interpretation of the amount of material and difference between "volcano" and "edifice" (e.g. edifices range from 0.045 to 633

---

[5] Subsequently published as: Apted, M., Berryman, K., Chapman, N., Cloos, M., Connor, C., Kitayama, K., Sparks, S. and Tsuchi, H. (2004) Locating a Radioactive Waste Repository in the Ring of Fire. *EOS, Transactions of the American Geophysical Union,* 85, No. 45, 465-471.

km^2). Some of these inconsistencies arise from lack of data, while some are probably different qualitative interpretations by the CQV producers. One of the main activities of the volcanology group in this period was evaluating the spatial distribution data for use in the probabilistic analysis. This involved a range of intensive activities including field 'ground truth' verification visits and, eventually, the development of a cladistic based approach to the classification of volcanic edifices. The other principal activity was the initial development of an approach to modelling statistical distributions of volcanoes and relating these to structural and geophysical information in the Case Study area. Codes were developed for doing this, using deterministic, empirical, probabilistic and Bayesian approaches and the first probability maps were produced. In parallel, initial progress was made on the use of random functions and random events modelling, using the Cox process modelling approach.

A second and equivalent milestone workshop entitled *"Development of a Deformation Index Map Methodology for Application to Siting Factors"* was held at Napier, New Zealand, also in January 2005. The rock deformation team was pursuing development of a probabilistic methodology for tectonic evaluation of sites, using a logic tree approach to capture uncertainties, which could be sampled using Monte Carlo analysis. Strain can be calculated using various parameters derived from different models. These models can be compared, incorporating as much expert opinion as possible to produce "community models". Strain models are integrated using logic trees that can accommodate all models and variants of individual models and then weight them. New or modified models can be incorporated as new information comes to hand. This is standard practice for NPP siting and PSHA. By the time of this workshop, considerable progress had been made on compiling and assessing the seismic, GPS and fault strain data for the Case Study area.

The ITM-4 meeting was held in Tokyo in March 2005 and was preceded by a field visit to examine monogenetic volcanoes in the Yamaguchi Prefecture. The ITM-4 meeting provided the opportunity, over a period of two days, for an intensive and lively discussion between the international team and Japanese experts and was the first time that definitive results of the methodology development had been presented to the Japanese geoscience community. By this stage, there had already been considerable progress in all areas. The impressive state of the scientific studies that had been presented at the workshop led to the proposal that a longer-term milestone should be the publication of a volume on tectonic hazard assessment at radioactive waste repository sites. In due course, this became one of the outstanding spin-offs of the ITM project, with the completion of a 700 page edited volume in mid-2008, scheduled for publication by Cambridge University Press in September 2009[6].

2.4.2 ITM-5

Work continued through 2005-6, focussed principally on the NE Japan (Tohoku) Case Study region. The volcanism work involved the production of a derivative database for hazards assessment, eliminating as far as possible ambiguities and inconsistencies and including the simple definitions of volcanoes proposed at ITM-4. This database was used to prepare a paper on the applications and potential for cladistic analysis to the classification of volcanoes which was submitted to, and subsequently published by, *Bulletin of Volcanology*[7].

Development continued of a series of alternative datasets on the spatial and temporal distribution of volcanoes for use to develop probabilistic hazards maps and assess the effects of the alternative interpretations and data depictions on the exclusion zones and distribution of probability. The datasets were presented and discussed at an interim volcanics workshop that was held in Oban, Scotland, in September 2005, to look into dynamical processes models to support the probabilistic studies. An associated field visit was made to examine volcanic structures and classical sites of magma intrusions modes on the Isle of Mull.

---

[6] Connor, C., Chapman, N. A. and Connor, L. (eds.) 2008, in press. *Volcanic and Tectonic Hazard Assessment for Nuclear Facilities.* Cambridge University Press.

[7] Hone, D. W. E., S. Mahony, R. S. J. Sparks and K. Martin (2007). Cladistics analysis applied to the classification of volcanoes. *Bulletin of Volcanology*, 70, 203−220.

In parallel, work continued to use empirical models based on geological data and models, applying probabilistic methods that rely on volcano distribution to assess hazards, and applying Bayesian methods that combine elements of the empirical and probabilistic approaches. Results from the Tohoku region strongly suggested that implementing these methodologies at the PIA scale would require a clear and defendable basis for expressing geological observations and models in a hazard framework. For example, how threshold values are established in empirical models; how geological models of structural controls on volcanic activity are translated into probability density functions. Specific activities included the continued analysis of available geophysical datasets (e.g., tomography, gravity, topography, geodetic) to develop a physical model for the relationship between these observations and generation of new volcanic activity. Inversion techniques have been developed to relate geophysical observations to the underlying properties of the mantle (density, percentage of partial melt, temperature) that give rise to the anomalies. The geophysical model was providing insight for assessment of the physical basis for clustering and longevity of clusters (governed by rates of heat and mass transfer in the asthenospheric wedge). The initial inversion results were presented at the American Geophysical Union (AGU) Fall Meeting, which was held in San Francisco in December 2005[8]. The statistical models of the distribution of volcanoes were further refined, along with the probability approach, which concentrated on using the refined dataset of volcano distribution to improve methods of estimating smoothing parameters used in these models. A systematic approach to estimating model uncertainty using Cox models with multivariate random potentials was also developed. These results were presented at the International High Level Radioactive Waste Meeting (May 2006, Las Vegas)[9].

The rock deformation methodology developed further to integrate the broad array of advanced earth science techniques and observations available in Japan, again applied to the Case Study region in northern Honshu, in coordination with the volcanic hazard group. An expert elicitation workshop on rock deformation interpretations of the northern Honshu study area was held in August 2005 in Tokyo. The objective was to use expert elicitation techniques to obtain opinions from the Japanese expert community to populate the Logic Trees being developed to address alternative conceptual models of rock deformation and associated uncertainties. The logic trees of three separate datasets (faulting, seismicity and GPS) were evaluated in successive half-day sessions. Each session began with a short introduction to the logic tree formulation for each dataset and was followed by group discussion on the data available and then on weightings for each of the nodes of the logic tree. The Japanese experts brought some database information within their field of expertise and engaged in the group discussions. Associated with this workshop, the international and Japanese experts visited the Ojika Peninsula to evaluate the rock formations and tectonic structures characteristic of this area.

The main strand of the rock deformation work involved the development of surface strain models for the Honshu case study area that can be presented as strain rate maps in a 5 km x 5 km grid base. A closely related activity was the development of a substantially updated active fault source model for the study area. The strain rate models produced by the different techniques could then be compared, with the eventual intent of deriving a single, composite measure of strain. All of this modelling was informed by the results of the data elicitation workshop. The results of the work were presented and discussed at an interim workshop that took place in New Zealand in December 2005. This workshop was associated with a short field visit to examine a major continental plate boundary fault and examples of flexural slip faulting in the South Island of New Zealand.

The ITM team worked with NUMO to finalise and present a paper for the ICEM ’05 meeting that was held in Glasgow, Scotland, in September 2005[10]. This was the first international

---

[8] Jaquet, O., Connor, C. and Connor, L. *Bayesian and Geostatistical Methodologies for the Long-term Estimation of Volcanic Hazard.*

[9] Jaquet, O., Connor, C. and Connor, L. Probabilistic Methodology for Long Term Assessment of Volcanic Hazards.

[10] Tsuchi, H., Kitayama, K. and Chapman, N. *Addressing Active Tectonics in HLW Repository Siting in Japan.*

meeting at which the total ITM approach and methodology had been exposed.

In 2006-7, ITM was converted from an information transfer to an R&D project to support the full methodology development work. Work continued throughout this year along the lines described above for 2005-6 and a second Case Study was added to the one that was already the focus of the work in this period. It was appreciated that the geological and tectonic situation of Kyushu and SW Honshu was considerably different to that of northern Honshu, where the Tohoku Case Study was located. The plate tectonic situation is more complex in the S and W of Japan and monogenetic, as opposed to polygenetic, volcanism is much more in evidence. Consequently, features such as the Quaternary volcanic front are less distinct in this region. Work thus began on this region, with the main focus on the large island of Kyushu itself.

The ITM-5 Meeting took place in Tokyo in July 2006 and was followed by a two day field visit to the Sengan area of Tohoku, whose objective was to allow 'ground truth' verification of some of the assumptions being made in the ITM technique development work, as this region forms the first 'Case Study' area. The two tectonic hazard evaluation methodology development projects that lie at its core had by now made sufficient progress that they were approaching a useable form. This meeting thus also provided an opportunity for the ITM members to begin to consider the key aspects of:

- integrating the two main project threads (probabilities of rock deformation and of volcanic events);
- linking the geological and statistical results to potential consequences of tectonic processes and events so as to determine what is safety-relevant and of importance in siting;
- defining how NUMO can begin to utilise the methodologies in the different stages of its siting programme.

The main vehicle for developing these aspects was to be an 'integration workshop' which was to take place shortly after the ITM-5 meeting (see below). The approaches had moved relatively quickly from a conceptual level to the point of practical realisation. As usual, the ITM-5 workshop was intended as a means of presenting progress in the ITM project to a wide range of Japanese tectonics experts and obtaining their feedback. As well as the ITM team members and NUMO staff, the workshop was attended by 22 Japanese experts in seismology, active fault geology, geodesy, volcanology and geodynamics. These experts came from eleven universities and research institutes, as well as from JAEA, TEPSCO, CRIEPI and RWMC.

The 'integration workshop' was held in September 2006 in Utah and had three technical objectives, shown below in order of priority, although each was considered important in its own right:

1. Volcano-tectonic interaction: discuss how to integrate the volcanic probability modelling with the strain probability maps by considering how strain is accommodated in the crust during magma intrusion in the arc environment;
2. Utilisation: prepare first outline advice on how NUMO can use (and present) the integrated probability maps at different scales and at different stages of their siting programme;
3. Consequences: brainstorm scenarios to place along one axis of a 'Consequences Matrix' that will relate potential styles of different tectonic events to sensitive features of the different repository concepts being considered by NUMO, thus allowing qualitative definition of impacts (i.e. from important to not relevant for safety);

The workshop was followed by a field visit to a number of type localities in Utah that illustrated in particular the style and mode of volcanic intrusions into the shallow crust, which was highly informative from the viewpoint of considering repository consequences. A short, follow-up workshop was held in February 2007 in Tampa, USA, to discuss the content and structure of the monogenetic volcano database catalogue being developed for Kyushu and to check that the information was in suitable format for analysis for the Kyushu Case Study.

2.4.3 ITM-6 and 7

By 2007-8 the Tohoku Case study was practically completed. The final report of the study was produced in draft form in March 2008 and finalised after editing by the end of the year. Work was well advanced on the Kyushu Case Study, with the project throwing up a range of new issues for the group to consider. The ITM methodology itself was, by this stage, sufficiently developed to require no further significant modifications to complete the case studies, although it was strongly emphasised that the methodology would need continued refinement before being used at actual sites by NUMO.

The 6th International Tectonic Meeting in Tokyo in February 2008 was held over a period of two days and involved 14 overseas experts from the ITM project, 24 Japanese national experts from Universities and research organisations, and 12 NUMO staff. It followed the pattern of previous meeting, being an opportunity to update national experts on the status of the project and obtain feedback and expert knowledge on specific issues that were being raised by members of the international team. With increased interest in the consequence aspect of the ITM project, there was an invited presentation by Harald Hökmark (Clay Technology, Sweden) on the work being carried out by SKB to evaluate post-glacial earthquake impacts on fracture displacement and their possible effect on a spent fuel repository in basement rocks.

By now, ITM had the basis of its methodology in place, but it was emphasised at the 6th meeting that the ITM methodology was not a simple ‘formula’ or an inflexible set of ‘instructions’ involving a linear series of steps that is applicable under all circumstances. The methodology has different avenues that can be taken in response to local conditions, so its application must be strongly conditioned by local knowledge, especially in complex regions. It was observed that, at the end of our project, the methodology would be complete, but not conclusive. In a subject area as dynamic and complex as tectonics, the methodology will need frequent updating and refinement. Inevitable new developments in our understanding of the tectonic mechanisms being studied are incorporated into the conceptual modelling of Steps 1 and 2 (see Section 3 for a description of the ITM Steps) and the strain model development of Step 3b. Additionally, new data from other Japanese scientific studies, as well as international developments in probabilistic hazard analysis, will need to be incorporated in NUMO’s database, right up to and through the DIA stage.

The final year of the ITM project involved principally the concluding work on the Kyushu Case study and additional refinement to the overall methodology. A central issue throughout the last three years of the work had been the need to integrate the results of both the rock deformation and the volcanism teams. Kyushu proved to be an ideal test-bed for doing this, owing to the evident strong structural controls on the temporal and spatial distribution of volcanism. A field visit to Kyushu in March 2008 provided an opportunity for both teams to examine these controls in detail. Strong links were made with local university and other research groups, with the project sponsoring one post-doctoral researcher to help provide data input to the Case Study. To conclude the integration work, a one-week integration workshop was held in Switzerland in November 2008, involving both teams.

The ITM methodology, as delivered, clearly provides information that feeds into the NUMO decision-making support system and the safety analysis work that will be undertaken in future. At the end of the project, which was completed in 2008-9, the results were presented to a wide Japanese audience (more than 120 participants, predominantly geoscientists) at the closing ITM-7 meeting in Tokyo in March 2009.

2.5 Disseminating the Project Results

Since the start of the ITM work and especially since the ITM Project began to develop a methodology for evaluating tectonic hazard, one of the aims of the work has been to keep a wide spectrum of the Japanese geosciences community informed about the concepts and progress in developing them. So far as possible, we have also tried to involve the community in regular discussions and several experts have had active participation in aspects of the project work itself.

Apart from the international project team and NUMO staff, the individuals identified in Table 2.1 have participated in the annual ITM workshops in Tokyo and we would like to thank them all for their interest, challenging questions and contributions to discussion, which have all helped to focus and improve the project and keep the team better informed.

As well as the final Case Study reports and numerous internal annual reports, the ITM project has resulted in the publication of 22 papers and articles in the scientific literature, as well as one book. These are shown in Table 2.2. Further publications are expected after the end of the project.

Table 2.1: Participants in the annual ITM workshops in Tokyo (excluding ITM international team and NUMO staff).

ITM-1	Daiei Inoue, CRIEPI, Japan Kazuhiro Tanaka, Yamaguchi University, Japan Akira Tokuyama, Fuji-Tokuha University, Japan Shizuo Yoshida, TEPSCO, Japan	Teruyoshi Hatano, CRIEPI, Japan Motoi Kawanishi, CRIEPI, Japan Kazuhiko Shimizu, JNC, Japan Kenji Terada, TEPCO, Japan
ITM-2	Dr Daiei Inoue, CRIEPI Professor Hiroki Kamata, Kyoto University Dr Andrew Martin, JNC Mr Noriyuki Saito, TEPCO Mr Kazuhiko Shimizu, JNC	Dr Shiro Tamanyu, Geological Survey of Japan Mr Kenji Terada, TEPCO Dr Akira Tokuyama, Fuji Tokoha University Dr Shizuo Yoshida, TEPSCO Dr Bill Arnold, Sandia Laboratories, USA
ITM-3	Professor Manabu Hashimoto, Kyoto University Dr Daiei Inoue, CRIEPI Professor Hiroki Kamata, Kyoto University Mr Toshihiro Kayama, TEPSCO Mr Hirofumi Kondo, CRIEPI Dr Andrew Martin, JNC Professor Yujiro Ogawa, Tsukuba University Mr Fumikiko Ono, TEPCO	Mr Toshihiro Seo, JNC Mr Kazuhiko Shimizu, JNC Dr Shiro Tamanyu, AIST Dr Yoshihiko Tamura, JAMSTEC-IFREE Mr Kenji Terada, TEPCO Dr Akira Tokuyama, Fuji Tokoha University Dr Shizuo Yoshida, TEPSCO
ITM-4	Mr Koichi Asamori, JNC Professor Manabu Hashimoto, Kyoto University Mr Ryuta Hataya, CRIEPI Professor Shintaro Hayashi, Akita University Professor Naoshi Hirata, University of Tokyo Dr Daiei Inoue, CRIEPI Professor Hiroki Kamata, Kyoto University Dr Motoi Kawanishi, CRIEPI Dr Hurohumi Kondo, CRIEPI Dr Hiroyuki Koyama, TEPSCO Dr Kin-ichiro Kusunose, AIST Dr Andrew Martin, Quintessa Japan Professor Yoko Ota, Yokohama City University	Professor Takashi Nakata, Hiroshima Inst. Technol. Dr Noriyuki Saito, TEPCO Professor Kunihiko Shimazaki, University of Tokyo Dr Kazuhiro Shimizu, JNC Professor Shizuo Yoshida, TEPSCO Dr Shiro Tamanyu, AIST Dr Yoshihiko Tamura, JAMSTEC Mr Kenji Terada, RWMC Professor Akira Tokuyama, Fuji Tokoha University Mr Koji Umeda, JNC Dr Minoru Yamakawa, AESTO Professor Hidekazu Yoshida, Nagoya Univ. Museum Professor Yasuhisa Yusa, Fuji Tokoha University
ITM-5	Professor Akira Tokuyama, Fuji Tokoha University Professor Shizuo Yoshida, TEPSCO Dr Kazuhiko Shimizu, JAEA Mr Kenji Terada, RWMC Dr Daiei Inoue, CRIEPI Professor Takashi Nakata, Hiroshima Inst. Technol. Professor Yoko Ota, Yokohama City University Dr Yuichi Sugiyama, AIST Professor Satoshi Miura, Tohoku University Professor Kunihiko Shimazaki , University of Tokyo Professor Naoshi Hirata, University of Tokyo	Dr Takuya Nushimura, GSI Dr Tsuyoshi Nohara, JAEA Mr Keiichi Ueta, CRIEPI Professor Hiroki Kamata, Kyoto University Professor Takehiro Koyaguchi, University of Tokyo Professor Shintaro Hayashi, Akita University Dr Yoshihiko Tamura, JAMSTEC Dr Hirofumi Kondo, CRIEPI Dr Koji Umeda, JAEA Dr Makoto Murakami, GSI Dr Takashi Sano, National Science Museum
ITM-6	Professor Akira Tokuyama, Fuji Tokoha University Professor Shizuo Yoshida, TEPSCO Dr Kazuhiko Shimizu, JAEA Mr Kenji Terada, RWMC Professor Hidekazu Yoshida, Nagoya Univ. Museum Mr Toshihiro Seo, JAEA Dr Daiei Inoue, CRIEPI Professor Takashi Nakata, Hiroshima Institute of Technology Professor Yoko Ota, Yokohama City University Professor Satoshi Miura, Tohoku University	Professor Naoshi Hirata, University of Tokyo Dr Takuya Nishimura, GSI Dr Tsuyoshi Nohara, JAEA Mr Keiichi Ueta, CRIEPI Mr Ryuta Hataya, CRIEPI Professor Setsuya Nakada, University of Tokyo Professor Dapeng Zhao, Tohoku University Professor Toshiaki Hasenaka, Kumamoto University Dr Hirofumi Kondo, CRIEPI Dr Takahiro Yamamoto, JNES Dr Makoto Murakami, GSI

Table 2.2: Books, papers and articles on the ITM project methodology and results, published by the ITM team during the course of the project.

2004	Apted, M., Berryman, K., Chapman, N., Cloos, M., Connor, C., Kitayama, K., Sparks, S. and Tsuchi, H. Locating a Radioactive Waste Repository in the Ring of Fire. *EOS, Transactions of the American Geophysical Union,* **85**, No. 45, 465-471.
2005	Jaquet O., Connor, C.B. & Connor L. Bayesian and geostatistical methodologies for the long term estimation of volcanic hazards, AGU Fall Meeting, San Francisco, California.
2005	Tsuchi, H., Kitayama, K. and Chapman, N.A. Addressing active tectonics in HLW repository siting in Japan. In Proceedings ICEM'05: 10th International Conference on Environmental Remediation and Radioactive Waste Management, Glasgow.
2006	Jaquet O., Connor, C.B. & Connor L. Probabilistic methodology for long term assessment of volcanic hazards. In: Proceedings International High-Level Radioactive Waste Management Conference, Las Vegas, Nevada, pp.154-161. American Nuclear Society.
2007	Hone, D. W. E., S. Mahony, R. S. J. Sparks and K. Martin. Cladistics analysis applied to the classification of volcanoes. *Bulletin of Volcanology*, **70**, 203−220.
2007	Chapman, N. A., J. Goto & H. Tsuchi. Likelihood of Tectonic Activity Affecting the Geological Stability of a Repository in Japan: Development of NUMO's ITM Methodology. OECD Nuclear Energy Agency: NEA Geosphere Stability in Crystalline Rock; Manchester, UK
2008	Jaquet O., Lantuéjoul C. & Goto J. Estimation of long-term volcanic hazard using a Cox process with a multivariate potential. VIII International Geostatistics Congress, GEOSTATS 2008, Santiago Chile, 167-176.
2008	Tsuchi, H., Goto, J., Chapman, N. and Kawamura, H. Tectonic Hazard and the Siting of Japan's HLW Repository: Preliminary Results of the Tohoku Case Study in the ITM Project. In: Proceedings IHLRWM, Las Vegas, 2008. American Nuclear Society.
2008	Jaquet, O., Connor, C. and Connor, L. Probabilistic Methodology for Long-Term Assessment of Volcanic Hazards. *Nuclear Technology*, **163 (1)**, 180-189
2008	Goto, J., Tsuchi, H., Chapman, N. and Kawamura, H. Siting Japan's HLW Repository 2: Addressing the Tectonic Issues in a Probabilistic Approach. In: Proceedings: International Geological Congress, Oslo.
2009	Wallace, L. M., Ellis, S., Miyao, K., Miura, S., Beaven, J. and Goto, J. An enigmatic, highly active left-lateral shear zone in southwest Japan explained by aseismic ridge collision. Geology, 37, 143-146.
2009	Connor, C., Chapman, N. A. and Connor, L. (eds.). Volcanic and Tectonic Hazard Assessment for Nuclear Facilities. *Cambridge University Press*
2009	Jaquet, O., and C. Lantuéjoul, Cox process models for the estimation of long-term volcanic hazard. In: C. B. Connor, N. A. Chapman, and L. J. Connor (eds.), Volcanic and Tectonic Hazard Assessment for Nuclear Facilities, Cambridge University Press, in press.
2009	Connor, C.B., and L. J. Connor, Estimating spatial density with kernel methods. In: C. B. Connor, N. A. Chapman, and L. J. Connor (eds.), Volcanic and Tectonic Hazard Assessment for Nuclear Facilities, Cambridge University Press, in press.
2009	Mahony, S. H. , R. S. J. Sparks, L. J. Connor and C. B. Connor, Exploring long-term hazards using a Quaternary volcano database. In: C. B. Connor, N. A. Chapman, and L. J. Connor (eds.), Volcanic and Tectonic Hazard Assessment for Nuclear Facilities, Cambridge University Press, in press.
2009	Connors, C., Sparks, R.S.J., Diez, M., Volentik, A.C.M.. The Nature of Volcanism. In Connor, C.B., Chapman, N and Connor L.J. (eds), Volcanism, tectonism and the siting of nuclear facilities. Cambridge University Press, Chapter 3, 86-129, 2009.
2009	Mahony, S., Sparks, R.S.J., Connor, C. and Connor, L. Assessing long-term volcanic hazards using volcano distribution databases. In Connor, C.B., Chapman, N and Connor L.J. (eds), Volcanism, tectonism and the siting of nuclear facilities. Cambridge University Press Chapter 13, 364-386, 2009.
2009	Litchfield, N., Y. Ota, D. Merritts. Tectonic uplift and subsidence. In Connor, C.B., Chapman, N and Connor L.J. (eds), Volcanism, tectonism and the siting of nuclear facilities. Cambridge University Press
2009	Wallace, L. M., J. Beavan, S. Miura, R. McCaffrey. Using global positioning system data to assess tectonic Hazards. In Connor, C.B., Chapman, N and Connor L.J. (eds), Volcanism, tectonism and the siting of nuclear facilities. Cambridge University Press
2009	Stirling, M., K. Berryman, L. Wallace, N. Litchfield, J. Beavan, W. Smith. Multidisciplinary probabilistic tectonic hazard analysis. In Connor, C.B., Chapman, N and Connor L.J. (eds), Volcanism, tectonism and the siting of nuclear facilities. Cambridge University Press
2009	Chapman, N. A., H. Tsuchi, K. Kitayama. Tectonic events and nuclear facilities. In Connor, C.B., Chapman, N and Connor L.J. (eds), Volcanism, tectonism and the siting of nuclear facilities. Cambridge University Press
2009	Kiyosugi, K., C. B. Connor, D. Zhao, L. J. Connor, K. Tanaka, Relationships between temporal-spatial distribution of monogenetic volcanoes, crustal structure, and mantle velocity anomalies: An example from the Abu Monogenetic Volcano Group, Southwest Japan, *Bulletin of Volcanology*, in review.

3 The ITM Methodology Road Map

This Section provides an outline of the overall concept and methodology that has been developed by ITM in the form of a ‘road map’. The methodology development is essentially complete and this road map represents a description and checklist for application to volunteer sites by NUMO staff and contractors in Siting Stages 1 and 2.

As discussed in Section 1, the methodology should be regarded as a living entity, as it must respond to new scientific knowledge and techniques that will arise over the next few years. Consequently, it will have to be revisited from time to time. This is especially true with respect to application in Siting Stage 3 (at the point where PIAs are being evaluated and compared in order to select a preferred site, or sites, for detailed investigation as DIAs), as this may be five or more years into the future.

3.1 Outline of the ITM Methodology

The overall structure of the ITM methodology consists of:

- assembling nationally available data and alternative models of the nature, causes and locations of tectonic processes and events;

- using probabilistic techniques to evaluate the likelihood and scale of future tectonic processes and events, shown as a function of their type and geographical distribution;

- feeding information on these potential likelihoods and impacts to NUMO’s performance assessment team so that feedback can be provided on repository performance under tectonic stress;

- providing clearly justified and traceable input to decision-making on consequent site suitability.

A **probabilistic** approach has been selected for the ITM methodology as it is seen as the only realistic means of addressing the uncertainties in predicting possible hazards when there is such variability in the spatial distribution, the timing, the intensity and the style of the volcanic and deformational events and processes being evaluated.

Naturally, the probabilistic approach being developed is based upon and strongly supported by **deterministic** models of the underlying tectonic processes that lead to magma intrusion, volcanism and rock deformation.

For convenience, the methodology for rock deformation and volcanic hazards assessment has been applied as two parallel tasks. This recognises the fact that, although the concept of each approach as shown above is similar, in some parts of the methodology they differ significantly in detail. Consequently, it was found that two teams with different specialities (structural, geophysics and tectonics specialists; volcanologists) worked efficiently in parallel. However, it is **most important** that, if carried out in this way in the future, the two teams integrate their work frequently, as there are clear overlaps in the processes being evaluated (e.g. magma intrusion impacts on rock stress regimes and vice versa). NUMO will need to ensure that such integration is carried out effectively when the methodology is applied to ‘real’ sites.

The broad structure presented above is shown in more detail in the top-level ‘road-map’ in Figure 3.1. It comprises a series of eight **Steps**, which are described in Section 3, distinguishing between the ‘rock deformation’ approach and the ‘volcanic’ approach, where they involve significantly different activities.

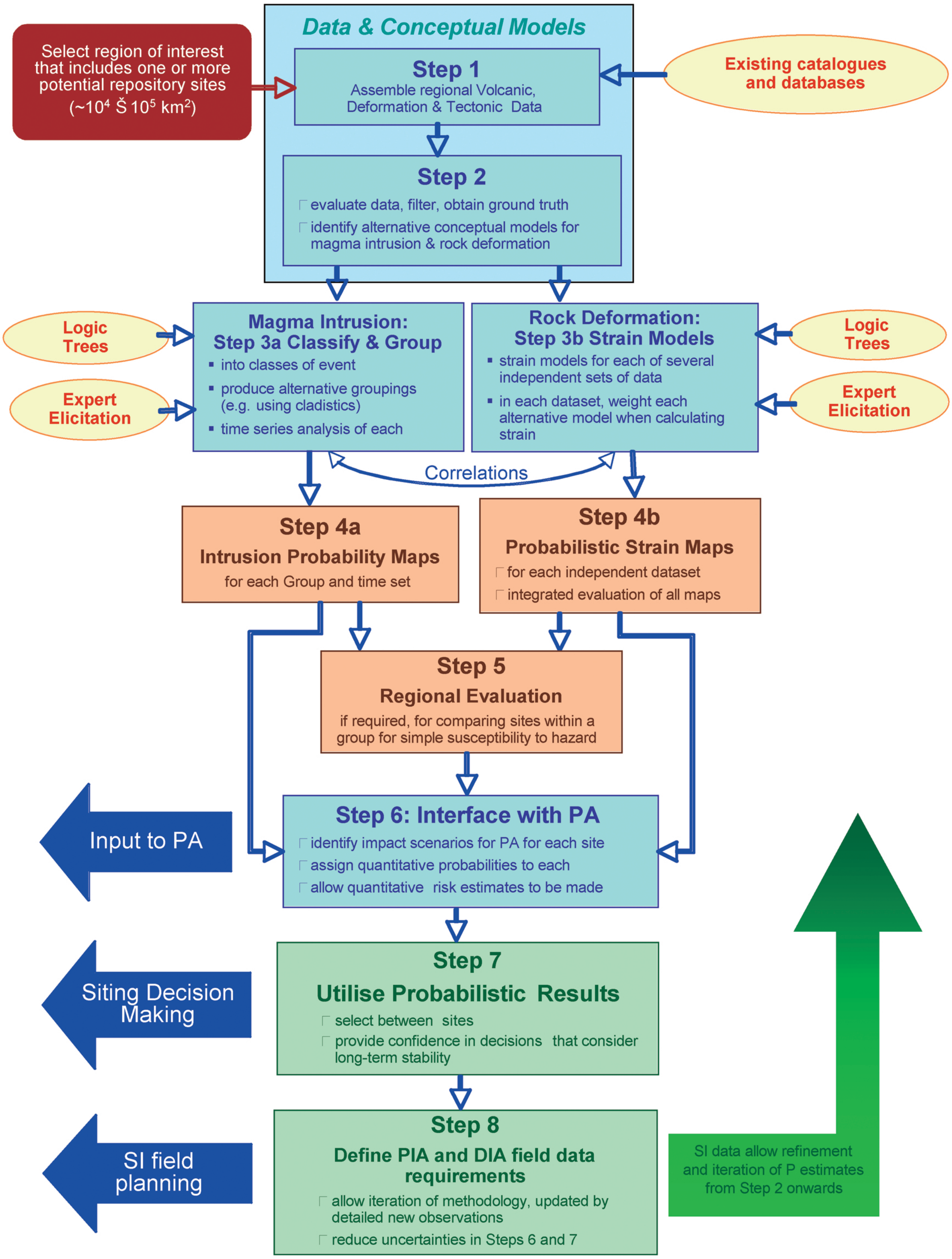


Figure 3.1: The Steps in the ITM methodology, shown as a top-level road-map.

There is considerable depth and detail to the application of the ITM methodology in each of the Steps. This road-map description is intended to provide a simplified overview. The complete detail of what is involved in each analysis is described in the two project Case Study reports.

3.2 The Steps in the ITM Methodology

STEP 1: Assembling the Data

Step 1.1: Define the region of interest: The region of interest should be defined. For deployment of the ITM methodology in **Siting Stage 1** (the LS stage), we expect that the region of interest identified around a site, or group of nearby sites, will be ~10^4 - 10^5 km^2. The larger area is more appropriate when comparing the situation of several siting options. This is based upon our experience in the Case Study areas. Regions need to be large enough both to contain a statistically large enough number of features that are manifestations of the processes being evaluated (e.g. volcanic edifices) and to contain a good spread of data-points for modelling these processes (e.g. GPS stations). They should also be internally consistent, at a rough approximation, with respect to tectonic regime. For example, in the Kyushu Case Study, it was found that the large overall region considered (approximately 100,000 km^2) had to be broken down into several intermediate blocks representing tectonically 'coherent domains', ranging in size from c. 20,000 to c. 50,000 km^2. A region of 10^4 km^2 is at the lowest end of the size range that is likely to be useable and the aim should be to have a region of at least some tens of thousands of square kilometres to ensure that the statistical approach adopted is meaningful.

For deployment at a single site scale (Stage 3: not considered in depth in the ITM project), the methodology is likely to require downscaling to 10^4 km^2 or perhaps 10^3 km^2, the scale depending upon the complexity of the tectonic setting. This has not been done in the Case Studies and would require further test application and probably some modification of the methodology. The regional scale deployment of the methodology described below is based upon estimating probabilities within 5 x 5 km areas. For site scale deployment, a finer grid will be required.

Step 1.2: Data gathering: Following definition of the region of interest, relevant data are obtained from the literature to constrain possible models of magma intrusion and rock deformation. The principal source data at Siting Stage 1 are likely to comprise a limited number of national databases, including the following:

- geological maps;
- uplift and subsidence data;
- topographic maps (onshore and offshore);
- gravity and magnetic maps;
- volcanic edifices/features location, nature and age (Catalogue of Quaternary Volcanoes);
- national onshore and offshore active fault map;
- recorded distribution of seismic events (locations, magnitudes, depths);
- velocity field measurements derived from GPS for all monitoring stations.

Additional geological and geophysical information, such as geological maps, heat flow data and interpretations of the geological, structural and tectonic histories of the region, are needed to support the development of conceptual models of the processes of interest (in **Step 3**). There may also be relevant scientific publications on specific volcanoes or tectonic features, and more generic research publications on relevant processes. This additional information should be augmented by discussions with academic and other research organisations in Japan. Such discussions will be an extremely important part of ensuring both the currency of the models used and the involvement of the national (and international) geosciences community.

When the methodology is applied later in the siting programme, for example, to evaluate tectonic hazard in more detail at a site already identified as a PIA, the integration of LS data from existing catalogues and databases with site investigation data gathered both in the PIA area and in the area of interest around it, will be an important activity. This will need to be done carefully and consistently, because the probabilistic evaluations may be being used at this stage to support quantitative estimates of radiological impacts.

STEP 2: Sorting the Data and Identifying Alternative Conceptual Models

Step 2.1: Data Sifting and Ground-truth: The data need to be evaluated and sifted. The databases used have not been gathered for the specific purposes of the ITM methodology, so they are not necessarily organised in an appropriate fashion and they may not contain data in the form in which they will be used in **Steps 3 and 4**. The data also need to be evaluated for reliability and consistency. In cases where inconsistent or anomalous data are identified, this needs to be taken into account in the assessment of uncertainty. Such issues have been found to be the case for the Catalogue of Quaternary Volcanoes, where mapped volcanic features include a wide range of different structures with differing significance in terms of processes of magma generation and intrusion. Consequently, this Step requires a close evaluation of what the data actually represent and whether datasets are internally consistent and of uniform quality. It may be necessary to develop derivative datasets that reduce or remove anomalies and inconsistencies, but it is important that such changes are transparent and carefully documented.

It will be essential to obtain ‘ground truth’ on observations included in some of the databases (but not all: e.g. GPS strain data). For the highest level of confidence in the statistical methods used in **Step 4**, ‘ground truthing’ is likely to involve a significant effort in a minimal resurveying of the region of interest (e.g. visits to all volcanic structures to ensure that their correct classification is known). NUMO needs to take this into account in its planning: even though field visits to prospective PIAs may be excluded at Siting Stage 1 (LS), regional observations by specialists (even ‘drive-by’ observations) would likely be most valuable.

An equivalent example for the rock deformation datasets is the requirement to remove the large-scale, elastic subduction-related interseismic overprint from the GPS velocity field. Only the residual strain is considered to be the ‘signal’ of interest, as it is related to faulting in the crustal rocks of the Japanese islands. It is therefore of use in developing maps that show differential strain for ‘cells’ across the region of interest that can be linked to localised rock deformation processes. The ITM methodology uses 5 x 5 km cells, as these 25 km^2 blocks represent a representative area to contain a repository that is likely to have an approximate footprint of 10 km^2, plus space around its margins, where there may be additional access works, for example. Clearly, other sizes of cell could be used in an analysis.

Step 2.2: Underlying Conceptual Models: Underlying conceptual geological models need to be identified (or developed) to explain the distribution of features (volcanic edifices) and different styles of rock deformation. These conceptual models have been developed during the ITM work to date. In simple terms, the models are as follows:

- **Distribution of polygenetic volcanoes:** during the Quaternary, and for the next tens of thousands of years (up to ~100 ka) this is controlled by variable magma generation potential in the mantle and crust overlying the subducting oceanic plates. The origin of this variability is not fully understood but is manifest in some structure to the distribution of these volcanoes; for example, ‘clusters’ of volcanoes with intervening ‘gaps’ in some areas. The distribution of clusters and gaps is correlated to varying extents to gravity, basement topography and the seismic tomographic structure of the crust and mantle wedge beneath the Japanese archipelago. There is also evidence for temporal variations in volcanism that need to be taken into account in the assessment of future volcanism, which is also not fully understood.

- **Distribution of monogenetic volcanoes:** this aspect of the ITM methodology was developed and tested in the Kyushu Case Study. One possibility is that locations of monogenetic volcanoes are influenced by local stress variations related to structure. A volume-predictable model appears to work best, and we have developed a model to suggest that in compressional tectonic settings with constant magma supply, monogenetic volcanism should be generally volume-predictable. In other words, the exact timing of future eruptions is uncertain, but in a given time interval a given volume of magma should erupt.

- **Regional and Local Strain Budgets:** the upper crustal rocks of the Japanese archipelago are undergoing progressive deformation as a result of horizontal and vertical strain responses to dynamic plate tectonic forces. The amount and style of deformation varies from region to region depending on the geological formations present and the location with respect to the major plate boundaries and other large-scale deformation zone features, such as major (>100 km long) strike-slip fault zones (including the distance from such boundaries/features). The deformation can vary from compression to extension and subsidence to uplift. The resultant strain is manifest as faulting (episodic movement along Quaternary active faults), folding and distributed deformation. The overall strain 'budget' for an area is accessible using a range of indicators, each of which characterises different strain manifestations: GPS data on relative surface movements; coseismic movements, accessible through the seismological database and surface uplift/subsidence rate (which can be combined with other indicators to give an estimate of surface deformation, or 'tilt').

There are also more local controls on strain and stress related to geological and structural heterogeneities. There may be local feedbacks between faulting, deeper ductile deformation and magmatism that results in local departures from regional variations related to plate scale processes.

Following Step 2, the volcanic and rock deformation analyses take separate paths, defined here as **Steps 3a to 4a** for the magma intrusion analysis and **Steps 3b to 4b** for the rock deformation analysis.

It is expected that there would be some feedback to Step 2 from Step 3b. There will be a requirement to update the conceptual models after strain rates are estimated. Feedback between modelling and data are an important aspect of ensuring that alternative models are not overlooked.

STEP 3a: Classifying and Grouping Magma Intrusion Features

For the evaluation of possible future magma intrusion in areas that have not been affected by intrusion in the last ~2 Ma, it is first essential to classify the indicators of past intrusion (starting with the mapped volcanic features in the Quaternary catalogue).

Depending on the area being considered, different means of classification may be reasonable and the first step is to carry out a **'classification analysis of events'** to determine how best to group the intrusion indicators. No internationally accepted scheme of volcano classification exists, so the ITM methodology developed a cladistic approach for the Tohoku Case Study (Chapman et al., 2009) as well as exploring alternative ways of defining volcanic events. In the Kyushu Case Study, where the tectonic environment and styles of intrusion were more complex, classification needed to consider groupings of intrusions based on geochemical affinities of magmas and correlations with tectonic structures that control the spatial occurrence of some groups of intrusion. In this case, there is an even stronger need to ensure that volcanic assessment is integrated with the rock deformation and tectonic structural assessment.

Step 3a.1: Classification Analysis:

Several approaches are possible to assign intrusion events to genetically related groups that can be treated in a consistent manner statistically (i.e. 'event definition'). The use of expert elicitation will greatly improve confidence in the classification schemes developed and, although the method was not trialled during the ITM project, logic trees represent a well-established approach to depicting the results of expert elicitation.

A cladistic approach has been developed to facilitate this classification, which is based on standard taxonomic approaches used for species classification in the biological sciences and for which analysis software is readily available. The methodology is described more fully in an ITM project publication (Hone et al., 2007). In simple terms, it involves defining characteristic properties (such as size, morphology, age, chemical composition, intrusive or eruption style) to each mapped feature and then using a software analysis package (PAUP) to assess all possible ways of grouping the features using these characteristics. The simplest possible groupings that explain the most characteristics are selected (the parsimony principle, or Ockham's razor). The different groups are called clades, although we use the term 'Alternative Groups' for simplicity and because techniques other than cladistic analysis can be used to form alternative groups. In the Tohoku Case Study, the cladistic method was found to work well for the polygenetic volcanoes and to provide a deeper understanding of the strengths and limitations of the volcano database.

Step 3a.2. Database analysis. The database of volcanic features is then analysed to identify alternative data bases, which can be used in the probabilistic analysis. This step involves using the clade groups and field data to verify alternative groupings of volcanoes and volcanic features.

Step 3a.3: Time-series analysis: It is then necessary to carry out a time series analysis of each alternative database to assess whether they display different periodicity (dormancy and activity) and whether this periodicity is structured (i.e. related to eruption history, rather than being random), which is used in **Step 4a**.

Step 3a.4: Sensitivity analysis: It is also important to test the sensitivity of the groupings to the size of the region considered (by extending or reducing the area the number of edifices included is increased or reduced and the statistical groupings may change) and by adding new 'synthetic' volcanoes: a large change in group characteristics could indicate instability in any model invoked to explain the distribution of volcanoes.

The sub-steps in Step 3a can thus be represented as shown in Figure 3.2**.**

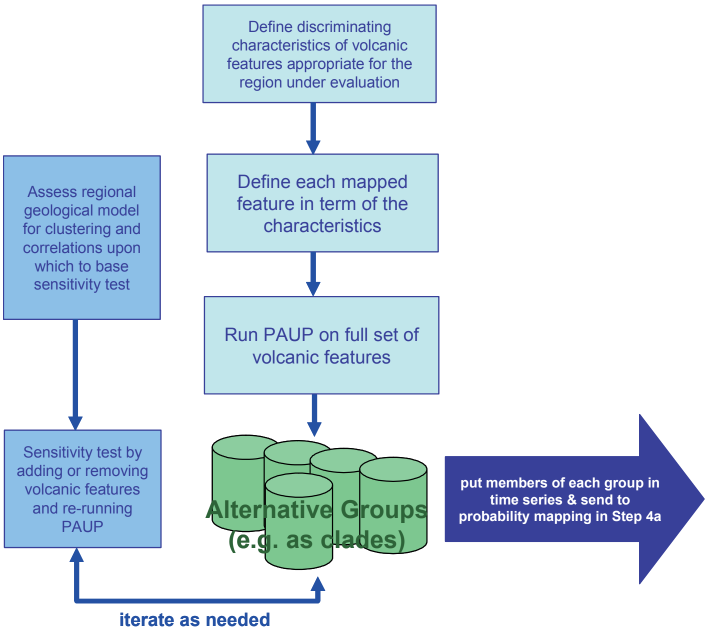


Figure 3.2: Flowchart showing sub-steps used in Step 3a.

STEP 3b: Developing Strain Models and Estimating Strain Rates for Each

For rock deformation, the objective is to calculate strain rates across the region of interest using independent data sources that reflect widely different time averaging: GPS derived strain (years), surface deformation (tens of thousands of years) and seismic strains from the seismic moment of earthquakes (centuries). These can then be compared. In **Step 4b** these are presented as strain maps.

Each data source may indicate strains that are the result of one or more processes, for each of which there may be alternative tectonic models and interpretations (e.g. boundaries of regions that can be defined as discrete tectonic blocks, dips of major fault zones, amount, degree and depth of subduction coupling). The way that strain is calculated from the raw data will need to account for the relative contributions of these different processes, factoring in the inherent uncertainty introduced by having alternative conceptual models. The contribution from different processes will thus have to be estimated by expert judgement, depending on the degree of belief in the importance of different processes/mechanisms (essentially, reflecting the alternative conceptualisations of what is driving rock deformation in the region).

Step 3b.1: Defining tectonic blocks: A first sub-step in Step 3b is to consider whether the region of interest (or an even larger area if appropriate) can conveniently be divided into stable rock blocks that behave internally in a relatively homogeneous way or respond in a similar way to external, large scale tectonic driving processes. This assessment forms the basis for the subsequent development of strain models, and there may be alternative ways of defining such blocks, which affects the number of models developed.

Step 3b.2: Assembling alternative conceptual models in a Logic Tree: The approach adopted in the ITM methodology is to use Logic Trees to bring together all alternative conceptual models identified; an example of which is shown in Figure 3.3.

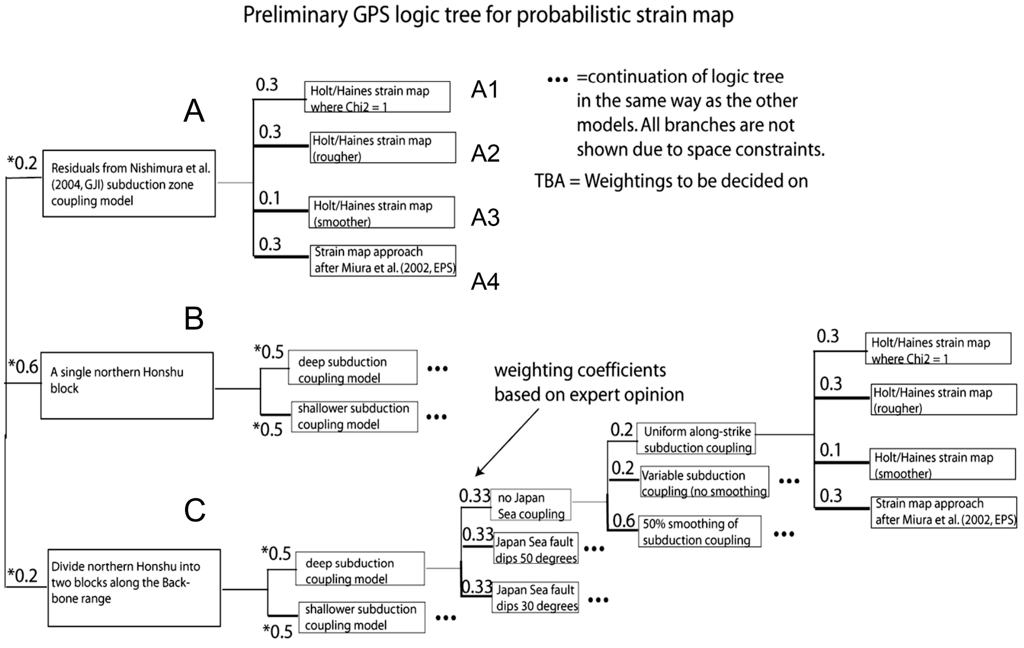


Figure 3.3: Example of part of a Logic Tree used in Step 3b to calculate strains from GPS data for the Tohoku Case Study area (Chapman et al., 2009).

As can be seen in Figure 3.3, the Logic Tree is constructed by asking questions of the form:

- How many alternative explanations (models) could describe strain in this block?': the answer requires a certain number of starting nodes to be established in the tree (A, B, and C in Figure 3.3).

- If Model A is correct, what are the alternative ways of describing its impact on deformation?': the answer produces branches from the node for Model A (A1, A2, A3 and A4 in Figure 3.3).

Continuing in this fashion a tree is generated that incorporates as many alternative conceptualisations of deformation mechanisms and associated uncertainties as are deemed feasible. Following down any one branch to the end defines how strain will need to be calculated for that particular set of model assumptions.

Use of expert judgement: Expert judgement, elicited from a group of experts in Japanese tectonics at a workshop, is factored into the construction of the tree to ensure that it is sufficiently comprehensive of alternative models. The experts then contribute by agreeing weightings for each branch (expressing their degree of belief in the validity of each alternative conceptualisation).

Each strain indicator requires its own logic tree, in order to calculate strain rates. In summary, the three indicators used to date to estimate strain as follows:

- Surface deformation and active faults = mm/km/a strain. The period over which this indicator has 'recorded' strain is ~10,000s years.
- Gradients in GPS velocity = mm/km/a strain. The period over which this indicator has 'recorded' strain is ~10s years.
- Recorded earthquakes = seismic moment + Kostrov equation[11] = strain. The period over which this indicator has 'recorded' strain is ~100s years.

Despite the fact that these indicators record strain over many orders of magnitude of time, the processes that they are recording are widely considered to have been stable in magnitude and direction for about 100,000 years.

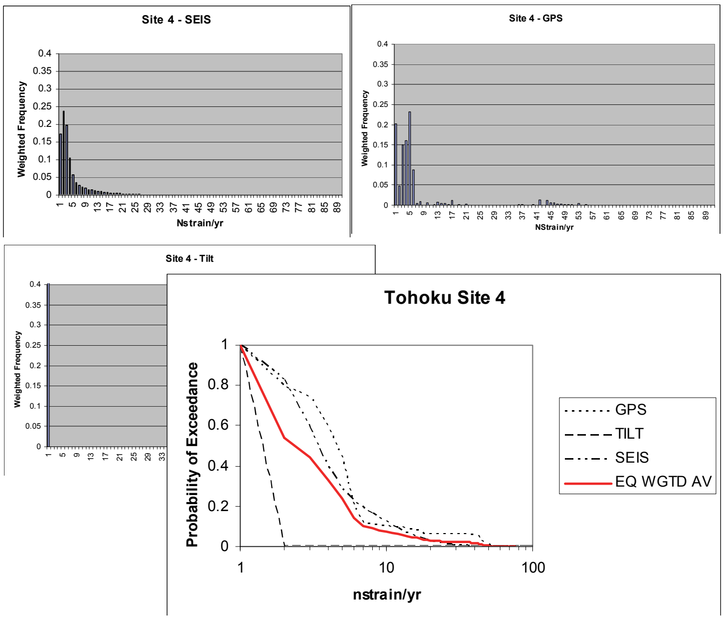


Figure 3.4: Strain rate (nanostrains/a) histograms for multiple model realisations for one of the 'example locations' in the Tohoku Case Study area, calculated (clockwise, from top left) from seismic data, GPS residuals and tilt data. The larger diagram shows the results compiled on a cumulative probability plot, showing the probability of exceeding any given value of strain. The red line is the equally weighted average.

---

[11] The Kostrov equation relates the seismic strain rate to the sum of the seismic moment tensors of all the earthquakes occurring in a given volume of the crust during a given time-interval.

Step 3b.3: Calculating Strain Rates: For the GPS logic tree example shown in Figure 3.3, there were 148 different strain models (branches) for the Tohoku Case Study. The strain rates for each of these models are calculated separately and as a weighted average. A histogram can be produced of the frequency of calculated strains of a given magnitude at a given location, using all the model results for a particular indicator, which can then combined with the same results from the other indicators (see Figure 3.4). The Step 3b sub-steps in setting up and using the logic trees are outlined in Figure 3.5.

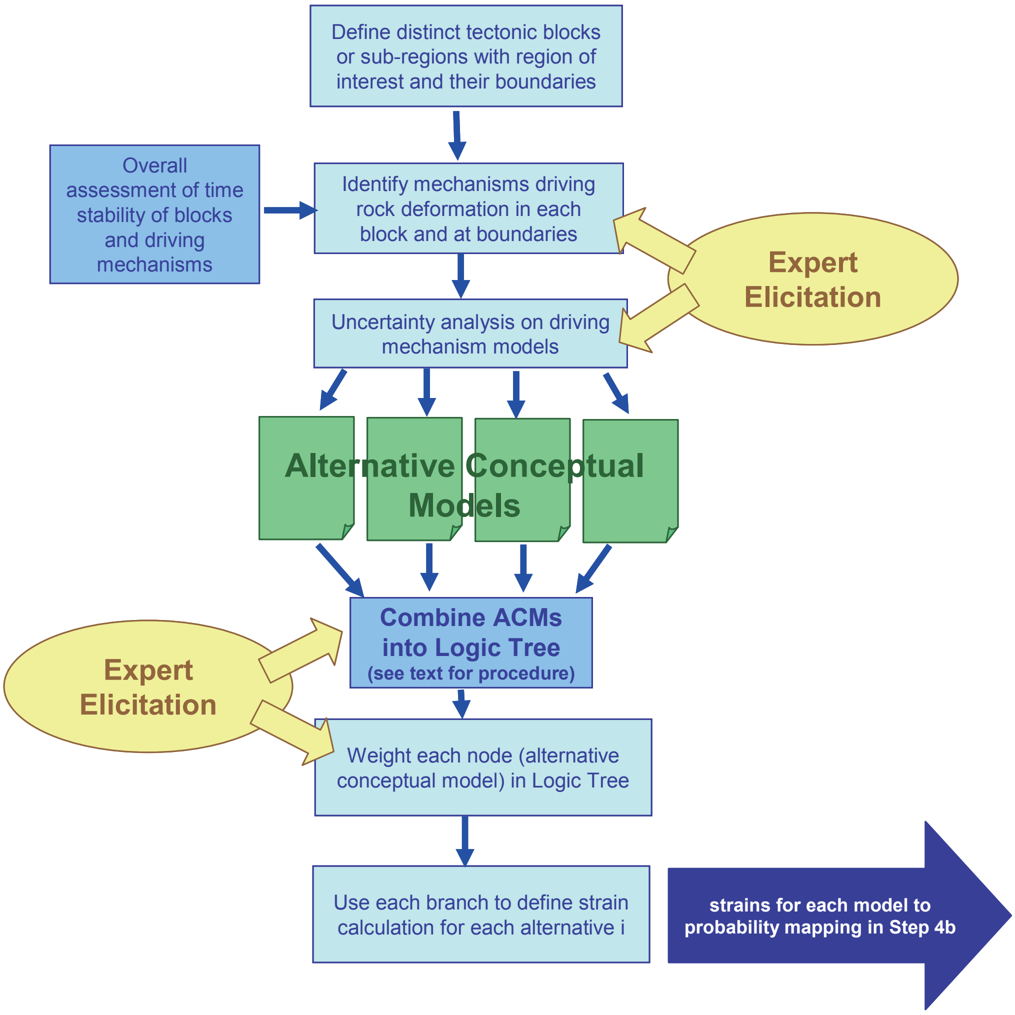


Figure 3.5: Flowchart showing sub-steps used in Step 3b.

STEP 4a: Magma Intrusion Probability Maps

Step 4a.1: Assessing Correlations: The first step in producing probability maps is to see how far the spatial distribution of volcanoes can be correlated with topographical and geophysical indicators of crustal processes. This provides evidence that distribution is not simply random. The check can be made both for all volcanoes in the region of interest and for the groupings derived from **Step 3a**. The probabilities and related uncertainties can then be suitably weighted to reflect these correlations. This sub-step may need to utilise expert elicitation.

As an example, in the Tohoku Case Study, the broad distribution of volcanoes is correlated (although by no means perfectly) to the isostatic gravity anomaly map of the region. The isostatic gravity anomaly map is produced by combining the Bouguer gravity anomaly map with the topographic map, making various assumptions. In the Tohoku study it was calculated assuming a thin elastic crustal plate 10 km thick. The isostatic anomalies reflect magma generation potential, with the rate of magma accumulation at the intra-crustal Conrad discontinuity and, possibly, the rate of magma flux at the surface (hence the likelihood of future volcanism) being indicated by isostatic anomalies. This can be tested by plotting the historic magma production rate against the isostatic anomaly per unit area, but this has not so far been tested in the ITM methodology development.

In Kyushu, the distribution of volcanism is closely tied to tectonic strain, manifest in the distribution of active faults, GPS-derived strain and the distribution of historical seismicity. On local scales, some volcanoes are closely associated with fault zones (Figure 3.6). Regionally, volcanism in Kyushu closely follows regional tectonic structure. For example volcanoes of the Northern Extensional arc are closely associated with the Shimabara-Beppu Graben. ITM methodology calls for development and implementation of probabilistic models that reflect these geological patterns.

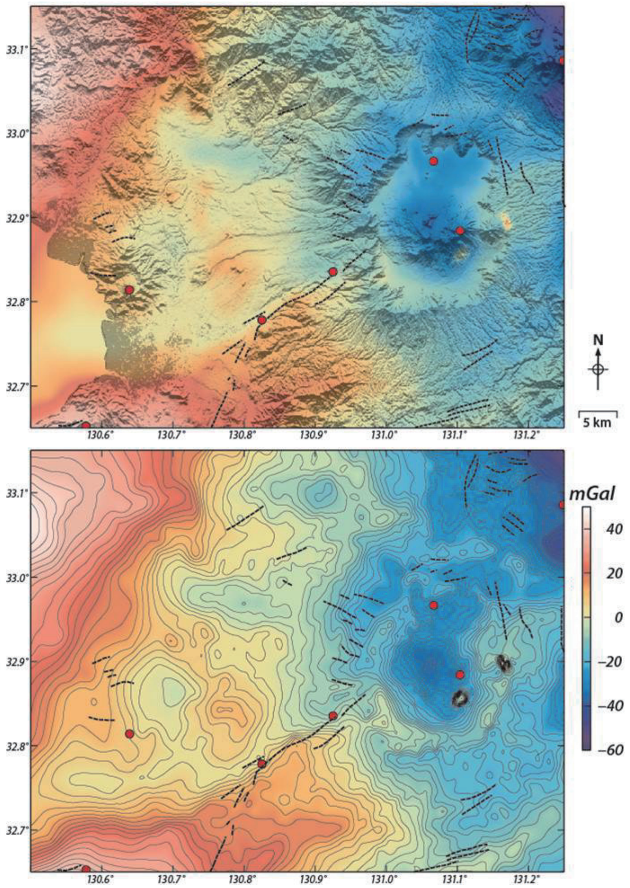


Figure 3.6: Regional gravity about Aso caldera and the SW Simabara-Beppu graben. Two small-volume Quaternary volcanoes (Akai and Omine) are found SW of Aso along graben-bounding fault. Active fault traces (dashed lines) differ in some areas from distribution of crustal-scale gravity anomalies. Volcanism in this area provides a clear example of volcano-tectonic interaction that is common in Kyushu.

Step 4a.2: Calculating Probabilities of Magma Intrusion: For the probabilistic mapping, three types of probability can be estimated:

- P1 – the probability of a volcano edifice forming in the region of interest during the period of interest (e.g. a probability of 2 x 10^{-4} for a period of one year)
- P2 – the probability that a volcano will form in a specific area within the region of interest, such as a 5 x 5 km block, or a region extending to 15 km beyond the boundaries of a PIA (e.g. a probability of 1 x 10^{-4} for an area of 25 km^2)
- P3 – given that a volcanic event occurs in this specific area, the probability that it will impact the repository site itself.

Then, the probabilistic volcanic hazard is given by P1 x P2 x P3. A variety of well-developed statistical methods is available for estimating such probabilities, and the estimations can be done either for all magma intrusion modes or for the various alternative groupings defined in **Step 3a**. For subsequent assessment of impact scenarios in **Step 6** it is important to assess the probability of different types of event occurring, so looking at each alternative group is a primary strategy of the ITM methodology.

The ITM methodology produces (principally) estimates of P2, in the form of regional probability maps, as these are of most use for assessing specific locations or sites. The same 5 x 5 km squares are used as for the rock deformation evaluation. Estimation of P3 will be a site-specific issue for Step 6, which will need to look at both the structural and geological properties of the location, the type of intrusion being considered and the repository concept that would match the site.

Geostatistical and Bayesian methodologies provide a way to assess conceptual, spatial and parametric uncertainty. The methods used in the ITM methodology are:

- **Kernel Method:** Generation of a non-homogeneous distribution map, using a Gaussian or Epanechnikov kernel method, with an applied smoothing function (with the effect of a range of bandwidths tested). The method is subject to uncertainties in calculated probabilities at any given point on the regional map, principally caused by local variability of data density (or overall sparsity in terms of the number of volcanic events over the last 2 Ma). These uncertainties vary from point to point. Figure 3.7 shows an example probability map for a small sub-region of the Tohoku Case Study area (Chapman et al., 2009), with the two green locations selected to show how uncertainty can vary depending on proximity to an existing cluster. Figure 3.8 shows example results for different alternative groupings of volcanoes. It can be seen that the optimum bandwidth for the kernel function is different for the two groups.

  As discussed under **Step 3a**, the introduction of additional 'synthetic' volcanoes can help quantify this uncertainty and the ITM methodology is also testing a Monte Carlo sampling approach for estimating uncertainty in probability at a given site for a given data set and a given smoothing bandwidth. An alternative method under test is to use adaptive kernel functions, where the value of the kernel depends on the local data density. The Monte Carlo approach is shown in the flow chart in Figure 3.9.

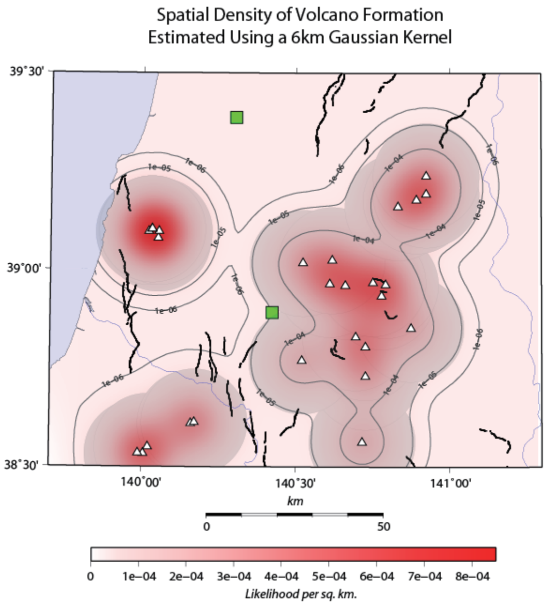


Figure 3.7: Spatial density of likelihood of new volcano formation in a sub-region of the area used in the Tohoku Case Study (Chapman et al., 2009). This realisation uses a 6 km Gaussian kernel and the probability refers to a period equivalent to that over which the mapped volcanic features were formed – about 2 Ma.

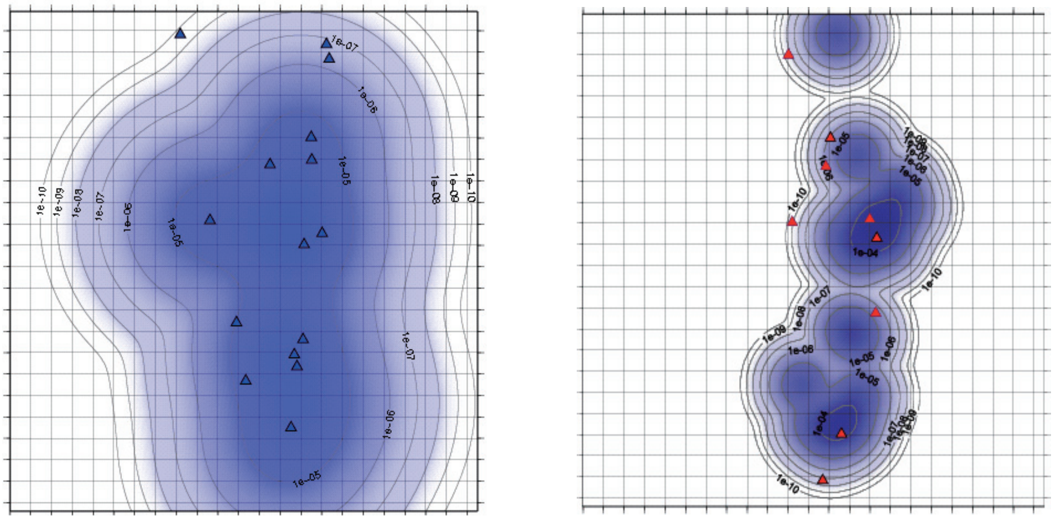


Figure 3.8: Probability contours (per year) for new volcanoes in part of the Tohoku Case Study area, showing the different kernel bandwidths that are required to provide an acceptable model for two different groups of volcano: left, explosive volcanoes, with a 33 km bandwidth; right, extrusive volcanoes, with a 12 km bandwidth.

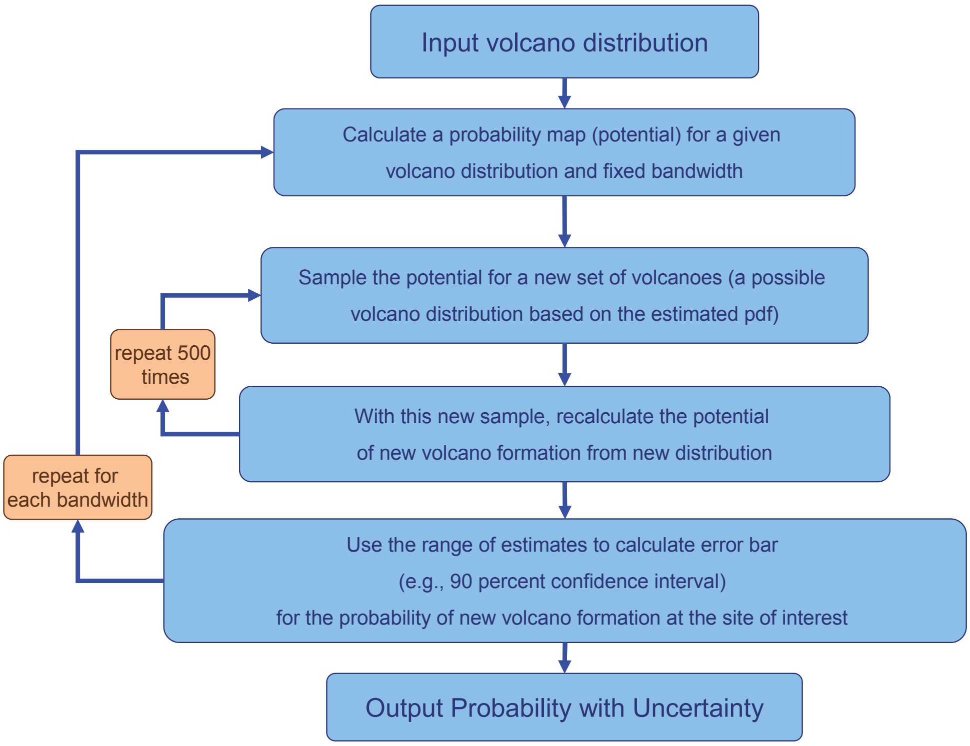


Figure 3.9: Flowchart showing the Monte Carlo sampling approach that is being developed to assess uncertainties in non-homogeneous probability mapping.

- **Cox Process Method:** This multivariate approach is able to use a range of different set of geoscientific data – for example, 3-D seismic velocity tomography of the crust and upper mantle, using a conceptual model where the tomographic features are related to magma generation potential. This is supported by the correlation of these structures with specific volcanoes or with Quaternary volcano clusters.

  The basis of the approach is to consider the potential for volcanism in an area to be randomly structured: even though our geological knowledge suggests there to be correlations with geological and geophysical data, randomness is brought on by our inherent uncertainty. Unlike Poisson distributions, which assume a constant potential with time for new volcanoes, and the non-homogeneous approach (see above: the other method used by the ITM methodology) which assumes a deterministic potential conditioned by selection of a kernel value, the Cox process approach assumes the potential to be entirely stochastic. The detailed methodology used is described by Jaquet et al. (2008a; 2008b; 2009).

  The Cox process approach allows the estimation of a volcanic potential map, which is then statistically correlated to the seismic tomography map, in order to produce a probability map by Monte Carlo simulations. The overall approach is shown in Figure 3.10, while Figure 3.11 shows one of the results from the Tohoku Case Study.

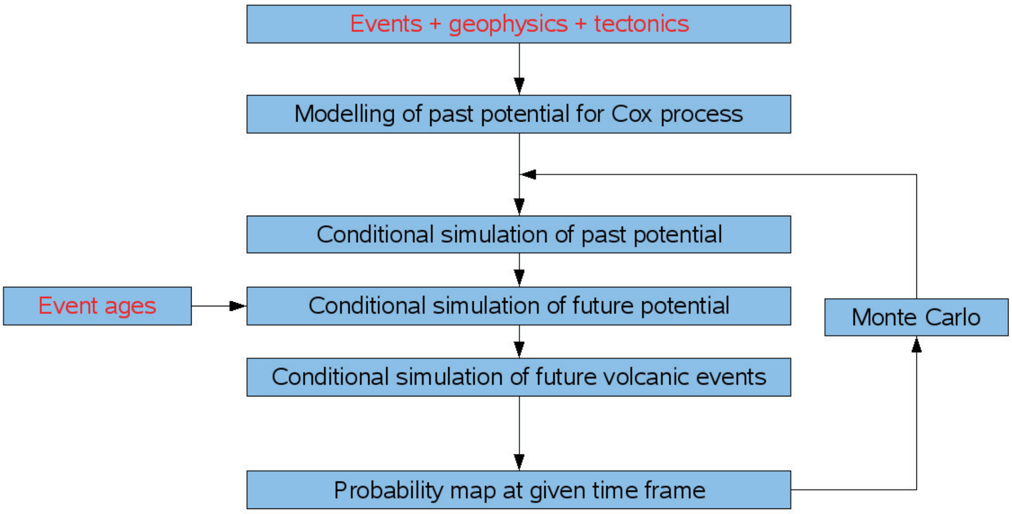


Figure 3.10: Flowchart showing the Cox process approach used to derive volcanic probability maps.

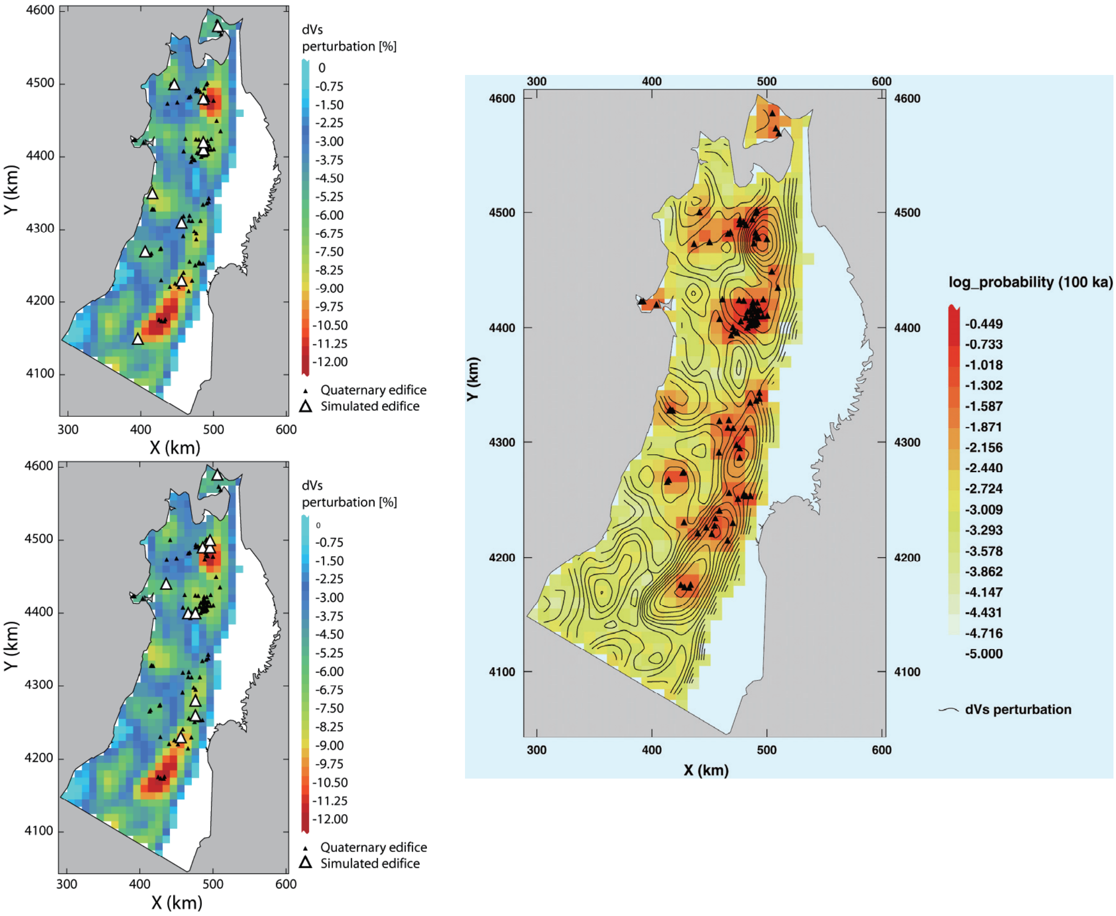


Figure 3.11: (a1) and (a2): left, top and bottom: Two Cox simulations with a multivariate potential of volcanism. The simulated events are likely to be located in zones with past activity as well as in zones with seismic anomalies. (b): right: Probability of formation of a new volcano in the next 100,000 years using the Cox process approach, correlated with the seismic tomography data for Tohoku region.

STEP 4b: Probabilistic Strain Maps

Step 4b.1: Constructing Different Strain Maps: For each indicator, the calculated strain rates from **Step 3b** are converted to strain maps for each conceptual model branch of the Logic Tree. The maps show calculated strains within the 5 km x 5 km areas. As noted above, this is a reasonable resolution for the datasets being used and is also a useful size with respect to expected repository footprint (~10 km^2), but site-scale rather than regional scale application of the methodology would require use of a finer grid. The strain rates are also presented together on a single map, combining them using the weightings assigned to each branch of the logic tree. The weighted map is thus a probabilistic representation of strain, representing the most likely strain averaged over the time period for which the particular indicator has been 'recording'. For application in later Steps, only the maps of the most highly weighted conceptual model alternatives (branches) and the combined, fully weighted probabilistic version are likely to be useful.

Step 4b.2: Comparison and Differencing: The weighted, probabilistic maps for each separate indicator (i.e. GPS, seismic and tilt) are then compared. Because the different strain indicators have variable coverage of a region, their use is complementary. The probabilistic weighted maps for each indicator can, for instance, be differenced to assess the overall correlation between strain indicators. This picks out areas where the datasets are inconsistent in their strain estimates. Combined with the variability shown in the strain rate histograms for any selected area, such inconsistencies will identify locations where there is significant uncertainty regarding deformation process, which may also be reflected in a wider range of strain rate potential (as can be seen in Figure 3.3, for example). If a potential repository site lies within such a region, this would require special attention in Step 8, to ensure that adequate data were gathered during the PIA investigation programme to try to reduce the uncertainty. An example of one of the strain maps generated in the Tohoku Case Study is shown in Figure 3.12, where the weighted average GPS strain data are shown together with the location of volcanoes.

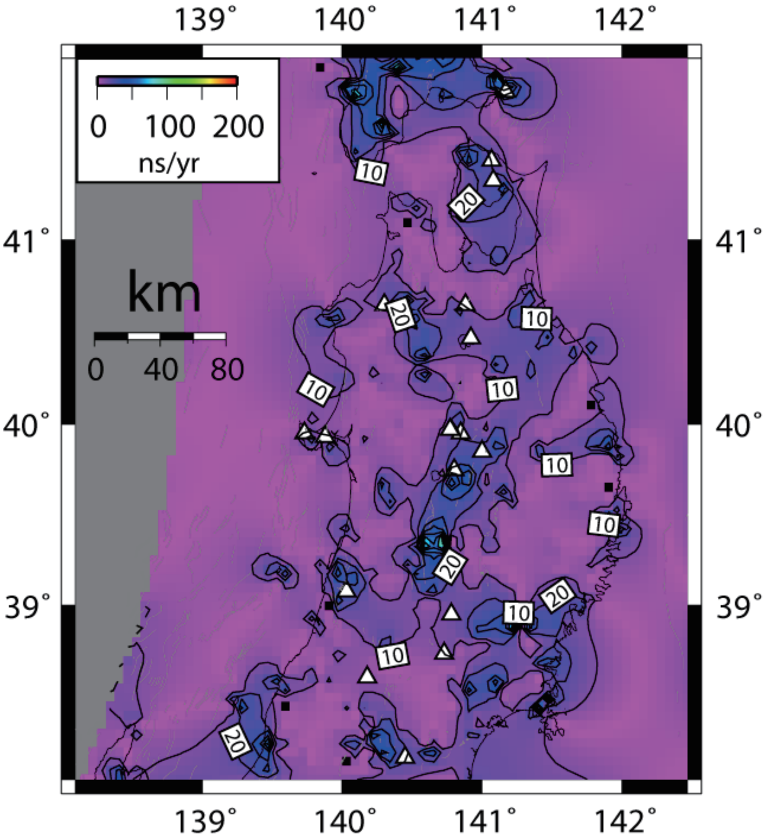


Figure 3.12: Weighted average strain map (contoured in nanostrains/a) for the Tohoku region, based on all 148 strain maps from the GPS-based logic tree (Figure 2.3). Here, the location of volcanoes is also shown (white triangles) as the integration of Steps 4a and 4b is a key exercise carried out in Step 5. A weak positive correlation can be seen between the location of the volcanic front and the location of elevated contractional strain, which is being investigated in the methodology development programme.

STEP 5: Integrated Evaluation of Each Potential Repository Site

The information from **Steps 4a and 4b** can be used directly in Step 6 – for example, to carry out a detailed assessment of a single site or a few alternatives. However, it is possible to combine the data from Steps 4a and 4b to carry out an evaluation of a larger group of sites so that they can be compared at a relatively simple level in terms of their overall susceptibility to tectonic hazard. This was the objective of the two Case Studies. The text below assumes that a large set of sites (say 5 – 10) is being compared.

Depending on the interpretations arising from the separate strain maps for each indicator, it may be considered useful to produce a combined, higher level logic tree that weights belief in relevance of the three strain measures and factors volcanic strain into the logic tree and the weighting process. Conversely, the likelihood of magma intrusion, as indicated on the probability maps, needs to be interpreted in the light of deformation history and the mapped strain rate variations around the site.

Figure 3.13 shows an example of the estimated uncertainties (1σ) in strain values for the different strain indicators at four different example locations from the Tohoku Case Study.

Step 5 combines the data from Steps 4a and 4b to carry out an evaluation of a large group of sites so that they can be compared at a relatively simple level in terms of their overall susceptibility to tectonic hazard. This was the objective of the two Case Studies. The text below assumes that a large set of sites (say 5 – 10) is being compared.

For multiple site comparisons, Step 5 produces individual site assessments that provide the following information in an identical format:

- description of the geological and tectonic setting of the site;
- evaluation of the likelihood of each different type of magma intrusion considered possible, in both the region around the site and at the site itself, over a period of up to 100,000 years[12];
- evaluation of the uncertainties in the likelihoods;
- evaluation of the best estimate rock deformation potential (expressed as strain probability histograms) and mechanisms over the same period of time – and the related uncertainties.

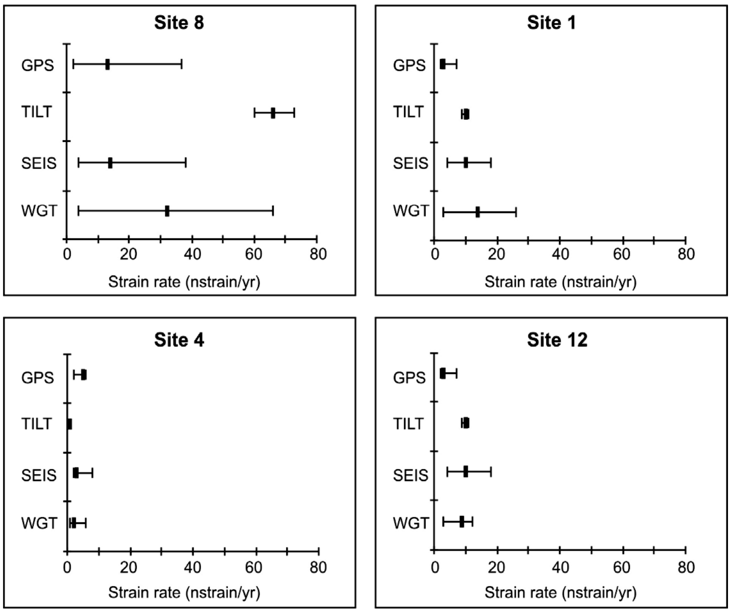


Figure 3.13: estimated uncertainties (1σ) in strain values for the different indicators (GPS, tilt and seismic, plus weighted average) at four different example locations from the Tohoku Case Study.

Depending on the interpretations arising from the separate strain maps for each indicator, it may be useful to produce a combined, higher level logic tree that weights the three strain measures, and factors volcanic strain into the logic tree and the weighting process. Conversely, the likelihood of magma intrusion, as indicated on the probability maps, needs to be interpreted in the light of deformation history and the mapped strain rate variations around the site.

Figure 3.14 shows the equally weighted average strains using all indicators for all the 14 example locations in the Tohoku Case Study (Chapman et al., 2009). These might be regarded as 'best estimate' values for the purposes of this methodology demonstration but, in a real site inter-comparison exercise, expert judgement would be required to assign weights to the different indicators, which would depend on confidence in both the data and the regional models. Clearly, these will vary from one area and one site to another.

---

[12] The methodology could be developed further to provide estimates for 1 Ma, but this would require the use of much larger (longer duration, ~10 Ma) datasets and would involve greater uncertainties (especially concerning the time stability of the underlying tectonic processes). Knowledge of future volcanic hazard is, in any case, of diminishing interest for safety assessment at times even after only 10,000 years, as the hazard of the waste has decreased to levels equivalent to natural uranium ores by this stage.

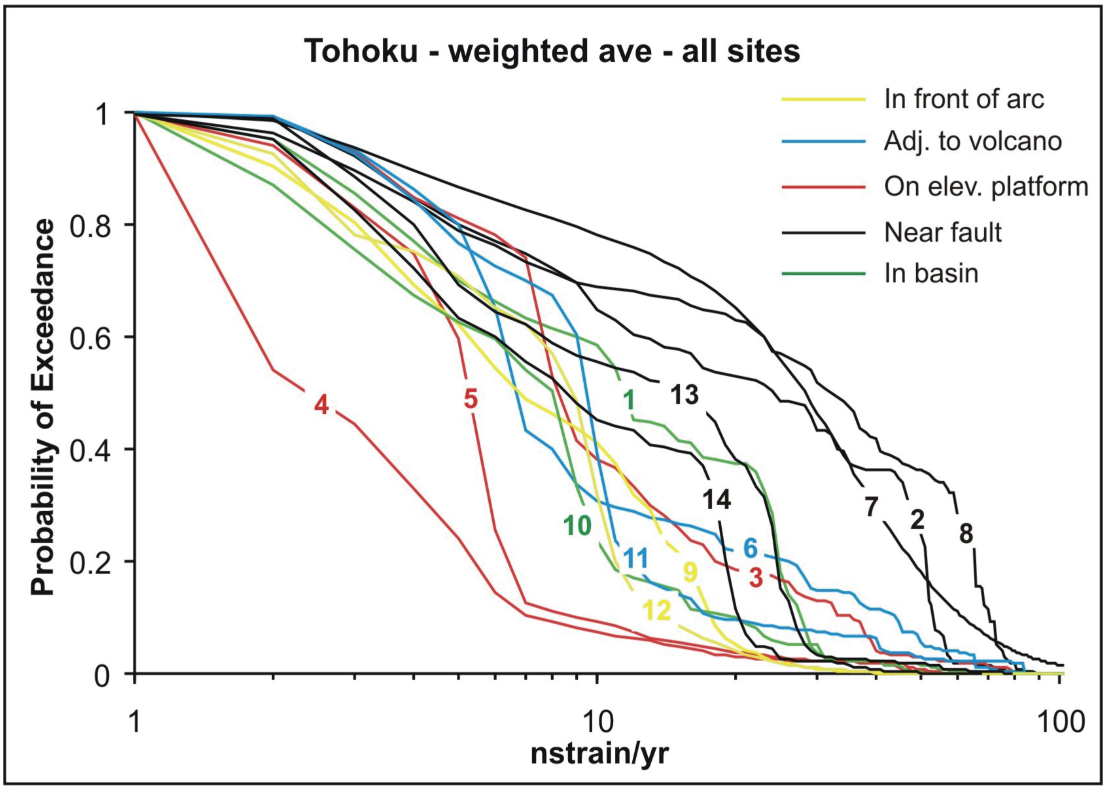


Figure 3.14: Graph showing the probability or likelihood of exceeding strains of given magnitude, based on the equally weighted average strains (using all three strain indicators) for all the 14 example locations in the Tohoku Case Study (Chapman et al., 2009).

STEP 6: Interfacing with the NUMO Performance Assessment work

The methodology up to this stage is designed to deliver a set of probability maps that have taken account of uncertainty in both conceptual models and data and which contain integrated interpretations of the sites being investigated by NUMO.

Knowledge of the likelihood of various tectonic hazards affecting a site is of limited value to NUMO unless it can evaluate whether the impacts would be acceptable or not (in terms of regulatory standards for radiological exposures to the public). This is a task for the NUMO safety assessment team, who will be carrying out detailed performance assessment studies of the long-term behaviour of the repository and its engineered barriers. However, information on both **likelihood** and **impacts** is essential for safety assessment and both **likelihood** and **consequences** are together directly linked through a specific ‘event definition’.

The role of the ITM methodology at this stage is thus to provide the PA team with information on the nature of the tectonic hazards, so that it can construct **scenarios** upon which to base these analyses, and to provide quantitative probability estimates of the likelihood of occurrence of these scenarios. As discussed in Section 1 of this report, two approaches have been adopted internationally to utilise this information in safety assessment:

- To calculate the health risk[13] to people in the future by combining the probability of a disruptive event occurring with its radiological consequences in terms of releases

---

[13] Health risk is normally defined as the risk of death or serious genetic effects.

from a repository: simply, risk = probability x consequence. With this approach, regulatory standards or targets can be defined in terms of risk to an individual.

- To consider the impacts of a disruptive event and calculate the radiological doses[14] to people in the future and then, separately, to discuss the likelihood that this might happen (the so-called 'disaggregated' approach). With this approach, separate regulatory targets for radiation doses might be set for events (or scenarios) with different degrees of likelihood (often expressed qualitatively; e.g. 'likely', 'less likely', 'highly unlikely').

In either approach, an appreciation of probability is essential: in the first 'risk approach' a sound quantitative estimate will provide more confident estimation of risk; in the second, some form of quantification of 'likelihood' is needed to decide which category to place an event or scenario into.

The information required for either of these approaches is generated in **Step 6** and comprises the following:

1. A description of the nature of each magma intrusion event and rock deformation process that could feasibly affect the repository (the basis for the scenario).

2. The likelihood of each magma intrusion event impacting both the repository directly and the surrounding rock mass.

3. The variation of this probability with time over the next 100,000 years.

4. The best estimate of the magnitude and duration of rock deformation that could affect the repository.

5. A description of how the events and processes would initiate, develop and progressively impact the repository and the barriers.

Using this information, the PA team will be able to develop scenarios for tectonic impacts and assign probabilities to them.

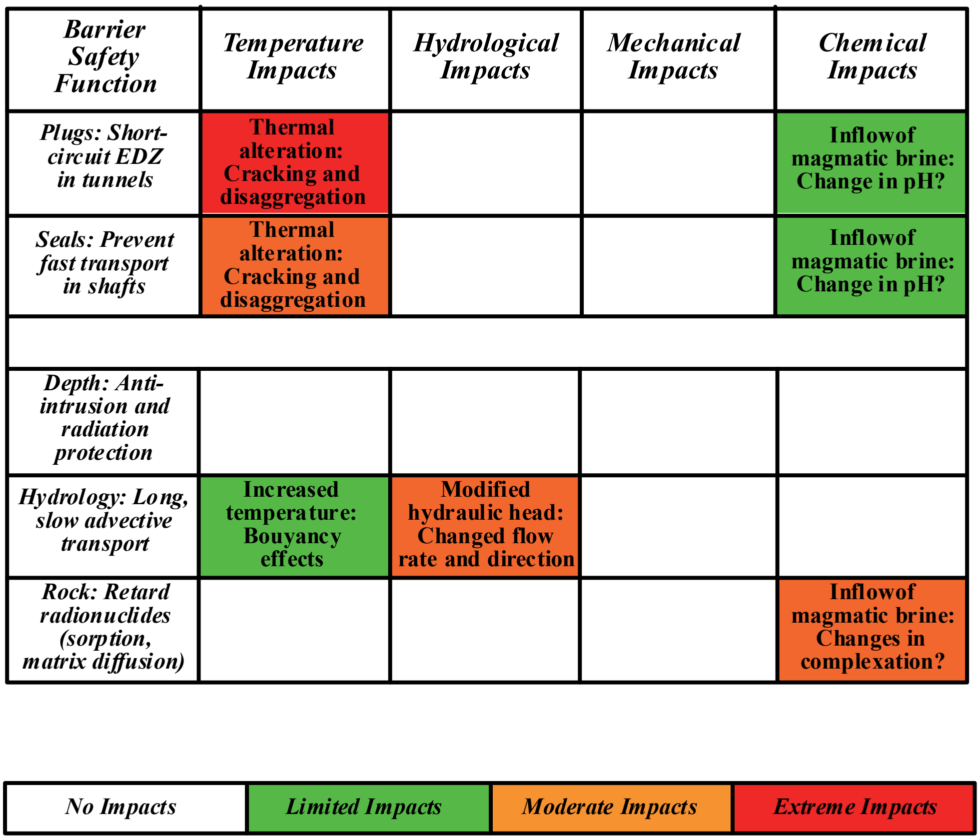
The ITM methodology involves the production of a matrix that will compile the information in items (1) and (5) above. This matrix can be used to inform the scenario development work, which could be carried out jointly by the PA team and the ITM group. Figure 3.15 shows a generic example of part of a matrix for indirect (hydrothermal) impacts on the repository structures (excluding the engineered barrier system – which is in a separate matrix) and the surrounding rock. This type of matrix could be developed to be considerably more detailed, depending on the requirements of the scenario analysis.

The matrix will need to take account of the types of repository design and engineered barriers that would be appropriate to the sites being studied, so input from NUMO repository design work will be required. Simple factors, such as repository depth and horizontal and vertical dimensions could have a significant bearing on the level of impact of each type of rock deformation or magma intrusion.

For the methodology development work, only one selected magmatic intrusion scenario and one rock deformation scenario have been evaluated and presented as illustrations. For eventual area and site-specific use of the ITM methodology, this exercise will have to be comprehensive.

---

[14] Of course, a radiological dose can also be expressed in terms of health risk, by applying accepted dose-to-risk conversion factors.



Barrier Safety Function	*Temperature Impacts*	*Hydrological Impacts*	*Mechanical Impacts*	*Chemical Impacts*
Plugs: Short-circuit EDZ in tunnels	🟥 **Thermal alteration: Cracking and disaggregation**			🟩 **Inflow of magmatic brine: Change in pH?**
Seals: Prevent fast transport in shafts	🟧 **Thermal alteration: Cracking and disaggregation**			🟩 **Inflow of magmatic brine: Change in pH?**
Depth: Anti-intrusion and radiation protection				
Hydrology: Long, slow advective transport	🟩 **Increased temperature: Bouyancy effects**	🟧 **Modified hydraulic head: Changed flow rate and direction**		
Rock: Retard radionuclides (sorption, matrix diffusion)				🟧 **Inflow of magmatic brine: Changes in complexation?**

⬜ *No Impacts*	🟩 *Limited Impacts*	🟧 *Moderate Impacts*	🟥 *Extreme Impacts*

Figure 3.15: Impact Matrix of the repository and surrounding rock for an illustrative indirect-volcanism impact scenario assuming imposition of a hydrothermal convection system 10 km from a polygenetic volcanic centre. Impacts can be categorised mainly as 'global, slow, 'permanent', and 'barrier degradation'.

STEP 7: Utilising the Probabilistic Results

Step 7 is where the probabilistic results and any safety assessment results based upon them are used by NUMO to assist in making siting decisions. Various decision points can be considered:

1. At the point where a single volunteer site comes forward in a non-excluded area. NUMO may wish to consider the overall susceptibility of the site to tectonic impacts before it accepts the site as a PIA, so that it can gain an initial impression of the extent to which tectonic issues might be critical to a future safety case. This will enable them to gauge 'programme risk' – whether they would be taking on a site with a low or high likelihood of proving unsuitable from the tectonic viewpoint. This would use the data from the LS up to the point of Step 4, possibly without carrying out any PA work in Step 6. The output would inform NUMO decision makers so that can be fully aware of any tectonic contribution to overall project risk and be able to answer questions about tectonic hazard with confidence.

2. Where there are several possible volunteer sites in the same region, so that the relative susceptibility of the sites can be assessed – essentially at Step 5, as illustrated in the two Case Studies and described further below. This comparative assessment could help NUMO to focus or prioritise the site investigations and decide the order in which sites are evaluated.

3. When one or two sites are being considered for the final DIA. At this point, PIA information would be available and the ITM methodology would have been iterated with progressively improving data. In addition, feedback would be available from quantitative

safety assessments in Step 6, using Step 4 information. By this stage, there should be a full understanding of the actual tectonic hazard for any sites being considered for the DIA and the ITM information should be at a sufficient level to feed directly into license application level documentation.

However, each of these possible decision points is a potentially far-reaching stage of NUMO's work and siting decisions will always involve many other factors (both technical and non-technical). At present, it is not clear how NUMO might wish to manage this Step for any of these three stages of their programme. Further development is consequently anticipated here, as the PIA siting programme begins to find potential sites, as the NUMO safety assessment work evolves and as the national regulatory standards become more developed and the use of likelihood and risk become clearer.

No impact analyses have been carried out so far as part of NUMO's parallel PA development work, so it is not possible at the moment to assess radiological impacts associated with any particular scenario. For the purposes of illustrating the methodology, Figure 3.16 shows an example of how probability values for volcanism, derived from Step 4a might contribute to understanding siting confidence, as might be required at the second decision point described above (comparing multiple sites). It shows, for the 14 Tohoku Case Study example locations, one example of how 'low, medium and high' levels of confidence might be allocated to each site with respect to susceptibility to a scenario of direct magmatic intrusion within the next 10,000 years. The quantitative boundaries between the levels of confidence are arbitrarily selected here, simply to illustrate the approach.

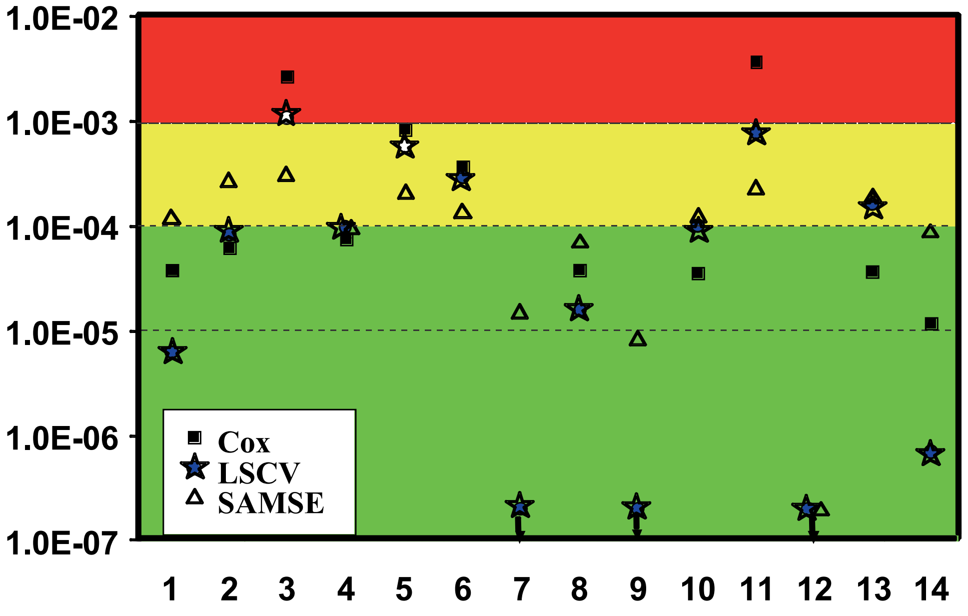


Figure 3.16: An example of 'low' (red), 'medium' (yellow) and 'high' (green) confidence levels allocated to each of the 14 Tohoku Case Study example locations, based on the probability of a direct magmatic intrusion scenario occurring within the next 10,000 years (for different statistical methods in Step 4a.2). The quantitative boundaries chosen for the levels are arbitrary examples, simply to illustrate the approach.

STEP 8: Defining PIA and DIA field tectonic data requirements

The aim of **Step 8** is to identify which additional data will be required from PIA site investigations to reduce the uncertainties in the evaluations in each previous Step. In particular, after Steps 4, 6 and 7 during the LS stage, the ITM methodology will need to be reiterated to produce more refined evaluations of probabilities and better definition of the nature of impacts for input to the decision to move from PIA to DIA (and to the progressive development of SAs, as work on the PIAs proceeds). The following classes of information feed into the ITM Methodology:

1. **Regional (data coverage):** filling gaps in the large regional databases that were used in **Step 3**. It is clear that some classes of information will be of patchy quality and coverage (e.g. age data for volcanic features; active fault parameters; seismic data), which contributes to the overall uncertainty in the **Step 4** probability mapping. Whilst it cannot hope to fill all such gaps, NUMO should be prepared to gather this type of information, so the development of an efficient programme that identifies the most important and 'fillable' gaps that would have maximum impact on reducing uncertainty is important. Definition of these critical data gaps is region-specific, but the two Case Studies have identified obvious improvements.
2. **Regional (ground truth):** ensuring that the key data used in **Step 3** are fully understood and being used correctly for classification and for setting up strain models. A certain amount of this work will already have been undertaken in **Step 2**, but it may be found that a more thorough evaluation is needed by the time **Step 7** has been reached. As was found for the Tohoku volcanics work (**Step 3a**), the results are highly dependent on what a catalogue entry is assumed to mean and field investigation has shown that all the data need to be checked. This is not necessarily a large operation, but it would involve field reconnaissance visits to features (volcanic, faults, etc) by experts across the whole of the region of interest, preferably during the LS stage, but repeated if needed during the PIA investigations.
3. **Local and Site-Scale:** many topics of relevance to the ITM methodology will be studied in any case during PIA investigations. For example, even *without* the need to develop the tectonic probability models and evaluations of ITM, NUMO will already be seeking evidence of hidden active faults, characterising local active faults in detail, measuring uplift rates and looking at geothermal heat flux as part of its 'normal' site investigation programme. However, the ITM methodology will provide better results if it has access to *additional* information. The scope of this information will be site-specific, but the following data needs will need to be considered (for the reasons given):
    - age and eruptive style/volumes of local volcanics to constrain the intrusion probability estimates and impact definition;
    - more detailed, local-scale gravity and magnetic surveys to identify hidden volcanic structures or deformation zones that would affect the probabilistic statistical evaluation;
    - strain mechanism and history of faults and other large deformation features in the neighbourhood of the site to constrain site context with respect to 'rock blocks' used in regional strain budget modelling;
    - establishment of local fixed and temporary GPS stations to localise GPS strain within the regional picture, seeking small differences that could reflect an overlay of site-scale deformation.

3.3 References for Section 2

Chapman, N., M. Apted, J. Beavan, K. Berryman, M. Cloos, C. Connor, L. Connor, O. Jaquet, N. Litchfield, S. Mahony, W. Smith, S. Sparks, M. Stirling, P. Villamor and L. Wallace (2009). Development of Methodologies for the Identification of Volcanic and Tectonic Hazards to Potential HLW Repository Sites in Japan: The Tohoku Case Study. Nuclear Waste Management Organisation of Japan, Tokyo. Technical Report: NUMO-TR-08-03. 135 pps.

Hone, D.W.E, Mahony, S.H., Sparks, R.S.J. & Martin, K.T. (2007). Cladistics analysis applied to the classification of volcanoes. *Bulletin of Volcanology*, **70**, 203−220.

Jaquet O., Lantuéjoul C. and Goto, J. (2009 in press). Cox process models for the estimation of long-term volcanic hazard. In Volcanism, Tectonism, and the Siting of Nuclear Facilities, edited by C.B. Connor, N.A. Chapman and L.J. Connor.Connor L. (2008a) Probabilistic methodology for long term assessment of volcanic hazards, Nuclear Technology, 163, pp. 180-189.

Jaquet O., Lantuéjoul C. and Goto J. (2008b) Estimation of long-term volcanic hazard using a Cox process with a multivariate potential, VIII International Geostatistics Congress, GEOSTATS 2008, Santiago Chile, pp.167-176.

Jaquet O., Lantuéjoul C. and Goto, J. (2009 in press). Cox process models for the estimation of long-term volcanic hazard. In Volcanism, Tectonism, and the Siting of Nuclear Facilities, edited by C.B. Connor, N.A. Chapman and L.J. Connor.

4 Assessing the Consequences of Low Probability Tectonic Event Scenarios

The ITM methodology described in the previous section (and in Chapman et al., 2007) has been successfully applied to two large study-regions in Japan; Tohoku and Kyushu. For each region, estimates on the probability of future disruptive tectonic and volcanic events have been developed based on geological, geophysical and seismological data. Such tectonic and volcanic events are important scenarios to be considered in any credible safety assessment for any geological repository to be located in Japan.

The purpose of this Section is to show how the probabilistic results from the ITM methodology can be incorporated into NUMO's safety assessment and performance assessment concerns – Step 6 of the ITM methodology. Specifically, the intent is to present a linkage between the probabilistic and the consequence aspects of natural-event scenarios, leading to a systematic classification of impacts on thermal, hydrological, mechanical and chemical (T-H-M-C) conditions and the degradation and loss of safety functions of natural and engineered barriers.

In the following sections, the results and implications of the ITM studies with respect to future safety assessments by NUMO will be discussed. Specific topic include:

- natural-event scenarios in safety assessment,
- the role of probabilities in safety assessment, including scenario probability
- linkage between probabilities and consequences in safety assessment of natural-event scenarios,
- systematic classification of natural-event scenario consequences (impacts), and
- examples of specific natural-event scenarios and their qualitative consequences on long-term repository performance and safety.

Two key messages focus on the necessity of factoring probabilities of natural events into any safety assessment approach that may be adopted by NUMO, and the need to organize and classify natural-event scenarios in ways to identify R&D needs and guide developments in safety assessment methodologies.

4.1 Safety Assessment Overview

All concepts for the geological disposal of nuclear waste involve the performance analysis and safety assessment (PA/SA) of a system of engineered and natural barriers. These barriers are assigned specific 'safety functions', defined as either a property or process by barrier that acts to contain or contribute to the long-term isolation of nuclear waste, preventing unacceptable future releases of radioactivity to the biosphere and human environment. Figure 4.1 presents an illustrative example of common barriers and basic safety functions for a vertical emplacement configuration; other geometries, dimensions, barriers and barrier materials are of course, possible, leading to different assignments of 'safety functions' for different concepts.

The beginning point for safety assessment is evaluating the performance of the multiple-barrier repository for the expected evolution of the repository. Safety assessment of the 'expected evolution', or 'base-case', scenario, assumes initial ambient temperature-hydrological-mechanical-chemical (T-H-M-C) conditions as determined by extensive site characterization. Underground construction and emplacement of heat-producing high-level waste induces changes to the ambient T-H-M-C conditions, followed by a gradual return to ambient conditions. Figure 4.2 (Kurikami, et al., 2009) presents a comprehensive illustration of the expected evolution for a representative repository concept.

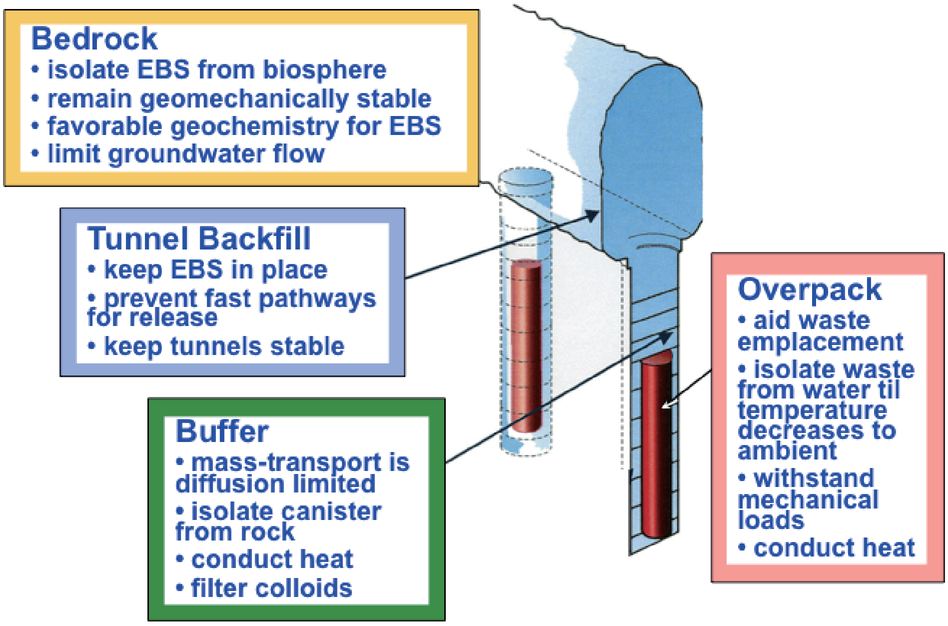


Figure 4.1: Safety features of the generic barrier system of a geological repository

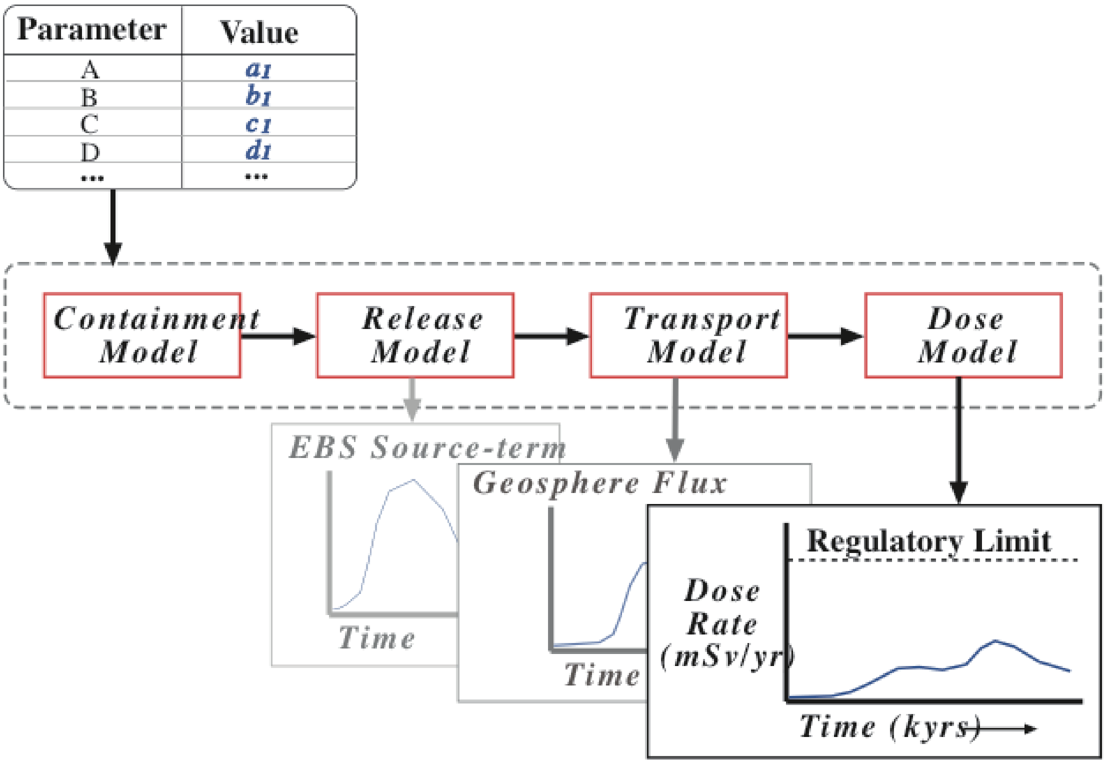
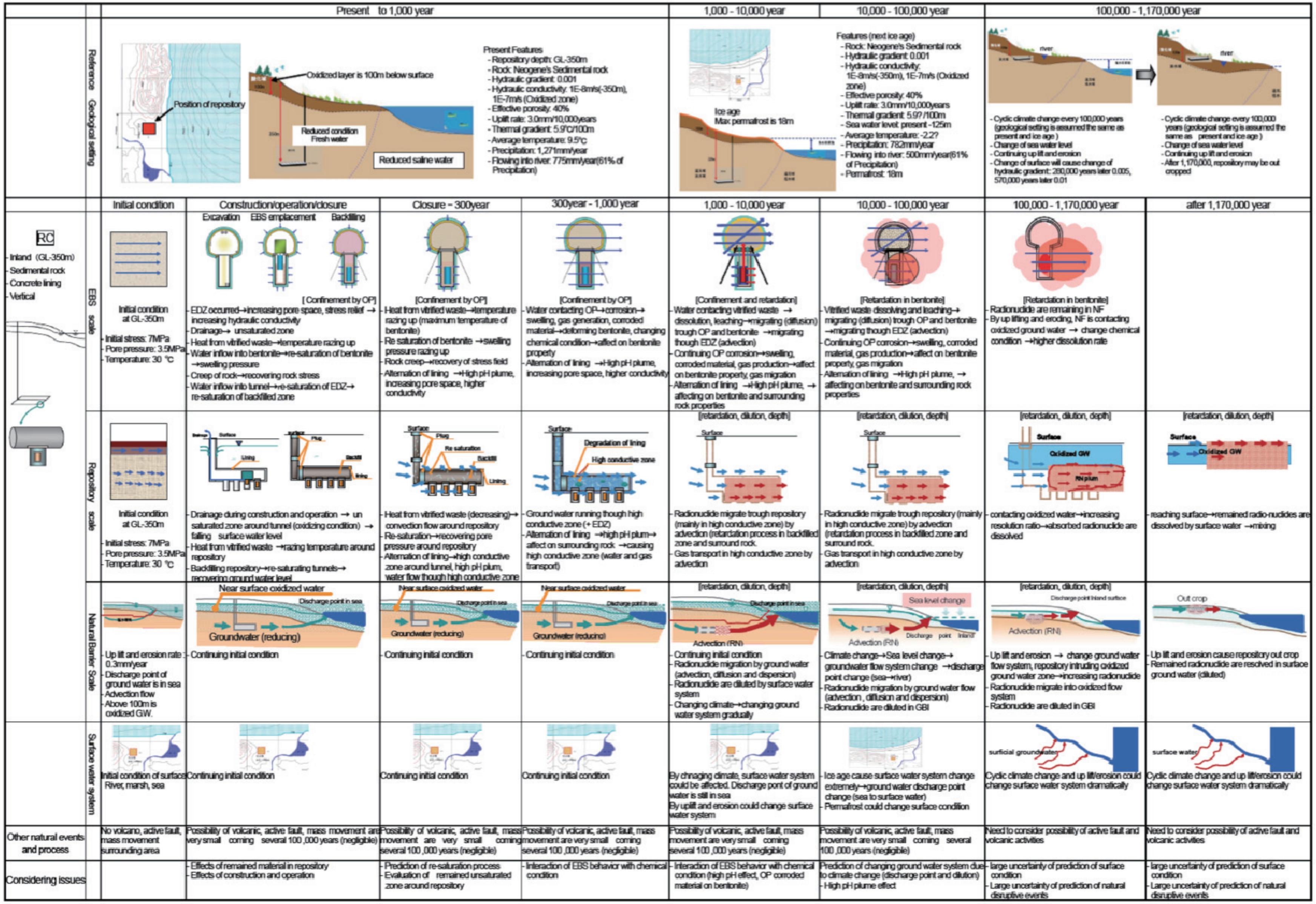


Figure 4.3: Schematic illustration of the chain of models in a basic safety assessment



		Present to 1,000 year				1,000 - 10,000 year	10,000 - 100,000 year	100,000 - 1,170,000 year	
	Reference Geological setting	Present Features: - Repository depth: GL-350m - Rock: Neogene's Sedimental rock - Hydraulic gradient: 0.001 - Hydraulic conductivity: 1E-8m/s(-350m), 1E-7m/s (Oxidized zone) - Effective porosity: 40% - Uplift rate: 3.0mm/10,000years - Thermal gradient: 5.9°C/100m - Average temperature: 9.5°C - Precipitation: 1,271mm/year - Flowing into river: 775mm/year(61% of Precipitation)					Features (next ice age) - Rock: Neogene's Sedimental rock - Hydraulic gradient: 0.001 - Hydraulic conductivity: 1E-8m/s(-350m), 1E-7m/s (Oxidized zone) - Effective porosity: 40% - Uplift rate: 3.0mm/10,000years - Thermal gradient: 5.9? /100m - Sea water level: present -125m - Average temperature: -2.2? - Precipitation: 782mm/year - Flowing into river: 500mm/year(61% of Precipitation) - Permafrost: 18m	- Cyclic climate change every 100,000 years (geological setting is assumed the same as present and ice age) - Change of sea water level - Continuing up lift and erosion - Change of surface will cause change of hydraulic gradient: 280,000 years later 0.005, 570,000 years later 0.01	- Cyclic climate change every 100,000 years (geological setting is assumed the same as present and ice age) - Change of sea water level - Continuing up lift and erosion - After 1,170,000, repository may be out cropped
		Initial condition	Construction/operation/closure	Closure - 300year	300year - 1,000 year	1,000 - 10,000 year	10,000 - 100,000 year	100,000 - 1,170,000 year	after 1,170,000 year
RC - Inland (GL-350m) - Sedimental rock - Concrete lining - Vertical	EBS scale	Initial condition at GL-350m - Initial stress: 7MPa - Pore pressure: 3.5MPa - Temperature: 30 °C	[Confinement by OP] - EDZ occurred→increasing pore space, stress relief → increasing hydraulic conductivity - Drainage→ unsaturated zone - Heat from vitrified waste→temperature razing up - Water inflow into bentonite→re-saturation of bentonite →swelling pressure - Creep of rock→recovering rock stress - Water inflow into tunnel→re-saturation of EDZ→ re-saturation of backfilled zone	[Confinement by OP] - Heat from vitrified waste→temperature razing up (maximum temperature of bentonite) - Re saturation of bentonite →swelling pressure razing up - Rock creep→recovery of stress field - Alternation of lining →High pH plume, increasing pore space, higher conductivity	[Confinement by OP] - Water contacting OP→corrosion→ swelling, gas generation, corroded material→deforming bentonite, changing chemical condition→affect on bentonite property - Alternation of lining →High pH plume, increasing pore space, higher conductivity	[Confinement and retardation] - Water contacting vitrified waste → dissolution, leaching→migrating (diffusion) trough OP and bentonite →migrating though EDZ (advection) - Continuing OP corrosion→swelling, corroded material, gas production→affect on bentonite property, gas migration - Alternation of lining →High pH plume, → affecting on bentonite and surrounding rock properties	[Retardation in bentonite] - Vitrified waste dissolving and leaching→ migrating (diffusion) trough OP and bentonite →migrating though EDZ (advection) - Continuing OP corrosion→swelling, corroded material, gas production→affect on bentonite property, gas migration - Alternation of lining →High pH plume, → affecting on bentonite and surrounding rock properties	[Retardation in bentonite] - Radionuclide are remaining in NF - By up lifting and eroding, NF is contacting oxidized ground water → change chemical condition →higher dissolution rate	
	Repository scale	Initial condition at GL-350m - Initial stress: 7MPa - Pore pressure: 3.5MPa - Temperature: 30 °C	- Drainage during construction and operation → un saturated zone around tunnel (oxidizing condition) → falling surface water level - Heat from vitrified waste →razing temperature around repository - Backfilling repository→re-saturating tunnels→ recovering ground water level	- Heat from vitrified waste (decreasing)→ convection flow around repository - Re-saturation→recovering pore pressure around repository - Alternation of lining→high conductive zone around tunnel, high pH plum, water flow though high conductive zone	- Ground water running though high conductive zone (+ EDZ) - Alternation of lining →high pH plum→ affect on surrounding rock →causing high conductive zone (water and gas transport)	[retardation, dilution, depth] - Radionuclide migrate trough repository (mainly in high conductive zone) by advection (retardation process in backfilled zone and surround rock. - Gas transport in high conductive zone by advection	[retardation, dilution, depth] - Radionuclide migrate trough repository (mainly in high conductive zone) by advection (retardation process in backfilled zone and surround rock. - Gas transport in high conductive zone by advection	[retardation, dilution, depth] - contacting oxidized water→increasing resolution ratio→absorbed radionuclide are dissolved	[retardation, dilution, depth] - reaching surface→remained radio-nuclides are dissolved by surface water →mixing
	Natural Barrier Scale	- Up lift and erosion rate : 0.3mm/year - Discharge point of ground water is in sea - Advection flow - Above 100m is oxidized GW.	- Continuing initial condition	- Continuing initial condition	- Continuing initial condition	[retardation, dilution, depth] - Continuing initial condition - Radionuclide migration by ground water (advection, diffusion and dispersion) - Radionuclide are diluted by surface water system - Changing climate→changing ground water system gradually	[retardation, dilution, depth] - Climate change→Sea level change→ groundwater flow system change →discharge point change (sea→river) - Radionuclide migration by ground water flow (advection , diffusion and dispersion) - Radionuclide are diluted in GBI	[retardation, dilution, depth] - Up lift and erosion → change ground water flow system, repository intruding oxidized ground water zone→increasing radionuclide - Radionuclide migrate into oxidized flow system - Radionuclide are diluted in GBI	- Up lift and erosion cause repository out crop - Remained radionuclide are resolved in surface ground water (diluted)
	Surface water system	Initial condition of surface River, marsh, sea	Continuing initial condition	Continuing initial condition	Continuing initial condition	By chnaging climate, surface water system could be affected. Discharge pont of ground water is still in sea By uplift and erosion could change surface water system	- Ice age cause surface water system change extremely→ground water discharge point change (sea to surface water) - Permafrost could change surface condition	Cyclic climate change and up lift/erosion could change surface water system dramatically	Cyclic climate change and up lift/erosion could change surface water system dramatically
Other natural events and process		No volcano, active fault, mass movement surrounding area	Possibility of volcanic, active fault, mass movement are very small coming several 100 ,000 years (negligible)	Possibility of volcanic, active fault, mass movement are very small coming several 100 ,000 years (negligible)	Possibility of volcanic, active fault, mass movement are very small coming several 100 ,000 years (negligible)	Possibility of volcanic, active fault, mass movement are very small coming several 100 ,000 years (negligible)	Possibility of volcanic, active fault, mass movement are very small coming several 100 ,000 years (negligible)	Need to consider possibility of active fault and volcanic activities	Need to consider possibility of active fault and volcanic activities
Considering issues			- Effects of remained material in repository - Effects of construction and operation	- Prediction of re-saturation process - Evaluation of remained unsaturated zone around repository	- Interaction of EBS behavior with chemical condition	- Interaction of EBS behavior with chemical condition (high pH effect, OP corroded material on bentonite)	Prediction of changing ground water system due to climate change (discharge point and dilution) - High pH plume effect	- large uncertainty of prediction of surface condition - Large uncertainty of prediction of natural disruptive events	- large uncertainty of prediction of surface condition - Large uncertainty of prediction of natural disruptive events

Figure 4.2 (continued on next page): ‘Storyboard’ representation of the evolution of a repository barrier system (Kurikami, et al., 2009)

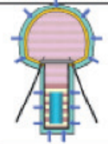
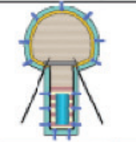
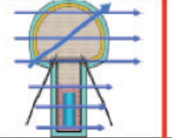
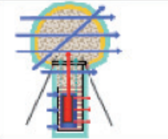
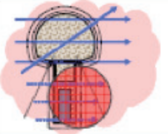
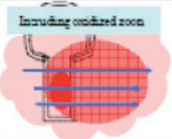
	Initial condition		Excavation	EBS Emplacement	Backfill to closure	Closure to 300years	300 to 1,000 years	1,000 to 10,000years	10k to 100k years	100k to 1,117k years	After1.117years
Evolution of EBS and radionuclide migration process											Erosion
Vitrified Waste:VW Initial properties: Heat Mechanical Chemical	Initial properties: Thermal: Hydraulic: Mechanical: Chemical:	T		Decay heat → high temperature	Decay heat → high temperature	Decreasing decay heat → temperature down	Decreasing decay heat → temperature down	—	—	—	Wash away by erosion and surface water
		H		—	—	—	—	Water intrusion saturation	Water intrusion saturation	Water intrusion saturation	
		M		Heat→expansion→thermal stress→fracture extension	Heat→expansion→thermal stress→fracture extension	Heat→expansion→thermal stress→fracture extension	Heat→expansion→thermal stress→fracture extension	OP + bentonite swelling →mechanical fracturing	OP + bentonite swelling →mechanical fracturing	Loss of mechanical properties	
		C		Decay heat → change chemical properties	Heat → change chemical properties	Heat → change chemical properties	Heat → change chemical properties	Water intrusion → dissolving glass matrix→RN release Microbial and organic activity change chemical properties	Continuing glass dissolution → RN release Microbial and organic activity change chemical properties	Contacting oxidized ground water→razing dissolution rate→ remained RN release	
Over Pack: : OP [Steel t=190mm] Initial properties: Heat Mechanical Chemical	Initial properties: Thermal: Hydraulic: Mechanical: Chemical:	T		Decay heat → razing temperature	Decay heat → razing temperature	Decay heat → razing temperature	Decay heat → razing temperature	—	—	—	Wash away by erosion and surface water
		H		—	—	—	Contacting water → keeping water tightness	Contacting water→corrosion→ lost of water tightness	Contacting water→corrosion→ lost of water tightness	—	
		M		Initial mechanical properties	Bentonite swelling pressure→ keeping strength	Bentonite swelling pressure→ keeping strength	Bentonite swelling pressure +corrosion expansion stress → keeping strength	Bentonite swelling pressure +corrosion expansion stress→ loss of water tightness → mechanical failure	Mechanical failure, corroded material →change mechanical properties	Corroded material properties	
		C		Surface corrosion by atmospheric water	Surface corrosion by bentonite pore water	Surface corrosion by bentonite pore water	Surface corrosion by bentonite pore water→ gas, corroded material	NR migration through corroded material and pore water (reduced) gas generation	NR migration through corroded material and pore water (reduced) gas generation	NR migration through corroded material and pore water (reduced)	
Bentonite buffer:BB [Bentonite block: Kunigel V1 70% Sand 30%, Dry density:1.6 Mg/m3]	Initial properties: Thermal: Hydraulic: Mechanical: Chemical:	T		Decay heat → razing temperature	Decay heat → razing temperature (max)	Decay heat → reducing temperature	Decay heat → reducing temperature	No effect of decay heat Back to initial temperature	Initial temperature	Near surface temperature	Wash away by erosion and surface water
		H		Initial property	Ground water intrusion → re-saturation, keep low conductivity	Ground water intrusion → re-saturation, keep low conductivity	Ground water intrusion → re-saturation, keep low conductivity	Keep low conductivity, RN migration (diffusion)	Alternation of property (keep low conductivity), RN migration (diffusion)	Alternation of property → change property RN migration (diffusion to advection)	
		M		Initial property: Contact ground water → swelling pressure	Ground water intrusion → swelling pressure (keeping initial property) OP weight→consolidation,	Ground water intrusion → swelling pressure (keeping initial property) OP weight→consolidation	Shelf swelling pressure, earth and hydraulic pressure corrosion expanding stress→ changing density	Shelf swelling pressure, earth and hydraulic pressure, corrosion expanding stress → deformation →changing density	Shelf swelling pressure, earth and hydraulic pressure corrosion expanding stress → deformation → changing density	Shelf swelling pressure, earth and hydraulic pressure corrosion expanding stress → deformation → changing density	
		C		Initial property, oxidizing High pH plum effect	Initial property, High pH plum effect	Initial property, High pH plum effect	High pH plume effect and steel corroded material effect → keeping initial properties	High pH plume and steel corroded products effect → changing pore water chemistry	High pH plume and steel corroded products effect → changing pore water chemistry	High pH plume and steel corroded products effect → changing pore water chemistry	
Tunnel and Pit lining system: - Concrete (OPC)	Initial properties: Thermal: Hydraulic: Mechanical: Chemical:	T	Hydration heat production	Surrounding temperature	Decay heat → razing temperature	Decreasing decay heat→ reducing temperature	Surrounding temperature	Surrounding temperature	Surrounding temperature	Near surface temperature	Wash away by erosion and surface water
		H	Un-saturated condition	Un-saturated condition	Ground water intrusion → re-saturation	Saturated condition (advection flow)	Alternation →high conductivity zone (ground water flow along EDZ: advection)	Alternation →high conductivity zone (ground water flow along EDZ: advection)	Alternation →high conductivity zone (ground water flow along EDZ: advection)	Alternation →high conductivity zone (ground water flow along EDZ:advection)	
		M	Initial property, overburden stress→deformation	Initial property, overburden stress→deformation	Initial property, overburden stress→deformation	Initial property, overburden stress→deformation	Alternation → reducing initial strength→failure	Altered material properties	Altered material properties	Altered material properties	
		C	Pore water chemistry : pH>14.0	Ground water intrusion → dissolution→high pH plume, Ca rich water	Reduced groundwater intrusion→dissolution→high pH plume, Ca rich water	Reduced groundwater intrusion→dissolution→high pH plume, Ca rich water	Reduced groundwater intrusion → dissolution → high pH plume, Ca rich water	Ground water intrusion → dissolution→high pH plume, Ca rich water	Keeping high pH condition	Contacting oxidized groundwater → changing chemistry	
Excavation damaged zone (EDZ)	Initial temperature: 30°C Thermal conductivity:	T	Hydration of concrete → razing EDZ temperature	Temperature decreasing by ventilation	Decay heat → razing temperature	Decreasing decay heat →decreasing temperature	Surrounding temperature	Surrounding temperature	Surrounding temperature	Near surface temperature	Wash away by erosion and surface water
	Hydraulic: 1E-7m/s	H	Drainage → un-saturated zone Excavation→stress release →increasing pore space→ increasing conductivity	Drainage → un-saturated zone Excavation→stress release →increasing pore space→ increasing conductivity	Backfilling→re-saturation Rock creep deformation→ decreasing pore space → recovery conductivity	Rock creep deformation→ decreasing pore space → recovery conductivity still remaining high conductive zone	Rock creep deformation → decreasing pore space → recovery conductivity still remaining high conductive zone	Preferential flow path along EDZ (RN migration by advection)	Preferential flow path along EDZ (RN migration by advection)	Preferential flow path along EDZ (RN migration by advection)	
	Initial stress: 7 MPa (GI-350m) Mechanical strength 10 MPa	M	Excavation→stress release → changing mechanical properties	Rock creep → recovery of stress field (changing properties)	Rock creep → recovery of stress field (changing properties)	Rock creep → recovery of stress field (changing properties)	Rock creep → recovery of stress field (changing properties)	Rock creep → recovery of stress field (changing properties)	Rock creep → recovery of stress field (changing properties)	Initial stress field (?)	
	Chemical: neutral, reducing	C	Oxidizing, high pH	Oxidizing, high pH	Oxidizing, high pH	Reducing, high pH	Reducing, high pH	Reducing, high pH	Reducing, high pH	Reducing to Oxidizing	
Uncertainties (not including any practical matters)	Heterogeneous conditions in each emplacement place				Recovery rate and properties	Mechanical and chemical interaction of each components	Mechanical and chemical interaction (high pH effect, mechanical, chemical) of each components	Changing NF condition due to interaction of EBS components Colloid formation, microbial effect	Changing NF condition due to interaction of EBS components Colloid formation, microbial effect	Changing NF condition exchange and up lift	

Figure 4.3 (continued): ‘Storyboard’ representation of the evolution of a repository barrier system (Kurikami, et al., 2009)

Safety assessment is conducted using an assembled chain of models that represent the containment and isolation processes for the different barriers of a repository. Figure 4.3 shows a simple schematic of this 'chain-of-models' concept, as well as the type of inputs and outputs typically included in such safety assessments. Inputs for various values of parameters are tabulated for the 'expected-evolution' scenario. While detailed modeling of the changes in T-H-M-C conditions can be part of the 'chain-of-models', it is typically true that the expected containment time for the overpack (300 to several 1000's of years) is longer than significant perturbations attributable to construction and waste emplacement, so that when the overpack eventually fails the repository conditions basically have returned to ambient values.

Note in Figure 4.3 that the prime output of SA models is typically a calculated dose rate to some stylized future human population. Regulators in different countries have taken different approaches to how dose rate calculations should be conducted and evaluated, a topic that is returned to later. Also note that SA models can also be constructed to provide information on the flux of radionuclides at various locations within a multiple barrier repository. Such insights can be extremely valuable to repository designers in assessing "which barriers" are contributing "how much performance" to the long-term isolation of nuclear waste.

Figure 4.4 extends the information in Figure 4.3 by recognizing that there are inherent uncertainties in information on parameters and processes, even for the expected-evolution scenario. The geosphere has natural variation in its properties, often termed "aleatory uncertainty', that may have significant impacts on the performance of the natural barrier. In addition, there are gaps and limitation knowledge, often called "epistemological uncertainty' that arise because of uncertainty measurement, testing, modelling and all other human-based aspects of safety assessment. It is necessary, therefore, that estimates of the ranges of these uncertainties be included in any safety assessment calculation. This can be done through logic trees, simple triangular or uniform distributions of data values vs. frequency, or through elaborate probability density functions if there is sufficient information to construct and defend such pdf's. The key point is that, to be fully credible, even safety assessment of the expected, normal-evolution scenario needs to encompass uncertainties within some form of a probabilistic framework.

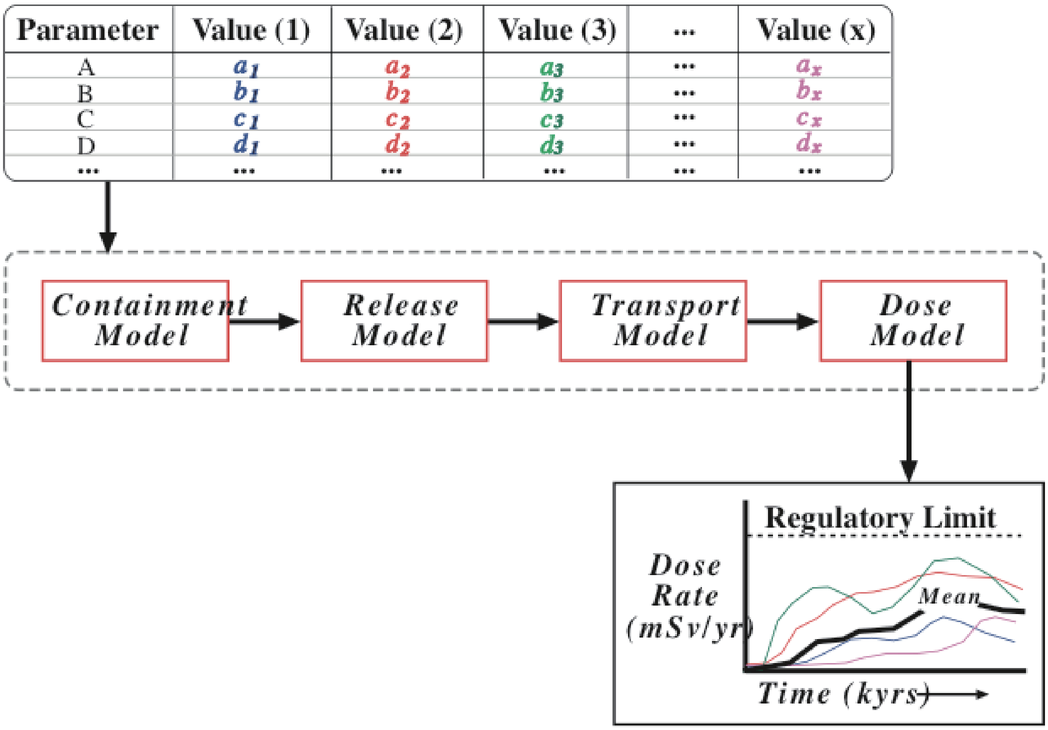


Figure 4.4: Schematic illustration of the treatment of probabilistic data inputs in a safety assessment

4.2 Natural-event Scenarios in Safety Assessment

Depending on the location and time-scale appropriate to a given repository site, the 'expected evolution' scenario can also include possible perturbations arising from natural events that are certain to occur in the future. This would include climate change (e.g., glaciation, change in sea level), or low-level seismicity that can be expected to occur at any site within the Japanese archipelago. Repository concepts must be robustly designed to assure continued safe isolation of nuclear waste even for typically minor perturbations arising from such natural-event scenarios.

Japan, however, located on the Pacific Ring-of-Fire (Apted et al., 2004) is subjected to possible re-occurring tectonic and volcanic/igneous events that could impose much more major perturbations on a nuclear waste repository. NUMO has already acknowledged concern for such major impacts by defining exclusionary siting criteria for a repository that includes not siting the repository across an active fault, nor siting a repository with 15 km of a known volcanic centre. Note, that such criteria inherently recognize location and proximity of a natural event to the repository is a key aspect in considering safety assessment impacts. This is a theme that is returned to later in this report.

The ITM project was initiated to aid NUMO in developing and applying methodologies for assessing the probability of either future tectonic or volcanic "natural-event" scenarios occurring at given locations (5 km by 5 km grid block), using the extensive geological, geophysical and seismological databases uniquely available in Japan (Chapman et al., 2007). Such tectonic and volcanic 'hazard maps at a regional scale have allowed NUMO to evaluate certain siting hypotheses (e.g., persistence of 'gaps' in past volcanic activities in Tohoku), limitations to geo-databases, and the complexities of extrapolating geological information to forecast future event-probabilities over different timescales (10,000 years vs. 100,000 years vs. 1,000,000 years).

Lastly, it must be recognized that 'natural-event scenarios' such as for tectonics and volcanism can occur in a wide variety of modes with a wide range in properties with a strong dependence on site-specific details. Tectonic scenarios, for example, could include faulting (both activation of existing faults or generation of new faults), folding, or uplift, depending on the site. Volcanism scenarios, for example, could include monogenetic, polygenetic, or large-scale caldera formation.

At this relatively early stage in the development and application of the ITM methodology to large (10^6 to 10^5 km^2) regions, certain limitations in identifying specific scenarios are recognized. The rather coarse 5 km by 5 km grid map for the Tohoku and Kyushu regions, as well as the absence of basic geological information such as rock lithologies and existing structures within such 5 km by 5 km blocks, prevent confident assignment of specific natural-events that might or might not occur in the future within such blocks. This limitation is particularly true for the tectonic 'strain rate' indicator because sustained strain rate accumulating over time can lead to a wide range of modes of stress relief, such as major displacement along on a single large fault, distributed smaller displacement along many faults, folding and several other stress-relief accommodations. Until more site-specific information can be obtained, the current 5 km by 5 km resolution necessarily means the natural-events discussed here should be considered illustrative of the advantages of the ITM methodology (Chapman et al., 2007), rather than a screening tool to assess the potential for natural event scenarios on a site-scale basis.

This same caution applies to the consequences analyses presented in this section, which are intended to be qualitative and illustrative of the how to link natural event probabilities to impacts on the environmental conditions and future performance of natural and engineered barriers with a geological repository.

4.3 The Role of Probabilities in Safety Assessment, Including Scenario Probability

As with probabilistic treatment of data uncertainties, there are probabilities of natural-event scenarios that need to be accommodated within a credible safety assessment methodology. There are several possible approaches to safety assessment, as noted below, but each eventually requires a technical defensible and quantitative estimate of the probabilities of natural-event scenarios.

In the now classic definition of the ‘risk triad’, three basic questions can be raised about natural-event scenarios:

- What can happen (defining the specific natural event)?
- How likely is the event (defining event probability or likelihood)?
- What are the consequences if the event occurs?

Colloquially, risk can then be defined as

Risk = Probability x Consequences

The risk-based approach basically allows for normalization of possible high dose consequences of an event by multiplying by the perhaps low probability of that event. Indeed, in the US Nuclear Regulatory Commission’s standard for HLW disposal at a repository in Yucca Mountain, Nevada, the risk-informed approach is applied in screening and elimination of possible natural-event scenarios, stating that the repository implementer should [10 CFR Part 63.114(d) and Part 63.342]:

> “Consider only events that have at least one chance in 10,000 of occurring over 10,000 years.”
>
> “DOE's performance assessments shall not include consideration of very unlikely features, events, or processes, i.e., those that are estimated to have less than one chance in 10,000 of occurring within 10,000 years of disposal.”

This is equivalent to excluding all natural-event scenarios with a likelihood of less than 1 occurrence in 100,000,000 years, no matter what might be the speculated consequences of that exceptionally rare event.

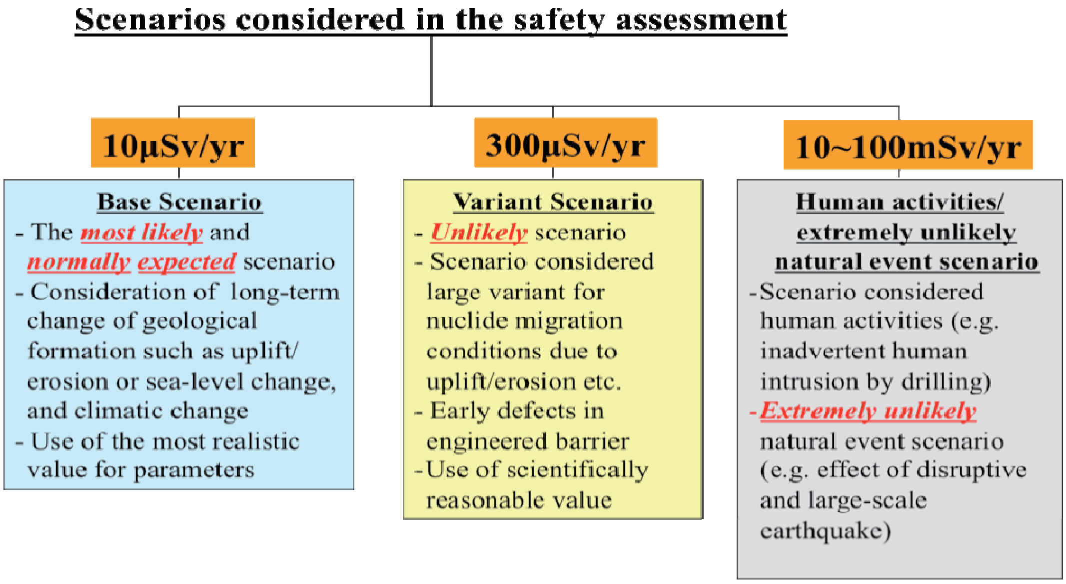
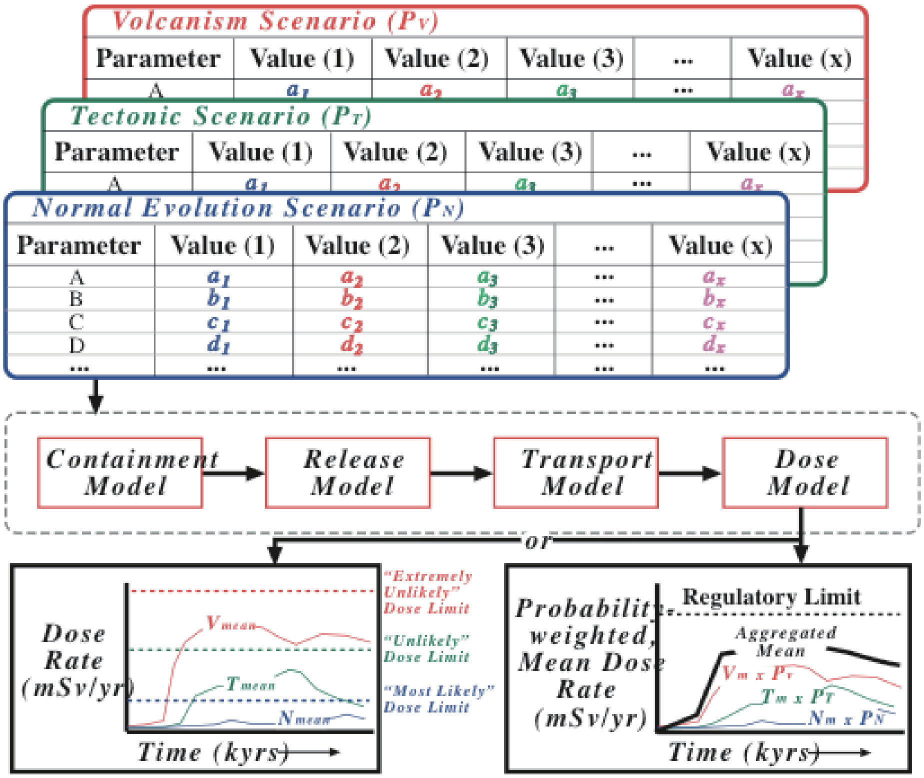


Figure 4.5: Schematic of proposed regulatory targets for different scenarios for the L1 repository at Rokkasho. Allowable dose rates for different ‘likelihoods’ of scenarios

There are also non-risk-based approaches to setting dose rates that nonetheless, eventually do necessitate explicit estimate of the probability of a natural-event scenario. Specifically, a key motivation for the ITM project on estimating probabilities of future natural events is the evolving perspectives in Japan on comparing SA calculations to specific allowable dose-rates. Figure 4.5 presents the current proposed dose rates for natural event scenarios, as formatted for the L1 disposal concept in Japan (disposal of LILW at depths of about 100+ m). This set of dose rates limits could eventually be applied to NUMO's own HLW and TRU disposal programme.

The three key undefined terms for scenarios in Figure 4.5 are "most likely", "unlikely" and "extremely unlikely", each category assigned a increasingly higher allowable dose rate for decreasing likelihood of occurrence. Setting aside possible comments on the absolute values for these three categories, an immediate concern is that the undefined "likelihood" terms do not recognize any specific timescale for their applicability. There is also a concern they may have been developed for a specific site (e.g., Rokkasho). And at this site, it may be currently believed that certain types of natural-event scenarios (e.g., volcanism, uplift, faulting) can be clearly assigned to specific "likelihood" categories, and that the associated dose rates ("consequences") for each of the three "likelihood" categories can be reasonably met. At other sites, however, various natural-event scenarios could have different "likelihoods" and/ or different consequences; great care should be reserved when considering applying basically a site-specific standard to become a general, nation-wide standard.

Figure 4.6 schematically illustrates and compares the risk-dose and "likelihood" based approaches as they might be applied in safety assessment. For both cases, different inputs, indeed different probabilistic inputs, for parameters and processes will be required for each scenario (i.e., "expected evolution scenario", "possible volcanism scenarios", "possible tectonic scenarios", etc.). For the risk-based approach, probabilities for scenarios will also be needed; the "likelihood" scenario would seem not to require such scenario probabilities, but as will be discussed below, this is only a temporary dodge of the necessity to define such scenario probabilities.



Parameter	Value (1)	Value (2)	Value (3)	...	Value (x)
A	a_1	a_2	a_3	...	a_x
B	b_1	b_2	b_3	...	b_x
C	c_1	c_2	c_3	...	c_x
D	d_1	d_2	d_3	...	d_x
...	...	...	...	...	...

Figure 4.6: Comparison of "risk-based" and "likelihood-based" Safety Assessments

The probabilistic inputs from each scenario are used to calculate dose-rate consequences separately. In the risk-based approach, the eventual output could be calculation of the probability-weighted, mean annual dose rate, an approach applied in the US and Swedish regulatory licensing requirements, for example. These probability-weighted, mean-annual dose rates for separate scenarios can, in turn, be aggregated together to present an aggregated probability-weighted, mean annual dose rate for all of the credible future events and evolution of the repository.

For the "likelihood" approach, the same probabilistic inputs from each scenario are used to calculate dose-rate consequences separately. Then, through some undefined step, each scenario and resulting consequence analysis would be assigned to one of the three categories in Figure 4.5. It can be conjectured that if any one scenario dose-rate results violated the assigned peak dose rate for that scenario's category, that the entire repository concept would be judged to be unacceptable. It could be that two or more different natural-event scenarios could be assigned to the same "unlikely" or "extremely unlikely" dose-rate category, even though there might be many order of magnitude differences in the actual probabilities among these scenarios grouped in the same category. Furthermore, there is no formulation to aggregate all of these diverse scenarios together to get an overall assessment of repository safety.

Ultimately, the issue with the three defined "likelihood" terms in Figure 4.5 is that it will require some responsible authority to assign each specific natural-event scenarios into a specific category, and to defend those assignments. Event "probabilities" (objective values), not "likelihoods" (subjective opinions) is the only defensible basis for supporting such decisions. Clearly, such objective probabilities can only be based on geological analysis of the site-specific geological record and broad understanding of the plate tectonic framework of Japan.

In closing, it is clear that for either a risk-based or "likelihood" based safety standard, that probabilities of natural-event scenario will, and should, be required. These probability estimates will need to be quantitative and credibly based on site-specific geological information and analysis. The ITM methodology is such a geological analysis (Chapman et al., 2007). If carefully applied, the ITM methodology can lead to specific, defensible estimates of various tectonic and volcanic event probabilities that will needed by NUMO, no matter how regulatory safety standards evolve in Japan.

4.4 Event Definition for Natural-event Scenarios

"Event definition" is a key concept that directly links the development of ITM probability estimates for natural-event scenarios (Chapman et al., 2007), and subsequent consideration of possible consequences of such natural-event scenarios. "Event definition" must include all of the relevant and distinguishing characteristics of a postulated future natural event that could unexpectedly perturb the performance of a deep geological repository.

Some of the important aspects and factors in "event definition" include:

- What might be the magnitude of the event?
- What might be the duration of the event?
- When might the event occur?
- Where might the event occur with respect to the repository barriers?
- What might be the frequency of the event (i.e., can the same event occur more than once within the repository)?

All of these aspects and factors should be identified as part of the derivation of event probability. For example, the probability of a monogenetic event at a site is likely to be much different than the probability of a polygenetic or caldera-forming event at the same site. The probability of displacement along an existing fault would increase proportionally over time. The probability of volcanism impacts might be a function not only from the probability of a future igneous event within the 5 km by 5 km block, but also from increased probability of a future igneous event occurring in an adjoining 5 km by 5 km block. It will be important, therefore, in future applications of the ITM methodology to clearly and concisely identify an "event definition" attached to the probability estimate.

The "event definition" characteristics, in turn, are the beginning of organization of a systematic consequence safety analysis. These 'event definition" characteristics impose important bounds and constraints on the subsequent evaluation of (1) perturbation on T-H-M-C processes and environmental conditions, and (2) associated degradation and loss of barrier safety functions, up to and including actual destructions of barriers. In the following section, a general classification scheme is proposed by which safety assessment modellers might usefully consider and propagate the "event definition" for various natural-event scenarios.

4.5 Systematic Classification of Natural-event Scenario Consequences

4.5.1 Volcanism Scenarios

Volcanic activity in Japan historically ranges from single-event monogenetic eruption centres, to sustained polygenetic eruption centres, to areally extensive, caldera-forming events. The eruption energetics (power), duration, eruption volume, chemical composition, eruption temperature, volatile (especially water) content, viscosity and many other characteristics also range widely, as previously illustrated in ITM's cladistic analysis (Chapman et al., 2007). Consequences on T-H-M-C conditions, as well as the degradation if not survival of barrier safety functions will be strongly impacted by such characteristics.

Perhaps even more importantly is consideration of where a future volcanic center might form with respect to a repository. Several different variants to the volcanism scenario can be broadly identified:

- Direct Intersection/ Polygenetic event: As illustrated in Figure 4.7, a repository directly intercepted by the central conduit of a polygenetic volcano will likely be completely destroyed by the thermal and stress perturbation associated with such conduits.
- Direct Intersection/ monogenetic event: In contrast, if only a single, relatively short-duration (few weeks to few years) monogenetic magmatic dike were to intercept the repository, destruction of the repository system might be localized in both time and space.
- Indirect Intersection: A third variant to the volcanism scenario might that the repository is not intercepted by any magmatic material, but could be indirectly subjected to the impacts from the hydrothermal circulation cell developed on the flanks of a volcanic eruptive centre. Such hydrothermal circulation cells might extend on the order of 15 km and persist for 10,000's of years around a polygenetic eruptive centre.

Of course sub-variants and ranges within these variant cases could also be specified. The intent in this report is simply to stress that there is no unique "Volcanism scenario"; there are instead a range of possible variant cases that can be readily classified according to aspect of the "event definition" (and thereby linked to a specific probability for that specific "event definition").

4.5.2 Tectonic (Rock-deformation) Scenarios

As with Volcanism Scenarios, there is a wide range of variant cases to Tectonic Scenarios. Indeed, the "strain rate" attribute used in the ITM methodology can be accommodated in an extremely wide variety of modes. The relative probability of such modes depends strongly on local, site-specific factors such as host-rock lithologies and existing structures that are more detailed than the current 5 km by 5 km block size utilized to demonstrate the ITM methodology.

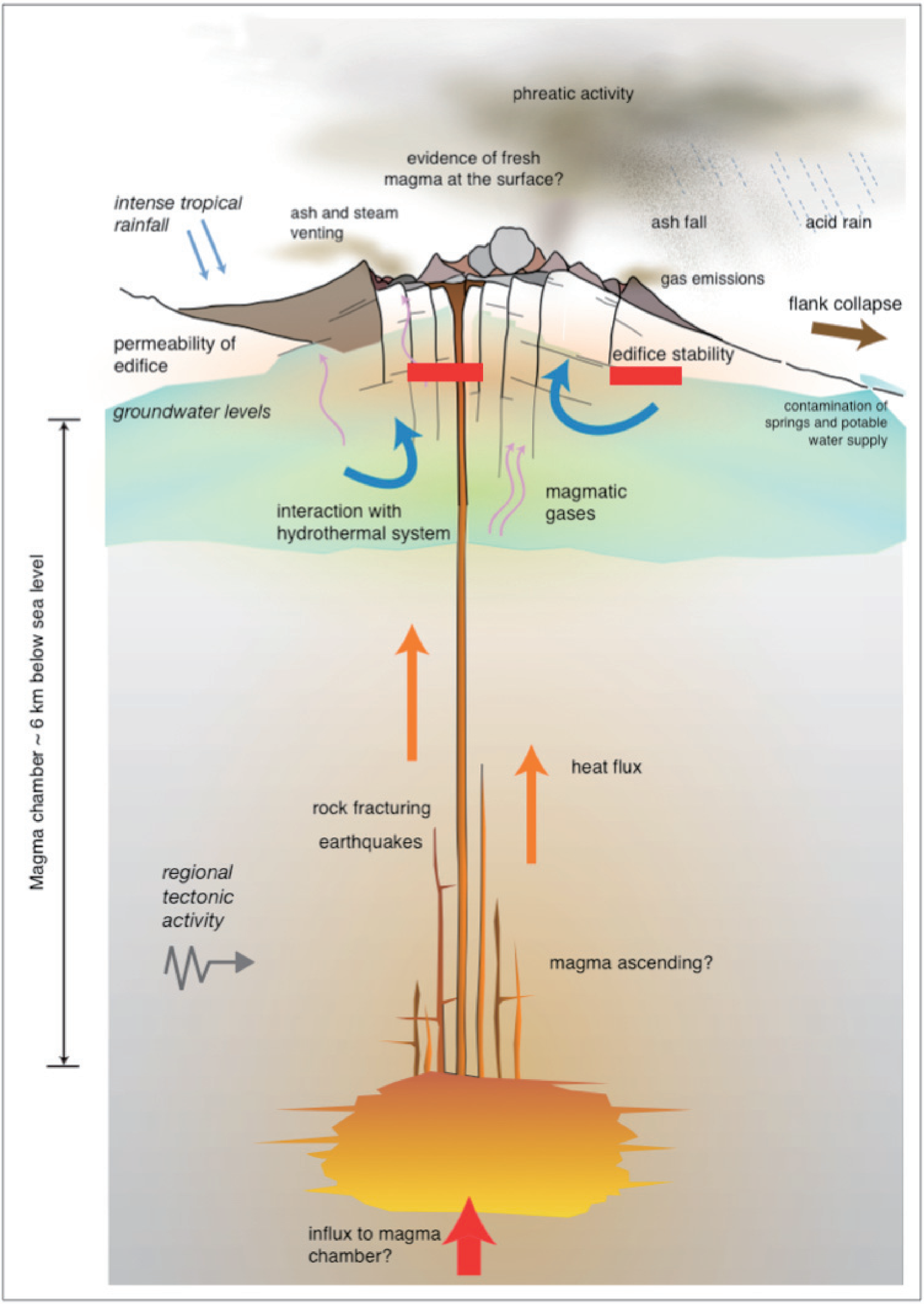


Figure 4.7: Cross-section of a volcanic centre, showing different T-H-M-C type impacts depending on location of repository (red rectangles).

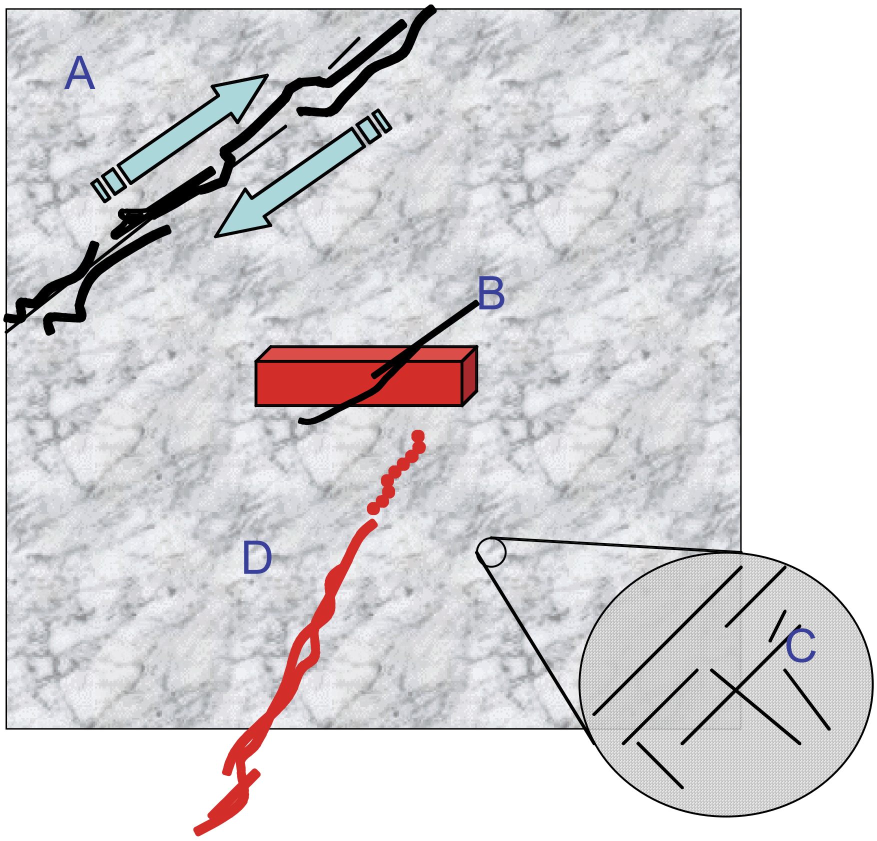


Figure 4.8: Schematic illustration of different modes by which repository host rock might accommodate sustained strain: A: all along major faults (old or new) some distance away (probably equating to a low hazard); B: distal strain uptake from A on small (c.100 m radius) fractures in the repository (probably equating to a medium to high hazard); C: volume deformation along many small, distributed fractures/planes (probably equating to a little or no hazard); D: hidden/new active fault below (probably equating to a medium hazard).

Figure 4.8 illustrates a partial set of such ”strain rate” accommodation modes:

- *Mode A*: all of the strain rate is accommodated along major faults (old or new) some distance away from the repository, which would likely have only minor impact on subsequent repository performance after fault movement.
- *Mode B*: the sustained strain rate is accommodated on small (c.100 m radius) fractures that intersect the engineered barrier system of the repository, which could have moderate to high impacts on subsequent repository performance depending on the amount of movement and inter-connectivity of such small, but widely distributed fractures.
- *Mode C*: strain rate might be accommodated by volume deformation along many small, distributed joints or cracks within the host rock, which might have moderate impact on repository performance if there are associated adverse perturbation of hydraulic conductivity of the host rock.
- *Mode D*: strain rate might be accommodated by activation of a new fault or activation of a hidden fault below the repository, leading to possibly low to medium impact on repository performance.

As with Volcanism Scenario, there are many possible variants to Tectonic Scenarios. Folding might be of concern for certain types of sedimentary rock formations. It might be expected, however, that sustained strain rates over the past would already be manifest in the folded rock fabric of such a site discovered during detailed site characterization, allowing possible exclusion of the site if the folding deformation is judged to be too adverse to assure long-term waste isolation. Of even greater concern is the possibility for sustained strain rate leading to uplift of a repository, accompanied by co-equal rates of erosion. While uplift of a repository to the surface would obviously lead to greatly enhanced exposure pathways, it is worth noting that adverse chemical impacts (change from reducing to oxidizing conditions) and mechanical impacts (formation of sub-vertical fracture zones due to mechanical unloading of the rock formation) could occur even when the repository would be uplifted to within 100 m or so to the surface.

While detailed classification and analysis of such multiple variants to natural-event scenarios is beyond the scope of the ITM project, it is possible to identify general sequencing of impacts from the wide array of such variants. The sequencing of impacts from natural-event scenarios include:

- *Spatial factors*: are the impacts local, affecting only a few waste packages or regions of rock, or are they global impacts, affecting all waste packages and all of the host rock?
- *Temporal factors*: do the impacts arise slowly or instantaneously?
- *Permanence*: are the impacts on either barrier properties or changes in T-H-M-C conditions permanent or only temporary?

As a final part of classifying natural-event scenarios within a safety assessment framework is consideration of the characteristics of impacts on the repository system. Two broad categories can be envisioned:

- degradation or loss of individual safety functions for one or more natural and engineered barriers,
- total destruction of the repository system, with loss of all barriers and barrier safety functions.

The importance of classifying scenarios with respect to characteristics of impacts is that the safety assessment experts need to understand at an early stage what assessment methods and calculational tools may be needed to conduct safety calculations. Degradation of individual safety functions can be handled by appropriate time-step changes in inputs of barrier properties; loss of individual safety functions can often be handled by the so-called "barrier-neutralization" approach, in which a property or process by a specific barrier is omitted or set to "zero" in the chain-of-models. For natural-event scenarios leading to total destruction of the repository system (i.e., direct intersection by a polygenetic or caldera-forming volcanic event), new dose-contributing pathways (e.g., airborne transport of radioactively contaminated tephra) may be needed.

It must be cautioned, however, that natural-event scenarios capable of destroying a multiple-barrier repository system may lead to non-radiological hazards and consequences that far exceed those represented by the resulting radiological hazard. An explosive eruption associated with caldera formation is an example of a regional catastrophic event of the kind that has occurred many times in the Quaternary, albeit in human terms very infrequently. Before initiating revised radiological safety assessments for such drastically disruptive natural events, it would be sensible to conduct at least a bounding analysis of all of the non-radiological as well as radiological impacts to human health arising from such an event.

Figure 4.9 presents a general logic-tree schematic of how event definition, sequencing of impacts and classification of variant cases for natural-events scenarios can be organized and classified. Further sub-divisions of such factors are possible. Figure 4.9 should be considered as a beginning logic-tree structure, suitable for subsequent refinement based on the exact type of natural-event scenarios of concern for a specific site. The purpose of such a logic-tree is to provide a visualization of the many factors that should be considered in preparing to conduct safety assessments for variants of natural-event scenarios that go beyond the basic "expected evolution" scenario.

In summary, early consideration of likely variant cases for natural-event scenarios and especially classifying such variants according to expected spatial, temporal and permanence factors, can be useful to safety assessment experts. In particular, such systematic classification of variants can help to identify the types of consequence analyses that may be necessary above and beyond the "chain-of-models" initially developed for the "expected evolution" scenario. Consideration and general classification of spatial, temporal and permanence factors for variant cases can provide safety assessment experts with insights into the relative severity of different types of variant cases. For example, impacts that are global in nature are likely to have more severe consequences on repository performance than are impacts that locally affect a few waste packages. Likewise, impacts that occur instantaneously might have greater consequences on repository performance than other impacts that occur only gradually over geological time scales. Obviously, permanent changes to barrier properties are always likely to have greater consequences on repository performance than are changes that eventually return to ambient, expect property values. Finally, evaluation and classification of variants using such factors would be best accomplished with an integrated team of site geologists, repository designers, and safety assessment experts.

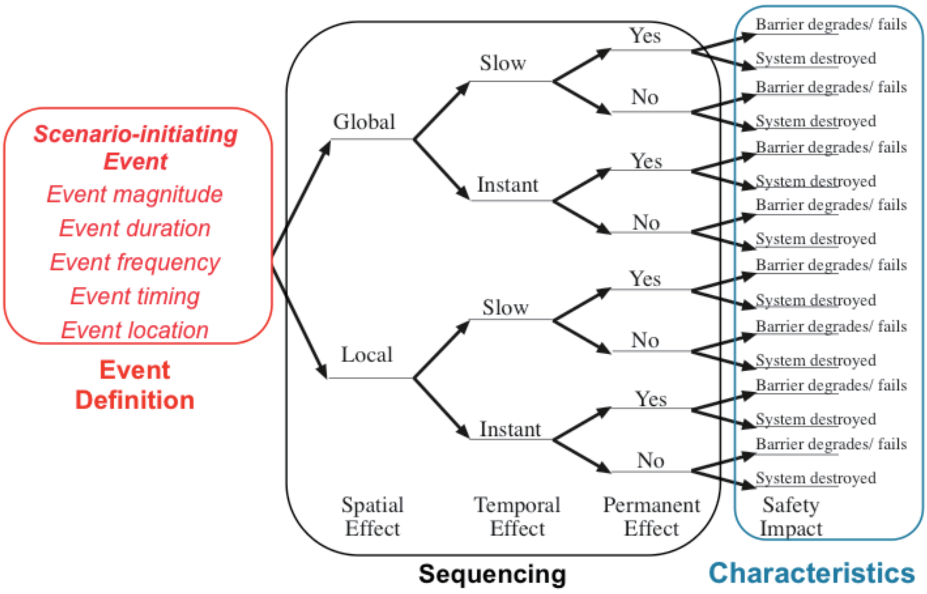


Figure 4.9: Generalised logic-tree schematic of how event definition, sequencing of impacts and classification of variant cases for natural-events scenarios can be organized and classified.

4.6 Qualitative Consequences for Example Natural-event Scenarios

Returning to Figure 4.2, NUMO has created a detailed storyboard of the "expected evolution" of the repository and the multiple barriers within that repository system. A useful division in the time sequencing is to consider an initial period (300 to 1000 years in Figure 4.2) of *containment* by the overpack, followed by a period (time greater than 100 years in Figure 4.2) of *slow release* of radionuclides (see associated safety functions, as identified in Figure 4.1). Of course, safety regulations are based on calculated peak dose rates, emphasizing the slow-release performance. Containment is extremely useful to prevent water from contacting HLW during the initial elevated thermal pulse (hence, the 300-1000 year time interval in Figure 4.2). "Containment time" by itself, however, is not likely to significantly reduce subsequent peak dose-rate performance of a repository. This is because of the extremely long-half-lives of most dose-contributing radionuclides [e.g., Se-79 with a 1 x 10^6 year half life, Cs-135 with a 2.3 x 10^6 year half life, Np-237 with a 2.1 x 10^6 year half life, which were the key dose contributing radionuclides in the H12 report (JNC, 2000)] compared to readily attainable containment times for saturated-site repositories.

Therefore, unless a natural event occurs within the 300-1000 year initial containment period, the major concern arising from a natural-event scenario are impacts on the mobilization, release and transport of radionuclides through the engineered and natural barriers.

Barrier	0 - 1000 years	1000 - 15,000 years	15,000 - 65,000 years	65,000 - 100,000 years	>100,000 years
HLW glass	Unreacted because no contact by water	Water-contact (when SS canister fails) start dissolving, release of radionuclides	HLW glass entirely reacted to nuclide-bearing/ solubility-limiting precipitates	HLW glass entirely reacted to nuclide-bearing/ solubility-limiting precipitates	HLW glass entirely reacted to nuclide-bearing/ solubility-limiting precipitates
Stainless steel canister	Unreacted because no contact by water	Corroding, possibly locally failed (mass-transfer constraints)	Multiple penetrations (decreasing mass-transfer resistance)	Multiple penetrations (decreasing mass-transfer resistance)	Essentially all oxides, no mass-transfer resistance
Overpack (mild steel)	Present but corroding	Mostly iron oxides, some iron present; nuclide sorption	All iron oxides; no mass-transfer resistance; sorption	All iron oxides; no mass-transfer resistance; sorption	All iron oxides; no mass-transfer resistance; sorption
Buffer	Dry increasing to saturated; swelling, buffering of chemistry by ion-exchange/ dissolution of minor minerals	Saturated, buffered by alumino-silicate hydrolysis; nuclide sorption, colloid filtration, non-steady-state release	Saturated, buffered by alumino-silicate hydrolysis; nuclide sorption, colloid filtration, attain steady-state release	Saturated, buffered by alumino-silicate hydrolysis; nuclide sorption, colloid filtration; steady-state release	Saturated, buffered by alumino-silicate hydrolysis; nuclide sorption, colloid filtration; steady-state release
Near-field (NF) Rock	Increase then decrease in temperature, readjustment of mechanical stresses, chemical buffering ambient conditions	Same properties as far-field rock (ambient temperature, stress, flow, etc.); nuclide sorption; non-steady-state release	Same properties as far-field rock (ambient temperature, stress, flow, etc.); nuclide sorption; attain steady-state release	Same properties as far-field rock (ambient temperature, stress, flow, etc.); nuclide sorption; steady-state release	Same properties as far-field rock (ambient temperature, stress, flow, etc.); nuclide sorption; steady-state release
Far Field (FF) Rock	No change/ ambient	No change/ ambient, radionuclide sorption; non-steady-state release	No change/ ambient, radionuclide sorption; non-steady-state release	No change/ ambient, radionuclide sorption; attain steady-state release	No change/ ambient, radionuclide sorption; steady-state release
Biosphere	No change/ ambient	No change/ ambient; increasing, non-steady-state radionuclide release	No change/ ambient, radionuclide sorption; non-steady-state release	No change/ ambient, radionuclide sorption; attain steady-state release	No change/ ambient, radionuclide sorption; steady-state release

Table 4.1: Generalised evolution of a representative repository focusing on factors affecting the mobilisation, release and transport of radionuclides through multiple barriers.

Table 4.1 follows the general format of Figure 4.2 developed by NUMO, but focuses on barriers and processes affecting slow release of radionuclides. It is suggested, therefore, that NUMO's primary attention of consequence analysis for natural-event scenarios be initially placed on evaluating how different variant cases might (1) affect the slow release of radionuclides from the EBS, and (2) affect the plume of released radionuclides already released from the EBS to the geosphere but not yet released from the geosphere to the biosphere (i.e., focus on the fate of released radionuclides throughout the repository system for times longer than 1000 years after repository closure).

Table 4.2 presents a tabulation of consequences arising for three different variant cases for the volcanism/ igneous-event scenario. For each variant, the event definition ("mode"), sequencing of impacts and classification of impacts are provided. In addition, the qualitative impacts on T-H-M-C conditions in the repository are also presented.

Table 4.2: Tabulation of consequences arising for three different variant cases for the volcanism/ igneous-event scenario.

Event Definition (Mode)	Host Rock Dependency	Event Sequencing	Consequences	THMC Impacts
Formation of hydrothermal circulation system from intrusion of <15 km distant magma chamber (INDIRECT)	None	• Gradual • Global • Permanent (duration of magmatic system ~1 Ma)	Inflow of warm, saline water, possible gradual metasomatism of clay buffer, changed radioelement solubilities and sorption behaviour	• T: <120 C • H: increased (buoyancy) flow rate? • M: None • C: increased salinity, dissolved magmatic volatiles, neutral pH, reducing
Intrusion of single (monogenetic) basaltic dyke, <10 m width, ~1000 C (DIRECT)	None	• Instant • Local (initial sheet-intersection followed by sustained eruption at a few conduits) • Permanent/transient (duration of intrusion ~ few years)	Intersection with a few waste packages leading to surface eruption of intact WPs or entrained HLW; transient and localised high-T and faulting of some adjoining WPs with loss of buffer and overpack functions; new, preferential flow path to surface	• T: up to 1000 C • H: increased (buoyancy) flow rate? • M: Local faulting of rock, buffer and overpack • C: minor and localised release of magmatic volatiles, re-melting and recrystallisation of HLW glass?
Intrusion of multiple (polygenetic) magmatic dykes (DIRECT)	None	• Instant • Global • Permanent	Loss of function of all repository barriers	• Extreme disruption

Table 4.3 tabulates event definition ("mode"), sequencing of impacts and characteristics of impacts for several different modes for variants of the tectonic, or "rock deformation" scenario. Note that impacts may especially vary depending on whether the host rock for the repository is a "soft" (sedimentary) rock versus a "hard" (igneous or metamorphic) rock. By contrast, impacts arising from variants of the volcanism scenario (Table 4.2) are generally the same irrespective of what type of host rock in which the repository is located. Qualitative impacts on T-H-M-C conditions in the repository are also identified in Table 4.3.

Table 4.3: Tabulation of event definition ("mode"), sequencing of impacts and characteristics of impacts for several different modes for variants of the tectonic, or "rock deformation" scenario.

Event Definition (Mode)	Host Rock Dependency	Event Sequencing	Consequences	THMC Impacts
Reactivate existing fault to become new 'major water-bearing feature'	'hard' or 'soft' rock, pre-existing structures	• Instant • Global (affects release from all WPs) • Permanent	Shortening of far-field pathway	• T: none • H: <100 m path in rock • M: none • C: none
Micro-fracturing/change in bulk rock permeability	'soft' rock, pre-existing structures	• Gradual • Global • Permanent	Increased flow rate in near-field rock	• T: none • H: increased flow rate • M: none • C: none
Shearing of waste package (>1 m displacement)	'hard' or 'soft' rock, pre-existing structures	• Instant • Local • Permanent	Loss of buffer and overpack functions, with higher flow in rock for failed WP	• T: none • H: higher flow, no diffusion control, no colloid filtration • M: loss of containment • C: none
Increased aperture of joints and fractures intersecting waste package	'hard' or 'soft' rock, pre-existing structures	• Gradual • Local • Permanent	Enhanced permeability/flow in rock; erosion of buffer, loss of buffer functions	• T: none • H: higher flow, no diffusion control, no colloid filtration • M: none • C: none
Uplift	'hard' or 'soft' rock, pre-existing structures	• Gradual • Global • Permanent	At 100 m depth, change to oxidising conditions, mechanical disruption of rock and EBS	• T: none • H: higher flow, no diffusion control, no colloid filtration • M: loss of EBS integrity • C: oxidising
Folding	'soft' rock, pre-existing structures	• Gradual • Local/Global • Permanent	Enhanced permeability/flow in rock; mechanical disruption of EBS	• T: none • H: higher flow, no diffusion control, no colloid filtration • M: loss of containment • C: none

4.7 Summary

Safety assessment for a geological repository containing HLW is based on calculating possible future doses from radioactivity eventually released from the repository to the biosphere and human population. Defensible dose rate calculations require evaluation of possible doses for the "expected evolution" scenario as well as possible doses arising from variants of credible "natural-event" scenarios.

The determination of the probability ("likelihood") of such natural-event scenarios must be based on multiple lines of climatological, geological, geophysical and seismological analyses conducted at a site-specific level. The ITM project has developed and successfully tested methodologies for obtaining such probabilities for volcanism and rock deformation (tectonic) events, albeit on a scale somewhat larger than an actual repository site (Chapman et al., 2007).

Whether a risk-based safety standard (i.e., the consequences of a natural event are normalized by the probability of that event) or a non-risk standard (i.e., allowable dose rates are assigned to scenarios having different "likelihoods") is applied, quantitative consideration of actual event probabilities is unavoidable. Indeed, in the absence of quantitative estimates of natural-event probability, it will be difficult to derive a bounded yet defensible safety assessment of radiological hazard for sites in Japan, which is experiencing complex plate subduction and associated volcanic activity.

For natural-event scenarios, a logic-tree formulation is proposed to aid NUMO in classifying variants of such natural-event scenarios to better plan and conduct safety assessments. Three key parts of this logic-tree organization are proposed (Figure 4.9):

- event definition
- sequencing of consequences, and
- classification of impacts

By considering the spatial, temporal and permanence aspect of consequences, as well as whether impacts consequences degrade or destroy the repository system, NUMO's safety assessment experts can evaluate the adequacy of their current safety assessment models and codes, and identify where possible modifications or additional models may need to be developed.

Finally, several illustrations of variants to natural-event scenarios are presented, leading to qualitative estimates of impacts on thermal, hydrological, mechanical and chemical (T-H-M-C) conditions of a repository. Without more detailed, site characteristics, event definition, and repository conceptual design, only such qualitative illustrations are sensible to be presented at this time. When site-specific and concept-specific information are available, however, it will be relatively easy for NUMO technical staff to propagate credible "event definitions" for variants of natural-event scenarios through the suggested logic-tree approach to guide future safety assessments.

4.8 References for Section 4

Apted, M.J., K. Berryman, N. Chapman, M. Cloos, C. Connor, K. Kitayama, S. Sparks, and H. Tsuchi, 2004. *Locating a Radioactive Waste Repository in the Ring of Fire*, EOS, American Geophysical Union, Vol. 85, No. 45, 9 November 2004.

Chapman, N., M. Apted, J. Beaven, K. Berryman, M. Cloos, C. Conner, L. Connor, O. Jaquet, N. Litchfield, S. Mahony, S. Sparks, M. Stirling, and L. Wallace, 2007. *Development of Methodologies for the Identification of Tectonic Hazards to Potential HLW Repository Sites in Japan*, MCM-TR-07-03, MCM Consulting, Baden, Switzerland.

JNC, 2000. *H12: Project to establish the Scientific and Technical Basis for HLW Disposal in Japan, Second Progress Report on Research and Development for the Geological Disposal of HLW in Japan*, Japan Nuclear Development Institute, Tokai-mura, Japan.

Kurikami, H., Suzuki, S., Wakasugi, K., Ueda, H., Ishiguro, K., Tsuchi, H., Kaku, K., Gaus, I. and Vomvoris, S., 2009. *Study on strategy and methodology for repository concept development for the Japanese geological disposal project*, NUMO-TR-09-04, p.52-53.